Human Exploration require advances in propulsion to get to the moon, Mars, and beyond. A major thrust of this research and development activity will be related to space launch propulsion technologies. This effort will include first stage engine development, non-toxic in-space engine demonstrations, and foundational propulsion research in areas such as new or largely untested propellants that can result in more capable and less expensive future rockets. NASA is interested in conducting foundational research to study the requirements and potential designs for advanced high-energy in-space propulsion systems to support exploration and to reduce travel time. These technologies could include nuclear propulsion and electric propulsion.

Subtopics

X2.01 Earth-to-Orbit Propulsion

Lead Center: MSFC

Participating Center(s): GRC, JPL, KSC, SSC

NASA is interested in innovative Earth-to-Orbit (ETO) propulsion systems and component technologies, as well as design and analysis tools used to support the assessment of the technical viability of those systems. Next generation launch systems will require propulsion systems that deliver high thrust-to-weight ratios, increased trajectory averaged specific impulse, reliable overall vehicle systems performance, low recurring costs, and other innovations required to achieve cost and crew safety goals.

Proposals should address technical issues related to Earth-to-Orbit (ETO) LOX/Hydrocarbon engines and LOX/Hydrogen second stage engines including engine and main propulsion systems design and integration, turbomachinery, combustion devices, valves, actuators, and ducts. Areas of specific interest for technology advancement and innovations include the following:

- Advancements in design and analysis tools applicable to assessment of ETO propulsion systems including engine systems, turbomachinery, valves, and combustion device concepts. Of particular interest are design and analysis tools that provide improved understanding and quantification of component, subsystem, and
system operating environments and that significantly enhance the overall systems engineering evaluation of potential ETO propulsion concepts. Examples include low and high fidelity tools suitable for component and parameter sensitivity analysis and optimization, dynamic environment prediction, quantification of system benefits to changes.

- Improved propulsion systems stability prediction analysis and design tools, along with stability aid concepts and demonstration of approaches (i.e., rotordynamic coefficients, turbopump cavitation, instabilities, combustion stabilities, structural-acoustic, propellant management, and fluid dampers.)

- Innovative tools for predicting the complex fluid and structural interactions within rocket nozzles and experimental methods and data for validating these tools. Specific areas of interest include nozzle side loads induced by nozzle flow separation during engine start and shutdown transients and the effect of fluctuating pressure during engine main stage.

- Improvements to tools that predict the environments in and around the engine during booster operation.

- Data to validate the accuracy of high fidelity design and analysis tools used for the prediction of internal rocket engine environments.

- Design concepts that improve performance, reduce cost, reduce weight or improve reliability of the propellant feed systems, valves. Of particular interest are:
  - Design concepts for high power density turbines,
  - Design concepts for low net positive suction pressure pumps,
  - Design concepts for low cost, reliable valves and their actuation system,
  - Demonstration of robust bearing design concepts for large, high speed rotors,
  - Identification and demonstration of high strength materials that are resistant to combustion in a high pressure, oxygen rich environment.

**X2.02 Non-Toxic In-Space Propulsion**

**Lead Center:** GRC

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

This solicitation intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. Non-toxic engine technology is desired for use in lieu of the currently operational NTO/MMH engine technology. Safety concerns with toxic propellants drive mission planners to the use of more costly propulsion modules that are fueled and sealed on the ground. Non-toxic engine technologies could range from reaction control class of 25-1000 lbf to main engines of up to 60,000 lbf with both pump fed or pressure fed systems.

Specific technologies of interest to meet proposed engine requirements include:

- Non-toxic bipropellant or monopropellants that meet performance targets (as indicated by high specific impulse and high specific impulse density) while improving safety and reducing handling operations as
compared to current state-of-the-art storable propellants.

