The primary goal of the Prometheus Nuclear Systems and Technology (PNS&T) Theme is to mature technology and develop systems to overcome current limitations of space power and propulsion in support of the Vision for Space Exploration. Developing and demonstrating safe and reliable nuclear fission-based spacecraft power and propulsion systems will enable human and robotic exploration, enhance scientific capabilities, and facilitate unprecedented levels of exploration and scientific return. Potential benefits of space nuclear power include very high total energy and total power capability, and high delta-V nuclear-electric propulsion that can enable a wide range of solar system exploration missions not possible today. To meet the goals of the Vision for Space Exploration, new exploration missions would have requirements exceeding what current power and propulsion systems can provide, particularly for surface and outer planet applications. Prometheus nuclear systems can provide a viable, enabling, alternative for those missions that have no other practical solution. The PNS&T Theme is comprised of two programs - the Nuclear Flight Systems program and the Advanced Systems and Technology program. The Nuclear Flight Systems program is focused on developing the first Prometheus demonstration of nuclear fission power in space, including development of nuclear reactor power, electric propulsion and other associated spacecraft systems. The Advanced Systems and Technology program is focused on conducting research and development of advanced systems and technologies beyond those needed for the first demonstration mission including research for advanced power and propulsion systems, materials development, integrated spacecraft systems, and other capabilities. This advanced technology development will be necessary to support NASA's goal of more distant, more ambitious, and longer duration human and robotic exploration of Mars and other destinations. Five key program research areas include advanced nuclear electric propulsion, advanced fission-based power systems, advanced nuclear propulsion systems, advanced nuclear vehicle and spacecraft systems, and long-range nuclear reactor systems technology development. The five PNS&T subtopics are focused on these Advanced Systems and Technology program areas.

Subtopics

X10.01 Long-Life Validation and Flight Qualification of Nuclear Space Systems Hardware Prior to Flight Use

Lead Center: MSFC

Participating Center(s): GRC, JPL

Nuclear space systems are expected to be an integral part of the national Vision for Space Exploration. Nuclear electric power would allow human and robotic exploration to reach beyond the constraints of solar power systems and is expected to be crucial for long-duration habitation and exploration of the Moon and Mars. Nuclear propulsion systems offer the potential for significantly higher specific impulse and/or significantly higher delta-V than chemical engines, reducing the amount of propellant and associated costs needed to perform a given mission. Nuclear
thermal propulsion (NTP) systems up to several hundred megawatts and nuclear electric propulsion (NEP) systems from 30 kW to hundreds of kilowatts and more, are being considered for the economical delivery of lunar and Mars cargo, rapid crew transit to Mars, and, in the case of nuclear electric propulsion, robotic exploration of the solar system and beyond. However, the long-duration performance and life testing of these high power nuclear space systems can be very expensive and poses several unique and significant challenges. The intent of this solicitation is to elicit new or significantly improved approaches that accelerate or simplify the long-life validation and flight qualification of high power nuclear space systems hardware.

While the testing of nuclear reactors is clearly beyond the scope of this solicitation, proposals are invited for innovative methods that simplify, accelerate, reduce the cost, or otherwise improve upon current techniques to ground test and validate the life and performance of non-reactor high power space nuclear power and propulsion components, subsystems, and systems. Also invited are proposals that address new and innovative approaches to seamlessly integrate high power space nuclear power and propulsion hardware elements into complete systems of systems, with corresponding methods for flight qualification prior to flight use.

Sample high power space nuclear power and propulsion areas that could benefit from accelerated or simplified performance and life validation include, but are not limited to: electric power conversion systems for in-space or planetary surface power; electric power management and distribution systems; accelerated testing of pulsed or steady-state high power electric thrusters or thruster arrays under appropriate vacuum and thermal conditions; performance and life testing of component materials and structures under simulated NTP hot hydrogen flows; the simulated operation, shut-down, and restart of NTP system components over simulated mission profiles in relevant vacuum, thermal, and radiation test environments; other space nuclear power and propulsion hardware elements that must operate in extreme environments over extended mission durations; and simplified or accelerated techniques for hardware integration and flight qualification of a complete system of systems prior to flight use. Proposed methods should substantially and demonstrably reduce the time and expense to validate the life and performance of space nuclear power and propulsion technologies compared to state of the art techniques.

