Future Spacecraft and instruments for NASA's Science Mission Directorate will require increasingly sophisticated thermal control technology. Innovative proposals for the cross-cutting thermal control discipline are sought in the following areas:

- Optical systems, lasers (ICESAT 2), and detectors require tight temperature control, often to better than +/- 1°C. Some new missions such as LISA require thermal gradients held to even tighter micro-degree levels. Methods of precise temperature measurement and control to tight temperature levels are needed.

- New generations of electronics used on numerous missions have higher power densities than in the past. High conductivity, vacuum-compatible interface materials to minimize losses across make/break interfaces are needed to reduce interface temperature gradients and facilitate heat removal.

- Detectors and optical systems at infrared wavelengths require efficient cooling methods to low temperatures. Advanced thermoelectric devices with higher Coefficients of Performance (COP) are required.

- More sensitive instruments are resulting in increased requirements for high electrical conductivity on spacecraft instruments and surfaces. This has increased the need for advanced thermal control coatings, particular with low absorptance, high emittance, and good electrical conductivity.

- Phase change systems are needed for Mars or Lunar applications. Reusable phase change systems are desired which can be employed to absorb transient heat dissipations during instrument operations. Technology is sought for phase change systems, typically near room temperature, which can then either store this energy or provide an exothermic process, which would provide heat for instrument power-on after the dormant phase.

- Future high-powered missions, some possibly nuclear powered, may require active cooling systems to efficiently transport large amounts of heat. These include single and two-phase mechanically pumped fluid loop systems which accommodate multiple heat sources and sinks; and long life, lightweight pumps which are capable of generating a high pressure head. It also includes efficient, lightweight, oil-less, high lift vapor compression systems or novel new technologies for high performance cooling up to 2 KW.

- Exploration science missions beyond earth orbit present engineering challenges requiring systems, which
can withstand extreme temperatures ranging from high temperatures on Venus to the cryogenic temperatures of the outer planets. High performance insulation systems, which are more easily fabricated than traditional multi-layer (MLI) systems, are required for both hot and cold environments. Potential applications include traditional vacuum environments, low-pressure carbon dioxide atmospheres on Mars, and high-pressure atmospheres found on Venus.

- Low-Cost Variable Conductance Heat Pipes for Terrestrial Balloons - Please see sub-topic S3.07 Terrestrial and Planetary Balloons to respond to this requirement.

- Thermal Control Systems for S3.10 Earth Entry Systems. Low mass/cost/power/complexity payload thermal control systems are needed, which can maintain the sample temperature in-flight, through impact, and post landing. Candidate thermal control systems must be able to maintain a payload up to 10 kg at temperature levels ranging from cryogenic up to -20°C (depending on specific mission requirements) for up to 1 day after landing/impact, and cannot exceed 20 kg in total mass.

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration. Phase II should deliver a demonstration unit for NASA testing at the completion of the Phase II contract.

Note to Proposer: Subtopic X3.04 Thermal Control Systems for Human Spacecraft, under the Exploration Mission Directorate, also addresses thermal control technologies. Proposals more aligned with exploration mission requirements should be proposed in X3.04.

S3.03 Power Generation and Conversion

Future NASA science missions will employ Earth orbiting spacecraft, planetary spacecraft, balloons, aircraft, surface assets, and marine craft as observation platforms. Proposals are solicited to develop advanced power generation and conversion technologies to enable or enhance the capabilities of future science missions. Requirements for these missions are varied and include long life, high reliability, significantly lower mass and volume, higher mass specific power, and improved efficiency over the state of practice for components and systems. Other desired capabilities are high radiation tolerance and the ability to operate in extreme environments (high and low temperatures and over wide temperature ranges).

While power generation technology affects a wide range of NASA missions and operational environments, technologies that provide substantial benefits for key mission applications/capabilities are being sought in the following areas.

Radioisotope Power Conversion

Radioisotope technology enables a wide range of mission opportunities, both near and far from the Sun and hostile planetary environments including high energy radiation, both high and low temperature and diverse atmospheric chemistries. Technology innovations capable of advancing lifetimes, improving efficiency, highly tolerant to hostile environments are desired for all thermal to electric conversion technologies considered here. Specific systems of interest for this solicitation are listed below.
Stirling Power Conversion: advances in, but not limited to, the following:

- System specific mass greater than 10 We/kg
- Highly reliable autonomous control
- Low EMI
- High temperature, high performance materials, 850-1200 C
- Radiation tolerant sensors, materials and electronics

Thermoelectric Power Conversion: advances in, but not limited to, the following:

- High temperature, high efficiency conversion greater than 10%
- Long life, minimal degradation
- Higher power density

Cubesat and Nanosat On-orbit Power Generation

NASA desires to build smaller spacecraft types carrying smaller instrument packages. However, power requirements to accommodate these instruments and spacecraft systems will not necessarily scale down in a similar fashion as spacecraft size. Therefore, power generation and power management technologies are sought that are compatible with small spacecraft geometries and sizes, especially in cubesat and nanosat form factors.

Photovoltaic Energy Conversion

Photovoltaic cell, blanket, and array technologies that lead to significant improvements in overall solar array performance (i.e. conversion efficiency >30%, array mass specific power >300 watts/kilogram, decreased stowed volume, reduced initial and recurring cost, long-term operation in high radiation environments, high power arrays, and a wide range of space environmental operating conditions) are solicited. Technologies specifically addressing the following mission needs are highly sought:

- Photovoltaic cell and blanket technologies capable of low intensity, low-temperature operation applicable to outer planetary (low solar intensity) missions
- Photovoltaic cell, blanket and array technologies capable of enhancing solar array operation in a high intensity, high-temperature environment (i.e. inner planetary and solar probe-type missions)
Lightweight solar array technologies applicable to solar electric propulsion missions. Current missions being studied require solar arrays that provide 1 to 20 kilowatts of power at 1 AU, are greater than 300 watts/kilogram specific power, can operate in the range of 0.7 to 3 AU, provide operational array voltages up to 150 volts and have a low stowed volume.

Thermophotovoltaic conversion is currently focused on follow-on technology for the International Lunar Network (ILN) and for the outer planets mission. Advances sought, but not limited to, include:

- Low-bandgap cells having high efficiency and high reliability
- High temperature selective emitters
- Low absorptance optical band-pass filters
- Efficient multi-foil insulation

Note to Proposer: Topic X8 under the Exploration Mission Directorate also addresses power technologies (X8.03 Space Nuclear Power Systems, and X8.04 Advanced Photovoltaic Systems). Proposals more aligned with exploration mission requirements should be proposed in X8.

S3.04 Propulsion Systems

The Science Mission Directorate (SMD) needs spacecraft with more demanding propulsive performance and flexibility for more ambitious missions requiring high duty cycles, more challenging environmental conditions, and extended operation. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies in the solar system (http://www.nap.edu/catalog.php?record_id=10432). Future spacecraft and constellations of spacecraft will have high-precision propulsion requirements, usually in volume- and power-limited envelopes.

This subtopic seeks innovations to meet SMD propulsion requirements, which are reflected in the goals of NASA’s In-Space Propulsion Technology program to reduce the travel time, mass, and cost of SMD spacecraft. Advancements in chemical and electric propulsion systems related to sample return missions to Mars, small bodies (like asteroids, comets, and Near-Earth Objects), outer planet moons, and Venus are desired. Additional electric propulsion technology innovations are also sought to enable low cost systems for Discovery class missions, and eventually to enable radioisotope electric propulsion (REP) type missions.

The focus of this solicitation is for next generation propulsion systems and components, including high-pressure chemical rocket technologies and low cost/low mass electric propulsion technologies. Specific sample return propulsion technologies of interest include higher-pressure chemical propulsion system components, lightweight propulsion components, and Earth-return vehicle propulsion systems. Propulsion technologies related specifically
to planetary ascent vehicles will be sought under S3.08 Planetary Ascent Vehicle.

**Chemical Propulsion Systems**

Technology needs include:

- Improved materials and manufacturing processes to produce Iridium/Rhenium apogee class thruster chambers with improved mechanical properties targeting a yield stress of 40ksi and an elongation of 10%;
- Advanced nontoxic mono-propellant rockets for in-space applications.

**Electric Propulsion Systems**

This subtopic also seeks proposals that explore uses of technologies that will provide superior performance in for high specific impulse/low mass electric propulsion systems at low cost. These technologies include:

- Efficient thrusters with up to 1 kW of input power that provide thrust up to 20 mN with a specific impulse between 1600 to 3500 seconds;
- A throttleable dual mode thruster that is capable of operating in both high thrust and high specific impulse modes for a fixed power;
- High power electric propulsion thrusters (>20 kW) and components including cathodes, ion optics, and low sputtering materials with long life (>1x108 N-s).

