NASA/TM—2007-214810 AIAA–2007–343

Cryogenic Fluid Management Technologies for Advanced Green Propulsion Systems

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December 2007

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Prepared for the
45th Aerospace Sciences Meeting and Exhibit
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 8–11, 2007

National Aeronautics and
Space Administration

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Cleveland, Ohio 44135

December 2007

Acknowledgments

The authors would like to thank the Exploration Technology and Development Program Office for their continued support in funding the work to enable NASA's Vision for Space Exploration.

This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

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

Available from

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Abstract

In support of the Exploration Vision for returning to the Moon and beyond, NASA and its partners are developing and testing critical cryogenic fluid propellant technologies that will meet the need for high-performance propellants on long-term missions. Reliable knowledge of low-gravity cryogenic fluid management behavior is lacking and yet is critical in the areas of tank thermal and pressure control, fluid acquisition, mass gauging, and fluid transfer. Such knowledge can significantly reduce or even eliminate tank fluid boil-off losses for long term missions, reduce propellant launch mass and required on-orbit margins, and simplify vehicle operations. The Propulsion and Cryogenic Advanced Development (PCAD) Project is performing experimental and analytical evaluation of several areas within Cryogenic Fluid Management (CFM) to enable NASA's Exploration Vision. This paper discusses the status of the PCAD CFM technology focus areas relative to the anticipated CFM requirements to enable execution of the Vision for Space Exploration.

Nomenclature

CEV	Crew Exploration Vehicle
CFM	Cryogenic Fluid Management
CoPV	Composite Overwrapped Pressure Vessel
EDS	Earth Departure Stage
LAD	Liquid Acquisition Device
LCH4	Liquid Methane
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LSAM	Lunar Surface Access Module
LO2	Liquid Oxygen
MLI	Multi-Layer Insulation
OMG	Optical Mass Gauge
OMS	Orbital Maneuvering System
PVT	Pressure, Volume, Temperature
RCS	Reaction Control System
RF	Radio Frequency
TVS	Thermodynamic Vent System
ZBO	Zero Boil-Off

I. Introduction

THE Vision for Space Exploration (VSE) mission objectives will require the use of high performance cryogenic propellants (hydrogen, oxygen, and methane). The fundamental challenges associated with the in-space use of cryogens are their susceptibility to environmental heat, their complex thermodynamic and fluid dynamic behavior in low gravity and the uncertainty of the position of the liquid-vapor interface if the propellants are not settled. Cryogenic Fluid Management (CFM) technology development is addressing these issues through ground testing and analytical model development, while having crosscutting applications and benefits to virtually all missions requiring in-space operations with cryogens. Liquid hydrogen (LH2) is the most challenging of the three propellants but has the larger technology database since it has been used as the test fluid for many CFM experiments since the 1960's.[1 2] There is less CFM test experience and data with liquid methane (LCH4) and liquid oxygen (LO2) and these propellants are the primary focus of the current development activity.

