NASA/TM—2012-217642

Cryogenic Propellant Storage and Transfer Technology Demonstration for Long Duration In-Space Missions

Michael L. Meyer, Susan M. Motil, Trudy F. Kortes, and William J. Taylor
Glenn Research Center, Cleveland, Ohio

Patrick S. McRight
Marshall Space Flight Center, Huntsville, Alabama

October 2012

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to *help@sti.nasa.gov*

- Fax your question to the NASA STI Information Desk at 443–757–5803

- Phone the NASA STI Information Desk at 443–757–5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2012-217642

Cryogenic Propellant Storage and Transfer Technology Demonstration for Long Duration In-Space Missions

Michael L. Meyer, Susan M. Motil, Trudy F. Kortes, and William J. Taylor
Glenn Research Center, Cleveland, Ohio

Patrick S. McRight
Marshall Space Flight Center, Huntsville, Alabama

Prepared for the
Space Propulsion 2012
sponsored by the AAAF, ESA, and CNES
Bordeaux, France, May 7–10, 2012

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2012

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

Cryogenic Propellant Storage and Transfer Technology Demonstration for Long Duration In-Space Missions

Michael L. Meyer, Susan M. Motil, Trudy F. Kortes, and William J. Taylor
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Patrick S. McRight
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama 35812

Abstract

The high specific impulse of cryogenic propellants can provide a significant performance advantage for in-space transfer vehicles. The upper stages of the Saturn V and various commercial expendable launch vehicles have used liquid oxygen and liquid hydrogen propellants; however, the application of cryogenic propellants has been limited to relatively short duration missions due to the propensity of cryogens to absorb environmental heat resulting in fluid losses. Utilizing advanced cryogenic propellant technologies can enable the efficient use of high performance propellants for long duration missions. Crewed mission architectures for beyond low Earth orbit exploration can significantly benefit from this capability by developing realistic launch spacing for multiple launch missions, by prepositioning stages and by staging propellants at an in-space depot. The National Aeronautics and Space Administration through the Office of the Chief Technologist is formulating a Cryogenic Propellant Storage and Transfer Technology Demonstration Mission to mitigate the technical and programmatic risks of infusing these advanced technologies into the development of future cryogenic propellant stages or in-space propellant depots. NASA is seeking an innovative path for human space exploration, which strengthens the capability to extend human and robotic presence throughout the solar system. This mission will test and validate key cryogenic technological capabilities and has the objectives of demonstrating advanced thermal control technologies to minimize propellant loss during loiter, demonstrating robust operation in a microgravity environment, and demonstrating efficient propellant transfer on orbit. The status of the demonstration mission concept development, technology demonstration planning and technology maturation activities in preparation for flight system development are described.

Introduction

Since the earliest days of the National Aeronautics and Space Administration (NASA), rocket propulsion experts have recognized the value for in-space transportation stages of the high specific impulse that can be achieved with cryogenic propellants (liquid hydrogen (LH_2)/liquid oxygen (LO_2)). However, the very low temperatures and unique thermodynamic and thermo-physical properties of these propellants create extreme challenges for efficient in-space propellant system design and operation. The cryogens have a propensity to evaporate (boil-off) and technologies for propellant management and gauging in microgravity have never been demonstrated. Early efforts to understand the behavior of these propellants utilized drop tower, sounding rocket, and subscale experiments carried out on Mercury missions to address the basic issues faced by the short duration cryogenic upper stages under development at that time, Centaur and Saturn S-IV (Ref. 1).

