The Exploration Systems architecture presents some propulsion challenges that require new technologies to be developed. Some of these technologies are for long term cryogenic propellant storage, management, and acquisition; deep throttle cryogenic propellant space engines; pressure-fed liquid oxygen\liquid methane propellant reaction control engines; and pressure-fed liquid oxygen\liquid methane propellant space engines. Furthermore, specific technologies are required in valves, regulators, combustion devices, turbo pumps, ignition, instrumentation, modeling, controls, materials and structures, pressurization, mass gauging, and cryogenic fluid management. The anticipated technologies to be proposed are expected to increase reliability, increase system performance, and be capable of being made flight qualified and certified for the flight systems and dates to meet Exploration Systems mission requirements.

Subtopics

X9.01 Cryogenic Propellant Storage and Distribution for Space Exploration Applications

Lead Center: GRC

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

This subtopic includes technologies for long term cryogenic propellant storage and distribution applications in-space as well as on the lunar surface. These technologies will impact cryogenic systems for space transportation orbit transfer vehicles, space power systems, spaceports, spacesuits, lunar habitation systems, robotics, and in situ propellant systems. Each of these applications has unique performance requirements that need to be met. The sizes of these systems range from the small (less than 20m³ for supercritical air and payload cooling) to very large (greater than 3400m³ for LOX and LH₂ 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 and active thermal control, pressure control, and propellant feed line conditioning. Innovative concepts are requested for cryogenic insulation systems, fluid system components, and instrumentation. 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. This subtopic solicits unique and innovative concepts in the following technologies:

1) Thermal Control

Passive Thermal Control:

Successful passive thermal control is enabling for all aspects of Cryogenic Fuel Management. The propellant boil-off losses attributable to the passive thermal control subsystem are influenced by Multi-Layer Insulation (MLI) design, MLI to tank attachment techniques and materials, tank to vehicle support structure and attachments, tank size and configuration, tank and insulation penetrations, insulation venting provisions for launch and ascent, flight and surface environments, vehicle orientation in those environments, and thermal control surface coatings and materials.

Applications/Technology Maturity: The Earth Departure Stage (EDS) and the Lunar Surface Access Module (LSAM) descent stage require LH\textsubscript{2} and LO\textsubscript{2} storage durations of 5 to 95 days in Low Earth Orbit (LEO).

The LSAM ascent stage requires LO\textsubscript{2} and LCH\textsubscript{4} storage durations of up to 95 days in LEO and up to an additional six months on the lunar surface.

Development Needs: Passive thermal control development needs include; integration of MLI with micro-meteoroid protection, tank support structure, and other insulation penetrations. Other development needs include; characterization of the potential advantages of subcooled propellants, investigation of options such as shading, advanced materials, mechanisms and other techniques for passive thermal control on the lunar surface.

Active Thermal Control:

Active thermal control combines the passive thermal control technology element with active refrigeration (cryocoolers) to allow storage periods from a few months to years with reduced boil-off losses.
Applications/Technology Maturity: Flight-type 20K (LH$_2$) cryocoolers of sufficient cooling capacity (20 watts) to eliminate LH$_2$ boil-off do not exist, and thus the development of 20K cryocoolers is a long-lead technology item. State-of-the-art cryocoolers in the 80K range (LO$_2$/LCH$_4$ temperatures) have been developed for cooling sensors and have flown on numerous satellites. However, the integration of these cryocoolers into an active thermal control system for propellant storage of LO$_2$ and LCH$_4$ and LH$_2$ is a technology issue.

Development Needs: Flight cryocooler to propellant tank integration techniques for large space-based storage systems, distributed cooling shields integrated with MLI and development and testing of active cooling techniques for tank penetrations and supports is required. Development of flight-type 20K, 20 watt capacity cryocoolers designed for integration into large space-based LH$_2$ storage systems is also required for application to Mars missions.

2) Pressure Control

Controlling cryogenic propellant tank pressure in low gravity with minimum boil-off losses without settling the propellants can be accomplished with a thermodynamic vent system (TVS). A TVS subsystem typically consists of a pump for circulation and mixing, a Joule Thompson expansion device/heat exchanger for heat removal, valves and a vent line.

Applications/Technology Maturity: A TVS will be required for the EDS, LSAM and the LO$_2$/LCH$_4$ version of the Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) for the CEV.

Development Needs: EDS, LSAM and CEV development needs include innovative TVS configurations and applications, system integration and control and modeling of low-gravity fluid dynamics and heat transfer for specific TVS designs. EDS, LSAM and CEV vehicle advanced development needs include integrated system testing with LH$_2$, LO$_2$ and LCH$_4$ to determine the effect of internal tank hardware configuration on fluid mixing.