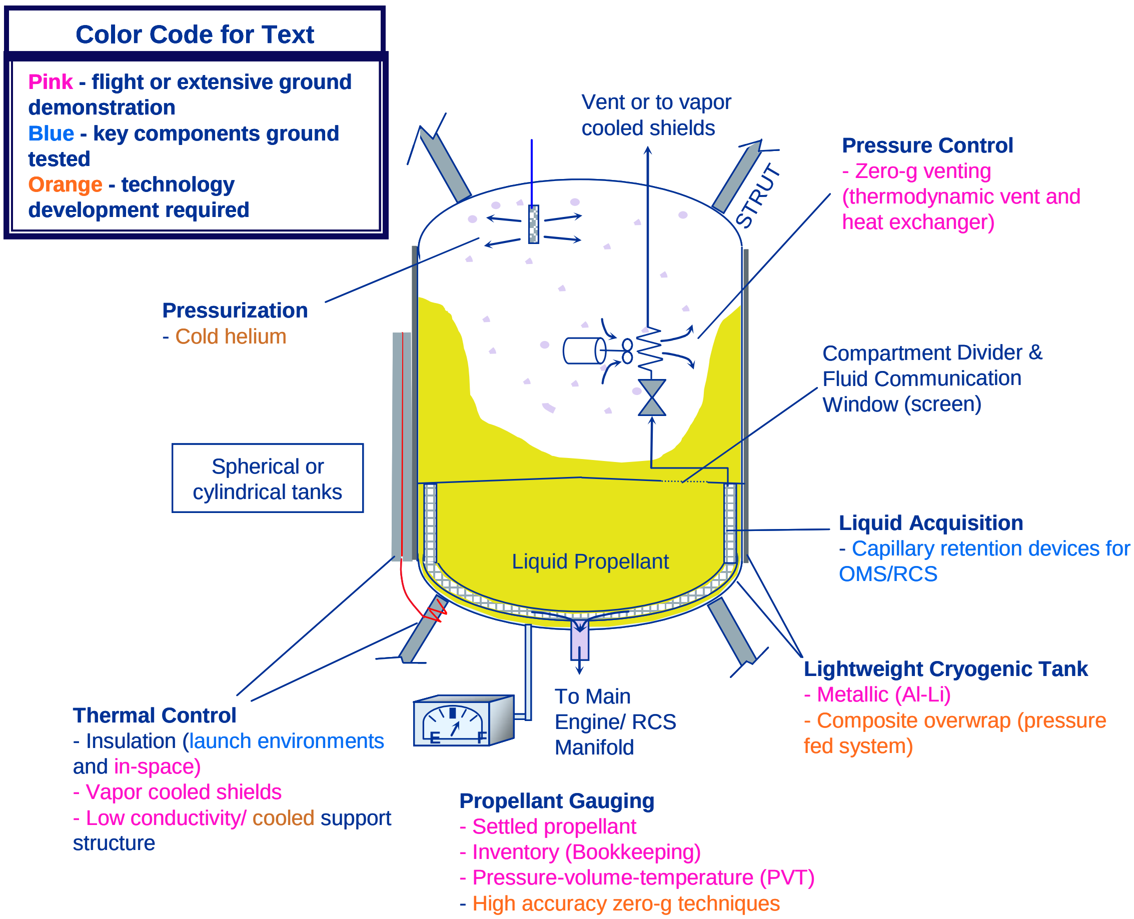

Figure 1. Conceptual exploration vehicle cryogenic propellant tank elements.

The primary CFM technology elements are: passive and active thermal control, pressure control, liquid acquisition, mass gauging and propellant feed line conditioning. Other CFM technology areas affecting in-space propulsion systems include leak-free couplings and disconnects, light weight composite tanks and support structure, leak detectors and component and subsystem integration. The conceptual tank schematic in Figure 1 illustrates how these elements are combined into a cryogenic propellant storage and delivery system.

The CFM development goal of allowing fluid management functions without settling propellants enables the exploration architecture and provides major propulsion system benefits by simplifying vehicle operations, reducing system mass, and expanding operational and architectural options. Performing these functions with settled propellants provides a potential backup mode, reducing the overall CFM risk.

The following discussion will summarize the function, current state of the art, performance goals, and development activities required to advance the state of the art and mature the CFM technology elements for application to specific exploration vehicles.

II. Thermal Control

Successful passive thermal control is enabling for all aspects of CFM. The propellant boil-off losses attributable to the passive thermal control subsystem are influenced by Multi-Layer Insulation (MLI) design, MLI to tank attachment techniques and materials, tank to vehicle support structure and attachments, tank size and configuration, tank and insulation penetrations, insulation venting provisions for launch and ascent, flight and surface environments, vehicle orientation in those environments, and thermal control surface coatings and materials.[3] Figure 2 has a photo of high performance insulation being applied to a 640 ft^3 test tank.

Figure 2. Application of Variable Density MLI to test tank.

Active thermal control combines the passive thermal control technology element with active refrigeration (cryocoolers) to allow storage periods from a few months to years with reduced boil-off losses. Studies predict that for specific propellant combinations and mission durations, the mass of the active thermal control elements (cryocooler, power supply, radiator and supporting equipment) can be substantially less than the propellant boil-off mass and the larger propellant tank required for a passive only thermal control system.[4,5,6]

A. Passive Thermal Control Technology Maturity and Applications

The Earth Departure Stage (EDS) and the Lunar Surface Access Module (LSAM) descent stage require LH2 and LO2 storage durations of 5 to 95 days in low earth orbit (LEO). Large diameter single tanks, such as proposed for the EDS, offer a significant storage efficiency advantage, due to the low tank surface area to volume ratios. Results from a 2006 NASA study indicate that an EDS LO2/LH2 stage, with high-performance MLI applied to a metallic tank, with careful material selection and design, will lose between 0.5% and 2% of its total propellant load per month with passive thermal control, depending on the specific mission scenario. The LSAM descent stage propellant losses will be higher (1.5% to 2.5% per month) because of the smaller, multiple-tank vehicle configurations and exposure to lunar orbit and surface environments.

