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CONCEPT DESIGN OF CRYOGENIC PROPELLANT STORAGE AND TRANSFER FOR SPACE EXPLORATION

James M. Free
Deputy Director, NASA Glenn Research Center, Cleveland, Ohio, USA, james.m.free@nasa.gov

Susan M. Motil
Project Manager, CPST Project, NASA Glenn Research Center, Cleveland, Ohio, USA, susan.m.motil@nasa.gov

Trudy F. Kortes
Chief, Space Technology Office, NASA Glenn Research Center, Cleveland, Ohio, USA, trudy.f.kortes@nasa.gov

Michael L. Meyer
Deputy Chief, Power and In-Space Propulsion Division, NASA Glenn Research Center, Cleveland, Ohio, USA, michael.l.meyer@nasa.gov

William J. Taylor
Chief Engineer, CPST Project, NASA Glenn Research Center, Cleveland, Ohio, USA, william.j.taylor@nasa.gov

NASA is in the planning and investigation process of developing innovative paths for human space exploration that strengthen the capability to extend human and robotic presence beyond low Earth orbit and throughout the solar system. NASA is establishing the foundations to enable humans to safely reach multiple potential destinations, including the Moon, asteroids, Lagrange points, and Mars and its environs through technology and capability development. To achieve access to these destinations within a reasonable flight time will require the use of high performance cryogenic propulsion systems. Therefore NASA is examining mission concepts for a Cryogenic Propellant Storage and Transfer (CPST) Flight Demonstration which will test and validate key capabilities and technologies required for future exploration elements such as large cryogenic propulsion stages and propellant depots. The CPST project will perform key ground testing in fiscal year 2012 and execute project formulation and implementation leading to a flight demonstration in 2017.

MISSION NEED

According to a recent United States National Research Council report, "Success in executing future NASA space missions will depend on advanced technology developments that should already be underway."[1] The development of cryogenic propellant storage and transfer technologies has been on-going for more than 50 years. Numerous ground based testing programs in support of proposed flight demonstrations have occurred since the 1960s including the Solar Thermal Upper Stage Technology Demonstrator (STUSTD), Cryogenic Fluid Management Flight Experiment (CFMFE), Cryogenic Orbital Testbed (CRYOTE), Cryogenic Storage and Transfer Flagship Demonstration (CRYOSTAT), and the Cryogenic On-Orbit Liquid Depot Storage and Transfer Experiment (COLD-SAT). In addition to these multiple ground-based programs, cryogenic propellants, liquid hydrogen (LH_2) and liquid oxygen (LO_2) were flown on the SIV-B stage for translunar injection during the Apollo program and have been in use on the upper stages of expendable launch vehicles since the 1960s due to the propulsion performance advantage they provide. Still, the state of the art for storage of cryogenic propellants on-orbit is only 9 hours with boil-off rates on the order of 30 percent per day. There is currently no demonstrated capability to store cryogenic fluids in space for more than these few hours, to gauge cryogenic propellant quantities accurately in a microgravity environment and to guarantee gas-free liquid cryogens transfer from a storage tank without first settling the cryogens over the tank outlet.

In September 2011 NASA announced plans to develop a heavy lift launch vehicle, the Space Launch System (SLS). The Cryogenic Propulsion Stage (CPS) of the SLS is planning on using LO_2 and LH_2 as the propulsion system propellants. In addition, Agency mission architecture studies include consideration of options for propellant resupply, either via tankers or in-space propellant depots. These mission elements have dictated the need for an advanced development program within NASA to mature the necessary cryogenic fluid management technologies required for in-space mission operations and provide a capability not currently available. These include the long duration storage of cryogenic fluids (both active and passive thermal control and microgravity tank pressure control), tank-to-tank transfer of cryogens, and unsettled propellant mass gauging. An in-space flight demonstration of necessary technologies is critical to providing the final steps of development for in-space cryogenic propulsion systems such as the CPS, would bridge current technology gaps, and provide a long-duration cryogenic propulsion system capability.