X10.02 Critical Technologies for In-Space Application of Nuclear Thermal Propulsion

Lead Center: GRC

 Participating Center(s): MSFC, SSC

NASA is interested in the development of critical technologies for first in-space applications of solid core nuclear thermal propulsion (NTP) systems for use in a variety of future exploration missions. For short, round trip, human missions to Mars, NTP systems may be enabling. It can potentially also help reduce launch mass or increase payload delivery for cargo and crewed missions to the Moon and other destinations. The first anticipated in-space application of solid core NTP systems could occur in the time frame of 2025 to 2030 and could be based on a high-thrust/high-Isp (~850 - 950s) NTP system that uses a fission reactor with U-235 fuel as its source of thermal energy. During the short primary propulsion maneuvers of a typical conceptual mission, large quantities of thermal power (100s of MWt) would be produced within the NTP system and removed using LH\textsubscript{2} propellant that is pumped through the engine's reactor core. The superheated hydrogen gas is then exhausted out the engine's nozzle to generate thrust. Recent NASA studies have shown that small engines (~15-25 klbf), used individually or in clusters, could support a broad range of mission types. Representative ranges of engine performance include: 1) hydrogen exhaust temperatures ~2500-2900 K; 2) propellant flow rates ~7-13 kg/s; 3) chamber pressures ~500 -1500 psi; and 4) nozzle expansion area ratio ~200:1-500:1.
Proposals are sought to further improve safety, performance, reliability, and life factors as well as reduce projected weight and costs for the first in-space NTP systems, subsystems, and components beyond that in previously achieved ground test systems. Proposals are solicited in the following key technology/concept areas:

- High temperature, radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and $\text{H}_2$ propellant flow rates over wide range of temperatures are desired;
- Long-life, lightweight, reliable hydrogen turbopump designs and technologies;
- Lightweight, long-life, high heat flux thrust chambers, regenerative-cooled nozzles and radiation-cooled skirt extensions that are compatible with hot hydrogen;
- Radiation tolerant materials compatible with above engine subsystem applications and operating environments;
- High temperature, low-to-moderate burn-up carbon- and ceramic-metallic (cermet)-based nuclear fuels for use in NTR and BNTR engines;
- Improved chemical vapor deposition (CVD)/coating techniques for heritage "Rover/NERVA" type carbon-based fuels that reduce and/or prevent cracking, fuel element erosion via $\text{H}_2$ attack, and release of fission product gases into the engine's $\text{H}_2$ exhaust stream;
- Mass-optimum neutron and gamma radiation shielding materials and designs that minimize exposure/damage to key engine components and subsystems (e.g., LH$_2$ turbopumps) and provide radiation protection for the crew; and
- Dual-use shielding materials and designs that also provide habitat protection against galactic cosmic rays and solar flares are also encouraged.

Note that any associated NTP simplified test approaches, power systems, and thermal management/heat rejection systems technologies should be submitted to subtopic areas X10.01, X10.03, and X10.04, respectively.

X10.03 Critical Technologies for Space-Based Nuclear Fission Power Systems

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

NASA is interested in the development of highly advanced systems, subsystems, and components for use with high-power, fission power systems for a variety of future robotic and manned exploration missions to the Moon, Mars, and beyond. Anticipated electric power levels range from 30 to 100s of kilowatts for the nearer-term and possibly up to multi-megawatts for the far-term. Fission-based systems are anticipated to enable long duration stays of approximately 45 to 90 days over the lunar night and may have in situ resource utilization applications. Power levels needs are anticipated to be between 30-50 kWe for these early exploration missions.

Potential Mars-surface human outpost applications for high-power space nuclear power systems could include
habitats, resource processing, propellant production/liquefaction/maintenance, and excavating and mining equipment. These potential Mars surface human mission activities could require power in the 100 kWe range. Also, space nuclear power systems could be needed for robotic outposts as a precursor to human Mars surface exploration with 50-500 day stays. Power levels of about 30-50 kWe may be needed to support these initial robotic outposts and other science applications such as: deep drilling, resource production demonstrations, rovers, weather stations, etc.