The LSAM ascent stage requires LO2 and LCH4 storage durations of up to 95 days in LEO and up to an additional six months on the lunar surface. As in the descent stage concepts, the LSAM ascent stage concepts under consideration, with relatively small, multiple-tank vehicle configurations, will have increased tank surface area to volume ratios and increased relative heat loads. Also, multiple tanks have multiple heat leak paths from support structure and tank penetrations, as well as other thermal control implications due to tank integration and vehicle configuration. Estimates based on an ascent stage concept from a 2006 NASA study show that an LSAM LO2/LCH4 ascent stage can be stored in LEO with a propellant loss of between 1.0% and 2.0% per month with passive thermal control, using high-performance MLI applied to a metallic tank, with careful material selection and design. Losses for the additional 6 months on the warmer lunar surface have a much greater uncertainty. Factors such as landing site latitude (polar or equatorial), the thermal implications of lunar dust contamination and other environmental and configuration unknowns complicate such analyses. A high-pressure (~ 300 psia), pressure fed propulsion system for ascent offers the possibility of using the sensible heat of the LO2/LCH4 to offset boil-off loss. However, estimates based on the ascent stage concept mentioned previously show that the propellant loss for a LO2/LCH4 ascent stage while on the lunar surface will be on the order of 1.5% to 3.0% per month with passive thermal control.

It should be emphasized that the boil-off percentages per month given here are based on Preliminary Design Studies and cannot be linearly scaled to longer or shorter storage durations.

B. Active Thermal Control Technology Maturity and Applications

Both NASA Glenn Research Center and Marshall Space Flight Center, in collaboration with NASA Ames Research Center, have demonstrated the feasibility of Zero Boil-Off (ZBO) storage during ground testing for 50 ft^3 and 640 ft^3 tanks with two commercially available 20K (LH2) cryocoolers and one 80K, (LO2) flight cryocooler developed for satellite instrument cooling. Flight-type 20K (LH2) cryocoolers of sufficient cooling capacity (up to 20 watts) to eliminate LH2 boil-off do not exist, and thus the development of 20K cryocoolers is a long-lead technology item. State-of-the-art cryocoolers in the 80K range (LO2/LCH4 temperatures) have been developed for cooling sensors and have flown on numerous satellites, demonstrating high reliability for up to 10 years of in-space operation. However, the integration of these cryocoolers into an active thermal control system for propellant storage of LO2 and LCH4 is a technology issue. Recent studies indicate that the integration of an 80K flight cryocooler with a Helium circulator system imbedded in the MLI of a LH2 propellant tank can significantly reduce the LH2 boil-off and can be a near term solution for using active thermal control for LH2 storage. Active thermal control requires further technology development but could be flight ready in the near term for the EDS and LSAM vehicles with a substantial increase in investment, if the propellant boil-off loss with only passive thermal control is deemed unacceptable.

C. Cryogenic Thermal Control Development Needs

Passive thermal control development needs include integration of MLI with micro-meteoroid protection, tank support structure, and other insulation penetrations and development of roll-wrapping MLI techniques for metallic and composite over-wrapped pressure vessels (CoPV). Other development needs include characterization of the potential advantages of subcooled propellants, investigation of options such as shading, advanced materials, mechanisms and other techniques for passive thermal control on the lunar surface.

Active thermal control development needs include completion of the technology advanced development program of flight cryocooler to propellant tank integration techniques for large space-based storage systems, distributed cooling shields integrated with MLI and development and testing of active cooling techniques for tank penetrations and supports. Development of flight-type 20K, 20 watt capacity cryocoolers designed for integration into large space-based LH2 storage systems is also required for application to Mars missions.

III. Pressure Control

Controlling cryogenic propellant tank pressure in low gravity with minimum boil-off losses without settling the propellants can be accomplished with a thermodynamic vent system (TVS).[7] A TVS subsystem typically consists of a pump for circulation and mixing, a Joule Thompson expansion device/heat exchanger for heat removal, valves and a vent line.