PROJECT OVERVIEW

The Cryogenic Propellant Storage and Transfer (CPST) Technology Demonstration Mission (TDM) Project was formed in fiscal year (FY) 2011 as a directed mission from the NASA Office of Chief Technologist's Technology Demonstration Mission Program Office to test and validate key cryogenic capabilities and technologies required for future exploration elements. The project was assigned to the NASA Glenn Research Center (GRC) in Cleveland, Ohio, USA. The overall responsibility for project management and both the engineering and technology development elements are managed and planned at GRC. The organization leverages the strengths and partnerships built over time with other NASA centers to bring the highest performing and most technically capable team to support the project. The primary partner center is the NASA Marshall Spaceflight Center (MSFC) serving as a supplier of engineering, technology and test facilities. Other centers contributing to the project are the NASA Goddard Spaceflight Center (GSFC) and the Kennedy Space Center (KSC) An organizational chart is shown in Fig. 1.

The CPST Project is comprised of three interdependent efforts: technology maturation, performance modeling, and the flight demonstration. The current baseline flight demonstration mission plan is to develop, launch and operate a free flying satellite in low Earth orbit to demonstrate and mature CFM technologies. The design concept involves launch aboard a small or medium class launch vehicle that delivers the CPST payload to a circular orbit of sufficient altitude to reduce atmospheric drag to acceptable levels minimizing reboost requirements over the desired mission duration. The spacecraft will likely 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 mission would conclude with re-entry of the CPST payload in compliance with NASA's policies for control of orbital debris.

The CFM technologies included 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 baseline approach is for the CFM payload to be integrated with a spacecraft bus, which will provide attitude control, communication, and propulsion functions for the integrated unit. The mission duration is currently estimated to be 6 months, which is based upon the time needed to complete the CFM subsystem and