Potential electric propulsion applications include high power space nuclear power systems for primary electric propulsion, vehicle housekeeping, cryogenic propellant maintenance, orbiting power assets and science payloads. Power levels in the 100-200 kWe range are envisioned for robotic vehicles. Far-term vehicles for human missions may also be needed and could require about 1-2 MWe for high-mass cargo vehicles to the Moon or Mars and the low 10s of MWe for piloted electric propulsion vehicles. Nuclear thermal propulsion systems could also be designed to produce electric power and power levels of about 50 kWe could be needed to meet crew habitat, propellant boil-off, and other spacecraft power requirements.

Proposals are sought in the following specific technologies areas:

- Advanced, high-efficiency, high-temperature high-power conversion >20%, 30-200 kWe for the nearer-term, and up to MWe-unit size for the far-term (with technical issues of scaling to high power unit);
- Electrical power management, control and distribution in the 1000-5000 V range;
- Deployment systems/mechanisms and innovative methodologies for surface mobility systems for remote emplacement of power systems and for use of indigenous shielding materials;
- Material compatibility with local environments;
- Systems/technologies to mitigate lunar and planetary surface environments including dust accumulation, lunar surface temperature extremes, wind, planetary atmospheres (CO₂, corrosive soils, etc.);
- Power system design considerations for long life (>10 years), autonomous control and operation, including sensor technologies; and
- Radiation tolerant systems and materials (including lunar, Mars and in-space environments) for robust, long-life operation.

In addition to reducing overall system mass, volume and cost, increased safety, and reliability are of extreme importance. It is envisioned that these high power space nuclear power system technologies could be used on robotic and human exploration missions and it is to NASA's advantage to develop those technologies that evolve from robotic to human exploration mission requirements with a minimum of redesign. Technologies that enable challenging missions such as, nuclear electric propulsion, planetary surface power, and in-space electric power generation are of particular interest. Technologies that easily and efficiently scale in power output and can be used in a host of applications (high commonality) are desired.

Proposals for thermal management systems and innovative materials computational engineering should be proposed to X10.04 and X10.05, respectively.
X10.04 Heat Rejection Technologies for Nuclear Systems

Lead Center: GRC
Participating Center(s): GSFC, JPL, MSFC

NASA is interested in the development of advanced heat rejection subsystems for use with high-power, fission-based power and propulsion systems for a variety of future robotic and manned exploration missions to the Moon, Mars, and beyond. Anticipated electric power levels for these high-power, space nuclear systems could range from 30 to 100s of kilowatts for the nearer-term and possibly up to multi-megawatts (2-20 MWe) for the far-term. Potential applications include in-space transfer vehicles and planetary orbiters, and surface bases with global site capability on the lunar and Mars surface. The heat rejection sub-systems for any of the possible high power space nuclear power plant choices would need to be matched with the thermodynamic cycles of the power plants in a manner that will maximize space nuclear power system performance while keeping heat rejection sub-system and overall power system specific mass (kg/kW) to a minimum. The levels of heat rejection could be from about 100 kilowatts to many megawatts, and the task could be even more challenging by the long life requirements imposed by deep space missions, the extreme radiation environments possibly encountered, and the unique challenges imposed by surface missions including the effect of an atmosphere, elevated sink temperature, and particle contamination. The radiator operating temperature range can vary greatly depending on the mission, but temperatures as low as 400K and in excess of 1000K are possible.

Typical heat rejection systems usually include a) a heat transport loop carrying heat to radiator surfaces for rejection to space, and b) a space radiator, which accomplishes the final heat rejection to space by thermal radiation. If the cycle working fluid is different from the radiator heat transport fluid, a "heat sink" heat exchanger and a fluid-circulating pump also need to be included in the design.

Proposals are sought in the following critical technologies areas:

- Low areal density heat rejection radiators (2);
- Innovative heat transfer approaches between heat transport loop and radiating surfaces;
- Development of light weight, radiation tolerant, thermally stable, high-performance components and pump loop systems including heat pipes and pumps in the low to intermediate temperature ranges (300K to 500K), intermediate temperature ranges (450K to 650K), and intermediate to high temperature ranges (700K to 1000K and higher);
- Pumped loops that take advantage of the abundance of waste heat and transport some of it to the spacecraft and payload components for thermal management. Waste heat source to spacecraft radiator distances will likely be too large for passive technologies, and pumped loops may offer a possible solution. Since rejection of megawatts of waste heat could require large radiating surfaces, loop heat pipes may provide a lightweight solution to distributing this heat over long distances. Specific areas of interest for this area include:
- Long term material/working fluid compatibility, lightweight material integration, and working fluid performance for the various temperature ranges; and

- High temperature, long-life pump technology, single- and two-phase systems, and thermal bus concepts involving multi-evaporators and condensers.

