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Thermodynamic analysis of a demonstration concept for the long-duration storage and transfer of cryogenic propellants

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ABSTRACT

In the development of a concept for an experimental platform for demonstrating technologies associated with the on-orbit handling, transfer and storage of cryogenic propellants, credibility is enhanced with simulations of operations using thermodynamic models. Predictions have further credibility if the modeling technique is verified against simulations of actual cryogenic fuel transfers during ground testing. This paper will demonstrate the capability of simulating the transfer of liquid hydrogen as preformed at NASA's Glenn Research Center. Results of simulations of an experimental space mission developed at Ball Aerospace will then follow. The mission concept is intended to demonstrate the technologies and storage methodologies for supporting long-term storage and transfer of cryogenic fuels in space.

1. Introduction

One method NASA is considering for sending rockets on deep space missions (e.g. lunar, Mars) involves refueling with cryogenic propellants in Earth orbit. The benefit over traditional single use rockets is significant improvement in delivered payload mass. Prior to deploying such infrastructure as fuel depots and Earth Departure Stages, demonstration missions are needed to prove necessary technologies such as cryogenic liquid-only transfer and long term fuel storage.

To this end, Ball Aerospace developed a concept for a Cryogenic Propellant Storage and Transfer (CPST) mission for NASA Glenn Research Center (GRC). The effort entailed conducting a detailed design of the demonstration mission concept with the goal of meeting all CPST program capabilities including remaining within a cost cap of $200M that includes launch vehicle and group operations.

Along with designing the hardware needed to demonstrate cryo-fluid management (CFM) technologies, Ball Aerospace developed thermodynamic system level models to simulate cryogenic storage and transfer operations. Concurrently, similar models proved highly accurate at simulating no-vent hydrogen transfers tests that were conducted at GRC in 1991. Verification of the thermal/fluid modeling technique provides confidence for the success of the demonstration mission and its extension to fuel depots and cryogenic propulsion stages (CPS).

2. Mission justification

Numerous studies of efficient access to deep space have noted the benefits of using orbiting fuel depots [1–4]. Not only can transferring cryogenic fuels in orbit increase the delivered mass to deep space destinations, but using this refueling option provides the potential to use the same reliable and less expensive rockets that currently insert satellites into low Earth orbit for longer duration missions.

With low fluid temperatures and two-phase conditions, high specific-impulse fuels present low-gravity fluid management challenges. Demonstration missions will be necessary to verify the feasibility of long term, in-space cryogenic propellant storage and zero-gravity transfer of cryogenic propellants. These missions must demonstrate the ability to repeatedly extract gas-free liquid fuel from propellant storage tanks, measure fluid quantities on-orbit as well as expel liquid-free gas for thermal management. Key technologies for making these operations possible include propellant management devices (PMD) for controlling the location of liquid in zero-gravity, validated micro-gravity mass gauging devices, and correlated fluid/thermodynamic simulations of fluid transfers and storage. Once flown, the CPST mission will validate these operations for future deep space flight programs.

3. Mission concept

The intent of the CPST mission is to demonstrate long term cryogenic fuel storage as well as liquid transfers. Ideally, fluid would be transferred in and out of the storage tank as would be

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the case for a fuel depot. A demonstration mission with such a capability would require greater complexity, limit verification of long term storage and likely exceed the cost goal. Thus, Ball Aerospace's CPST mission concept includes a single 1650 liter hydrogen storage tank containing a propellant management device (PMD), a single 110 liter tank to which fluid is transferred and two pressurant tanks all supported above a spacecraft bus module as shown in Fig. 1. A cross-section of the supply tank is shown in Fig. 2.

Additionally, a fully functional propellant storage depot must be capable of delivering oxygen as well as hydrogen. This CPST concept demonstrates fluid transfers with LH2 alone (LH2 being the colder and more difficult to manage of the two fluids), accomplishing the vast majority of NASA's objectives for a CPST while remaining within the cost cap goal. The complete CPST mission concept includes ground operations for loading and conditioning hydrogen prior to launch and is addressed in the concept description report [5].

The primary operation intended to be demonstrated is the reliable and repeatable transfer of vapor-free liquid propellant at cryogenic temperatures. This is accomplished in the Ball mission concept by autogenous transfers of LH2 from the storage tank to the transfer tank using higher pressure gaseous hydrogen. Once a transfer has been completed, heaters on the transfer tank drive out the liquid propellant to space so that a second transfer operation can be performed. Following these transfers, the fuel tank will demonstrate its long term storage capability using a highly efficient multi-layer insulation (MLI), a thermodynamic vent system (TVS) and a vapor cooled shield (VCS). A final fuel transfer operation occurs when only 15% of the original quantity remains in the supply tank. A fuel transfer near the end of the mission will show the capability of the transfer process regardless of storage tank fill level. Fig. 3 shows a simplified schematic of the design.