Although the S-IV and Centaur stages have been successful, the mission designers and cryogenic propellant technologists recognized that these short duration capabilities limited the mission architectural options. In-space transportation stages that can loiter in LEO or deep space for extended durations, or propellant depots that can separate propellant launches from those launching high value hardware, can allow mission architects to greatly improve mission performance. Indeed through the ensuing decades since the last S-IVB flew, technologists have significantly advanced the state of the art in cryogenic fluid management (CFM) through extensive ground testing and additional subscale and simulant fluid drop tower and flight experiments. However, critical CFM phenomena are dependent on the effects of gravity, fluid properties, and the thermal environment of space, and the risks associated with these effects cannot be fully mitigated through ground or subscale testing. Many of these technology development efforts are summarized in references (Refs. 2 and 3). Over this timeframe, NASA developed plans for integrated cryogenic propellant flight demonstrations that would mitigate the technical risk for designers of future long duration in-space transportation stages, but these plans were never realized. These proposed demonstration missions included the Cryogenic Orbital Nitrogen Experiment (CONE) and the Cryogenic Fluid Management Experiment (CFME), but perhaps the most significant effort was that of the COLD-Sat team in the late 1980s and early 1990s (Refs. 4 and 5). COLD-Sat proceeded beyond Phase-A planning and was conceived to be a free flying LH_2 long duration storage and transfer experiment. The COLD-Sat design included three cryogen tanks, a primary storage tank and two tanks for receiving transfer and additional technology demonstrations.

As part of current U.S. National Space Policy, NASA is seeking an innovative path for human space exploration, which strengthens the capability to extend human and robotic presence throughout the solar system. NASA is laying the groundwork to enable humans to safely reach multiple potential destinations, including the Moon, asteroids, Lagrange points, and Mars and its environs. The Agency is leading the Nation on a course of discovery and innovation that will provide the technologies, capabilities and infrastructure required for sustainable, affordable human presence in space. As part of that plan, NASA is embarking on a mission to conduct an in-space Cryogenic Propellant Storage and Transfer (CPST) technology demonstration. This flight demonstration mission will test and validate key cryogenic capabilities and technologies required for future exploration elements, opening up the architecture for large cryogenic propulsion stages and propellant depots. This paper summarizes NASA's efforts to date to formulate and execute this flight demonstration mission.

Project Overview

NASA's Office of the Chief Technologist began a project formulation effort for the CPST Technology Demonstration Mission (TDM) in March 2011 with a goal to identify, develop and implement the appropriate balance of technology maturation activities, including ground and/or flight elements, such that a cryogenic propellant storage and transfer capability technology infusion point, needed for deep-space human exploration missions, is possible in 2017. The specific primary project goal of this exploration-specific TDM Project is to enable the capability of storing, transferring, and measuring quantities of cryogenic propellants in-space with scalability to much larger exploration-relevant systems. The primary objectives of the CPST TDM Project are to store cryogenic propellants in a manner that maximizes their availability for use regardless of mission duration, efficiently transfer conditioned cryogenic propellants to an engine or tank situated in a microgravity environment, and accurately monitor and gauge cryogenic propellants situated in a microgravity environment.

The current baseline mission concept is to develop, launch and operate a free flyer in low earth orbit to demonstrate and mature CFM technologies. The cryogenic fluid management (CFM) technologies in review for inclusion in the planned flight demonstration mission are passive and active cryogenic propellant storage, tank thermal and pressure control, liquid acquisition, and various types of mass gauging. The mission duration is currently estimated to be 6 months, which is based upon the time needed to complete procedures for CFM payload and spacecraft checkout, active and passive storage demonstration, and transfer cycles, both unsettled and settled, and ullage transfer conditions. After the mission is complete, data will be analyzed, and a final mission report will be completed for project closeout. Figure 1 shows the notional mission architecture.

