Settled Cryogenic Propellant Transfer

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Abstract

Cryogenic propellant transfer can significantly benefit NASA’s space exploration initiative. LMSSC parametric studies indicate that “Topping off” the Earth Departure Stage (EDS) in LEO with ~20 mT of additional propellant using cryogenic propellant transfer increases the lunar delivered payload by 5 mT. Filling the EDS to capacity in LEO with 78 mT of propellants increases the delivered payload by 20 mT. Cryogenic propellant transfer is directly extensible to Mars exploration in that it provides propellant for the Mars Earth Departure stage and in-situ propellant utilization at Mars.

To enable the significant performance increase provided by cryogenic propellant transfer, the reliability and robustness of the transfer process must be guaranteed. By utilizing low vehicle acceleration during the cryogenic transfer the operation is significantly simplified and enables the maximum use of existing, reliable, mature upper stage cryogenic-fluid-management (CFM) techniques. Due to settling, large-scale propellant transfer becomes an engineering effort, and not the technology development endeavor required with zero-gravity propellant transfer. The following key CFM technologies are all currently implemented by settling on both the Centaur and Delta IV upper stages: propellant acquisition, hardware chilldown, pressure control, and mass gauging. The key remaining technology, autonomous rendezvous and docking, is already in use by the Russians, and must be perfected for NASA whether the use of propellant transfer is utilized or not.

Nomenclature

CaLV Cargo launch vehicle (>100 mT class)
CEV Crew Exploration Vehicle
CLV Crew Launch Vehicle
EDS Earth Departure Stage
g Earth’s Gravity
LAD Liquid Acquisition Device
LEO Low Earth Orbit
LOI Lunar Orbit Insertion
LSAM Lunar Surface Access Module
PMD Propellant Management Device
SM Service Module
TEI Trans Earth Injection
Introduction

In January 2004 President Bush announced a new vision for NASA’s Space Exploration Program. He challenged America to return to the moon, and explore worlds beyond our own. In response, NASA developed a baseline lunar exploration architecture (ref. 1) centered on the launch of a CaLV and CLV with LEO rendezvous (fig. 1).

ESAS Baseline Architecture

The ESAS baseline exploration architecture utilizes the CaLV to launch the EDS and LSAM. This architecture requires the EDS to burn ~45 percent of its 170 mT of LO₂ and LH₂ to achieve Earth orbit. Following rendezvous with the CEV, the EDS completes a second burn sending the LSAM and CEV on their trajectory to the moon.

The use of the EDS to achieve Earth orbit and accelerate the stack to Earth departure velocity results in a stage that is much heavier than if it were sized strictly to complete the Earth departure burn starting in LEO. This oversized stage also provides a sizeable side wall profile, absorbing significantly more heat than a smaller stage would. This heating increases propellant boil-off during the up to 95 days of on-orbit waiting for the launch of the CEV.

Benefit of Topping Off the Earth Departure Stage

The oversized EDS provides NASA’s exploration architecture with an excellent opportunity to significantly increase the lunar delivered payload, or alternatively reduce the CaLV payload requirement. Through the use of cryogenic propellant transfer, NASA could top off the EDS in LEO. Following the LEO insertion burn, the EDS retains ~92 mT of its 170 mT propellant capacity (ref. 2). After the LEO burn, the EDS could be filled with up to an additional 78 mT of propellant.

“Topping off” the EDS with ~20 mT in LEO, using cryogenic propellant transfer, increases the useful, lunar delivered payload by 5 mT (fig. 2). Filling the EDS to capacity in LEO with 78 mT increases the delivered payload by over 20 mT.

Figure 1.—The ESAS baseline architecture consists of the launch of the EDS and LSAM with a CaLV followed by the CEV launch on a CLV.
Cryogenic Propellant Transfer Made Easy

Typically, cryogenic propellant transfer has been synonymous with zero-g propellant depots (fig. 3). Large scale cryogenic depots envisioned as refueling stations for robust exploration are sufficiently massive that operations must be conducted in a zero-g environment. Transferring cryogenic propellants in zero-g places significant technological hurdles on propellant transfer, such as: zero-g mass gauging, propellant acquisition, and pressure control (table I). This ideal cryogenic propellant transfer is frequently coupled with the desire for zero boil-off and zero vent fill. Although admirable goals, these “ideal” propellant transfer features have erected technological barriers that have successfully blocked the implementation of cryogenic propellant transfer, and prevented realization of the enormous benefits that propellant transfer offers.