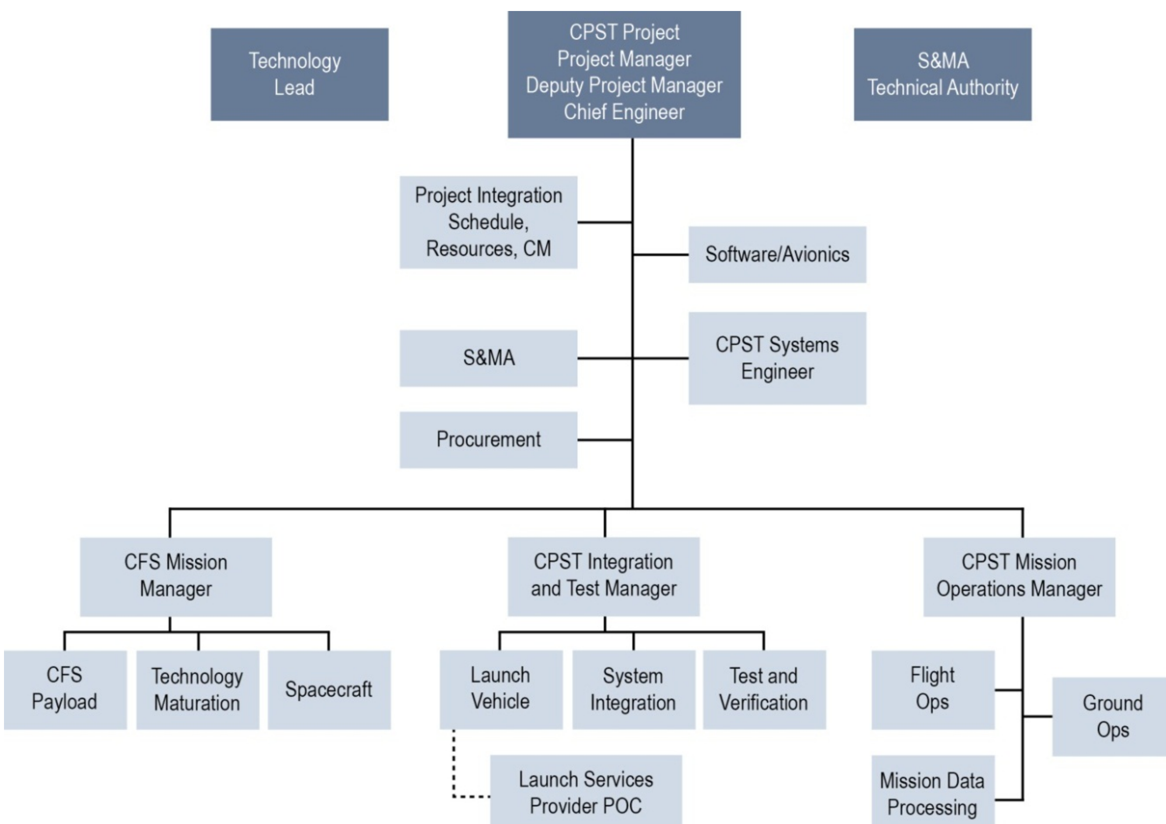

Fig. 1: Project Organization

spacecraft checkout, active and passive storage demonstration, and several transfer cycles at both unsettled and settled conditions. After the mission is complete, data will be analyzed, and a final mission report will be completed for project closeout.

While a baseline has not yet been finalized, the project has five primary requirements to meet: demonstration of propellant storage; validating techniques for thermal conditioning of cryogens; demonstration of propellant transfer via the delivery of gas-free propellants; obtaining critical performance data for LO_2 and LH_2 necessary for critical scaling issues; and providing the development of performance models necessary for designing full-scale long duration cryogenic propellant space systems.

In 2011, the CPST TDM Project conducted Mission Concept Studies, utilizing four industry awardees of Broad Agency Announcement (BAA) opportunities: Analytical Mechanics Associates Inc., Ball Aerospace & Technologies Corporation, The Boeing Company, and Lockheed Martin. These four aerospace companies and United Launch Alliance (via a no-cost Space Act Agreement) submitted mission concept studies for the project. These concepts are being utilized by the government as part of a synthesis activity focused on validating the flight demonstration requirements can be implemented within the project cost and schedule constraints. The basic elements of the Government Point of Departure concept and a summary of the Industry Mission Concept Studies are discussed in the "System Architecture" section of this paper.

GROUND DEVELOPMENT

The technology maturation plan for the CPST TDM project was developed as a three-pronged approach which involves performing CFM ground technology development tests, conducting studies, and developing and utilizing a variety of analytical tools. The combination of these activities will achieve a Technology Readiness Level (TRL) of 5 (defined as component and/or breadboard validation in a relevant environment) for selected storage, transfer, liquid supply, and instrumentation technologies which will be included on the flight mission payload. The execution of this plan has been underway over the course of the last 16 months and is scheduled to be completed by December 2012.

The project team conducted an assessment of several CFM sub-elements and components currently at a TRL 4, and selected technologies to be included on the CPST payload from a broad suite of options and down selected the technologies to be included on the CPST payload. Factors considered as part of the assessment included needs, goals, and objectives for the CPST project; cost and schedule constraints; input from potential technology users; subject matter expert and engineering assessments of technology maturity; and government and industry mission concept studies. In their decision making process, the team also determined whether the various technologies enabled future architectures or simply enhanced them. Out of this process, 12 technologies were chosen to be demonstrated during the CPST TDM mission, are highlighted in blue in Table I.[2]

The technologies chosen to prove out long duration storage are in the areas of passive and active thermal control and microgravity pressure control. Multilayer Insulation (MLI) and a foam substrate will be applied to the propellant storage tank in order to assist in temperature control and uniformity. The MLI will reduce the rate of radiation heat transfer in space and the foam substrate will serve the purpose of reducing the rate of convection heat transfer during ground hold. Low conductivity struts will provide structural support of the tank and also reduce the conductive heat leak into the storage tank. On the active thermal control system, a tube-on-shield broad area cooling (BAC) approach along with a 90 K cryocooler will circulate cold gas to provide active "refrigeration". For microgravity pressure control, a thermodynamic vent system and a fluid mixer will be included inside of the storage tank to help prevent stratification and enable efficient venting without propulsive settling thrust. Technologies related to liquid transfer are microgravity transfer line and receiver tank chilldown, liquid acquisition device, and no-vent fill of the receiver tank. In addition to a suite of pressure and temperature sensors, instrumentation on the payload will include advanced wet/dry point sensors for settled mass gauging and radio frequency unsettled mass gauging, which will be government developed and provided.