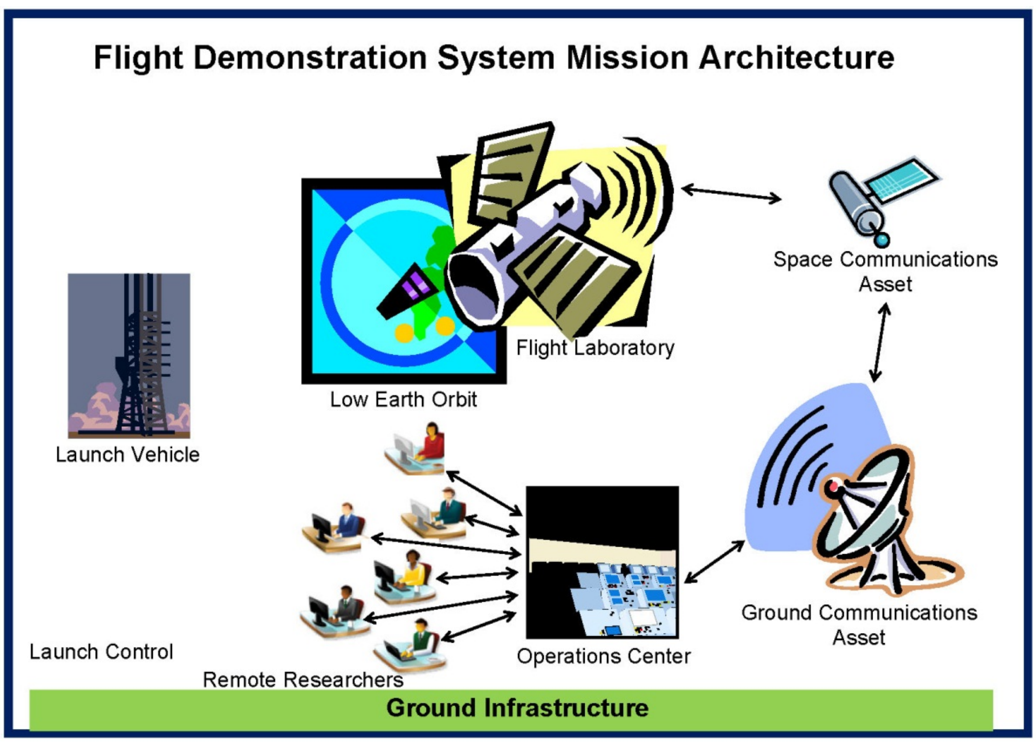

Figure 1.—Mission Architecture

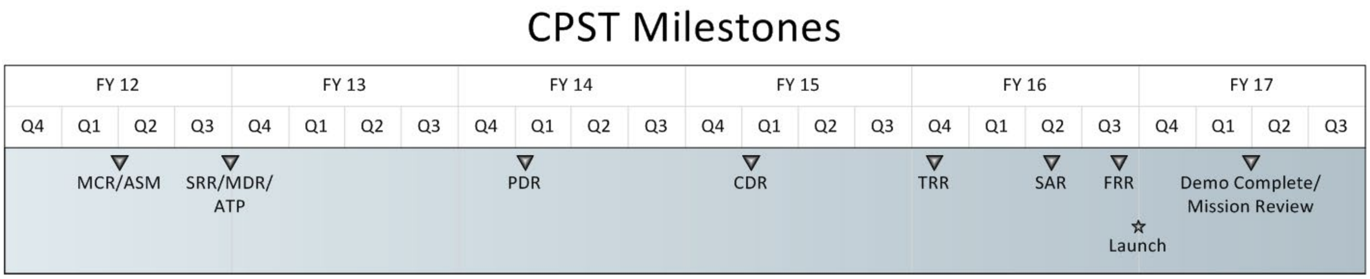

Figure 2.—Notional Project Schedule

Figure 2 shows the notional project schedule including project milestones and projected launch date. The project recently completed a Mission Concept Review. Upcoming milestones include a System Requirements Review and Mission Design Review. At this point, technologies will be at TRL 5 and authority to proceed (ATP) is expected to be granted by NASA's Office of the Chief Technologist to the project to proceed as planned. In FY14, the project will conduct a Preliminary Design Review followed by a Critical Design Review in FY15. A Test Readiness Review covering integrated system testing, System Acceptance Review, and Flight Readiness Review are all expected to occur in FY16 followed by the launch of the CPST TDM late in the fiscal year.

The current plan also includes technology maturation consisting of various ground tests, studies, and analytical modeling. The goal is to achieve a Technology Readiness Level of technologies which will be included in the payload, to TRL 5 which is defined as component and/or breadboard validation in a relevant environment. This suite of activities will focus on the structural and thermal performance of the broad area cooling shield integrated with tank applied multilayer insulation (MLI), thermal performance of composite struts, and liquid acquisition device outflow and transfer line chill down. The plan also includes a ground based LO_2 zero boil-off test, which is not in the critical path of the schedule for the mission.

There are five program level requirements which will eventually be decomposed into project-level requirements and approved at an upcoming System Requirements Review. These requirements pertain to the demonstration of propellant storage, demonstration of propellant transfer, obtaining critical performance data for both LO_2 and LH_2, and the development of performance models.