- Low-mass propellant injectors that provide stable, uniform combustion over a wide range of propellant inlet temperature and pressure conditions.
- High temperature materials, coatings and/or ablative for injectors, combustion chambers, nozzles, and nozzle extensions.
- Combustion chamber thermal control technologies such as regenerative, transpiration, swirl or other cooling methods, which offer improved performance and adequate chamber life.
- Technologies are also solicited that enable deep-throttling turbopumps to operate at off-design flow coefficients while eliminating flow instabilities such as cavitating surge.
- Highly-reliable, long-life, fast-acting propellant valves that tolerate long duration space mission environments with reduced volume, mass, and power requirements is also desirable.
- Cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours.

Note to Proposer: Subtopic S3.04 under the Science Mission Directorate also addresses in-space propulsion. Proposals more aligned with science mission requirements should be proposed in S3.04.

X2.03 Nuclear Thermal Propulsion

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

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 future exploration missions. For short round trip missions to MARS, NTP systems may be enabling by helping to reduce launch mass to reasonable values and by also increasing the payload delivered for Mars exploration missions.

Preliminary solid core NTP system concepts could be based on a high thrust/high ISP (~850-950s) NTP system that would use 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 (100's of MWt) would be produced within the NTP system and removed using liquid hydrogen 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. Representative ranges of engine performance include: (1) hydrogen exhaust temperatures ~2500 - 2900K, (2) propellant flowrates ~7 - 13 kg/s, (3) chamber pressures ~500 - 1500 psi, and (4) nozzle expansion area ratios ~200:1 - 500:1.

Proposals are sought to further improve factors contributing to safety, performance, reliability, and life 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, low burn-up carbide- and ceramic-metallic (cermet)-based nuclear fuels with improved coatings and/or claddings to reduce fission product gas release into the engine's hydrogen exhaust stream;
- Reliable, high temperature materials, fabrication techniques, and concepts for non-reactor portions of NTP systems;
- Light-weight, multi-use shielding materials and designs;
- 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 liquid hydrogen propellant flow rates over wide range of temperatures desired;
- Long life, lightweight, reliable hydrogen turbopump designs and technologies;
- Lightweight, long life, 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.

X2.04 Electric Propulsion Systems

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

The goal of this subtopic is to develop innovations in high-power (100 kW to MW-class) electric propulsion systems. High-power (high-thrust) electric propulsion may enable dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers. At very high power levels, electric propulsion may enable piloted exploration missions as well. Improved performance of propulsion systems that are integrated with associated power and thermal management systems and that exhibit minimal adverse spacecraft-thruster interaction effects are of interest. Innovations are sought that increase system efficiency, increase system and/or component life, increase system and/or component durability, reduce system and/or component mass, reduce system complexity, reduce development issues, or provide other definable benefits. Desired specific impulses range from a value of 2000 s for Earth-orbit transfers to over 6000 s for planetary missions. System efficiencies in excess of 50% and system lifetimes of at least 5 years (total impulse > 1 x107 N-sec) are desired. Specific technologies of interest in addressing these challenges include:

- Long-life, high-current cathodes (100,000 hours);
- Electric propulsion designs employing fuels that are more readily available (whether from Earth or in situ space resources) and easy to store/handle;
- Electrode thermal management technologies;
- Innovative plasma neutralization concepts;
- Metal propellant management systems and components;
- Cathodes for metal propellants;
- Low-mass, high-efficiency power electronics for RF and DC discharges;
- Lightweight, low-cost, high-efficiency power processing units;
- Low-voltage, high-temperature wire for electromagnets;
- High-temperature permanent magnets and/or electromagnets;
- Application of advanced materials for electrodes and wiring;
- Highly accurate propellant control devices/schemes;
- Miniature propellant flow meters;
- Lightweight, long-life storage systems for krypton and/or hydrogen;
- Fast-acting, very long-life valves and switches for pulsed inductive thrusters;
- Superconducting magnets;
- Lightweight thrust vector control for high-power thrusters; and
- High fidelity methods of determining the thrust of ion, Hall, and advanced plasma engines without using conventional thrust-stands.

Note to Proposer: Subtopic S3.04 under the Science Mission Directorate also addresses in-space propulsion. Proposals more aligned with science mission requirements should be proposed in S3.04.