To mature the technologies highlighted in Table I to TRL 5, additional technology maturation testing was determined to be required. These activities included an LH_2 Active Cooling Test, a Composite Strut Thermal Performance in LH_2 Test, a MLI/BAC Shield Structural Integrity Test, a thick MLI Penetration Heat Leak Study, and a Liquid Acquisition Device (LAD) Outflow and Line Chill Down test. The LH_2 Active Cooling Thermal Test will provide a demonstration of a flight representative active thermal control system for reduced boil-off (RBO) storage of LH_2 for extended duration in a simulated space thermal vacuum environment.[3] This integrated test of the BAC shield, cryocooler, and radiator is necessary to reach TRL 5. The MLI/BAC Structural Integrity Test will assess the structural performance of an MLI/BAC shield assembly subjected to representative launch acoustic and vibration loads. MLI has flown on multiple small scale dewars, however, extending

Table I: CFM Technologies and Associated TRLs

CFM Technologies			TRL
Category	Subset	Specific	$(LH_2)/(LO_2)$
Long Duration Propellant Storage	Passive Thermal Control	Tank Multilayer Insulation (MLI) With Foam Substrate	(4/6)/(4/6)
		Low Conductivity Structure/Strut	(4/6)/(4/6)
		Vapor Cooled Shields	(5/9)/(N/A)
		Para to Ortho Conversions	(5)/(N/A)
		Densified Propellants	(4/5)/(5)
		Sacrificial Structures	(4)/(4)
		Solar Shield	(4)/(4)
	Active Thermal Control	Cryocooler Development (20 K/90 K)	(2)/(6)
		Cryocooler Integrated BAC Shield—Tube-on-Shield	(4)/(N/A)
		BAC Shield—Tube-on-Tank	(3)/(4)
	Microgravity Pressure Control	TVS	(5)/(5)
		Fluid Mixer	(5)/(5)
Liquid Transfer	Settled/Unsettled	Microgravity Transfer Line Chill Down	(4)/(4)
		Microgravity Receiver Line Chill Down	(5)/(5)
		Pressurization Systems	(5)/(5)
		Two-Phase Fluid Tolerant Transfer Pumps	(3)/(3)
		Automated Fluid Couplings	(4)/(4)
Liquid Supply	Unsettled Liquid Acquisition Devices	Bubble Point Pressure (BPP) Measurement	(4/5)/(5)
		LAD Outflow	(4)/(5)
	Propellant Positioning Using External Forces	Spacecraft Spin	(3)/(3)
		Magnetic Positioning	(2)/(2)
	Autogenous Pressurization	Heat source, heat exchanger, control logic	(3)/(3)
Instrumentation	Mass Gauging	Settled Mass Gauging: CryoTracker	(5)/(5)
		Unsettled Mass Gauging: RF Gauging	(5)/(5)
	Automated Leak Detection	Vacuum compatible distributed sensors	(5)/(5)
	Two-Phase Mass Flow Meters		(3)/(3)
Fluid Handling	Slosh Control	Baffles	(9)/(9)
	Vanes		(6)/(6)
		Technologies selected for flight demonstration	

technology to very large systems has only been done analytically with limited supporting ground test work. The MLI Penetration Heat Leak Study measured MLI thermal performance degradation due to tank structural supports penetrating the MLI, and compared some novel penetration close-out approaches with classical solutions for minimizing the degradation to the MLI thermal performance. The LH_2 LAD Outflow and Line Chill Down test was recently completed at the GRC's Small Multipurpose Research Facility ((SMIRF) see Fig. 2). This test quantified LH_2 screen channel (gallery) LAD stability due to transfer line chill-down transient dynamic pressure perturbations during liquid outflow. Through testing a screen channel LAD flowing LH_2 in a 1-g environment, it was possible to show differences in LADs break-down during flowing conditions versus previous standard static bubble point testing. In addition, testing to optimize line chill-down operations, which included visualization of the two-phase flow, was successfully conducted, which will support development of the flight system.

Two additional ground test activities are planned. The first is a LO_2 zero boil-off demonstration. This test will be similar to the LH_2 Reduced Boil-off test except that the cold gas circulation tubing will be attached directly to the LO_2 tank to intercept environmental heat from entering the tank. For the second test, an Integrated System Ground Test Article will be constructed and tested under thermal vacuum conditions to demonstrate flight-scale system operation and interactions, identify design and control issues, and to provide input for early demonstration payload software development.

In addition to the ground testing, a variety of analytical activities are underway. An active thermal control study and a Thick MLI study are being completed as part of the technology maturation plan. The Active Thermal Control Scaling Study will show the relevance of active thermal control flight data to a full scale CPS or depot application. And the Thick MLI Study will review extensibility by looking at the optimum approach for the attachment of 40 to 80 layers MLI to very large tanks. To ensure the results of the demonstration can be applied to future in-space cryogenic systems, a comprehensive suite of analytical tools is being developed and ultimately validated by the flight results. These tools range from component models (MLI Ascent Venting/Heating, a Generalized Fluid System Simulation Program for propellant loading with tank and transfer line chill down, a No Vent Fill Transfer Model) to integrated cryogenic system thermal and sizing

Fig. 2: Cryogenic Testing in Small Multi-Purpose Research Facility (SMIRF). Test personnel lower test tank hardware into the SMiRF vacuum chamber in preparation for test operations. The SMiRF is a low-cost, medium-scale screening facility simulating space and launch environments for propulsion concepts and component testing with LH_2, methane, and LO_2. Testing includes reduced boil off storage, efficient transfer, and accurate quantity gauging of cryogens in support of the Cryogenic Propellant Storage and Transfer Technology Demonstration Mission (CPST-TDM).[4]

analysis (CryoSIM and TankSIM),[5] A more detailed computational fluid dynamics (CFD) capability is also being developed and validated by the CPST TDM.

The carefully selected group of components and well thought-out plan to develop technologies to an appropriate level of readiness is a key step in accomplishing the objective of flying an in-space experiment, leading to a new capability in space exploration.

SYSTEM ARCHITECTURE AND MISSION CONCEPTS

The generic system architecture for the CPST flight demonstration features a launch element, an orbital element, a communications element, and a mission and technology operations element. The orbital element consists of the cryogenic fluid system technology demonstration payload and the spacecraft bus functionality. The launch element delivers the orbital element to space. The communications element provides the command and data link between the orbital element and the mission and technology operations element. The mission and technology operations element is responsible for the planning and performance of the technology operations along with the on-going engineering housekeeping associated with operating a spacecraft in orbit over the duration of the mission. All of the NASA and Industry Mission Concepts incorporated these basic architectural elements.

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 point-of-departure (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.

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 that would 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, an instrumented transfer line, and a helium pressurization system. The LH_2 storage tank features 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) 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.[6]

After evaluating integrated and separated bus functions, the team selected an architecture that includes a 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.

In preparing for the CPST Mission Concept Review, industry was solicited to provide Mission Concept Studies via a BAA. The primary purpose of these studies was to explore the trade space of alternative mission concepts from other than the government perspective. 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 basic 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 responding to the BAA 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 a dedicated launch on 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. Pressurization methods included both helium and 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. All of these concepts were utilized to demonstrate that viable mission concepts existed within the cost and schedule constraints identified, allowing the CPST TDM project to successfully complete the Mission Concept Review in April of 2012.

NEXT STEPS

Since its inception, the CPST Project has been focused on moving towards a launch date as soon as possible to support NASA's long term exploration through enabling in-space cryogenic propellant depots, orbital loiter of cryogenic propulsion stages in-orbit for extended periods and storage of cryogens for fuel cell feeding to maintain electrical power aboard exploration vehicles. In order to meet the earliest possible schedule and to maintain proper controls and technical rigor, the CPST Project has been closely aligned with and following NASA's program management, project management and technical guidelines.

Per NASA guidelines, the project will step through a series of technical and programmatic reviews followed by Key Decision Points (KDP). The project has completed its Mission Concept Review (MCR) and its KDP-A. The next major project milestone is completion of Acquisition Strategy planning. Following that, the project will proceed through the final phases of the formulation stage with a System Requirements Review scheduled for the last quarter of 2012. Project preliminary and critical design reviews are to take place in 2015. A launch date is tentatively slated for December 2016.

The top level project schedule is shown in Fig. 3.