In order to formulate and execute this project, the project team is organized according to NASA NPR 7120.5 (Ref. 6), as depicted in Figure 3. The team is led by a Project Manager and Deputy Project Manager and has cross-cutting functions such as a Chief Engineer, a Lead Systems Engineer, a Safety & Mission Assurance Lead, a Software and Avionics Lead, Technology Lead and Integration Manager under which schedule and resources are managed. This structure includes Integrated Product Teams (IPTs) which are managed by three lead positions, the CFS Mission Manager, the CPST Integration and Test Manager and the CPST Mission Operations Manager. These IPTs can be viewed as being grouped by major hardware item or event, as they happen chronologically in the project. Specifically, technology maturation feeds into the payload system, followed by payload and spacecraft integration happening first in the hardware development cycle. This is followed by payload/spacecraft bus integration with the launch vehicle followed by testing of the integrated system. Finally, the integrated system is launched, with the Mission Operations IPT handling flight and ground operations as well as mission data processing.

CFM Technologies for Demonstration

During 2011, the technology team considered a full range of potential CFM technical solutions that could address various aspects of the primary and secondary objectives of the flight demonstrator. As all missions are constrained by budget and schedule, every potential technology could not be demonstrated. Thus, it was necessary to develop a"government recommended" reference set of technologies that could address at least the primary mission objectives at a minimum. This list would be used to support project formulation and in developing a Government Mission Concept. It was also recognized that this technology set was likely to evolve as the project matured and as industry partners provided input.

One approach the government team considered for reducing mission cost was to fly a single propellant instead of both LO_2 and LH_2. For this option, LH_2 was chosen as the demonstration propellant. Due to its significantly lower normal boiling point temperature, density, viscosity, and surface tension, LH_2 is considered the more challenging propellant. Additionally, it should be possible to extrapolate data collected with LH_2 to LO_2 systems. Twelve candidate technologies were recommended to be the core technologies demonstrated on the Cryogenic Propellant Storage and Transfer mission. Eleven of these technologies were identified as enabling technologies for either long duration storage of cryogenic propellants or cryogenic propellant transfer. These technologies were also consistent with existing customer requirements as well as other potential applications. Table I lists the recommended technologies for this option and the government team's assessment of each technology's current TRL.

