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Experimentation for the Maturation of Deep Space Cryogenic Refueling Technologies

David J. Chato
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June 2008

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Summary

This report describes the results of the "Experimentation for the Maturation of Deep Space Cryogenic Refueling Technology" study. This study identifies cryogenic fluid management technologies that require low-gravity flight experiments to bring technology readiness to levels 5 to 6; examines many possible flight experiment options; and develops near-term low-cost flight experiment concepts to mature the core technologies. A total of 25 white papers were prepared by members of the project team in the course of this study. The full text of each white paper is included, and 90 relevant references are cited. The team reviewed the white papers that provided information on new or active concepts of experiments to pursue and assessed them on the basis of technical need, cost, return on investment, and flight platform. Based on this assessment, the "Centaur Test Bed for Cryogenic Fluid Management" was rated the highest. "Computational Opportunities for Cryogenics for Cryogenic and Low-g Fluid Systems" was ranked second, based on its high scores in state of the art and return on investment even though scores in cost and time were second to last. "Flight Development Test Objective Approach for In-space Propulsion Elements" was ranked third.

Symbols

Bo	Bond number $= a\rho R^2/\sigma$
g_0	Earth gravitational acceleration = 32 ft/s^2
G	Gravity ratio a/g_0
We	Weber number $= \rho V^2 R/2\sigma$
ρ	Density, g/cm^3
σ	Surface tension g/s^2

List of Acronyms

AC	Atlas Centaur
ACS	attitude control system
AFB	Air Force Base
ALV	advanced launch vehicle
ARC	Ames Research Center
AXAF	Advanced X-ray Astrophysics Facility
BB	Black Brant
CARS	customer accommodations and requirements specifications
CEV	crew exploration vehicle
CFD	computational fluid dynamics
CFE	capillary flow experiment
CFM	cryogenic fluid management
CLASS	cryogenic liquid acquisition storage and supply
CMG	compression mass gauge
COLD–SAT	Cryogenic On-Orbit Liquid Depot–Storage, Acquisition and Transfer
CTB	Centaur testbed
CTM	cryogenic transport module
DARPA	Defense Advanced Research Project Agency
DoD	Department of Defense
DFI	developmental flight instrumentation
DTO	development test objective
EDS	Earth departure stage
ELV	expendable launch vehicle
ET	external tank
EVA	extra vehicular activity
ESR&T	Exploration Systems Research and Technology
FARE	fluid acquisition and resupply experiment
FOV	field of view
GAS	get away special
GRC	NASA Glenn Research Center
GSFC	NASA Goddard Space Flight Center
HH	Hitchhiker
HVSS	high-velocity separation system
In-STEP	In-Space Technology Experiment Program
ISS	International Space Station
JSC	NASA Johnson Space Center
LAD	liquid acquisition device
LaRC	NASA Langley Research Center
LCT	liquid crystal thermography
MACDAC	McDonnell Douglas Aeronautics Corporation
MDSCR	Experimentation for the Maturation of Deep Space Cryogenic Refueling
MIT	Massachusetts Institute of Technology
MLI	multilayer insulation
MMOD	micro meteoroid and orbital debris
MOP	maximum operating pressure
MSFC	NASA Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCSER	National Center for Space Exploration Research

NSROC	NASA Sounding Rocket Operations Contract
NSRP	NASA Sounding Rocket Program
OMS	orbital maneuvering system
OMV	orbital maneuvering vehicle
ORU	orbital replaceable unit
OTV	orbit transfer vehicle
OV	orbital vehicle
PIV	particle imaging velocimetry
PMD	propellant management device
PODS	passive orbital disconnect strut
PRSD	power reactant storage and distribution
PVT	pressure volume temperature
RCS	reaction control system
RLV	reusable launch vehicle
SEP	solar electric propulsion
SHOOT	superfluid helium on-orbit transfer
SIRTF	Space Infrared Telescope Facility
SMFD	storable fluid management demonstration
SPARCS	Solar Pointing Attitude Rocket Control System
SRPO	Sounding Rockets Program Office
STC	strategic technical challenges
STS	space transportation system
STV	space transport vehicle
TC	Titan Centaur
TEAMS	technology experiments for advancing missions in space
TMP	Technology Maturation Program
TM	thermomechanical
TPCE	tank pressure control experiment
TRL	technology readiness level
TVS	thermodynamic vent system
UAH	University of Alabama in Huntsville
VCS	vapor cooled shield
VJ	vacuum jacketed
VTRE	vented tank resupply experiment
WFF	Wallops Flight Facility
WIRE	Wide-field Infrared Explorer
WSMR	White Sands Missile Range
ZBOT	Zero Boil-Off Tank

Introduction

Technologists have relied on flight tests to develop cryogenic fluid management (CFM) technologies since the beginning of space travel. Drop tower, sounding rocket flights, and subscale experiments carried out on the Mercury missions provided vital information for the design of the Saturn IV and Centaur cryogenic upper stages. Information from these experiments and the subsequent full-scale demonstration flights successfully addressed the issues of propellant slosh, settling, short-term storage, and pressure control.

As a part of its technology suite, the National Aeronautics and Space Administration (NASA) Exploration Systems Research and Technology (ESR&T) office commissioned the study "Experimentation for the Maturation of Deep Space Cryogenic Refueling Technology" abbreviated as MDSCR. Cryogenic refueling supports the ESR&T mission by addressing the strategic technical challenges listed in table I.

TABLE I.—STRATEGIC TECHNICAL CHALLENGES (STC)

STC no.	STC description	Project support or impact
1	Reusability	Refueling of propellants essential to reuse of propulsion stages
2	Affordable logistics prepositioning	Refueling technologies required to make use of in situ resource produced cryogenic propellants
3	Energy rich systems and missions	High performance of cryogenic propellants essential to energy rich systems and missions. Refueling technologies increase usability of cryogenic propellants

The goals of MDSCR project were to

- Identify CFM technologies requiring low-gravity flight experiments to reach technology readiness level (TRL) 5 to 6
- Study many possible flight experiment options including sounding rockets, International Space Station (ISS) shuttle-based experiments, low-cost free flying spacecraft, and re-flight of existing shuttle/ISS experiments
- Develop near-term low-cost flight experiment concepts to mature core-refueling technologies

The MDSCR project team, led by the Glenn Research Center at Lewis Field (GRC), involved key members of other NASA centers as well as industry and academic partners. NASA centers playing a key role in this project include Ames Research Center (ARC), Goddard Space Flight Center (GSFC), Johnson Space Flight Center (JSC), Kennedy Space Flight Center (KSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC). Industry partnerships were formed with the Boeing Company and Lockheed Martin Space Systems. The Case Western Reserve University's National Center for Space Exploration (NCSER) also assisted. MDSCR supported the In-Space Technology Experiment Program (In-STEP) Element Program within the Technology Maturation Program (TMP).

An initial assessment of technologies (ref. 1) produced the list of technologies shown in table II. Note that the continuing investigation suggested several additional technologies to consider, which will be discussed later.

TABLE II.—FLIGHT TESTING REQUIREMENTS OF CFM TECHNOLOGIES

CFM technology element	Current TRL	Past 1-g accomplishments	Low-g issues	Flight testing
Passive storage	5	• 3 percent loss per month, demonstrated with large scale LH_2 test	Low-g thermal stratification effects unknown	Highly desirable for stratification
Active storage (zero boil-off)	4 LO_2/CH_4 3 LH_2	• Subscale demo with LN_2 and 10 W at 97 K cryocooler • Large scale demo with commercial cryocooler	Low-g thermal stratification effects unknown	Highly desirable for stratification
Pressure control	4	• Large scale demo of thermodynamic vent system (TVS) with spray bar • Subscale test of TVS with axial jet mixer	Low-g heat transfer and fluid dynamics affects mixing, de-stratification, and cycle rate	Highly desirable
Mass gauging	3	• Component testing with simulant fluids, LN_2, and limited LH_2	Some concepts strongly affected by low-g heat transfer and fluid behavior	Highly desirable
Liquid acquisition	3	• Bubble point testing with LN_2 • Historical data (1960s)	Low-g heat transfer significantly affect liquid acquisition device (LAD) performance	Required
Fluid transfer	3	• Subscale demo of chill and no-vent fill testing	Transfer operation strongly effected by low-g	Required

Early flight testing of these technologies would benefit the NASA exploration program. Early flight testing of liquid acquisition, mass gauging, and pressure control technologies would enable the use of cryogenic propellant in low-gravity (low-g) in the 2012 crew exploration vehicle (CEV). Early flight testing of fluid transfer technologies may enhance future missions by providing on-orbit assembly options for stages that cannot be launched in a single mission.

The MDSCR project was conducted as a series of research tasks. The first task was to review the prior literature for previous flight experiments, carriers, and launch systems. These were then documented in two-page technical white papers. The second task was to conduct a technical assessment of current research by meeting with team members. Four technical assessment meetings were conducted covering the majority of research teams. Unfortunately, restrictions placed on the release of architecture studies prevented the inclusion of the results of the LaRC and JSC teams in this report. The third task was to transform the findings of the technical assessments into white papers. These were added to the white papers accumulated in the first task. The fourth task was to convene the team to review the white papers produced initially, and rank them on the basis of technical need, cost, return on investment, and flight platform. Only white papers that provided information on new or active concepts of experiments to pursue were evaluated. The evaluation findings are reported in section 3 of this report. The fifth task was to prepare monthly reports to NASA Headquarters as well as the final report. This final NASA Technical Publication serves as the conclusion of the MDSCR study.

White Papers

One of the principal outputs of the MDSCR study was a series of technical white papers. The objectives of the white papers were to

- Provide quick reference summary of CFM experiment concepts
- Enable rapid review and comparison between experiment concepts
- Provide publishable documentation of the options explored by the research effort

The following additional instructions were provided to the preparers:

- Constrain papers to technologies that are unique to “cryogens” or “space refueling”
- Highlight areas of flight test
- Provide a comprehensive bibliography
- Limit the paper to two pages of 10-point font (some exceptions were granted)

The objectives were different than those of an ordinary white paper, which typically advocates a position rather than providing a technical review. What was required was something similar to a case study, but much briefer to avoid being overwhelmed with detail.

A total of 25 white papers were prepared during the MDSCR study. To help organize the white papers they were separated into five groups. The first group was “Carriers and Launchers” which talked about ways to provide access to low gravity without discussing specific experiments. The second group was “Experiments Historical” which discussed flight experiments that have already been completed. The third group was “Instrumentation” that would be helpful to experiment design, but were not complete experiments in themselves. The fourth group was “Experiments Proposed” for experiment concepts in design and development. The final group was “Maturation Strategies,” which were broad statements of approach and philosophy on the maturation of cryogenic technologies without proposing specific experiments.

To limit the number of white papers, old flight experiments that had been proposed but never flown were excluded from the study. An exception was made for the CLASS experiment at JSC request. Another exception was made for the Cryogenic Propellant Depots, which includes the Cryogenic On-Orbit Liquid Depot—Storage, Acquisition and Transfer (COLD–SAT) experiment as well as historical depot designs. Both of these white papers were placed in “Experiments Historical” since they are no longer in active development.

Complete white papers are included in appendices A through E. A brief description of each white paper can be found below. Also noted below are the references cited by each white paper.

Carriers and Launchers

Most of these carriers have a payload users’ manual reference to provide detailed information.

The Hitchhiker (HH) Shuttle Small Payloads Carrier (GSFC)

This paper describes the capabilities of the HHbridge-mounted in the shuttle cargo bay. This was the carrier used for both the superfluid helium on-orbit transfer (SHOOT) and vented tank resupply experiments (VTRE) described in later white papers. Key references include 2 and 3.

Pegasus Air Launch System (GSFC)

This paper describes the methodology used to fly cryogenic payloads such as Wide-field Infrared Explorer (WIRE) on the Pegasus launch vehicle (refs. 4 and 5).

NASA Sounding Rocket Program (GSFC)

This paper summarizes the capabilities and constraints of NASA’s current stable of sounding rockets (refs. 6 and 7).

Cryogenic Ground Serving/Launch Operations (KSC)

This paper describes current capabilities and methodologies for handling cryogens on current launch vehicles. Also included is a brief discussion of potential upgrades and handling of highly subcooled “densified” cryogens.

Falcon Launch Vehicle Family (KSC)

This paper describes a DARPA/SpaceX effort to provide very low-cost launch vehicles (ref. 8).

Experiments Historical

Aerobee Sounding Rocket CFM Tests (GRC)

This paper describes a sounding rocket effort in the early 1960s conducted with liquid hydrogen to understand the behavior of cryogens in low gravity (refs. 9 to 18).

Saturn IVB Fluid Management Qualification (GRC)

This paper shows the flight qualification of the techniques to handle cryogens for the Saturn rockets used to launch the Apollo missions to the Moon (refs. 19 to 25).

Flight Qualification of Centaur CFM (GRC)

This paper explains flight tests used to develop fluid management strategies for the Centaur upper stage (ref. 26).

Titan Centaur CFM Flight Tests (GRC)

This paper explains flight tests piggybacked on the Titan/Centaur mission to further develop CFM for the Centaur upper stage (refs. 27 to 29).

Vented Tank Resupply Experiment (GRC)

This paper details an experiment mounted in three getaway special canisters (GAS cans) attached to a cross-bay HH bridge to study the ability of vane propellant devices to control liquid during propellant transfer, tank venting, and boiling (ref. 30).

Tank Pressure Control Experiment (GRC)

This paper describes a series of single GAS can experiments mounted on the shuttle cargo bay sidewall to study low-gravity tank mixing, boiling, and pressure control (refs. 31 to 35).

Storable Fluid Management Demonstration/Fluid Acquisition and Resupply Experiment SMFD/FARE Flight Experiments (GRC)

This paper describes a series of shuttle mid-deck locker experiments to study vane and screen-channel liquid acquisition devices. Room temperature water was used as test fluid, which limited the experiments to fluid dynamic effects only (refs. 36 to 39).

Capillary Flow Experiment (GRC)

This paper explains a very small subscale experiment to study fundamentals of vane devices on space station. Launch on cargo mission provided quick turnaround as well as station access during the Columbia stand-down (refs. 40 and 41).

Cryogenic Liquid Acquisition Storage and Supply Experiment (JSC)

This paper outlines a cryogenic experiment side-mounted on the shuttle cargo bay was planned to support the replacement of the shuttle storable system with a nontoxic oxygen/ethanol propulsion system. This experiment was carried to the preliminary design phase only.

Microgravity Science Support on the NASA Sounding Rocket Program (GSFC)

This paper reports a history of recent NASA microgravity sounding rocket experiments.

SHOOT Flight Demonstration (GSFC)

This paper reports on an experiment to study the fluid management of superfluid helium. It was flown on the shuttle HH cross-bay bridge (refs. 42 to 54).

Cryogenic Propellant Depots (GRC)

This paper provides a review of prior depot design efforts. Extensive references are included (refs. 55 to 79).

Instrumentation

Cryogenic Flowmeters (JSC)

This paper describes ground tests of a series of potential cryogenic flowmeters, which were carried out to support on-orbit resupply designs (ref. 80).

SHOOT Cryogenic Instrumentation Applicable to Cryogenic Depots (GSFC)

This paper explains instrumentation developed as part of the SHOOT program (ref. 43 and refs. 81 to 89).

Experiments Proposed

These experiments are still in active development. Detailed documentation is as yet unpublished.

Zero Boil-Off Technologies (ZBOT) Experiment (NCSER/GRC)

The project involves performing a small-scale ISS experiment to study tank pressurization and pressure control in microgravity.

Centaur Testbed (CTB) (Lockheed Martin)

The Lockheed Martin team provides a conceptual design for a small cryogenic experiment tank attached to the aft end of a Centaur stage.

Maturation Strategies

As stated previously, these are broad statements of approach and philosophy to the maturation of cryogenic technologies without proposing specific experiments. Most are evolving as time progresses and missions change, but they do provide ideas and concepts for the future.

Settled Transfer (Lockheed Martin)

Lockheed Martin submitted this vision for evolving from current upper stage CFM practices to a full on-orbit capability.

CFD Tools (Boeing)

Computational modeling tools for the design of cryogenic and low-gravity fluid space systems offers both development cost savings and improved designs.

On-Orbit CFM (Boeing)

Boeing reviewed the baseline technology plan and provided their view of research. In general Boeing agrees with the baseline. However they added elements for the development of incorporating micrometeoroid and orbital debris protection into the insulation system and reducing the thermal conductivity of multilayer insulation penetrations (refs. 1 and 74).

Shuttle Development Test Objective (DTO) (JSC)

JSC submitted this paper describing the approach used to design and qualify the space shuttle propulsion system and how this could be applicable to a cryogenic system.

For the final review each participant was asked to answer evaluation questions on the submitted white papers. Evaluation questions are included in appendix F. After some discussion it was decided to evaluate only white papers that provided information on new or active concepts of experiments to pursue. As a consequence of this decision, only white papers in “Experiments Proposed” and “Maturation Strategies” were evaluated completely. To reduce the potential for bias evaluations for each white paper from its author or author’s organization were discarded. Summary sheet tabulating the number of responses to each value of the multiple choice questions and reproducing the comments received in each narrative section are included in appendix F. For the return-on-investment, the multiple choice question response and the narrative response have been combined.

Compiled Narrative Summary of White Paper Reviews

ZBOT

This concept has the advantages of low cost and the ability to repeat test numerous times. However its small scale and use of noncryogenic test fluid raised issues of scaling. An intensive modeling effort somewhat mitigates the scaling issue. Its use of the ISS was also perceived as risky given the current status of the ISS program.

CTB for CFM

This concept is very attractive due the low cost and use of cryogenic liquids. Its use of the Atlas “secondary” payload provided low-cost access to space as well as numerous flight opportunities. Concerns included limited communication with the payload during the mission, limited mission duration (one day), and reliability required to assure the success of the primary payload. Scaling concerns were raised by one reviewer, but the 1 m^3 size and use of actual cryogens make the scaling required much less than ZBOT.

Computational Opportunities for Cryogenic and Low-g Fluid Systems

This white paper provides a good summary of the current state-of-the-art computational modeling cryogenic and low-g fluid systems. It also makes a clear case as to why advancing the state of the art in modeling these systems should be a part of any research program. It did not; however, address what experiments were required to anchor the computational model. Concerns were expressed by the reviewers that a complete validation and verification would require very expensive, difficult-to-perform experiments.

Settled Cryogenic Transfer

This paper describes the use of existing Centaur hardware for testing results in a low-cost, rapid development for the experiment. Unfortunately the constraints on the experiment prevent the significant advancement of CFM technologies. Also, the use of settling would lock the architecture into a complex methodology that was less than optimal.

On-Orbit CFM Technologies

This paper provided a good summary of technology risk items and the required level of technical maturation to achieve them. However, its recommendation of using dedicated development would result in substantially higher costs than most of the other approaches.

Flight Development Test Objective Approach for In-Space Propulsion Elements

Incremental approach proposed in this white paper is low risk and evolutionary. Unfortunately this approach also results in a long time and high cost to evolve the final capabilities. The benefits of the initial cryogenic technologies to vehicle performance will be quite limited as well.

Numerical Comparison of White Papers

In order to compare white papers it was necessary to convert the survey questions to an average numerical score. For the cost and schedule questions, points were assigned as follows: (a) 1 point, (b) 2/3 point, (c) 1/3 points, and (d) 0 points. For advancing the state of the art, yes was assigned 1 point, no—0 points, and uncertain answers—1/2 point. For return on investment, “Below average” was assigned 0 points, “Average”—1/2 point, and “Above Average”—1 point.

Points were totaled for each question and then divided by the number of responses to the question to generate an average score. An additional step was taken to generate overall cost and time scores. The average scores for the two cost questions were then combined and averaged to create an overall cost score. The average scores for the two time questions were combined in the same fashion. Once numerical scores were available white papers were ranked according to score (for time and cost—lowest score to highest, for advancing the state-of-the-art and return on investment—highest score to lowest). Results are shown in table III. An overall ranking was assigned by averaging the scores for each category. Based on this assessment the “Centaur Test Bed for Cryogenic Fluid Management” was rated the highest. “Computational Opportunities for Cryogenics for Cryogenic and Low-g Fluid Systems” was ranked second based on its high scores in “state of the art” and “return on investment” even though scores in cost and time were second to last. “Flight Development Test Objective Approach for In-space Propulsion Elements” was ranked third, which is consistent with its third place score in all categories other than time.

TABLE III.—ORDERED RANKING OF WHITE PAPERS

White paper title	Ranking				
	Lowest cost	Least time	Advancing state-of-the-art	Return on investment	Overall
Centaur Test Bed for Cryogenic Fluid Management	4th	2nd	1st	1st*	1st
Computational Opportunities for Cryogenic and Low-g Fluid Systems	5th	5th	2nd	1st*	2nd
Flight Development Test Objective Approach for In-space Propulsion Elements	3rd	4th	3rd	3rd	3rd
Settled Cryogenic Transfer	1st	1st	4th*	5th*	4th
Zero Boil-Off Technologies	2nd	3rd	4th*	4th	5th
On-Orbit Cryogenic Fluid Management Technologies	6th	6th	4th*	5th*	6th

*Tied scores

Summary

Although the MDSCR study ended prematurely due to changing NASA priorities, it will leave a legacy of ideas for future research. A number of the white papers document historical experiments and approaches. These should prove valuable to future researchers. The commonality of approaches to CFD and technology maturation should give confidence when laying out future research efforts. Several white papers highlight new and novel concepts especially in the experiments proposed and maturation strategies groupings. These will serve as a head start for preparing experiments in the future. Ideas from this effort are already being adapted for use in advanced development for CEV. As NASA’s focus moves on to Lunar and Mars exploration the results of MDSCR will provide a valuable reference for the design of the flight experiments required for those challenging missions.

Appendix A—Carriers and Launchers

Cryogenic Ground Serving and Launch Operations

William Notardonato (KSC)

Executive Summary

NASA has developed techniques for servicing spacecraft and launch vehicle cryogenic propulsion systems since the late 1950s. Techniques have evolved as hardware and software capabilities have developed, and each current program has some vehicle- and pad-specific systems and operations required. However, the basic approach remains similar, and servicing capabilities (in terms of quality of propellant loaded) are nearly identical. These systems, or derivatives of them, are capable of meeting the needs of an in-space cryogenic depot, provided this depot uses propellant at or above the normal boiling point, and free venting of boil-off in space is permitted. Conditioning of propellants via advanced ground storage systems has the potential to minimize cost and safety risks, while maximizing launch performance.

Capability Description

Current philosophy

The current method of large-scale cryogenic storage and distribution is very similar across all programs at KSC and Cape Canaveral Air Station. Cryogens (LH_2 and LO_2) are produced offsite, delivered via tanker trucks, and transferred to ground storage tanks days or weeks prior to launch. Cryogens in the tanks are stored as a saturated liquid, and boil-off gas is not recovered. During launch countdown, as late as possible into the count, the cryogens are transferred to the flight tank, and in the event of a launch scrub, are drained back into the ground storage tanks. Details on how this is accomplished vary across programs and are discussed below.

Space transportation system (STS)

Hydrogen is purchased from Air Products New Orleans plant and delivered via 13 000-gal road tankers. Periodic sampling of tankers is done to ensure the propellant meets purity specifications. Waves of up to five tankers can be offloaded at a time, and two waves can be done in a day. Prior to offload, transfer lines are purged with gaseous helium and then sampled. The tank is vented, and valves are opened to start chilldown. Product losses from tank venting and transfer line chilldown are free-vented at the top of the pad storage tank. After offload is complete, transfer lines are purged of hydrogen. The pad storage tank holds 850 000 gal of liquid, with 10 percent ullage on top. The tank has a vacuum jacket and perlite bulk fill insulation. The cross-country lines have a 10 in. inner diameter, are 1500 ft long, and are vacuum-jacketed (VJ) with multilayer insulation (MLI). The storage tank is pressurized using vaporizer heat exchangers.

Prior to launch, the tank must be filled to 700 000 gal, which is enough for three launch attempts. Loading of the STS external tank begins at T-minus 6 hr on the countdown clock. Purges to the various disconnect cavities are initiated, and transfer-line blanket pressure is vented. The external tank (ET) vent valve is opened, chilldown line valve is opened, and chilldown of cross-country lines begins. Then the storage tank is self-pressurized, and slow-fill (1000 gpm) to the lower ET liquid level sensors is completed. The main transfer valve is then opened and fast-fill to 98 percent is initiated, with a flow rate of 8500 gpm. When the ET ullage pressure rate reaches a limit, LH_2 topping at 775 gpm is initiated until the upper liquid level sensor reads 100 percent wet. Then the replenish valve controls the flow to maintain 100 percent, usually less than 300 gpm. At T-minus 1:57 min, replenish mode terminates. Overall, 383 400 gal are loaded into the ET, with 48 000 gal lost during chilldown and 40 000 gal lost during replenish. These vapor losses are burned in a flare stack. If the launch is scrubbed, drainback procedures are initiated.

LO_2 operations are similar to LH_2. Up to four waves of LO_2 tankers can be offloaded in a day, due to increased availability of LO_2 from the local supplier Praxair. Differences include the fact the LO_2 tank is filled with perlite and purged with dry GN_2, not evacuated, and some of the LO_2 transfer lines are not VJ insulated. In addition, LO_2 is pump fed, not pressure fed, and maximum flow rates through the 5-in. cross-country lines are 1200 gpm. The LO_2 losses are drained in a dump basin, while ET boil-off is vented out the top through the vent cap.

Atlas V

The Atlas V vehicle has up to three common core first stages, powered by LO_2/kerosene, with a second stage LO_2/LH_2 Centaur. As such, there is a considerable quantity of LO_2 but a small amount of hydrogen storage at the pads. Much of the pad operations and loading procedures are similar to the STS, including waves of tankers filling the pad storage vessel, chilldown, slow-fill, fast-fill, and topping modes, as well as drain-back procedures and vent and/or dump procedures. The main difference in hardware between the STS and Atlas V pads is the Atlas V uses pressure-fed LO_2 transfer to the boosters, not pump-fed. As such, there is a greater need for vaporizers, and all the lines in the system are VJ. The Atlas V also has separate tanks for the booster LO_2 and the Centaur LO_2. In addition, the Atlas V uses autocouplers to connect the ground cryogenic system to the launch platform, as opposed to manual mating done in the STS system. Also, the subcoolers previously used by the Atlas II to condition the propellants have been removed in the newer Atlas V.

Delta IV

The Delta IV uses LO_2/LH_2 propellants in all stages. The Delta IV ground support is almost identical to the STS system, which is not surprising since the flight systems were designed by many of the same Rocketdyne engineers who worked the shuttle main propulsion system. The hydrogen system has five tanker fill connections, VJ lines with MLI and VJ tank with perlite. Hydrogen is pressure fed to the vehicle, with vaporizers as the pressure source. Countdown timelines are similar, with chilldown, slow-fill, fast-fill, topping, and replenish modes. Hydrogen vapors are disposed in the flare stack. The LO_2 system also has five tanker ports, with a mix of VJ and noninsulated piping, and a dry GN_2 purge on perlite tank. LO_2 is pump fed, using similar heritage pumps as the shuttle. The main differences between STS and Delta IV arise because of the modernity of the Delta IV program, as opposed to 1960s-era hardware. Also, the Delta IV depends more on automated processes during the loading procedure, as opposed to the labor-intensive process the STS uses.

Key Cryogenic Refueling Technologies

Current ground operations concepts are robust and reliable and are capable of servicing a wide range of spacecraft and launch vehicle storage volumes. All current servicing methods take propellants at or near the normal boiling point, and slightly subcool the liquid using gaseous pressurization. In most cases, this amount of pressure is low, and the propellants are pump fed into the engines. If this storage technique is what is desired by the in-space storage depot, current ground-servicing equipment and operations are sufficient.

There may be some advantages to exercising more control of the propellant thermodynamic state while still in ground storage. Propellant densification systems have been proposed and tested several times over the past decade. Integrating a cryogenic refrigerator with a storage and distribution system could provide an advanced ground propellant handling system capable of liquefaction, zero-loss storage, and densification/subcooling. Properly designed, such a system could provide cost, safety, reliability, and performance benefits over current state of the art. This increases the capability of a depot in space by maximizing fluid density while decreasing boil-off losses.

Key Findings

All major programs at KSC use similar philosophies in cryogenic ground operations. This approach has developed over the years to be sufficient and reliable enough to meet current launch vehicle needs.

Gap Analysis

If the quantity of propellant to be delivered from Earth to an in-space depot is much larger than the current logistics chain can support, propellant production and liquefaction capability should be added to the launch site. If control of the propellant thermodynamic state is required, advanced integrated refrigeration and storage systems should be developed. This approach required a major change in the way current ground operations are performed and there will be a substantial, associated learning curve.

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Falcon Launch Vehicle Family

William Notardonato (KSC)

Executive Summary

Space Exploration Technologies is developing a low-cost family of launch vehicles capable of sending small to medium-size payloads into low Earth orbit. The initial vehicle, Falcon I, features a reusable first stage powered by LO_2/kerosene pump-fed engines and an expendable second stage powered by a LO_2/kerosene pressure-fed engine. Developmental testing of the Falcon I engines is complete, and the launch vehicle has been transported to the launch pad at Vandenberg Air Force Base. Due to range safety constraints with the Titan program, the initial flight has been delayed until at least July 2005. The Falcon V is also a two-stage partially reusable vehicle. Falcon V uses the same engines, avionics, structural architecture, and launch infrastructure as the Falcon I, to minimize development risk. First flight of the Falcon V is expected in mid 2006. SpaceX has firm launch commitments for the first four flights, including two from Department of Defense (DoD)/DARPA.

Capability Description

Flight costs

The Falcon family of vehicles is designed to reduce the cost to orbit, initially by a factor of 4 and eventually by a factor of 10. The Falcon I vehicle costs $5.9 million, compared to a Pegasus cost of $31 million. The Falcon V vehicle costs $15.8 million for a full flight, but a small satellite can purchase a half bay flight for $8.9 million. This is compared to a Delta II cost of $85 million.

Performance predictions

Table I details predicted performance of the Falcon I and Falcon V launch vehicles for a variety of orbital locations. Launch sites are available at Vandenberg Air Force Base (AFB), the Marshall Islands, and SpaceX is negotiating long-term lease of LC 36 at Cape Canaveral (Atlas II pads abandoned in 2004).

TABLE I.—ORBITAL PERFORMANCE

	Falcon I	Falcon V
200 km, 28°	670 kg	6020 kg
400 km, 51°	580 kg	5450 kg
700 km, Sun-synchronous	430 kg	4780 kg
Geosynchronous transfer orbit, 9°		1920 kg
Escape velocity		1200 kg

Reliability

The Falcon family is designed to offer high reliability and simplicity. Engines are not designed to push the performance envelope, and extensive ground testing has occurred. Engine start performance is verified prior to releasing ground hold-down bolts. The Falcon V uses five engines, and offers engine-out capability. Propellant tanks are machined with integrated flanges and ports, minimizing welds. Friction stir welding is used on required weld points. Stage separation mechanisms are flight proven on other launch vehicles. Avionics systems use triple redundant flight computers and inertial navigation systems.

Payload interface

A complete payload users' guide is available from SpaceX for the Falcon I. Separation interfaces have been defined and are provided by the launch vehicle, and are not counted against performance estimates given in table I. A GN_2 purge capability is available as an option, and an access door is included for on-pad commodity servicing. Electrical interfaces are defined and two 15-pin connectors are available for satellite use with maximum load of 3 A each. Four relay commands are available.

All facilities for payload processing are provided by SpaceX, for a maximum time of 3 weeks prior to launch. Temperature, humidity, and contamination control is provided. Specific ground support equipment must be provided by the payload customer, and hazardous operations are not allowed in the payload processing facility.

The Falcon was designed to have a benign payload environment, with low thrust-to-weight accelerations, low dynamic pressure, and a single staging event. Axial and lateral-g loads are defined and the maximum accelerations are 6g at first stage burnout. The random vibration, acoustic, and shock environments have been defined in the user's manual.

Figures 1 and 2 detail the geometric constraints of the payload fairings for the Falcon I and V launch vehicles, respectively. All dimensions are in meters.

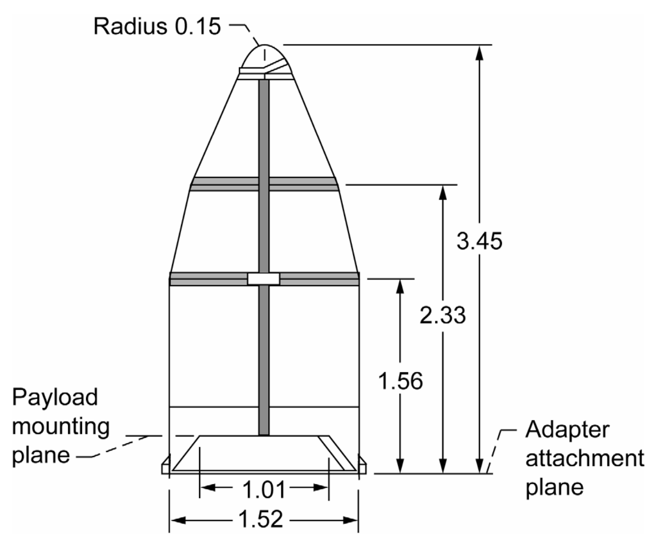

Figure 1.—Falcon I fairing dimensions in meters.

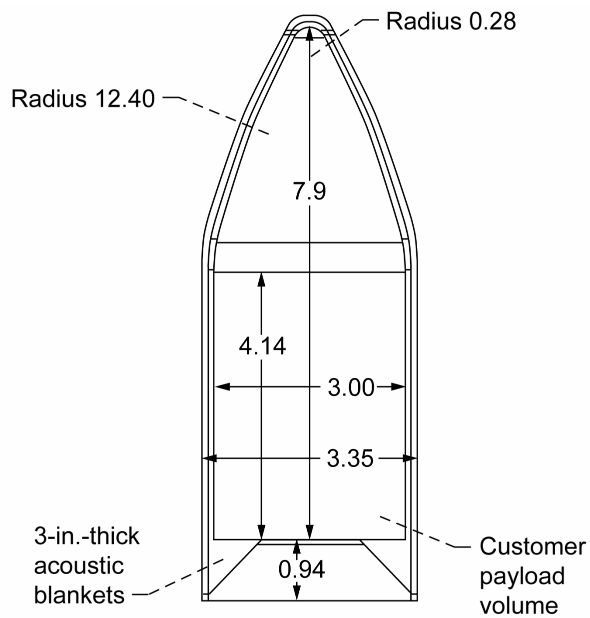

Figure 2.—Falcon V fairing dimensions in meters.

Key Cryogenic Refueling Technologies

The nature of low-gravity cryogenic refueling requirements makes it very difficult to prove in the laboratory or a "relevant environment." Surface tension and viscous forces can be simulated for cryogenic liquid acquisition devices (LADs) using similarity principles, but gravitational effects on Earth cannot be ignored. Likewise, lack of thermal stratification and tank pressurization and/or mixing effects found in low-g environments cannot be duplicated in ground-based testing. However, scaling issues and transient thermal processes make performance testing in drop towers or parabolic flight profiles insufficient. The best method of advancing in-space cryogenic handling technologies is long-duration orbital testing, but funding constraints have eliminated dedicated launch opportunities in the past. Some testing has occurred on the space shuttle in the past, but political constraints make this option less likely in the future.

Key Findings

Provided the debut launch of the Falcon I vehicle is successful, a low-cost alternative to existing launch vehicles may be available by 2006. A launch of a 670-kg satellite in a 200-km, 28° orbit will cost $5.9 million. Payload interfaces and environments have been defined. An experimental satellite can be designed during the In-STEP–005 program to take advantage of this opportunity to test and prove in-space cryogenic fluid storage and transfer technologies in an actual flight environment.

Gap Analysis

Lack of affordable launch options in the past has eliminated the possibility of dedicated spacecraft designed to prove in-space CFM. Small commercial companies are using private money to develop low-cost access to space. If successful, program costs for a dedicated CFM satellite may be reduced to the point of obtaining feasible funding levels.

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The Hitchhiker (HH) Shuttle Small Payloads Carrier

Michael DiPirro (GSFC)

Executive Summary

The HH program was established in the mid-1980s to provide low-cost, mission-of-opportunity access to space aboard the space shuttle with real-time command to and telemetry from the payload. HH payloads were classified as secondary shuttle payloads, meaning that their requirements cannot determine major mission parameters. Nevertheless, several HH payloads were successful in requesting astronaut involvement and shuttle maneuvers, for instance. Many HHs were flown. Among these were several cryogenic- and cryo-depot-related payloads.

Capability Description

HH started as a side-mounted system managed by GSFC (Hitchhiker-G) and a cross-bay carrier managed by MSFC (Hitchhiker-M). These were later combined at GSFC. The HH carriers are now designated Hitchhiker-S (fig. 1) and Hitchhiker-C (fig. 2), respectively. Both carriers have the same electrical systems and provide the same electrical interfaces and services for customer equipment. Either carrier can accommodate equipment mounted in a standard canister or on a standard vertical mounting plate. The cross-bay version also has horizontal top mounting plates. The canisters may be pressurized. Because of its hazardous nature, liquid hydrogen has not been flown in the shuttle cargo bay. However, several HH payloads have used liquid cryogens, including LH_2 on SHOOT (ref. 1).

Extensive details on the interfaces, allowances, and customer requirements are contained within customer accommodations and requirements specifications (CARS). In addition, special arrangements can be made to permit on-pad servicing as close as 65 hr prior to launch, allowing topoff and conditioning of cryogens. The following information is extracted from the CARS document (ref. 2).

TABLE I.—POWER, DATA, AND MASS BUDGETS

Power, kW	< 1.3
Energy, kWh	< 60
Low rate downlink, Mb/s	6
Medium rate downlink, Mb/s	1.4
Canister-mounted mass, kg	< 90
Side directly mounted mass, kg	318
Cross-bay plate-mounted mass, kg	272

(Note: Multiple plates are mounted on a cross-bay carrier. The carrier mass capacity is much greater than this number, but requires structural analysis.)

Gap Analysis

No LH_2 may be flown in the shuttle cargo bay. However, a simulant fluid, such as normal liquid helium ($2.2 < T < 4.5$ K), may be flown. In fact, the SHOOT flight demonstration lifted off with liquid helium in the normal state, and pumped this liquid down on orbit to <2 K. SHOOT demonstrated the safe handling of normal as well as superfluid helium in the shuttle cargo bay.

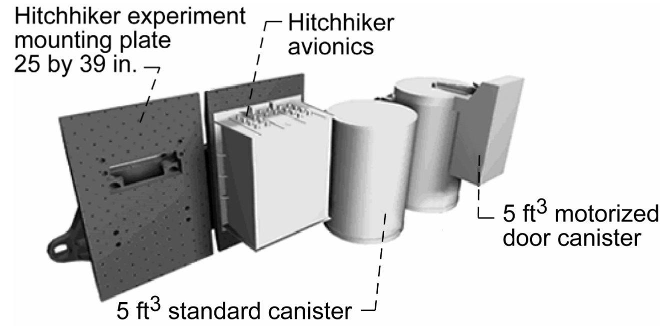

Figure 1.—Hitchhiker-S side mount carrier.

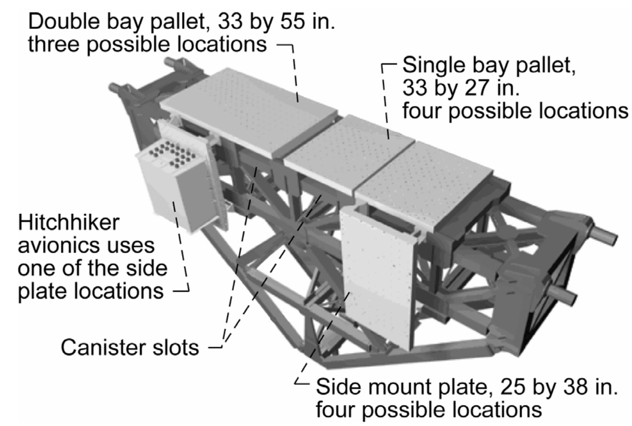

Figure 2.—Hitchhiker-C cross-bay carrier.

The HH program was disestablished several years ago. Presently, much of the hardware associated with the project itself has been transferred to other NASA centers (JSC) and other Government agencies. We are attempting to locate hardware used by SHOOT in its flight on HH in June 1993. In particular, the cross-bay carrier and avionics box would be required for a reflight of the SHOOT hardware. An update will be given when the component search is completed.

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Pegasus Air Launch System

Michael DiPirro (GSFC)

Executive Summary

The Pegasus Air Launch System was developed to provide cost-effective access to space for the small satellite community. The Pegasus is a mature and flight-proven small launch system that has achieved consistent accuracy and dependable performance. Since the initial launch in 1990, the Pegasus has conducted 36 missions, launching more than 70 satellites.

The three-stage Pegasus is used by commercial, government, and international customers to deploy small satellites weighing up to 1000 lb into low Earth orbit. Pegasus is carried aloft by the "Stargazer" L–1011 aircraft to approximately 40 000 ft over open ocean, where it is released and then free falls in a horizontal position for 5 s before igniting its first-stage rocket motor. Pegasus typically delivers satellites into orbit in a little over 10 min.

Capability Description

- A range of custom payload interfaces and services to accommodate unique small spacecraft mission
- Payload support services at the Pegasus Vehicle Assembly Building at Vandenberg AFB
- Horizontal payload integration
- Shared payload launch accommodations for more cost-effective access to space as dual launches
- Air-launched mobility enables launch from anywhere worldwide
  - Demonstrated launch capability from U.S. Air Force Western Range, Eastern Range, NASA's Wallops Flight Facility, Canary Islands, and Kwajalein launch sites
  - Flight proven with demonstrated success record
- Fast, cost-effective, and reliable access to space

Capability Benefits/LH_2 Capability

Pegasus demonstrated LH_2 accommodation capability when the Wide-field Infrared Explorer (WIRE) payload, a Small Explorer (SMEx) mission, was launched aboard a Pegasus XL rocket early in 1999. Orbital Sciences Corporation developed venting hardware and procedures for the Pegasus to allow a hydrogen payload. The venting system consisted of a T–0 disconnect from the rocket to the carrier aircraft and a vent around the aircraft fuselage as shown in figure 5.

- WIRE contained two tanks with a total of 5 kg of solid hydrogen. As a liquid, this would be equivalent to 70 liters.

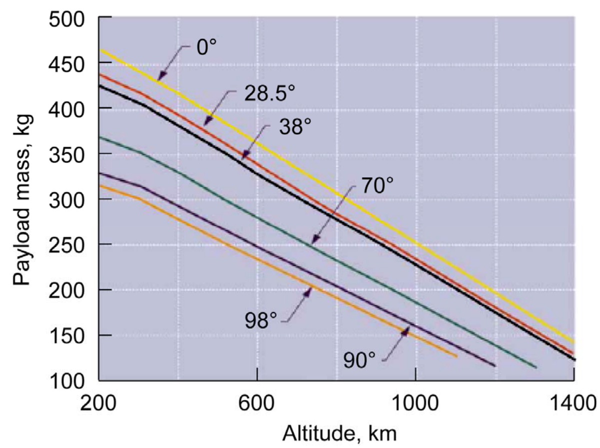

Figure 1.—Pegasus performance capabilities.

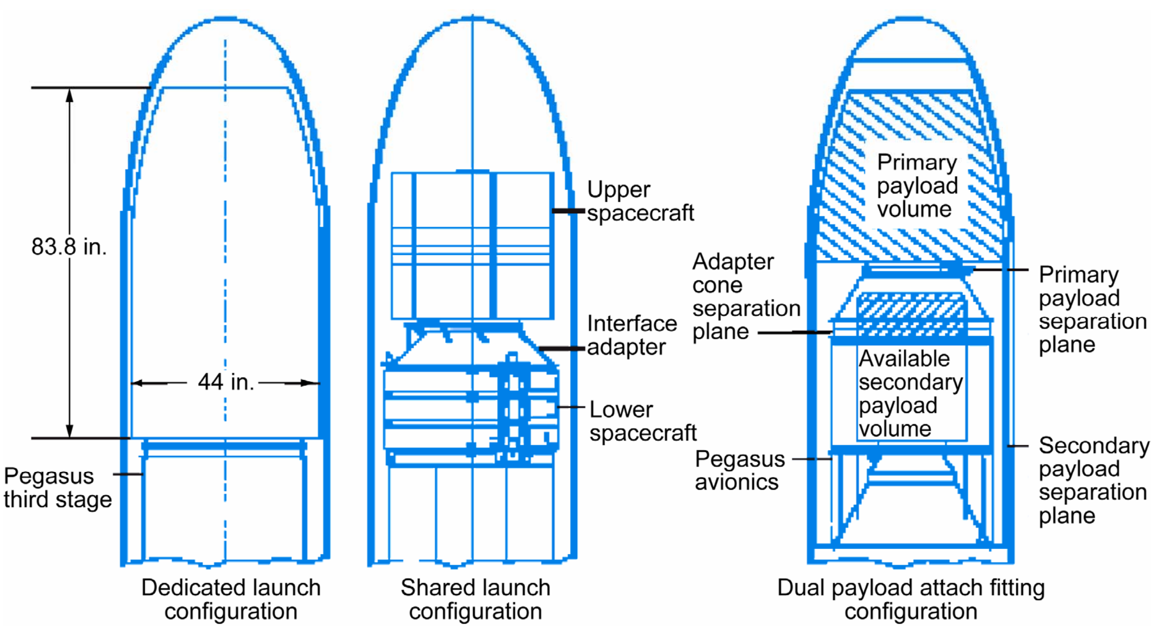

Figure 2.—Pegasus payload accommodations.

Figure 3.—WIRE in the payload processing facility at WTR at Lompoc, California. This facility is set up to safely handle hydrogen.

Figure 4.—WIRE mounted into the Pegasus fairing. Note the fairing door used to service the experiment on the "hot pad."

Figure 5.—Pegasus attached to L–1011 Aircraft. Note the band around the fuselage containing the hydrogen vent. The helium dewars in the pictures are for maintaining the hydrogen as a solid prior to launch.

Gap Analysis

- Carrier costs and mission planning timelines are greater when compared to alternate suborbital carriers.
- Special accommodations are required for hydrogen use; however, the WIRE mission was completed utilizing unique hardware and procedures developed by Orbital Sciences Corporation. Although process and hardware may be available, additional costs may be required for implementation.

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NASA Sounding Rocket Program

Brian Hall (GSFC)

Executive Summary

The NASA Sounding Rocket Program (NSRP) is a suborbital space flight program that primarily supports NASA-sponsored space and Earth sciences research activities, other Government agencies, and international sounding rocket groups and scientists. Since its inception in 1959, approximately 2800 missions have flown with high overall scientific success rates and vehicle performance success rates. The program is a low-cost, quick-response effort that currently provides 20 to 30 flight opportunities per year to space scientists involved in upper atmosphere, plasma physics, solar physics, planetary atmospheres, galactic astronomy, high energy astrophysics, and microgravity research.

NSRP customers consist primarily of university and government research groups; however, some research activities involve the commercial sector. The program has contributed major scientific findings and research papers to the world of suborbital space science, validated satellite tracking and instrumentation, and served as a proving ground for spaceship and space station components.

Capability Description

Program

The NSRP is managed as a low-cost, quick-response, highly reliable program offering access to the space environment. The program has a long history of developing and implementing sounding rocket projects for a wide variety of scientific customers, including development teams pursuing the maturation of technologies. The NSRP has the full end-to-end capability to fulfill the customer's requirements, including the in-house capability to design, develop, fabricate, integrate, and qualify flight hardware prior to launch.

Vehicles and payload support systems

The NSRP offers an existing suite of launch vehicles that can provide apogees above 1400 km (870 miles) for payload weights of 114 kg (250 lb) and apogees above 400 km (249 miles) for payload weights up to 500 kg (1100 lb) (figs. 1 and 2).

Sounding rockets consist of one or more motor systems, often including low-cost surplus military stages, and spacecraft systems. Spacecraft systems include a payload bay and any combination of the following subsystems: stage interface, spacecraft attitude control, power distribution systems, data acquisition and management module, recovery system, and payload ejection systems (fig. 3). Sounding rocket payloads offer a variety of experiment volumes with typical diameters ranging from 14 to 22 in. and lengths up to 120 in., depending on the carrier vehicle and the project subsystem requirements.

Vehicles and spacecraft payload support systems

- Use of low-cost, highly reliable suborbital carriers dramatically reduces the overall risk, enabling the development teams to focus on the technologies being matured
- Offers a variety of sounding rocket vehicles with varying performance capabilities to suit a wide array of experiment needs
- Offers numerous standardized spacecraft payload support systems with extensive flight history. Designs are robust and adaptive to accommodate a variety of experiment needs

Launch facilities

- Multiple fixed launch-range opportunities, including Wallops Flight Facility, White Sands Missile Range, and Poker Flat Research Range
- Mobile range assets, including launchers, telemetry, tracking radar, command systems, that can be deployed to remote sites worldwide in support of sounding rocket launches

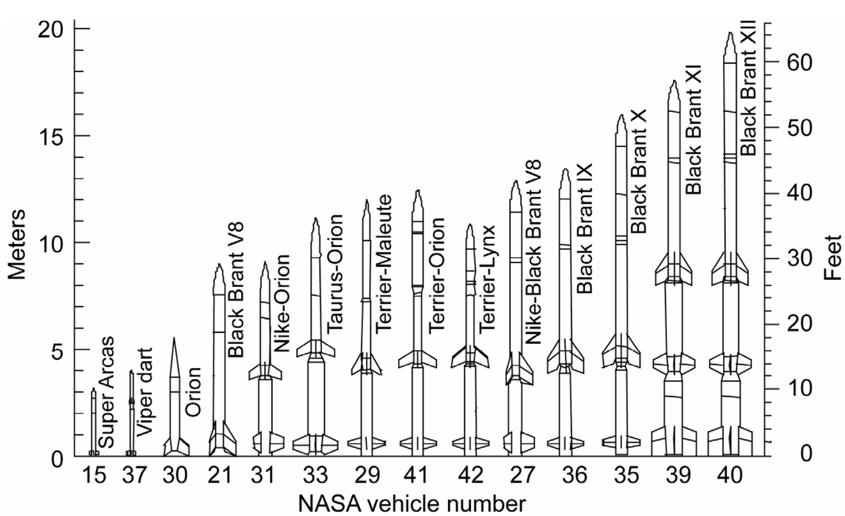

Figure 1.—NASA sounding rocket program launch vehicles.

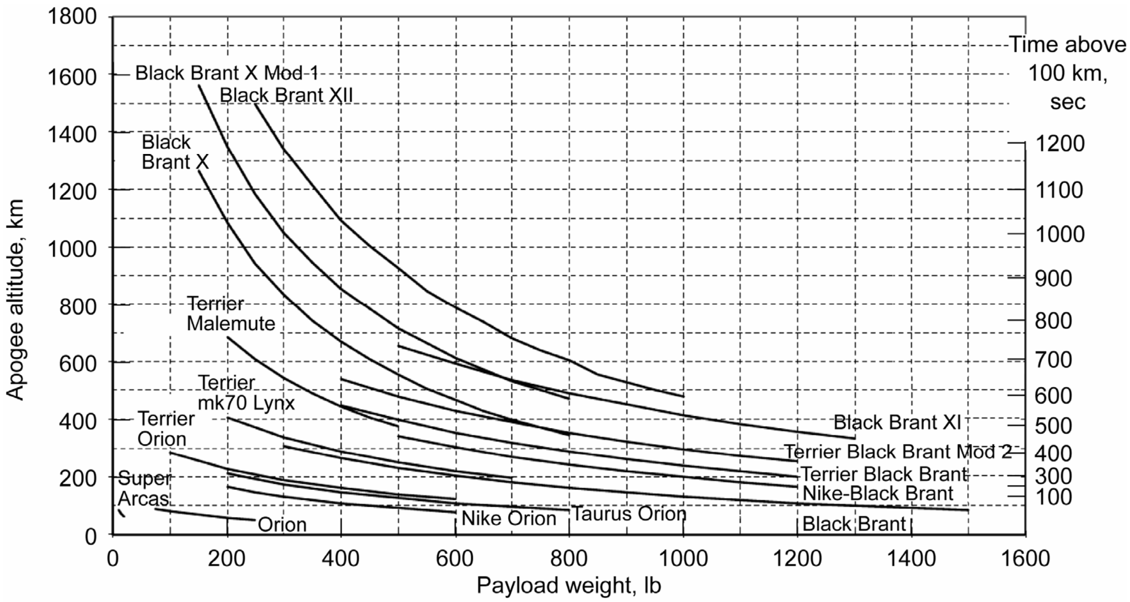

Figure 2.—NSRP launch vehicle performance.

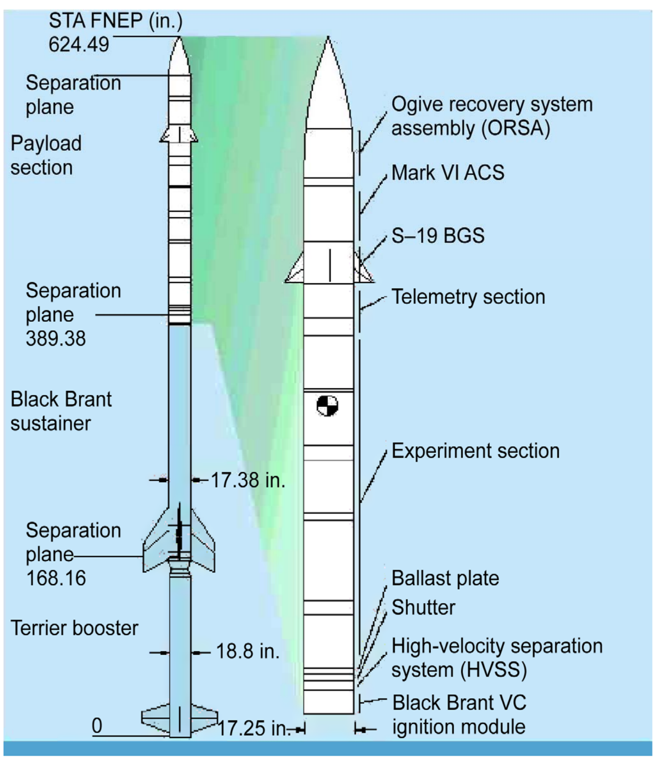

Figure 3.—Spacecraft subsystem description.

Gap Analysis

The NSRP is respected as a low-cost, reliable program that provides access to the space environment. Although the program maintains a variety of sounding rocket launch vehicles with varying performance capabilities, near-term experiments would be limited to the existing suite of vehicles. However, the NSRP continues to evaluate launch vehicles with enhanced performance and payload carrying capabilities. The NSRP sounding rockets may offer reduced volume allowances and weight carrying capabilities when compared to larger orbital vehicles. The NSRP sounding rockets will offer reduced flight experiment time when compared to orbital missions.

The low-cost, high-reliability, short-implementation requirements, and launch flexibilities demonstrated by the NSRP should be weighted against the cost, and experiment flight time offered by other carrier systems.

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Appendix B—Experiments Historical

Aerobee Sounding Rocket Cryogenic Fluid Management Tests

David J. Chato (GRC)

Executive Summary

In the early 1960s, a series of sounding rocket tests were conducted to understand the behavior of LH_2 in low gravity. The test equipment was capable of observing behavior in a 9-in. sphere of hydrogen for approximately 5 min of acceleration, 10^{-4} times smaller than normal gravitational acceleration. Nine flights were conducted, but the results of only seven have been published in the open literature. A flight of a very similar 9-in. hydrogen sphere was conducted in a secondary payload pod attached to an Atlas intercontinental ballistic missile, which provided for 21 min of free fall. Unfortunately residual rotation of the pod produced a 10^{-3} times normal-gravity acceleration. Aydelott conducted a ground test with a similar 9-in. sphere and used the results from all three tests to develop simple models of hydrogen tank pressure rise in low gravity.

Capability Description

Hardware (see fig. 1)

- 9-in. diameter sphere
- 10-in. diameter shield with heater strips and LN_2 cooling coils (ground use only)
- 11-in.-diameter vacuum jacket
- Ports for lights and camera
- LH_2 fill and drain lines
- De-spin table

Instrumentation (typical slight variations test to test)

- 18 wall-mounted temperature transducers
- 1-g level sensor
- Camera
- Four accelerometers
- Pressure transducer

Key Cryogenic Depot Technologies

- Passive storage
- Pressure control
- Liquid acquisition

Key Findings

Key parameters of the flight program are summarized in table I. Important results included the observation of nucleate boiling in hydrogen in low gravity, observation and the collection of LH_2 via a standpipe in low gravity, and the measurement of pressure rise in low gravity. Aydelott comparison to ground testing that neither pressure rise rate could be predicted by either a homogenous mixture model or a surface evaporation model. However, in this scale of tank the actual pressure rise was bounded on the high end by the surface evaporation. He also found that ullage heating was an important factor in pressure rise rate

Gap Analysis

Issues encountered included de-spin problems, lighting failures, liquid retention in liquid-vapor sensors, and loss of camera film. Although Aydelott found the surface evaporation as an upper bound for this size tank, subsequent flight test of full size tanks produced even higher pressure rise rates. Analysis of the full-scale data linked the issue to the other finding of Aydelott that ullage heating controlled the pressure rise rate. Despite these difficulties, overall the projects served as a valuable stepping stone to flight demonstration and built confidence in the ability to handle hydrogen in low gravity.

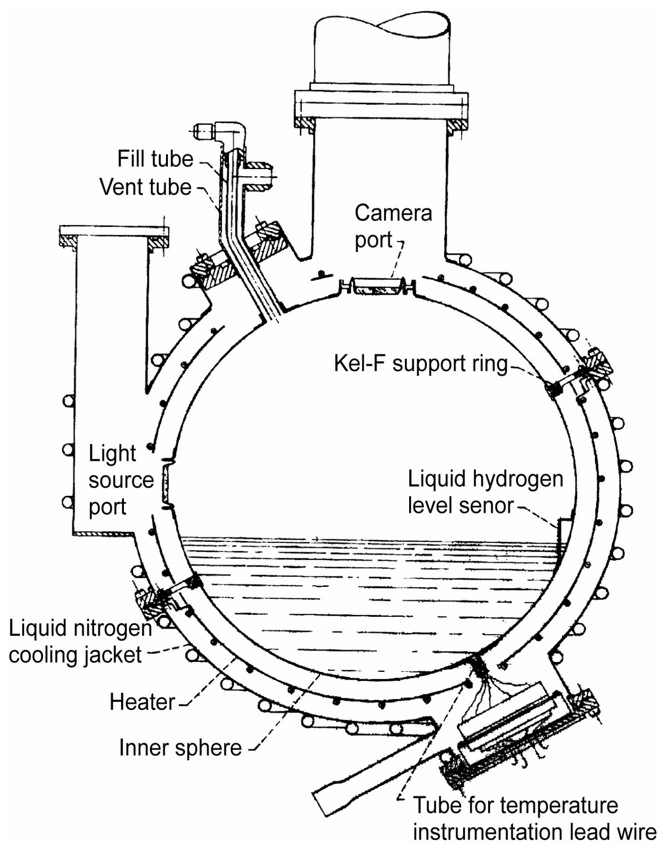

Figure 1.—Zero-gravity heat-transfer apparatus.

TABLE I.—KEY PARAMETERS OF FLIGHT PROGRAM

Flight	Fill, %	Heat flux, btu/ft^2 hr	Film	Comments
1	22.5	270	Film not recovered	Spinning at 2.5 cps
2	32	132	Light source dimmed by electrical failure at 120 s. Light source failed at 194 s. Surface motion obscured by liquid over camera port	Electrical problems with electric spin table resulted in tank spin-up from 186 to 199 s and 212 to 326 s
3	32	132	No light source failure prior to low-gravity portion	Contained unsuccessful prototype zero gravity level
4	25.1	61.5	Yes	Only ½ of tank heated
6	20.6	267	Yes	Spinning at 2.73 cps contained standpipe for liquid acquisition. Only ½ of tank heated
7				
9	78.3	145	Yes	
Atlas Pod	36	25	No camera ports	Liquid position determined by four sets of internal temperature rakes (four sensors per rake)

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Saturn IVB Fluid Management Qualification

David J. Chato (GRC)

Executive Summary

The Apollo Lunar mission required the Saturn IVB stage have a capability to coast in low Earth orbit for up to 4½ hr then restart. Because of the lack of understanding of low-gravity phenomena, a dedicated flight demonstration was conducted. The mission known as AS–203 was launched July 5, 1966. The flight experiment was very successful in achieving its goals. Continuous settling via vent thrusters achieved both the objective of maintaining liquid positioning and tank pressure control at the cost of a considerable loss of hydrogen. However, the experiments at the end of the mission indicated that recovering liquid from a low-gravity coast was relatively easy, so continuous settling was probably not required. The engine chilldown tests although effective gave another indication of over-design based on ground test. The experiment did provide a good source of data for benchmarking both slosh and pressure-control modeling effort.

Capability Description

The Apollo Lunar mission required the Saturn IVB stage have a capability to coast in low Earth orbit for up to 4½ hr then restart. To obtain this capability required the ability to maintain liquid over the engine feedlines and cool the engine feedlines down prior to engine restart. A strategy was developed to maintain continuous liquid settling during the coast period. After engine cutoff the propellants were settled by 5×10^{-4} thrust for 77 s (pair of 70 ullage rockets on Saturn emulated by oxygen tank vent in the test flight.)

After the initial transition to low-gravity liquid position would be maintained by continuous hydrogen venting producing 2×10^{-5}g. Due to the lack of understanding of low-gravity phenomena, a dedicated flight demonstration was conducted. The objectives of the flight demonstration were to

- Verify low-gravity performance of S–IVB stage
- Obtain data on heat transfer and fluid behavior in reduced gravity

Hardware

S–IVB stage launched on S–IB rocket. Off load of oxygen tank to provide 5000 lbm LO_2 and 19 000 lbm LH_2 at orbit insertion.

Instrumentation

- Television system
- 57 temperature sensors
- Nine pressure sensors
- Seven liquid-vapor sensors
- Five accelerometers
- Three calorimeters

television signal was downlinked to ground stations in Corpus Christi, KSC, Bermuda, and Carnarvon, Australia. The first three stations provided a band of 14 min. of continuous coverage when the stage was above them, so most experiments were planned for this portion of the orbit

Experiment Procedure

- First orbit obtain orbital slosh data and maintain liquid settling
- Chill engine for 5 min
- Second orbit obtain orbital slosh data and maintain liquid settling
- Chill hydrogen side only for 5 min
- Third and fourth orbits
- Observe behavior of liquid after termination of settling thrust and during rapid depressurization finally determine closed tank pressure rise rate

Key Cryogenic Refueling Technologies

- Passive storage
- Pressure control
- Liquid acquisition
  - Elimination of boost phase slosh
  - Maintenance of liquid settling

Key Findings

The mission known as AS–203 was launched July 5, 1966. It achieved all its objectives. Detailed findings follow.

Liquid dynamics

Two slosh waves were detected after boost phase termination. The sources of the waves were attributed to both the amplification of boost phase slosh as well as the possible surge from fuel suction duct. Both slosh waves were caught by deflector. Both waves damped after 73 s.

No disturbances were detected after switching to the hydrogen vent thrusters. The liquid surface began boiling at 166 s into the flight resulting in vapor fog. The hydrogen vent system provided adequate control of liquid position during the required coast period

Engine chilldown

- First hydrogen line chilldown. Hydrogen line cooled by 290 s of recirculation with recirculation pump
- 20 s of prevalve with recirculation
- 10 s prevalve no recirculation
- 12.5 s of outflow

Chilldown transients were less severe than ground testing. Chilldown was achieved prior to opening the prevalve.

Oxygen line chilldown

- 290 s recirculation cooling
- 12.2 s prevalve open with recirculation
- 51 s outflow

Unstable recirculation flow occurred near the end of recirculation period due to low oxygen level, but oxygen line chilldown was achieved.

Second hydrogen line chilldown

- Timeline was the same as first but without outflow. Lack of subcooling in the hydrogen made the recirculation pump flow highly variable
- Hardware temperatures lower than expected throughout flight due to liquid residuals in the engine

Liquid motion after settling thrust termination

Free coast caused liquid to reorient to the forward end due drag deceleration of approximately 1.9×10^{-6} (bond number 7). After 5 min the liquid was resettled via the oxygen vent thrusters, and the hydrogen vent thrusters restarted.

Rapid depressurization

- First blowdown (3 min under 3.7×10^{-4}g) produce first fog then large liquid blobs in the ullage even though bulk fluid remained settled
- Second and third blowdown (90 s each under 2×10^{-5}g) were similar to first blowdown. Boiling of saturated bulk liquid caused only 2.3 pressure drop in third vent

Closed tank experiment

- Was started with 16 000 lbm of hydrogen at 12.4 psi It reached 37.7 psi in 5360 s an average rise rate of 17.0 psi/hr (predicted was 3.2 psi per hour)
- Common bulkhead rupture believed to have exploded tank at a pressure difference of 34.9 psi shortly after loss of signal 22 680 s after liftoff

Gap Analysis

The Saturn IVB flight experiment was very successful in achieving the goals laid out for it, but several issues arise for future designers. Since the stage performed the nominal mission as expected no changes to the design were required for the actual Apollo missions. Continuous settling via vent thrusters achieved both the objective of maintaining liquid positioning and tank pressure control at the cost of a considerable amount of lost hydrogen. However, the experiments at the end of the mission indicated that recovering liquid from a low-gravity coast was relatively easy, so continuous settling was probably not required. The engine chilldown tests although effective gave another indication of over-design based on ground test. The experiment did provide a good source of data for benchmarking both slosh and pressure-control modeling effort.

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Flight Qualification of Centaur Cryogenic Fluid Management

David J. Chato (GRC)

Executive Summary

It was determined that the launch window for the surveyor missions could be significantly enhanced by adding an orbital coast and an engine restart in low gravity. Based on the information available, a test flight designated Atlas Centaur (AC)–4 was conducted. Two 2-lbf thrusters were added to the basic Centaur to provide settling thrust throughout coast at a Bond number of 240. However propellant disturbances at main engine cutoff caused liquid entrainment into the vent. This liquid entrainment into the vent then caused spacecraft to tumble out of control. To correct these difficulties a number of new systems (listed below) were added to a second test flight designated AC–8.

Hardware AC–8

Centaur stage with equipment added to prevent boost phase surge including

- Dissipater on volute bleed
- Recirculation line dissipater
- Pressurant gas diffuser
- Slosh baffle channel ring with 12 antiswirl baffles
- Settling thrust increased to 100 lbf for 100 s after main engine cutoff
- Settling thrust upped to 6 lbf for coast phase (Bond number 360)

Instrumentation

- 32 custom liquid-vapor sensors
- 16 custom ullage temperature sensors
- 45 wall-mounted temperature sensors
- Absolute pressure and vent gas temperature in each vent
- Five calorimeters
- Two accelerometers
- Two pressure transducers each tank

Key Cryogenic Depot Technology

- Slosh control
- Pressure control
- Liquid acquisition via settled thrust

Key Findings

AC–8 demonstrated successful propellant retention for entire coast phase. At 917 s irregularities in two of the four settling thrusters caused a backup pair of 50-lbf thrusters to fire. The 50-lbf thruster then set up a slosh wave, which persisted for four cycles (532 s). Figure 1 shows liquid position as measured by the internal level sensors during the first propellant slosh wave cycle. The AC–8 propellant sidewall heat flux was measured at rates from 10 to 6 Btu/ft^2/hr. Forward heat flux was measured from 43 to 22 Btu/ft^2/hr. Due to a failure unrelated to the cryogenic fluid management (CFM) systems, successful engine restart was not achieved. Successful engine restart was demonstrated on the following test flight AC–9.

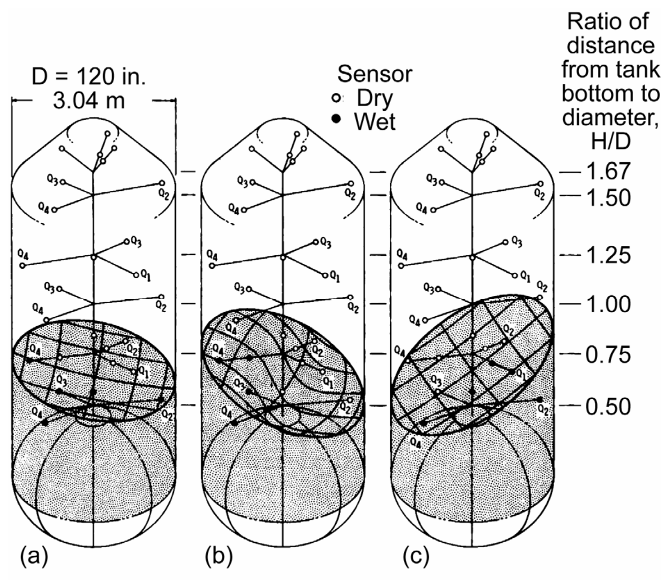

Figure 1.—Liquid position in AC–8 hydrogen tank during first slosh wave 919 to 1062 s after first main engine cutoff. (a) Time, 955. (b) Time, 955. (c) Time, 1060.

Gap Analysis

Subscale modeling and drop tower analysis suggested bond of 240 as adequate to address the steady-state settling requirements. Unfortunately the driving requirement turned out to be the slosh transient at the start of the low-gravity coast. To fix the problem quickly, all possible sources of the problem were addressed and then tested together. What was not done was a systematic investigation of each of the problems to determine the real culprits and the minimum necessary to correct the problem. Because of the cost and complexity of flight testing, once AC–8 proved an operational system, no further adjustment of the Centaur CFM system were conducted.

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Titan Centaur Cryogenic Fluid Management Flight Tests

David J. Chato (GRC)

Executive Summary

Two cryogenic fluid management tests were conducted using propellant leftover from missions with excess payload capacity. Testing indicated it was perfectly feasible to allow the Centaur to coast in zero-g, and then use settling thrust to collect the liquid prior to restart. Titan Centaur (TC)–2 conducted two additional engine firings with coast times as long as 3 hr. TC–5 demonstrated five additional engine firings with coasts as long as 5.25 hr. The TC–5 mission of 9.5 hr is still the longest Centaur mission conducted.

Capability Description

Excess payload capacity made propellant available for extended mission testing of Titan-Centaur upper stage. Two test flights were conducted: TC–2 and TC–5.

Hardware

- Centaur upper stage
- Three-layer MLI sidewall insulation to reduce LH_2 heating from 28 000 Btu/hr to 500 Btu/hr
- Two 6-lbf H_2O_2 thrusters for liquid collection after coast (Bond number 990)
- Vent control system
- Revised tank pressurization technique to reduce pressurant consumption
- Instrumentation
- 12 liquid-vapor sensors in the hydrogen tank
- Pressure gauge
- Ullage temperature sensors both LH_2 and LO_2 tank

Propellant load at start of extended mission

- TC–2 17 percent
- TC–5 14.5 percent LH_2, 12 percent LO_2

Planned tests

- TC–2
  - 1-hr zero-g coast
  - Settling maneuver
  - Engine restart
  - 3-hr coast
  - Settling maneuver
  - Engine restart
- TC–5
  - Five 25-hr coast
  - Settling maneuver
  - Engine start
  - 30-min coast
  - Settling maneuver
  - Engine start
  - 20-min coast
  - Settling maneuver
  - Engine start
  - 5-min settled coast
  - Engine start
  - 2-hr coast
  - Engine start

Key Cryogenic Depot Technology

- Passive storage
- Pressure control
- Pressurization
- Liquid acquisition via settling thrust
- Settled venting

Key Findings

TC–2 was launched December 10, 1974. During the first coast, liquid position was quite different than pretest prediction due to liquid retention in the crevice section of the hydrogen tank. Figure 1 shows the estimated liquid position based on level sensor readings and a mass balance. Settling thrust was high enough to cause a columnar liquid flow along the centerline as well as wall bound flows. Liquid collected in 40 s, rather than the pretest prediction of 110, or the scheduled thruster firing of 300 s. No venting was required. Engines were restarted successfully.

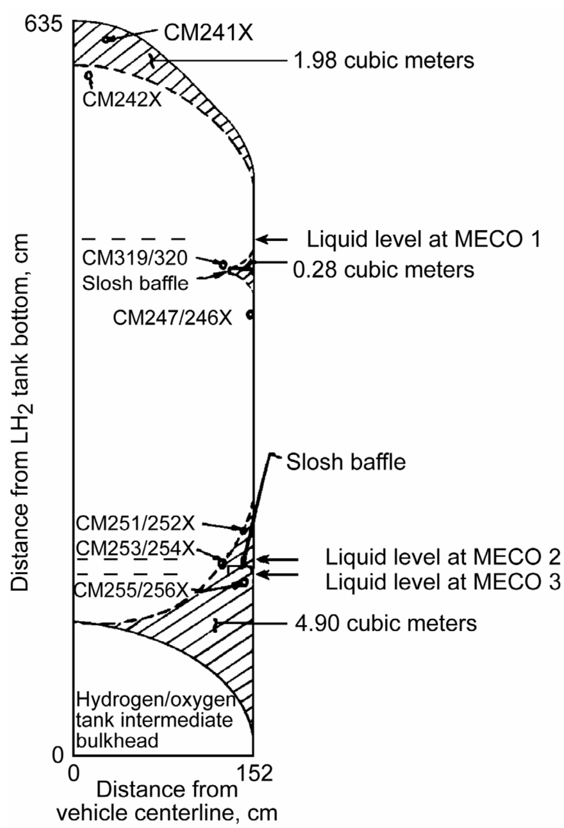

Figure 1.—Liquid hydrogen position during TC–2 first coast prior to propellant settling for vent.

During the second coast, liquid position was very similar to that observed in the first coast. At 8560 s into the coast, settling thrusters were fired for 180 s. Liquid again collected in about 40 s. After settling, the tank was vented for 40 s. During the vent, the topmost liquid sensor rewet. Tank liquid distribution returned to the previous location for a continued coast of 1590 s. Then the settling thruster fired again, collecting the liquid in 37 s. Following the settling, the main engines were successfully restarted.

TC–5 was launched January 15, 1976. During the first coast, liquid behavior was very similar to TC–2. Liquid was settled after 20 s of thruster firing, and the engine successfully restarted. After firing, the liquid returned to the previous liquid condition. Liquid was settled after 20 s of thruster firing, and the engine successfully restarted again. After this engine firing, insufficient liquid was available to rewet the forward end. The liquid remained trapped in the hydrogen tank crevice for the remainder of the flight. All remaining engine starts were successful, although the engine burn started after the short-settled coast showed significant cavitation in the oxygen boost pump. This was attributed to a start transient caused by not letting the boost pump spin down prior to engine start.

Gap Analysis

The Titan Centaur CFM tests provided a wealth of information on the performance of propellants in low gravity and demonstrated long coast capabilities with fairly simple modifications. The “piggybacking” off of operational missions made the cost reasonable, but prevented them from carrying as extensive instrumentation as the previous Atlas test flights. