

Settled Cryogenic Propellant Transfer

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Bernard F. Kutter^{*}, Frank Zegler[†], Steve Sakla[‡],
John Wall[§], Greg Saks^{**}, Jack Duffey^{††} and Josh Hopkins^{‡‡}

Lockheed Martin Space Systems Company

Denver, CO

David Chato^{§§}

NASA Glenn Research Center

Cleveland, OH

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.

^{*} Sr. Staff, Atlas Advanced Programs, Lockheed Martin P. O. Box 179 Denver Co 80201 MS T9115, AIAA Member.

[†] Sr. Staff, Atlas Propulsion. Lockheed Martin P.O. Box 179 Denver Co 80201 B3300, AIAA Member.

[‡] Staff, Atlas Propulsion. Lockheed Martin P.O. Box 179 Denver Co 80201 B3300, AIAA Member.

[§] Sr. Staff, Atlas Propulsion. Lockheed Martin P.O. Box 179 Denver Co 80201 B3300, AIAA Member.

^{**} Mgr, Space Exploration, Lockheed Martin 4800 Bradford Dr., Bldg 403, Huntsville Al 35807

^{††} Staff, Space Exploration, Lockheed Martin 4800 Bradford Dr., Bldg 403, Huntsville Al 35807,

^{‡‡} Staff, Exploration Architecture, Lockheed Martin P. O. Box 179 Denver Co 80201 MS T9115, AIAA Member.

^{§§} Aerospace Engineer, NASA Glenn Research Center. 21000 Brookpark Road, Cleveland, OH MS 86-2, AIAA Associate Fellow.

Acronyms

| | |
|------|--------------------------------------|
| 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 |

I. 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 architecture¹ centered on the launch of a CaLV and CLV with LEO rendezvous, Figure 1.

A. 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% 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.

B. 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 capacity². 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, Figure 2. Filling the EDS to capacity in LEO with 78 mT increases the delivered payload by over 20 mT.

II. Cryogenic Propellant Transfer Made Easy

Typically, cryogenic propellant transfer has been synonymous with zero-g propellant depots. (Figure 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 1) 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.

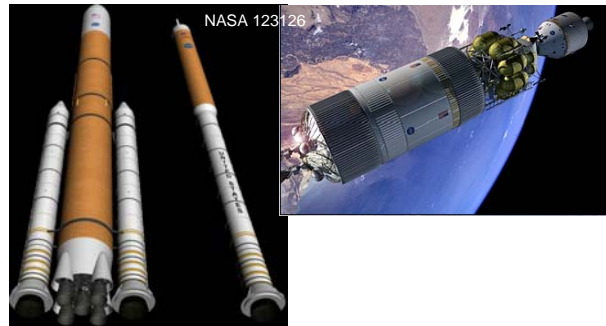


Figure 1. The ESAS baseline architecture consists of the launch of the EDS and LSAM with a CaLV followed by the CEV launch on a CLV. Credit NASA

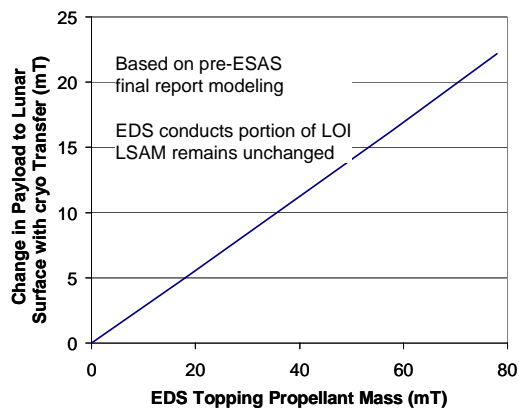


Figure 2. Topping off The EDS results in a Tremendous Increase of Lunar Delivered Payload.

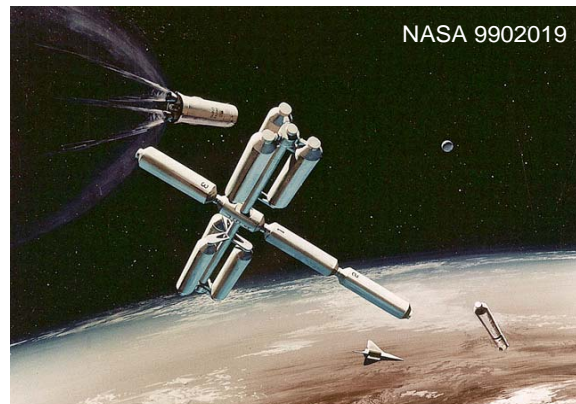


Figure 3. Permanent Space Based Propellant Depot. Credit NASA

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. (Figure 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/hour. This settling propellant could easily consist of warm vented GH2 and GO2 extracted from the EDS for pressure control during the propellant transfer process.

III. 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 2.

C. Low Acceleration Settling

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} g 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 minutes and 2 hours, Centaur has further reduced the settling acceleration to 8×10^{-5} Gs.

In the quest for even more performance, Centaur has demonstrated effective propellant control at accelerations down to 10^{-5} g, Figure 5. Similarly, in the 1960's Saturn¹⁰ also demonstrated effective settling at 2×10^{-5} g.

D. Propellant Acquisition

Propellant acquisition through settling has been used reliably for all large scale cryogenic upper stages. Expulsion efficiencies well in excess of 99.5% 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.

Table 1. Settled cryogenic propellant transfer can benefit from the vast CFM experience used on Centaur and other cryogenic upperstages.

| Cryo Transfer Technology | TRL | |
|---------------------------------|------------------|---------|
| | 0-G ⁶ | Settled |
| System Chilldown | 8 | 8 |
| Propellant acquisition | 3 | 9 |
| Passive Long Duration Storage | 5 | 5 |
| Ullage & Liquid Stratification | 3 | 9 |
| Propellant Expulsion Efficiency | 3 | 8 |
| Mass Gauging | 3 | 9 |
| Pressure Control | 4 | 9 |
| Fluid Coupling | 6 | 6 |
| AR&D | 6 | 6 |
| Transfer System Operation | 3 | 6 |

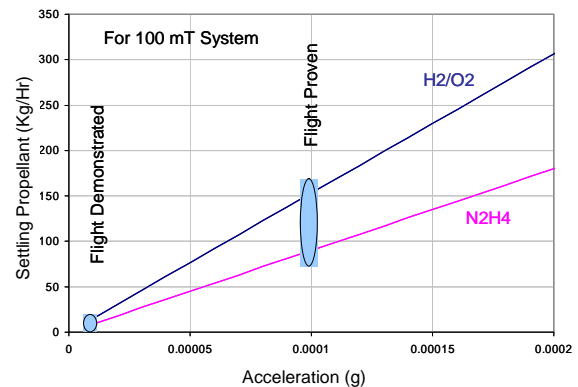


Figure 4. With low acceleration, propellant consumption for settled cryogenic propellant transfer is reasonable.

Table 2. Centaur has conducted numerous CFM flight demonstrations relevant to cryogenic propellant transfer .

| | |
|--------------------------------------|----------------------------|
| Liquid Control (10^{-5} to 6 G's) | Long Coast (to 17 hours) |
| System Warming & Chilldown | Pressurization Sequencing |
| Propellant acquisition | Blush characterization |
| System Thermal Interaction | Vent Sequencing |
| Ullage & Liquid Stratification | Pressure Collapse |
| Propellant Utilization | Bubbler vs. Ullage Pressn. |
| Mass Gauging | Unbalanced Venting |

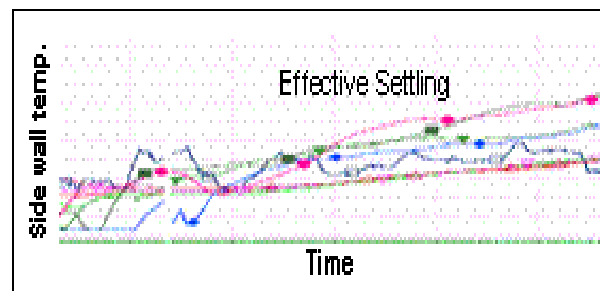


Figure 5. Centaur has demonstrated effective propellant control at 10^{-5} G's, well below the acceleration required to make settled propellant transfer attractive.

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%, Figure 6.

E. System Chardown

The Centaur upper stage has demonstrated highly efficient hardware chardown procedures that are directly applicable to cryogenic transfer. Chardown of ducting, tank walls and the engine have been demonstrated with multiple alternate chardown procedures. Chardown effectiveness using full, trickle, and pulse LH2 & LO2 flow has been demonstrated in the low g space environment. Pulse chardown 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.

F. 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, Figure 7. The cryo tracker^{3, 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% 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.

G. Pressure Control

Low-g settling provides a flight proven, reliable method to separate liquid and gas. (Figure 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.

H. Long Term Cryogenic Storage

A recent study on the Centaur indicates how robust passive long term LO2/LH2 storage can be accomplished⁵. The study shows that efficient passive cryogenic storage for periods up to a year is feasible with proper system design.

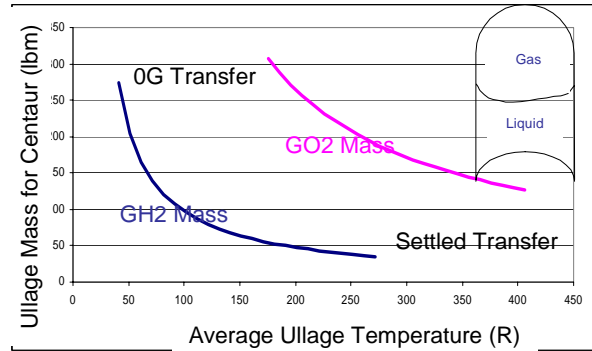


Figure 6. Low acceleration effectively separates the ullage and liquid enabling pure gas venting while reducing the gaseous residuals .

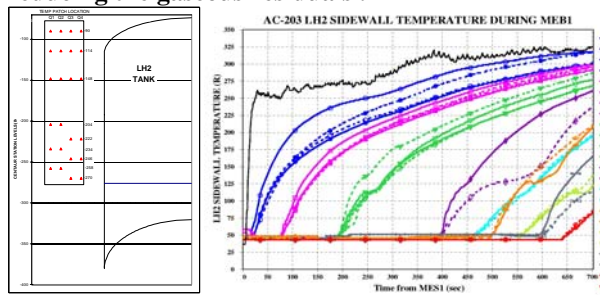


Figure 7. Centaur externally mounted thermal couples effectively measure liquid level.

I. 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.

J. 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 Bed⁸ (CTB), Figure 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 GRC⁹.

K. 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.

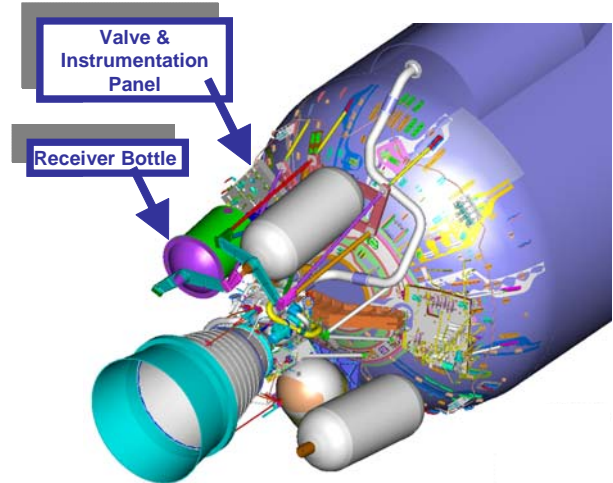


Figure 8. The Centaur Test Bed (CTB) offers a near term, low cost method to demonstrate in-space cryogenic propellant transfer.

IV. 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.

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