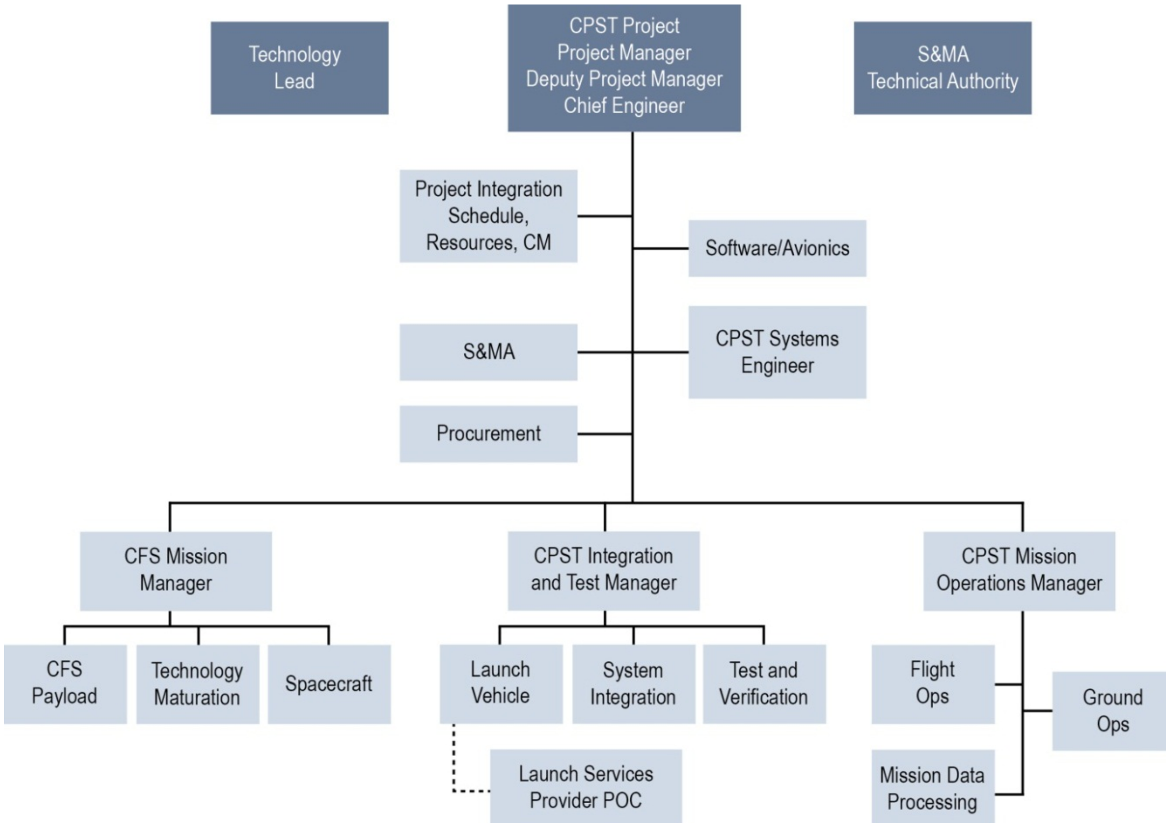

Figure 3.—Project Organizational Structure

TABLE I.—RECOMMENDED TECHNOLOGY SUITE FOR INITIAL GOVERNMENT LH_2 ONLY OPTION
Note: When multiple TRLs are provided, the first is for LH_2 and the second for LO_2.

	CPST Technology	TRL
		Now
1	Active thermal control: Cryocoolers with tube-on-shield heat collection	4
2	Thick multilayer insulation with foam substrate	4/6
3	Low conductivity structures: High strength composite struts	4/6
4	Microgravity pressure control: Thermodynamic vent system	5
5	Microgravity pressure control: Mixing pumps	5
6	Unsettled liquid acquisition devices	4/5
7	Microgravity transfer line chilldown	4
8	Pressurization systems	5
9	Settled mass gauging: Wet/dry silicone diode sensors	5
10	Unsettled mass gauging: Radio frequency gauging	5
11	Microgravity chilldown tank	5
12	Automated leak detection	5

Each of these selected technologies addresses a primary mission objective with the exception of item 12, which addresses a secondary objective and was included because the team evaluated the cost of doing so as minimal.

To reduce risk that development of a technology element might have an unplanned cost or schedule impact on the demonstration mission, NASA decided that the maturity of each cryogenic fluid management technology be ready for infusion into the design of the flight demonstrator prior to the Authority to Proceed (ATP) and provided funding for 1 year of "technology maturation." The team selected the items with TRL highlighted in light shading in Table I as those requiring maturation prior to ATP.

Table II summarizes the technology maturation activities currently in process by NASA in FY12 to address those items that were not considered ready for infusion into the CPST flight system design. The scope includes five major component test activities, various study and analytical tool development activities, some tasks preparing the instrumentation technologies, and an integrated systems test. The Pathfinder Integrated System Test (Ground Test Article or GTA), is being developed in FY12, but will be assembled and executed later such that information gained during the component technology maturation activities can be incorporated where practical.

Mission Concept

NASA conducted an internal conceptual design study from March to October 2011 with the objective of defining a preliminary design concept to enable initial assessments of mission viability and to enable early project formulation activities. The 2011 study also served as a point of departure (POD) for assessing alternative concepts from the U.S. aerospace industry as the CPST TDM Project prepared for its mission concept review in March-April, 2012.

The POD study built upon a series of related NASA studies conducted by the same core team in 2010-2011 in which NASA specialists evaluated a wide range of alternatives involving various launch platforms, fairing sizes, payload accommodations, and propellant selections. Study participants made extensive reference to historical studies such as the COLDSAT studies conducted in the early 1990s and summarized by NASA GRC in 1998 (Ref. 5). The POD study focused on lowering overall costs and shortening schedules while fully addressing CPST's stated needs, goals, and objectives.