- High temperature, lightweight heat rejection system materials. Such materials may include those to enable lightweight radiators and heat pipes. Work in this area should address harsh radiation environments, launch/landing loads, and long life issues;

- Durable low-absorptivity/high-emissivity and variable emissivity coatings for radiating surfaces;

- Novel and efficient deployment systems/mechanisms for radiators in zero gravity and/or non-zero gravity fields to minimize mass, complexity, and stowed area/volume;

- Systems and technologies to mitigate adverse effects of planetary surface operating environments, such as cosmic and fission process induced radiation, dust accumulation, wind loading, planetary atmospheric effects due to CO₂, and variable sink temperatures;

- Design considerations for heat rejection subsystems should include long service life (>10 years) and autonomous operation;

- Development of advanced, high temperature heat pump technologies based upon conventional vapor compression cycles, absorption/adsorption cycles, and advanced thermoelectric and/or thermo-acoustic technologies;

- Advanced eutectic working fluids capable of extended duration use that would mitigate design issues related to the freezing and subsequent reuse of thermal management coolants; and

- Alternate cooling technologies for the rejection of waste heat from large capacity planetary or surface nuclear power systems. Such systems may include, but are not limited to, deployable cooling towers and/or optimized radiators.

In addition to reducing overall system mass, volume, radiator area, and cost, increased safety and reliability are of prime importance. Technologies are desired that readily scale in heat rejection capability for various power plant outputs, and thus can be used in a range of applications.

X10.05 Computational Material Science Tools for Space Nuclear Systems Design

Lead Center: GRC

Participating Center(s): MSFC

NASA is interested in the development of highly advanced systems, subsystems, and components for use with high-power, fission power and propulsion systems for a variety of future robotic and manned exploration missions, including in-space, lunar-surface, and Mars-surface applications. Advanced high-power space nuclear power and propulsion systems for robotic and human exploration missions involve a range of specialized materials for the reactor, heat transfer system, energy conversion system, propulsion system, and other nuclear vehicle systems. These materials may include carbon-carbon, super alloys, refractory alloys, structural ceramics, ceramic matrix composites, and other high-temperature space nuclear systems materials. Long-term stability greater than 10 years.
is critical for long-life space nuclear power system applications. Materials would be subjected to fission process radiation while exposed to in-space (plasma, out-gassing, etc.) and/or planetary operating environments.

This subtopic is focused on the development of computational materials science tools to develop and select these specialized space nuclear systems materials. Many considerations go into selection of materials for demanding applications. These include strength, creep resistance, phase stability, oxidation/corrosion resistance, nuclear capture cross-section, and radiation tolerance. In recent years computational materials science has assisted with not only the selection of existing materials with a given set of properties but also with the development of new materials with those properties. These tools include first principles calculations of phase equilibria, computational thermodynamics (the CALPHAD technique), and creep modeling.

Proposals are sought for the specific technologies areas:

- A computational ‘toolbox’ for material selection with particular emphasis on space nuclear power and propulsion systems requirements;
- Computational tools to address particular issues in mechanical property degradation in space nuclear power and propulsion systems over long times. This includes, but is not limited to, long-term creep modeling;
- Computational tools to predict long-term oxidation/corrosion and flow-induced erosion issues in the high temperature portions of these systems, including the heat transfer system. This includes thermodynamic modeling of heat transfer media attack of alloys;
- Computational tools to predict long term stability of various joining techniques used in these space nuclear systems. This includes diffusion modeling in alloys; and
- Computational tools to predict interaction of the radiation environment. This includes effective capture cross-section for complex materials systems and production of secondary energy and potential impact on components.

It is anticipated that Phase 1 will focus primarily on the new computational tools for material selection and development with some limited experimental verification. Later phases should involve more extensive verification, to the point where these tools could be readily utilized for the design of space nuclear systems.