Utilizing acceleration during the cryogenic propellant transfer procedure significantly simplifies the operation by enabling the maximum use of existing, mature upper stage cryogenic-fluid-management (CFM) techniques. With settling, large-scale propellant transfer becomes an engineering effort, not a technology development endeavor. The key technologies: propellant acquisition, hardware chilldown,
pressure control, and mass gauging are all currently in use on the Atlas V Centaur and the Delta IV upper stage. The key remaining technology, rendezvous and docking is required regardless of the use of propellant transfer.

Historically, settled propellant transfer between vehicles has been ruled out because of the assumed large quantity of propellant required for settling. However, at sufficiently low settling levels this settling propellant becomes manageable (fig. 4). For a representative 100 mT system, settling consumes 100 lb/hr of settling propellant, at $10^{-4}$ g. At $10^{-5}$ g this settling consumption decreases to 10 lb/hr. This settling propellant could easily consist of warm vented GH$_2$ and GO$_2$ extracted from the EDS for pressure control during the propellant transfer process.

### Key Enabling Technologies

The enabling technologies allowing implementation of cryogenic propellant transfer are currently in use on existing cryogenic, multi-burn stages. A partial list of relevant CFM capabilities that have been demonstrated on Centaur is provided in table II.
TABLE II.—CENTAUR HAS CONDUCTED NUMEROUS CFM FLIGHT DEMONSTRATIONS RELEVANT TO CRYOGENIC PROPELLANT TRANSFER

<table>
<thead>
<tr>
<th>Liquid control (10⁻³ to 6 g’s)</th>
<th>Long coast (to 17 hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System warming and chilldown</td>
<td>Pressurization sequencing</td>
</tr>
<tr>
<td>Propellant acquisition</td>
<td>Slosh characterization</td>
</tr>
<tr>
<td>System thermal interaction</td>
<td>Vent sequencing</td>
</tr>
<tr>
<td>Ullage and liquid stratification</td>
<td>Pressure collapse</td>
</tr>
<tr>
<td>Propellant utilization</td>
<td>Bubbler vs. Ullage Pressn.</td>
</tr>
<tr>
<td>Mass gauging</td>
<td>Unbalanced venting</td>
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</tbody>
</table>

Over the past 15 years, Centaur has spearheaded the development of ultra low settling for CFM. Centaur has reduced the standard parking orbit coast settling from 10⁻³ to 2×10⁻⁴ g for short coast missions; realizing a significant performance enhancement, while maintaining adequate propellant control. For intermediate coast durations between 20 min and 2 hr, Centaur has further reduced the settling acceleration to 8×10⁻⁵ g’s.

In the quest for even more performance, Centaur has demonstrated effective propellant control at accelerations down to 10⁻⁵ g (fig. 5). Similarly, in the 1960s Saturn (ref. 10) also demonstrated effective settling at 2×10⁻⁵ g.

**Low Acceleration Settling**

Propellant acquisition through settling has been used reliably for all large scale cryogenic upper stages. Expulsion efficiencies well in excess of 99.5 percent of liquids are achieved on Centaur, even at the relatively low accelerations encountered during pre-start and blowdown. Expulsion efficiency at 10⁻⁵ g is yet to be demonstrated.

With settled operations, expulsion efficiency is further increased by the ability to maintain a warm ullage. Settling effectively separates the liquid and gas in a tank enabling the ullage to remain warm during the expulsion process. By allowing the ullage to remain warm, there is the potential to increase total expulsion efficiency by ~0.9 percent (fig. 6).
System Chilldown

The Centaur upper stage has demonstrated highly efficient hardware chilldown procedures that are directly applicable to cryogenic transfer. Chilldown of ducting, tank walls and the engine have been demonstrated with multiple alternate chilldown procedures. Chilldown effectiveness using full, trickle, and pulse LH₂ and LO₂ flow has been demonstrated in the low g space environment. Pulse chilldown has proven to be especially effective at chilling down the feed lines and engine due to the ability to gain the full benefit of the heat of vaporization and vapor expansion cooling.

Mass Gauging

With settling, mass gauging can be accomplished using numerous accurate and reliable techniques. Measuring the acceleration achieved with a known settling thrust provides a simple method that accurately gauges total system mass. Thermal couples and liquid sensors internal to the tank, or mounted to the outside of a thin walled tank have proven very effective in defining the station level of the liquid/gas interface (fig. 7). The cryo tracker (refs. 3 and 11) concept promises a simple robust system for accurate liquid surface gauging at low acceleration. At the higher accelerations realized during a burn, tank head pressure has proven to be very effective at measuring liquid mass, ensuring >99.9 percent relative LO₂/LH₂ propellant expulsion efficiency for Centaur. Understanding the propellant mass during
the high acceleration environment during a burn can be coupled with book keeping propellant vented during a coast to provide an accurate understanding of the propellant remaining in the tank. All of the above methods other than cryo tracker, have been successfully used on Centaur during actual flights to understand the quantity of LH₂ and LO₂ remaining in the tanks.