The POD study targeted two primary mission goals: (1) demonstrating long-duration in-space storage of cryogenic propellants and (2) demonstrating in-space transfer of cryogenic propellants. The study also focused heavily on reducing development risks for eventual human-rated and robotic missions involving long-term storage of subcritical cryogenic liquids; therefore extensibility of selected concepts and technologies to future missions was a key consideration. These future space missions include cryogenic propulsion stages, tankers, depots, landers, ascent vehicles, nuclear thermal stages, and systems involving in-situ production and storage of cryogenic propellants on the surface of the Moon or Mars.

The resulting design concept involves launch aboard a medium class launch vehicle that delivers the CPST payload to a circular lower Earth orbit of sufficient altitude to reduce atmospheric drag to acceptable levels. The spacecraft, shown in Figure 4 in its on-orbit configuration, would fly in a solar-inertial attitude with the aft end of the spacecraft pointed toward the sun to reduce solar heating of cryogenic tanks and cold structure. The nominal 6-month mission duration would conclude with a controlled re-entry.

TABLE II.—TECHNOLOGY MATURATION ACTIVITIES BEING FUNDED IN FY12
[Note that GTA continues beyond FY12]

Task name	Objective
LH_2 Reduced Boil-Off (RBO) Active Cooling Thermal Demonstration	Demonstration of a flight representative active thermal control system for RBO storage of LH_2 for extended duration in a simulated space thermal vacuum environment
LH_2 RBO Broad Area Cooling Shield/MLI Structural Integrity	Assess the structural performance of an MLI/BAC shield assembly subjected to launch environmental representative loads
Composite Strut Thermal Performance in LH_2	Measurement of heat leak due to composite struts integrated with MLI
Liquid Acquisition Device (LAD) Outflow and Line Chill	Quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow
MLI Penetration Heat Leak Study	Measurement of heat leak due to struts penetration integrated with MLI
Active Thermal Control Scaling Study	Conduct study to show relevancy of CPST-TDM active thermal control flight data to full scale CPS or Depot application
Thick MLI Extensibility Study	Assess optimum approach for attachment of thick (40 to 80 layer) MLI to very large tanks
Analytical tools	Continue development of tools to be validated by CPST
Pathfinder Integrated System Test (GTA)	Demonstrate flight-scale system operations and interactions; demo tank manufacturing; early software development
Instrument Advancement	Mature Radio Frequency Mass Gauge flight avionics and leak detection sensor system for vacuum environment

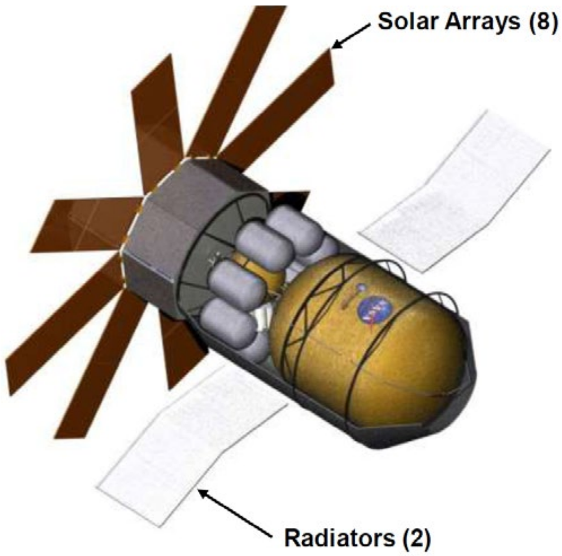

Figure 4.—On-orbit configuration with solar arrays deployed

To meet cost constraints, the POD study opted for a single cryogenic fluid. Based on industry input and internal NASA assessments, the study team opted for LH_2 (rather than oxygen or methane) as the more challenging fluid and the fluid more likely to yield more useful data for correlating analytical models. The POD concept features a large LH_2 storage tank, a smaller LH_2 receiver tank for demonstrating tank-to-tank transfer, a valved transfer line, and a helium pressurization system. LH_2 storage tanks feature both active and passive cryogenic fluid elements, including a cryocooler with tube-on-shield heat collection, a thermodynamic vent system, mixing pumps, multilayer insulation, foam insulation to mitigate pre-launch and ascent heating, and low-conductivity structures to reduce heat leak into the tanks. Liquid acquisition devices within each tank would demonstrate liquid acquisition technologies (e.g., screens, vanes, and sponges) with LH_2 in microgravity. Finally, the POD concept also features a prototype gauging system for accurately and reliably measuring LH_2 levels inside the tanks under both settled and unsettled conditions.