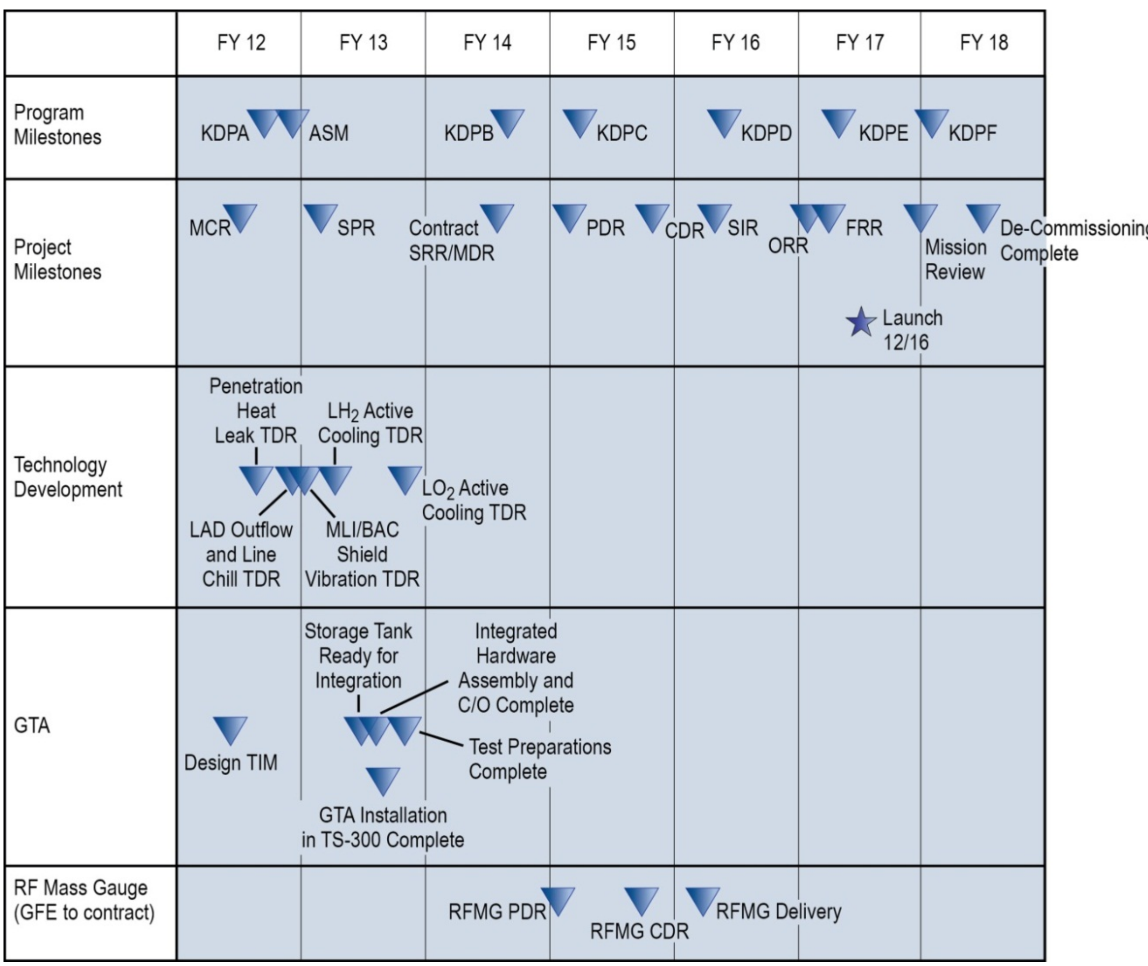

Fig. 3: Notional CPST TDM Project Schedule

CONCLUSION

Cryogenic propellant storage and transfer technologies are at a tipping point. A small amount of additional investment will provide the capability to store and transfer cryogenic propellants in space for long durations.[1] This exploration-specific TDM project will, for the first time, demonstrate the capability of storing cryogenic propellants in-space for an extended period of time. A demonstration mission would serve to advance these systems to enable their practical use on long duration space missions by demonstrating the ability to store cryogenic propellants in a manner that maximizes their availability, transfer conditioned cryogenic propellant to an engine or tank, and accurately monitor and gauge cryogenic propellants in microgravity. The technologies developed and matured during the execution of this mission could then be infused into future in-space and planetary applications including in-situ resource utilization systems, tankers, landers, ascent vehicles, nuclear thermal systems, and a cryogenic propulsion launch vehicle stage. This will ultimately advance the state-of-the-art of a system critical to the advancement of space exploration and provide a space exploration capability that is not currently available.

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