3) Propellant Feed Line Conditioning:

Maintaining vapor-free liquid propellant between the tank outlet and the OMS/RCS engine inlet is a significant technology challenge. For lunar in situ cryogenic applications, systems are needed to store and transfer to warm tanks in the dusty lunar surface environment.
Applications/Technology Maturity: Propellant feed line conditioning will be required for all vehicles with a cryogenic OMS/RCS. Specific feed line configuration, routing and heat loads for each vehicle must be addressed.

Development Needs: CEV, EDS and LSAM vehicle development needs includes integrated system testing with LH₂, LO₂ and LCH₄ to address vehicle specific feed line routing and heat loads, and couplings for lunar in situ propellant systems.

**X9.02 Cryogenic Propellant Mass Gauging and Liquid Acquisition for Low Gravity Applications**

*Lead Center: GRC*

*Participating Center(s): MSFC*

This subtopic includes technologies for applications related to cryogenic propellant management in low gravity. Liquid Acquisition Device (LAD) and Mass Gauging (MG) technologies will principally impact cryogenic systems for Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) for orbit transfer vehicles for in-space transportation applications, and are critical to successful liquid propellant delivery to Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) propulsion system and allowance of smaller propellant tank residuals to assure mission success. 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: liquid acquisition devices and mass gauging/advanced instrumentation. Innovative concepts are requested for devices that interface with the tank and provide vapor-free liquids for on-orbit propulsion systems, low-gravity mass gauging technologies to enable accurate and reliable measurements of cryogenic liquid mass in low-gravity storage tanks without propellant settling or undue constraints on mission, and cryogen leak detection technologies. 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. This subtopic solicits unique and innovative concepts in the following technologies:

1) **Liquid Acquisition:**

Providing vapor free cryogenic propellants to in-space propulsion systems at expulsion efficiencies less than 98% without settling the propellants is the objective of the liquid acquisition technology element. Capillary liquid acquisition devices (LADs) are state-of-the-art for toxic propellants, but have not yet been developed for cryogens.
Existing cryogenic upper stage main engine restarts use auxiliary thrusters to settle the propellants.

Applications/Technology Maturity: Cryogenic LADs will be required for the LO$_2$/LCH$_4$ version of the OMS/RCS for the CEV and LSAM and possibly the EDS. LH$_2$ LAD performance represents the primary challenge while LO$_2$ and LCH$_4$ performance risk is substantially less if the liquids are sub-cooled relative to the propellant tank ullage pressure.

Development Needs: Liquid acquisition technology needs include investigation of helium solubility and heat entrapment effects, propellant tank LAD integration, LAD materials selection, analytical performance model development, and techniques to minimize vaporization inside the LAD channel caused by incident heating through tank wall/lines and/or changes in tank pressure. CEV, LSAM and possibly the EDS vehicle advanced development needs include integrated system testing with LH$_2$, LO$_2$ and LCH$_4$ to determine the effect of internal tank hardware configuration on LAD performance.

2) Mass Gauging/Advanced Instrumentation:

The need for a reliable, accurate method for measuring cryogenic propellant mass without settling the propellants is the principal objective of the mass gauging technology element.

Applications/Technology Maturity: Applications for cryogenic mass gauging include the EDS, LSAM and the CEV OMS/RCS. A measurement uncertainty metric of less than 3% of full-tank mass has been established for the propellant mass measurements for these vehicles.

Development Needs: Methods of determining liquid quantity gauging in propellant tanks in low gravity, high accuracy differential pressure transducers which can operate submerged in liquid cryogen, and in-space cryogenic fluid leak detectors.

X9.03 Cryogenic and Non-Toxic Storable Propellant Space Engines
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 toxic but currently operational nitrogen tetroxide and monomethylhydrazine 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. There are also concerns with exhaust residue from toxic systems, which may be carried into habitats for lunar and Mars systems.

The primary mission will be to support lunar ascent/descent reaction control engines and lunar ascent engines. These engines can be compatible with the future use of in situ propellants such as oxygen, methane, and methanol. Key performance parameters:

- Reaction control thruster development is in the 100-500-lbf thrust class with a target vacuum specific impulse of 325-sec. These RCS engines would operate cryogenic liquid-liquid for applications requiring integration with main engine propellants; or would operate gas-gas or gas-storable liquid for small total impulse type applications.

- Ascent engine development is projected to be in the 3,500-6,000-lbf thrust class with a target vacuum specific impulse of 355-sec. The engine shall achieve 90% rated thrust within 0.5 second of the issuance of the Engine ON Command.