After evaluating integrated and separated bus functions, the team selected an architecture that includes separate spacecraft bus and cryogenic payload. This architecture allows separation of conventional storable propellants and heaters on the bus from the cryogenic tanks and cold structures on the CFS payload and allows for parallel development of bus and payload elements resulting in a shorter schedule.

Finally, the POD study also evaluated the impact of potential funding reductions, prioritizing mission objectives and evaluating the impact of potential descope options in terms of cost savings, technology infusion potential for future missions, and programmatic risks for the CPST mission itself.

Industry Mission Concepts

In order to augment the Government POD study and gain a perspective from the U.S. aerospace industry, NASA released a Broad Agency Announcement (BAA) for CPST Mission Concept Studies in April 2011. NASA selected four of the responding companies, Analytical Mechanics Associates, Ball Aerospace, Boeing, and Lockheed Martin to perform the studies. In addition, United Launch Alliance offered to perform a study at no cost to the Government.

The key study elements were to assess the mission justification and mission goals and objectives, identify CFM technologies and any technology maturation activities required to mature the proposed technologies for incorporation into the flight mission, define a mission concept balancing the technology objectives with cost and schedule constraints, provide a detailed analysis of the flight system, formulate a mission cost estimate and schedule, provide information on potential government and industry partnerships for the project formulation and implementation, and identify major risks to mission success.

The BAA requested mission concepts developed with a target cost of \$200M, with an upper bound of \$300M if sufficient additional value could be demonstrated. The development time for the mission was to be 36 months from authority to proceed (ATP), with up to 12 months of technology maturation activities prior to ATP. The specific capabilities sought included systems to provide zero boil-off storage of LO_2 and LH_2, zero-g mass gauging of cryogenic fluids, and methods to transfer cryogenic fluids in microgravity. The studies also had to show extensibility of the demonstrated capabilities to future space exploration applications such as cryogenic propulsion stages. In addition to the mission goals and objectives, the study participants were asked to cover cryogenic propellant acquisition, cryogenic fluid transfer, cryogenic fluid mass gauging, instrumentation, and tank pressurization methods.

The five studies all concentrated on the flight mission cost challenge. With the mission being defined as deployed in low earth orbit, two of the large cost drivers for any concept are the launch costs and the spacecraft bus functions (e.g., Command & Data Handling, Attitude and Reaction Control, and Power). A third cost driver that factored into the trade studies was the ground loading configuration. The launch costs were attacked in two fashions, either focusing on a dedicated launch on a small low cost launch vehicle or a ride-share, or dual manifest, configuration. The ride share configurations could be larger, taking advantage of the larger payload volumes permissible on a large launch vehicle while not incurring the higher costs associated with those vehicles. The spacecraft bus functionality was implemented either by: 1) a similar architecture to that adopted for the POD with a payload and a separate spacecraft bus or 2) in an attempt to generate additional value by expanding the technology base for future systems by utilizing the cryogenic fluid(s) into the reaction control system. All of the studies identified a ground loading system relying on umbilical connections for loading the cryogens during the launch countdown as a significant cost and schedule challenge. In response to this challenge, approaches that included vacuum jacketed tanks that could allow the experiment tanks to be loaded remotely or facilitate tanking without launch umbilicals, and propellant scavenging from a launch vehicle upper stage once orbit is achieved were developed.

Overall the technologies selected to be demonstrated were similar to technologies selected for the POD. However the experiment configurations varied significantly between the different concepts. Most concepts incorporated both LH_2 and LO_2 into the cryogenic fluid system however the fluid inventories varied over a wide range. At least one concept took a similar approach to the POD, settling on hydrogen as the primary fluid of interest and eliminating oxygen due to cost. As with the POD, thermal control was implemented using a combination of active and passive systems, however several of the concepts emphasized the need to use integrated MLI. Pressurization methods included both helium and pseudo-autogenous pressurization using high pressure hydrogen and oxygen. Several innovative methods for controlling tank stratification and liquid acquisition were also identified.

