Achieving space flight remains a challenging enterprise. It is an undertaking of great complexity, requiring numerous technological and engineering disciplines and a high level of organizational skill. Human Exploration requires advances in operations, testing, and propulsion for transport to the earth orbit, the moon, Mars, and beyond. NASA is interested in making space transportation systems more capable and less expensive. NASA is interested in technologies for advanced in-space propulsion systems to support exploration, reduce travel time, reduce acquisition costs, and reduce operational costs. The goal is a breakthrough in cost and reliability for a wide range of payload sizes and types (including passenger transportation) supporting future orbital flight vehicles.

Lower cost and reliable space access will provide significant benefits to civil space (human and robotic exploration beyond Earth as well as Earth science), to commercial industry, to educational institutions, for support to the International Space Station National Laboratory, and to national security. While other strategies can support frequent, low-cost and reliable space access, this topic focuses on the technologies that dramatically alter acquisition, reusability, reliability, and operability of space transportation systems.

Subtopics

H2.01 Cryogenic Fluid Management Technologies

Lead Center: GRC

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

This subtopic solicits technologies related to cryogenic propellant storage, transfer, and instrumentation to support NASA's exploration goals. Proposed technologies should feature enhanced safety, reliability, long-term space use, economic efficiency over current state-of-the-art, or enabling technologies to allow NASA to meet future space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Specifically:

- Innovative concepts for cryogenic fluid instrumentation are solicited to enable accurate measurement of propellant mass in low-gravity storage tanks, sensors to detect in-space and on-pad leaks from the storage system, and minimally invasive cryogenic liquid mass flow measurement sensors, including cryogenic two-phase flow.
- Passive thermal control for Zero Boil-Off (ZBO) storage of cryogens for both long term (>200 days) and short term (~14 days) in all mission environments. Insulation systems that can also serve as Micrometeoroid/orbital debris (MMOD) protection and are self-healing are also desired.
- Cryogenic storage technologies for alternate propellants such as xenon.
- Active thermal control for long term ZBO storage for space applications. Technologies include 20K cryocoolers and integration techniques, heat exchangers, distributed cooling, and circulators.
- Zero gravity cryogenic control devices including thermodynamic vent systems, spray bars, mixers, and liquid acquisition devices.
- Advanced spacecraft valve actuators using piezoelectric ceramics. Actuator should reduce the size and power while minimizing heat leak and increasing reliability.
- Propellant conditioning and densification technologies for propellant storage and transfer. Specific component technologies include compact, efficient and economical cryogenic compressors, pumps, Joule-Thompson orifices and heat exchangers. Also, subcooling of propellants for ground processing and long-term in-space cryogen storage and transfer.
- Liquefaction of oxygen for in space applications. This includes passive cooling with radiators, cryocooler liquefaction, or open cycle systems that work with high-pressure electrolysis.
- Efficient small to medium scale hydrogen liquefaction technologies (1-10k gal/day) including domestically produced wet cryogenic turboexpanders.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, and delivering a demonstration package for NASA testing at the completion of the Phase II contract.

**Phase I Deliverables** - Research to identify and evaluate candidate technology applications to demonstrate the technical feasibility and show a path towards a demonstration. Bench or lab-level demonstrations are desirable. The technology concept at the end of Phase I should be at a TRL range of 3-4.

**Phase II Deliverables** - Emphasis should be placed on developing and demonstrating the technology under simulated mission conditions. The proposal shall outline a path showing how the technology could be developed into mission-worthy systems. The contract should deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL range of 4-5.

Potential NASA Customers include:

- Cryogenic Propulsion Storage and Transfer Technology Demonstration Mission.
- Office of Chief Technologist - Game Changing Development Cryogenic Propulsion Stage Program.

**H2.02 In-Space Propulsion Systems**

**Lead Center:** GRC

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

**OCT Technology Area:** TA02

This solicitation intends to examine a range of key technology options associated with cryogenic, non-toxic storable, and solid core nuclear thermal propulsion (NTP) systems for use in future exploration missions.

Non-toxic engine technology, including new mono and bipropellants, is desired for use in lieu of the currently operational NTO/MMH engine technology. Handling and safety concerns with toxic chemical propellants can lead to more costly propulsion systems. NTP systems using nuclear fission reactors may enable future short round trip missions to Mars, by helping to reduce launch mass to reasonable values and thereby increasing the payload delivered for Mars exploration missions.

Non-toxic and cryogenic engine technologies could range from pump fed or pressure fed reaction control engines
of 25-1000 lbf up to 60,000 lbf primary propulsion engines. Pump fed NTP engines in the 15,000-25,000 lbf class, used individually or in clusters, would be used for primary propulsion.