A. Cryogenic Pressure Control Technology Maturity and Applications

A TVS will be required for the EDS, LSAM and the LO2/LCH4 version of the OMS/RCS for the CEV. NASA and industry experience acquired during the last 40 years has established a solid data-base for the development of a TVS for specific applications. In the 1984-87 timeframe a TVS was developed and flight qualified for the LH2 tank on the Centaur G – prime upper stage for the STS. TVS concepts have been tested in ground demonstrations with LH2, LN2 and LCH4 in a large-scale (640 ft^3) tank. The existing TVS test database assures that geometric effects of the large EDS LH2/LO2 tanks can be scaled with confidence. Also the expected LEO heat load on the EDS LH2/LO2 propellant tanks is well within the range of TVS ground testing conducted to date. Separate test programs with LCH4 and LO2 TVS systems are planned for 2007 and will address fluid specific component and thermodynamic performance for the LSAM ascent stage and the cryogenic version of the CEV. The vehicle-specific propellant tank internal hardware configuration (baffles, instrumentation, fluid acquisition devices, etc.) will need to be tested in an integrated system test to determine their effect on fluid mixing. Figure 3 illustrates the repeatability of the pressure control cycles during a recent hydrogen TVS demonstration.

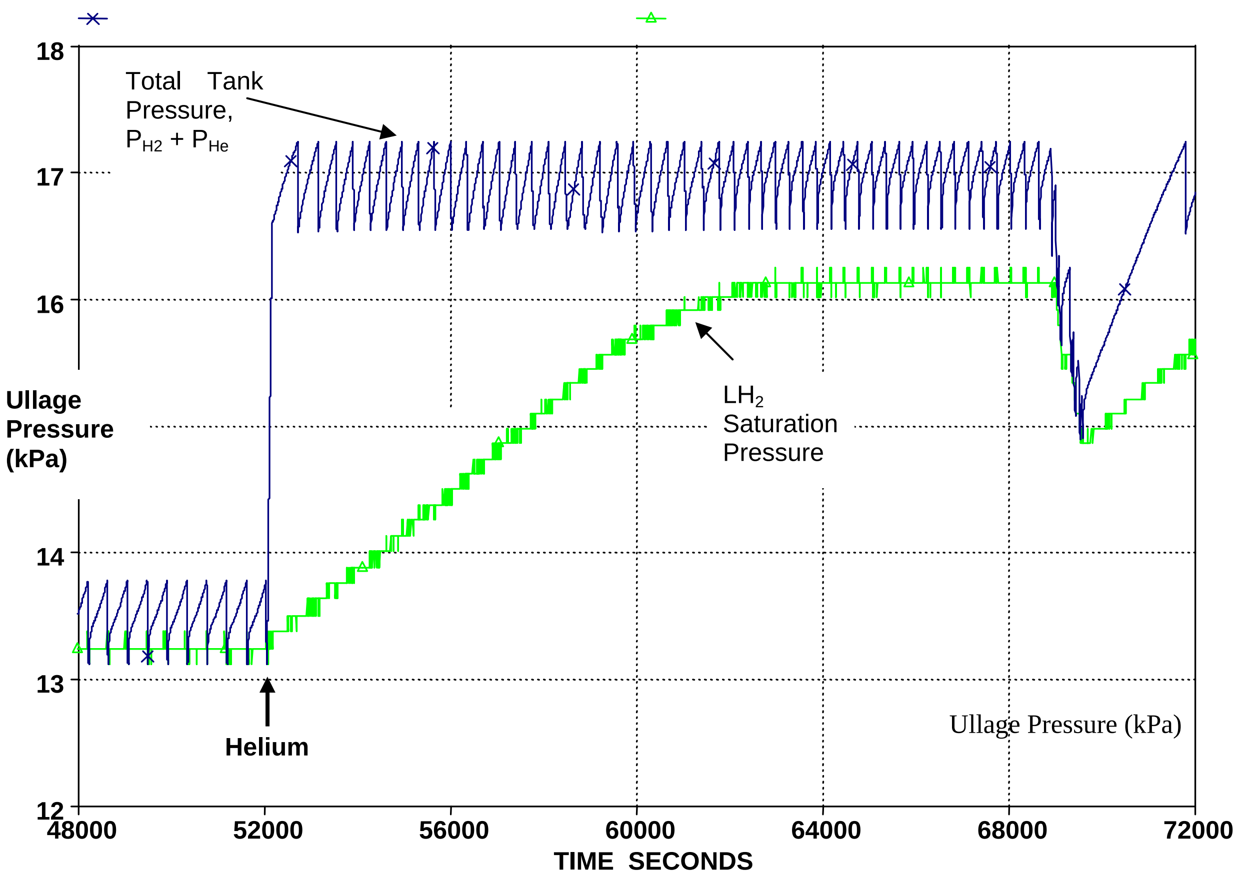

Figure 3. Pressure control cycles for TVS demonstration test in a 640 ft^3 tank.

B. Cryogenic Pressure Control Development Needs

EDS, LSAM and CEV technology advanced development needs include completion of the TVS component testing with LO2 and LCH4 in 2007 and modeling of low-gravity fluid dynamics and heat transfer for specific TVS designs. EDS, LSAM and CEV vehicle advanced development needs include integrated system testing with LH2, LO2, and LCH4 to determine the effect of internal tank hardware configuration on fluid mixing.

IV. Liquid Acquisition

Providing vapor free cryogenic propellants to in-space propulsion systems at expulsion efficiencies greater than 98% without settling the propellants is the objective of the liquid acquisition technology element (also referred to as propellant management devices). Capillary liquid acquisition devices (LAD's) can meet this objective for frequent, short-duration, omni-directional burns of OMS/RCS-type engines. Such devices are state-of-the-art for toxic propellants, but have not yet been developed for cryogens. Existing cryogenic upper stage main engine restarts use auxiliary thrusters to settle the propellants.

A. Liquid Acquisition Technology Maturation and Applications

Cryogenic LAD's will be required for the LO2/LCH4 version of the OMS/RCS for the CEV and LSAM, and possibly the EDS. LH2 LAD performance represents the primary challenge while LO2 and LCH4 performance risk is substantially less if the liquids are sub-cooled relative to the propellant tank ullage pressure. There is a reasonable possibility that the ground testing currently underway at NASA (Figure 4) can provide assurance that the LAD's, with sub-cooled LO2 and LCH4 propellants, function essentially like State-of-the-Art toxic propellant LADs. The cryogenic capillary LAD requires further technology advanced development but could be flight ready in the near term for the EDS and LSAM vehicles with a conservative design approach and constrained mission operations to assure acceptable performance.

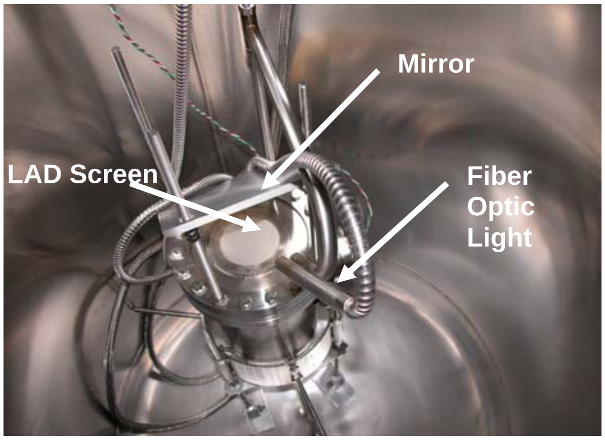

Figure 4. Bubble point measurement hardware for cryogenic propellant acquisition screens.

B. Liquid Acquisition Development Needs

Liquid acquisition technology advanced development needs include completion of the technology advanced development program, verification of the maximum capillary screen pressure drop for LH2/LO2/LCH4 at both saturated and sub-cooled fluid conditions, investigation of helium solubility and heat entrapment effects, propellant tank LAD integration, LAD materials selection and analytical performance model development. CEV, LSAM and possibly the EDS vehicle advanced development needs include integrated system testing with LH2, LO2 and LCH4 to determine the effect of internal tank hardware configuration on LAD performance.[8,9]

V. Mass Gauging

The need for a reliable, accurate method for measuring cryogenic propellant mass without settling the propellants is the objective of the mass gauging technology element. Several promising techniques are currently under development. They include the pressure-volume-temperature (PVT) method, the optical mass gauge (OMG) which senses the fluid quantity by measuring absorption of light in the tank, and a Radio Frequency (RF) mass gauge, which senses shifts in electromagnetic tank resonances due to the propellant.

C. Mass Gauge Technology Maturation and Applications

Applications for cryogenic mass gauging include the EDS, LSAM and the CEV OMS/RCS. A measurement uncertainty metric of less than 3% of full-tank mass has been established for the propellant tank mass measurements for these vehicles with a goal of better than 1% uncertainty. For the three techniques described above extensive hardware development, ground testing and analysis is currently underway to meet the mass gauging objectives (figures 5).[10], [11], [12] The low gravity mass gauge requires further technology advanced development but could be flight ready in the near term for the EDS and LSAM vehicles with a conservative design and redundancy to assure acceptable performance.

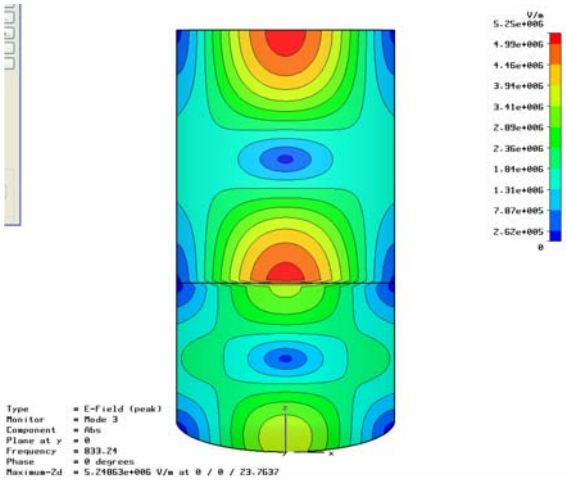

Figure 5. Example result from simulation of RF response modes in partially filled propellant tank (ref. 12).

D. Mass Gauge Development Needs

Mass gauging technology advanced development needs include completion of the technology advanced development program to quantify propellant mass uncertainty as a function of tank fill level, pressure and thermal stratification (PVT), and the effect of internal tank hardware and surface finish (OMG/RF), low-gravity aircraft testing, computational and analytical model development. EDS, LSAM and CEV vehicle advanced development needs include integrated system testing with LH2, LO2 and LCH4 to determine the effect of internal tank hardware configuration on mass gauge performance.

VI. Propellant Feed Line Conditioning

Maintaining vapor-free liquid propellant between the tank outlet and the OMS/RCS engine inlet is a significant technology challenge. While sufficiently sub-cooled propellants can absorb much of the parasitic heat, additional measures are required to accommodate all operational aspects of the missions. One approach uses a passive TVS attached to the feed line, which has the potential to absorb this heat with low propellant loss when flow to the engines is not a sufficient heat sink. The passive TVS subsystem generally consists of a TVS line attached to the propellant feed line acting as a heat exchanger, a Joule-Thomson expansion device and a line vent valve.

A. Propellant Feed Line Technology Maturation and Applications

Propellant feed line conditioning will be required for all vehicles with a cryogenic OMS/RCS. On-going ground testing in 2007 and 2008 will quantify the passive TVS performance. Specific feed line configuration, routing and heat loads for each vehicle must be addressed.

B. Propellant Feed Line Development Needs

Completion of the LO2 and LCH4 feed line conditioning testing currently underway at the White Sands Test Facility is required to validate design and analysis methodology. CEV, EDS and LSAM vehicle advanced development needs includes integrated system testing with LH2, LO2 and LCH4 to address vehicle specific feed line routing and heat loads.

VII. Summary

CFM addresses a wide range of technical issues associated with managing cryogens in low gravity. This diversity makes it difficult to characterize the technology with a simple or single metric. Many parameters have strong influences on performance, applicability and the benefits of a given technology element, and theCFM elements are at different levels of maturity. Passive thermal and pressure control are ready for near-term applications while liquid acquisition, mass gauging, active thermal control and feedline conditioning require further development. Characterizing the combined influence of the CFM subsystems on component performance in a fully integrated system test is a common development need.

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

1. REPORT DATE *(DD-MM-YYYY)*
01-12-2007

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Cryogenic Fluid Management Technologies for Advanced Green Propulsion Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Motil, Susan, M.; Meyer, Michael, L.; Tucker, Stephen, P.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 253225.04.01.01.03.01

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-15965

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORS ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2007-214810

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 20
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
Cryogenic storage for propulsion systems

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	14	STI Help Desk (email:help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(include area code)* 301-621-0390