Specific technologies of interest to meet proposed engine requirements include:

- Low-mass propellant injectors that provide stable, uniform combustion over a wide range of propellant inlet conditions;

- Combustion chamber designs using high temperature materials, coatings and/or ablatives for 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;

- Highly-reliable, long-life, fast-acting cryogenic valves that tolerate high thermal loading due to heat soakback in low-thrust, pulsing propulsion systems (Thermal Isolation less than 1 Btu/hr) with reduced volume and size is also desirable;

- Highly-reliable, long-life, fast-acting propellant valves for gaseous propellants with reduced power, volume and size.

A key risk related to the use of cryogenic and gaseous propellants such as oxygen and methane are the ability to reliably ignite the propellants in a timely manner. This is of particular importance on ascent engines during abort
operations. Recently NASA has been conducting a number of investigations into the ignition characteristics for oxygen and methane, primarily for spark torch systems. NASA continues to be interested in new and innovative methods which may be used as primary or back-up systems. Proposals are also solicited for igniter exciter technologies. In particular, for reaction control systems involving multiple engines that are not all co-located, issues between distributed vs. centralized exciter architectures must be balanced when selecting an exciter design. A "distributed" system refers to an integral exciter at each spark plug, whereas a "centralized" arrangement has at least some exciter components (e.g., DC-DC converter, control electronics, etc.) remotely located (e.g., with other avionics) and shared by multiple engines/spark plugs. Specific technologies of interest include:

- Reliable ignition systems such as spark torch, catalytic, microwave, combustion wave, laser, etc.;
- Exciters to support either capacitive (CDI) or inductive (IDI) discharge ignition types;
- High cycle spark plugs for use with cryogenic and/or gaseous propellants;
- Cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours.

X9.04 Launch Vehicle Propulsion and Pyrotechnic Technologies

Lead Center: MSFC
Participating Center(s): GRC

The goal of this subtopic is the development of innovative components, manufacturing techniques, health management systems, and design and analysis tools for launch vehicle propulsion and pyrotechnic systems. Performance, reliability, and cost of operations improvements to existing and planned Constellation launch vehicle propulsion and pyrotechnic systems are needed. Technologies that would contribute to decreased sensitivity to manufacturing and handling effects, that will lead to reduction in development and qualification testing, and that will lead to reduction in touch labor during ground operations and vehicle turnaround are particularly welcomed. Also solicited are proposals that would reduce the time, cost, and complexity associated with designing and analyzing launch vehicle propulsion and pyrotechnic systems. While solid or hybrid rocket propulsion is specifically emphasized, compelling proposals related to liquid engine boost propulsion are also invited.

Specific areas of interest include:

- Concepts for solid or hybrid propulsion systems and related components that would lead to increased payload mass fraction over current solid rocket motors.
- Concepts for solid or hybrid auxiliary propulsion systems that can be throttled to provide enhanced vehicle
maneuverability; technology that supports applicability of these systems for in-space primary propulsion is also of interest.

- Health management technologies, including embedded sensors and modeling methodologies, that would improve the ability to monitor the reliability of solid or hybrid rockets during manufacturing, handling, and flight.

- Manufacturing techniques improvements that allow for reductions in the cost and schedule required to fabricate and test solid or hybrid rockets.

- New propellant ingredients or formulations that would increase the propellant specific impulse while maintaining a Department of Transportation Class 1.3 hazard classification; proposals that would experimentally synthesize and characterize new ingredients, or formulate and demonstrate new propellants are encouraged.

- Retrofitable technologies to existing boost liquid engines that address the goals of performance enhancement and/or lower operations cost.

- Improvements in explosive bolt technology, both for traction as well as ejector bolts, to improve handling safety and increasing robustness of installation.

- Improvement to detonators to reduce the required initiation power, or to provide integrated safe-and-arm functions within detonator.

- Wireless or optical approaches for initiation of explosive bolts and frangible nuts for reduced system weight and improved safety.

- Improvements to explosive cutters, cutting chords, and specialty cutting charges to reduce installation labor, check-out labor, and sensitivity to environmental, handling, and ageing effects without reducing reliability.

- Analysis tools that support development and operation of launch vehicle propulsion systems (liquid, solid, or hybrid) by allowing for a more accurate definition of the environment internal to the propulsion system. Test data that provides for validation of existing design and analysis tools is also sought.

- Improvement to the design and analysis tools that support pyrotechnic devices development and integration into the launch vehicle system, especially those tools that define the induced environments created during and immediately after the action time of the pyrotechnic device; Test data to validate and quantify uncertainty in launch vehicle pyrotechnic devices design and induced environments.

Proposals that address more than one of these items are highly encouraged.