3.1. Storage tank fluid management design

One of the most critical design features of the CPST storage tank that has only poor ground test verification capability is the propellant management device (PMD). Successful fuel transfer requires guaranteed access to vapor-free fuel. For emergency pressure control, however, access to liquid-free vapor is also necessary, even with a tank liquid fill fraction as great as 95%. The PMD designed for this demonstration mission is show in Fig. 4 and consist of 16 perforated and tapered panels supported radially from a center post.

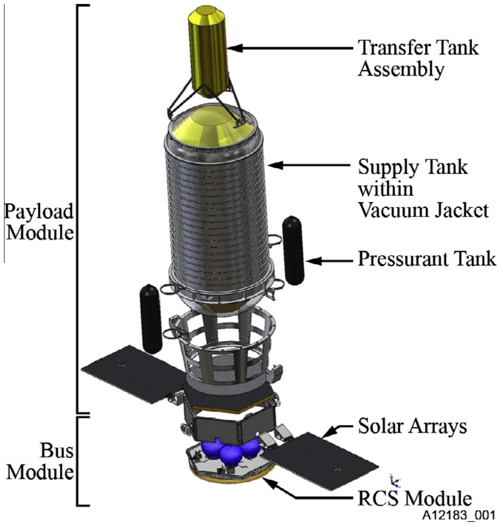

Fig. 1. Expanded view of the CPST spacecraft components.

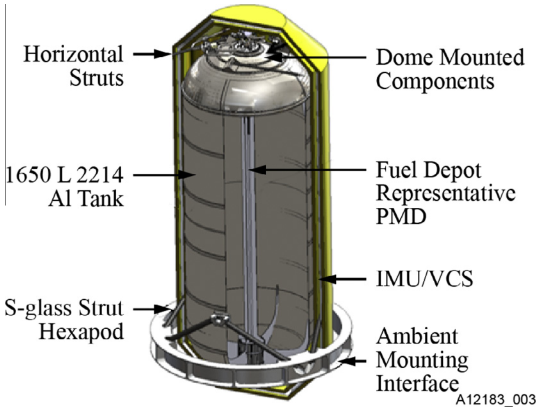

Fig. 2. Cut-away view of CPST storage tank.

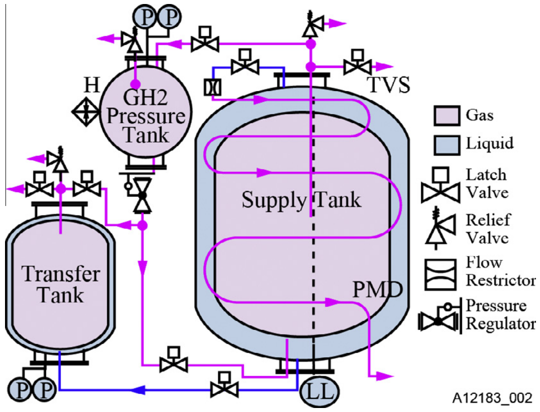

Fig. 3. Simplified CPST Schematic.

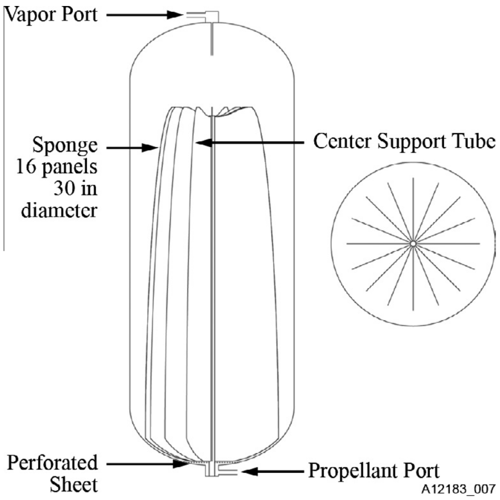

Fig. 4. CPST supply tank PMD concept.

A similar PMD was used successfully in the Viking Orbiter 0.91 m (36 in.) diameter, 1.37 m (54 in.) long propellant tank. The titanium panels had a thickness of 0.18 mm (0.007 in.) [6].

At a fill fraction of 95%, the corresponding vapor bubble that would exist in a microgravity environment is supported at the open end of the tank where a vent tube can extract vapor. The