Proposals should show an understanding of the state of the art, how there technology is superior, and of one or more relevant science needs. The proposals should provide a feasible plan to fully develop a technology and infuse it into a NASA program.

Note to Proposer: Topic X2 under the Exploration Mission Directorate also addresses advanced propulsion. Proposals more aligned with exploration mission requirements should be proposed in X2.

**S3.05 Power Management and Storage**

*Future NASA science objectives will include missions such as Earth Orbiting, Venus, Europa, Titan, Lunar Quest and Space Weather. Under this subtopic, proposals are solicited to develop energy storage and power electronics to enable or enhance the capabilities of future science missions. The unique requirements for the power systems...*
for these missions can vary greatly, with advancements in components needed above the current State of the Art (SOA) for long life, high reliability, low mass/volume, radiation tolerance, and wide temperature operation.

**Energy Storage**

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes from -100°C for Titan missions to 400°C to 500°C for Venus missions, and a span of -230°C to +120°C for Lunar Quest. In addition, high energy-density rechargeable electrochemical battery systems that offer greater than 50,000 charge/discharge cycles (10 year operating life) for low-earth-orbiting spacecraft, 20 year life for geosynchronous (GEO) spacecraft, are desired. Advancements to battery energy storage capabilities that address one or more of the above requirements for the stated missions combined with very high specific energy (>200 Wh/kg for secondary battery systems) and energy density, along with radiation tolerance are of interest.

In addition to batteries, other advanced energy storage/load leveling technologies designed to the above mission requirements, such as flywheels, supercapacitors or magnetic energy storage, are of interest. These technologies have the potential to minimize the size and mass of future power systems.

**Power Management and Distribution (PMAD)**

The "New Frontiers in the Solar System: An Integrated Exploration Strategy" ([http://www.nap.edu/catalog.php?record_id=10432](http://www.nap.edu/catalog.php?record_id=10432)), the 2006 Solar System Exploration Roadmap ([http://nasascience.nasa.gov/about-us/science-strategy](http://nasascience.nasa.gov/about-us/science-strategy)) and the Science Plan for NASA's Science Mission Directorate ([http://nasascience.nasa.gov/about-us/science-strategy](http://nasascience.nasa.gov/about-us/science-strategy)) all describe the need for radioisotope power systems (RPS) for planetary exploration. In conjunction with the RPS, intelligent, fault-tolerant PMAD technologies are needed to efficiently manage the system power for these deep space missions. Advances in electrical power technologies are required for the electrical components and systems for these future platforms to address program size, mass, efficiency, capacity, durability, and reliability requirements. Of importance are expected improvements in energy density, speed, efficiency, or wide-temperature operation (-125°C to over 450°C) with a number of thermal cycles. Advancements are sought for power electronic devices, components and packaging for Venus type missions with power ranges of a few watts for minimum missions up to a few kilowatts for large missions.

For the lower power applications (up to 20 watts), NASA desires to build smaller spacecraft types carrying smaller instrument packages. However, power requirements to accommodate these instruments and spacecraft systems will not necessarily shrink in a similar fashion as spacecraft size. Therefore, power management technologies are sought that are compatible with small spacecraft geometries and sizes. These Electrical Power Systems should be compatible with Space Plug and Play (SPA) architectures.

Overall technologies of interest include:

- Intelligent, fault-tolerant electrical components and PMAD systems
- High temperature devices and components (up to 450°C)
- Advanced electronic packaging for thermal control and electromagnetic shielding
- Plug and Play compatibility for low power applications

Power Conversion and Distribution relevant to Command, Data Handling, and Electronics, will be covered under subtopic S3.01.

Power Storage for Terrestrial Balloons will be covered under sub-topic S3.07 Terrestrial and Planetary Balloons.

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase II emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into science-worthy systems.

Other subtopics, which could potentially benefit from these technology developments include O5 - Low-Cost and Reliable Access to Space (LCRATS), S5.05 - Extreme Environments Technology, and S5.01 - Planetary Entry, Descent and Landing Technology. Battery development could also be beneficial to X6.02 - Advanced Space-rated Batteries, which is investigating some similar technologies in the secondary battery area but with very different operational requirements. Power Management and Distribution could be beneficial to X8.05 - Advanced Power Conversion Systems AND Management and Distribution (PMAD), which is investigating similar technologies, but with very different power levels.