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.

- **Manufacturing techniques** that lower the cost of manufacturing complex components such as injectors and coolant channels. Examples include, but are not limited to, development and demonstration of rapid prototype techniques for metallic parts, powder metallurgy techniques, and application of nano-technology for near net shape manufacturing.

- **High temperature materials, coatings and/or ablative or injectors, combustion chambers, nozzles, and nozzle extensions.**

- **Long life, lightweight, reliable turbo-pump designs and technologies** include seals, bearing and fluid system components. Hydrogen technologies are of particular interest.

- **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.

- **High temperature, low burn-up carbide- and ceramic-metallic (cermet) based nuclear fuels** with improved coatings and/or claddings to maximize hydrogen propellant heating and to reduce fission product gas release into the engine's hydrogen exhaust stream.

- **High temperature and cryogenic 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 are desired. Sensors need to operate for months/years instead of hours.

Note to Proposer: Subtopic S3.03 under the Science Mission Directorate also addresses in-space propulsion. Proposals more aligned with science mission requirements should be proposed in S3.03.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, and delivering a demonstration package for NASA testing at the completion of the Phase II contract.

**Phase I Deliverables** - Research to identify and evaluate candidate technology applications to demonstrate the technical feasibility and show a path towards a demonstration. Bench or lab-level demonstrations are desirable. The technology concept at the end of Phase I should be at a TRL range of 3-4.

**Phase II Deliverables** - Emphasis should be placed on developing and demonstrating the technology under simulated mission conditions. The proposal shall outline a path showing how the technology could be developed into mission-worthy systems. The contract should deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL range of 4-6.
Potential NASA Customers include:

- Office of Chief Technologist/Game Changing Development Program - In-Space Propulsion Project.
- Office of Chief Technologist/Game Changing Development Program - Manufacturing Innovation (MIP).
- Cryogenic Propulsion Stage/Advanced Upper Stage Engine Program.
- Human Exploration and Operations Directorate/Advanced Exploration Systems - Nuclear Cryogenic Propulsion Stage.

H2.03 Advanced Technologies for Propulsion Testing

Lead Center: SSC

Nuclear Thermal Propulsion (NTP), Rocket Based Combined Cycle (RBCC) and Turbine Based Combined Cycle (TBCC) propulsion systems have been identified as high priority NASA technology areas by the United States National Research Council. The goal of this subtopic is to foster development of advanced technologies with commercialization potential that will be needed for component and system level ground testing of these systems during the development and certification phases of their life-cycle.

NTP could be an enabling technology to reduce transit time and mission risk to Near-Earth Objects, Mars, and other deep space destinations. Nuclear power and propulsion technologies are key enabling technologies for future NASA exploration missions. Technology development to facilitate ground testing of NTP is required in the following areas:

- Advanced high-temperature and hydrogen resistant materials for use in a hot hydrogen environment (3000 °F).
- Efficient non-nuclear generation of high flow rate (100 lb/sec), high temperature hydrogen.
- High temperature fluid and thermal management systems.
- High temperature flow control and relief systems.
- High temperature power conversion systems.
- High temperature process piping systems and associated components.
- High temperature instrumentation.

RBCC and TBCC could be enabling technologies to reduce cost for and increase frequency of access to space and allow for rapid transit within the Earth's atmosphere, far exceeding our nation's current capabilities. Technology
development to facilitate ground testing of RBCC and TBCC is required in the following areas:

- Thrust take-out and thrust measurement systems that address the unique challenges of a RBCC / TBCC test facility design.
- Non-intrusive velocity / temperature / pressure profile measurement of inlet and exhaust flows.

For the above technology subject areas, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward hardware and/or material development as appropriate which occurs during Phase II and culminates in a proof-of-concept system.

**Phase I Deliverables** - Phase I deliverables shall include a final report describing design studies and analyses, system, sensor, or instrumentation concepts, prospective material formulations, testing, etc. Prototype systems, components, sensors, instruments or materials can be developed in Phase I as well. The designs or concepts should have commercialization potential. For Phase II consideration, the final report should include a detailed path towards Phase II hardware proof-of-concept system or component or material manufacturing and testing as applicable. The technology concept at the end of Phase I should be at a TRL of 3-4.

**Phase II Deliverables** - Phase II deliverables shall consist of working proof-of-concept systems, tested material formulations with samples, tested component, sensor, or instrumentation hardware, etc. which have been successfully demonstrated in a relevant environment and delivered to NASA for testing and verification. The technology at the end of Phase II should be at a TRL of 6-7.

Potential NASA Customers include:

- Rocket Propulsion Test Program.
- Nuclear Thermal Propulsion Program.