**Pressure Control**

Low-g settling provides a flight proven, reliable method to separate liquid and gas (fig. 6). This settling can be continuous for short coast durations, or intermittent, separating long zero-g periods, potentially weeks with adequate tank insulation, for long coasts. This liquid/gas separation enables heat rejection via venting for long coasts and has been demonstrated on 183 Centaur flights, 8 Delta III and IV flights, and 8 Saturn S4B flights. Settled venting results in extremely robust tank heat rejection. This robustness is due to the fact that any localized propellant warm spots, due to penetration or other high heating sources, causes the propellant to boil regardless of the location in a tank. Alternative, zero-g vent systems rely on mechanical mixers to distribute the point cooling during venting. The mixer must ensure complete tank mixing, otherwise localized hot spots will develop resulting in potentially uncontrollable tank pressure.

Similarly, settling allows venting during propellant transfer to maintain pressure in the receiver tank at desired levels. With extremely low acceleration, propellant entering the receiver tank may geyser. To prevent liquid venting, the propellant transfer process may need to be accomplished in pulse mode, where propellant transfer and venting are conducted sequentially.

**Long Term Cryogenic Storage**

A recent study on the Centaur indicates how robust passive long term LO₂/LH₂ storage can be accomplished (ref. 5). The study shows that efficient passive cryogenic storage for periods up to a year is feasible with proper system design.

**Fluid Coupling**

Robust but heavy cryogenic fluid couplings are routinely used for cryogenic launch vehicle tanking. Numerous concepts have been considered for flight capable variants of these ground systems. One option for a cryogenic fluid coupling is derived from the Centaur LO₂ feedline slip duct that is currently used on Centaur. This slip duct is a flight proven component that provides the required cryogenic sealing, coupling and decoupling, and high-flow capacity with minimal thermal mass. Development of a coupling that can mate autonomously on-orbit will require significant development.

**Centaur Test Bed**

The end to end demonstration of cryogenic propellant transfer can be demonstrated as a low cost, ride share payload on near term Atlas Centaur missions. The Centaur Test Bed (CTB) (ref. 8, fig. 8), is a ride share payload concept that would be mounted to the Centaur aft bulkhead. Following delivery of the primary payload the CTB would then take advantage of the thousands of pounds of residual LO₂ and LH₂ typical of upcoming Atlas missions to demonstrate the actual fluid coupling, chilldown, transfer and pressure control processes. Such an end to end demonstration could be cost effectively repeated multiple times defining preferred process operations and repeatability. This would set the stage for successful, low risk implementation of large scale cryogenic propellant transfer in support of exploration. Development of the CTB concept was conducted under contract to NASA Glenn (ref. 9).
Simplified Stages

By sizing the EDS sufficiently to accommodate all of the propellant required for a lunar mission, the other transportation elements comprising exploration, LOI, Lunar Descent, Lunar Ascent, and TEI could be designed to be launched empty. Once these elements are on orbit, propellant could be transferred from the EDS into these propulsion stages that are strictly designed to contain propellants in the space environment. By eliminating the need to accommodate propellant during ground operations and launch, these elements could be made significantly lighter by eliminating the foam insulation required while in the atmosphere, and designing the structure for the significantly reduced loads. Weight savings on the LSAM and TEI stages are the most critical since they both are carried through significant delta velocities.

Conclusion

NASA’s current exploration architecture can significantly benefit from the use of on-orbit refueling to increase the lunar delivered payload, or alternatively reduce the CaLV payload requirement. Through the use of cryogenic propellant transfer NASA could top off the EDS in LEO. “Topping off” the EDS with \(~20\) mT in LEO, using cryogenic propellant transfer, increases the lunar delivered payload by 5 mT. Entirely filling the EDS in LEO with 78 mT increases the delivered payload by over 20 mT.

Utilizing low level acceleration during the cryogenic propellant transfer procedure significantly simplifies the entire operation, enabling the maximum use of existing, mature upper stage cryogenic-fluid-management (CFM) techniques. Settled methodologies for propellant acquisition, hardware chilldown, pressure control and mass gauging are already in service on Atlas V Centaur and Delta IV upper stage. The vital remaining technology, autonomous rendezvous and docking is required regardless of the use of propellant transfer. Although the key CFM technologies have been independently developed and demonstrated, the complete system operation in the space environment must be demonstrated. Near term ride share opportunities, such as CTB, can be used to demonstrate the system functionality of cryogenic propellant transfer.
References

2. Stage and propellant mass were derived from the ESAS final report, reference 1, updated with personal communication with multiple sources at MSFC.
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