**S3.06 Guidance, Navigation and Control**

Advances in the following areas of guidance, navigation and control are sought.

**Navigation systems** (including multiple sensors and algorithms/estimators, possibly based on existing component technologies) that work collectively on multiple vehicles to enable inertial alignment of the formation of vehicles (i.e., pointing of the line-of-sight defined by fixed points on the vehicles) on the level of milli-arcseconds relative to the background star field.

**Light-weight sensors** (gyroscopic or other approach) to enable milli-arcsecond class pointing measurement for individual large telescopes and low cost small spacecraft.

**Isolated pointing and tracking platforms** (pointing 0.5 arcseconds, jitter to 5 milli-arcsecond), targeted to placing a scientific instrument on GEO communication satellites that can track the sun for > 3 hours/day.
Working prototypes of GN&C actuators (e.g., reaction or momentum wheels) that advance mass and technology improvements for small spacecraft use. Such technologies may include such non-contact approaches such as magnetic or gas. Superconducting materials, driven by temperature conditioning may also be appropriate provided that the net power used to drive and condition the "frictionless" wheels is comparable to traditional approaches.

Proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

**S3.07 Terrestrial and Planetary Balloons**

All proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

**Terrestrial Scientific Balloons Planetary Balloons**

Innovations in materials, structures, and systems concepts have enabled buoyant vehicles to play an expanding role in planning NASA's future Solar System Exploration Program. Balloons and airships are expected to carry scientific payloads at Titan and Venus that will perform in situ investigations of their atmospheres and near surface environments. Both Titan and Venus feature extreme environments that significantly impact the design of balloons for those two worlds. Proposals are sought in the following areas:

(1) Titan Montgolfiere Balloons: Recent NASA mission studies have recommended the use of radioisotope-heated Montgolfiere balloons for future in situ Titan exploration. Proposals are sought for the design, fabrication and Earth atmosphere flight testing of prototypes that can support an eventual Titan Montgolfiere balloon mission. Particular importance is attached to the acquisition of test data that can help validate thermodynamic and fluid mechanic models that will ultimately be used to design the Titan flight balloon. The size of balloon required for Titan will be approximately 10 m in diameter and will require 2 kW of thermal energy to float the balloon at an expected Titan temperature of 85 to 95 K. Any proposed Earth-test prototype will require an alternate heat source that nevertheless adequately mimics the effects of using radioisotope energy at Titan.

(2) Gas Management Systems for Titan Aerobots: Hydrogen-filled aerobots at Titan must contend with the problem of gas leakage over long duration (1 year or more) flights. Proposals are sought for the development and testing of two kinds of prototype devices that can be carried on the aerobot to compensate for these gas leakage problems: one device is to produce make-up hydrogen gas from atmospheric methane; the other device is to remove atmospheric gas (mostly nitrogen) that leaks from the ballonets into the hydrogen-filled blimp. Both kinds of devices will need to operate on no more than 15 W of electrical power each while compensating for a leakage rate of at least 40 g/week of hydrogen or 500 g/week of nitrogen.
Metal Balloons for High Temperature Venus Exploration: Balloons made of metals are a potential solution to the problem of enabling long duration flight in the hot lower atmosphere of Venus. Proposals are sought for metal balloon concepts and prototypes that provide 1-5 m$^3$ of fully inflated volume, areal densities of 1 kg/m$^2$ or less, sulfuric acid compatibility at 85% concentration, and operation at 460 °C for a period of up to 1 year.

S3.08 Planetary Ascent Vehicles

NASA aims to design, build and test vehicles that will be launched from the surface of other planets and small bodies and place a payload, Orbiting Sample (OS), into orbit. We are seeking proposals for the development of innovative technologies to support future planetary ascent vehicles. Immediate focus is the Mars ascent vehicle. Technology innovations should either enhance vehicle capabilities (e.g., launch success probability, mission success, improved performance or margins, and improved environmental robustness) or ease implementation in space borne missions (e.g., reduce size, mass, power, and thermal requirements, improve reliability and ability to withstand the ~20 g lateral g-loading, or lower cost). The areas of interest for this call are listed below.