All of the contractors validated the needs, goals, and objectives of the CPST TDM while providing individual mission concepts that took different approaches to satisfying them, significantly enriching the analysis of alternatives and expanding the trade space for the mission implementation going forward.

Summary

NASA's Cryogenic Propellant Storage and Transfer Technology Demonstration Mission is a critical step in enabling future exploration missions extending beyond low Earth orbit. The project, currently in its formulation stage, is well on its way to the execution of a successful design and build of a payload that will prove out critical CFM technologies. The investment is critical to informing the development of multiple potential exploration applications and would be the culmination of over 50 years of research and ground-based technology development progress. This demonstration mission would result in the advancement of the state of the art of key cryogenic fluid management technologies necessary for future exploration missions.

References

1. Dawson, V.P., and Bowles, M.D., *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket 1958-2002*, NASA/SP—2004-4230, National Aeronautics and Space Administration, Washington D.C., 2004.
2. Motil, S.M., Meyer, M.L., Tucker, S.P., "Cryogenic Fluid Management Technologies for Advanced Green Propulsion Systems," NASA/TM—2007-214810, AIAA-2007-343, AIAA 45th Aerospace Sciences Meeting and Exhibit, 2007.
3. Chato, D.J., "Flight Development for Cryogenic Fluid Management in Support of Exploration Missions," NASA/TM—2006-214262, AIAA-2006-0940, AIAA 44th Aerospace Sciences Meeting and Exhibit, 2006.
4. Martin Marietta Space Systems Inc., "Cryogenic Orbital Nitrogen Experiment (CONE) Design Study," NAS3-25063, September 1990.
5. Kramer, E., "Cryogenic On-Orbit Liquid Depot-Storage, Acquisition and Transfer (COLD-SAT) Experiment Conceptual Design and Feasibility Study," NASA Technical Paper 3523, 1998.
6. NASA Headquarters Office of the Chief Engineer, "NASA Program and Project Management Processes and Requirements," Revision D-NID, 2007.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-10-2012	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE Cryogenic Propellant Storage and Transfer Technology Demonstration for Long Duration In-Space Missions		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Meyer, Michael, L.; Motil, Susan, M.; Kortes, Trudy, F.; Taylor, William, J.; McRight, Patrick, S.		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER WBS 645454.01.04.04.02
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191		**8. PERFORMING ORGANIZATION REPORT NUMBER** E-18200-1
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001		**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
		11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2012-217642

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 20
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The high specific impulse of cryogenic propellants can provide a significant performance advantage for in-space transfer vehicles. The upper stages of the Saturn V and various commercial expendable launch vehicles have used liquid oxygen and liquid hydrogen propellants; however, the application of cryogenic propellants has been limited to relatively short duration missions due to the propensity of cryogens to absorb environmental heat resulting in fluid losses. Utilizing advanced cryogenic propellant technologies can enable the efficient use of high performance propellants for long duration missions. Crewed mission architectures for beyond low Earth orbit exploration can significantly benefit from this capability by developing realistic launch spacing for multiple launch missions, by prepositioning stages and by staging propellants at an in-space depot. The National Aeronautics and Space Administration through the Office of the Chief Technologist is formulating a Cryogenic Propellant Storage and Transfer Technology Demonstration Mission to mitigate the technical and programmatic risks of infusing these advanced technologies into the development of future cryogenic propellant stages or in-space propellant depots. NASA is seeking an innovative path for human space exploration, which strengthens the capability to extend human and robotic presence throughout the solar system. This mission will test and validate key cryogenic technological capabilities and has the objectives of demonstrating advanced thermal control technologies to minimize propellant loss during loiter, demonstrating robust operation in a microgravity environment, and demonstrating efficient propellant transfer on orbit. The status of the demonstration mission concept development, technology demonstration planning and technology maturation activities in preparation for flight system development are described.

15. SUBJECT TERMS
Cryogenic rocket propellants; Cryogenic storage; Cryogenic tanks; Cryogenic temperature; Cryogenics; Cryogenic cooling; Cryogenic fluids; Joule-Thomson effect; Liquid hydrogen; Liquid oxygen

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	14	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802