Alternate propellants, thrusters and propulsion system technologies for the planetary ascent vehicles:

- Higher performing monopropellants with specific impulse >240 secs;
- "Green" propellants;
- High chamber pressure thrusters > 500 psia;
- Pressurization component technologies to reduce system mass (filters, solenoid valves, latch valves, tanks, fill and drain and check valves);
- Small lightweight pump technologies to operate at >500 psi output pressure especially non-electrically driven;
- Non-pyrotechnic isolation valves.

Advanced solid propellant engine system technologies:

- Solid propellant technology with specific impulse performance potential higher than HTPB and CTPB;
- Propellant blend with high performance low storage impacts, and operating capability down to 150 K;
- Low temperature seals and components;
- Light weight and reliable thrust vector control;
- Other lightweight system and component technologies.
Proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

Launch vehicle technologies relevant to Earth are not sought under this sub-topic. For launch vehicle technologies related to Earth, see X2.01 Earth-to-Orbit Propulsion. Proposals more aligned with exploration mission requirements should be proposed in X2.01.

S3.09 Unmanned Aircraft and Sounding Rocket Technologies

Sounding Rockets

The NASA Sounding Rocket Program (NSRP) provides low-cost, sub-orbital access to space in support of space and earth sciences research and technology development sponsored by NASA and other users by providing payload development, launch vehicles, and mission support services. NASA utilizes a variety of vehicle systems comprised of military surplus and commercially available rocket motors, capable of lofting scientific payloads, up to 1300lbs, to altitudes from 100km to 1500km. NASA launches sounding rocket vehicles worldwide, from both land-based and water-based ranges, based on the science needs to study phenomenon in specific locations.

NASA is seeking innovations to enhance capabilities and operations in the following areas:

- Autonomous vehicle environmental diagnostics system capable of monitoring flight loading (thermal, acceleration, stress/strain) for solid rocket vehicle systems.
- Location determination systems to provide over-the-horizon position of buoyant payloads to facilitate expedient location and retrieval from the ocean.
- Flotation systems, ranging from tethered flotation devices to self-encapsulation systems, for augmenting buoyancy of seal payload systems launched from water-based launch ranges.
- High-glide parachute designs capable of deploying at altitudes above 25,000 ft to facilitate mid-air retrieval and/or fly-back/fly-to-point precision landing.

Unmanned Aircraft Systems

Unmanned Aircraft Systems (UAS) offer significant potential for Suborbital Scientific Earth Exploration Missions over a very large range of payload complexities, mission durations, altitudes, and extreme environmental conditions. To more fully realize the potential improvement in capabilities for atmospheric sampling and remote sensing, new technologies are needed. Scientific observation and documentation of environmental phenomena on both global and localized scales that will advance climate research and monitoring; e.g., U.S. Global Change Research Program as well as Arctic and Antarctic research activities (Ice Bridge, etc.).
NASA is increasing scientific participation to understand impacts associated with worldwide environmental changes. Capability for suborbital unmanned flight operations in either the North or South Polar Regions are limited because of technology gaps for extremely remote telemetry capabilities and precision flight path control requirements. It is also highly desirable to have UAS ability to perform atmospheric and surface sampling.

(1) Telemetry, Tracking and Control: Low cost over-the-horizon global networks are needed to enable unmanned collaborative multi-platform earth observation missions that are more efficient and cost effective.

(2) Avionics and Flight Control:

- Precision Flight Path Control solutions in smooth atmospheric conditions.
- Aircraft control in violent atmospheric conditions.
- Low cost 

Precise/repeatable flight path control capabilities are needed to enable repeat path observations for earth monitoring on seasonal and multi-year cycles. In addition, long endurance atmospheric sampling in extreme inclement weather conditions (hurricanes) and volcanic plumes can provide high fidelity time and spatial resolution data.

(3) UA Integrated Vehicle Health Management:

- Fuel Heat/Anti-freezing
- Unmanned platform icing detection and minimization

(4) Guided Dropsondes: NASA Earth Science Research activities could utilize more capable dropsondes than are currently available as market items. Specifically, dropsondes that could effectively be guided through atmospheric regions of interest such as volcanic plumes could enable unprecedented observations of important phenomena. Capabilities of interest include:

- Compatibility with existing drop-sonde dispensing systems deployed on the NASA/NOAA P-3 and planned for the NASA Global Hawk
- Guidance schemes, autonomous or active control
- Cross-range performance and flight path accuracy
- Operational considerations including airspace utilization and conflicting traffic

All proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

_S3.10 Earth Entry Vehicle Systems_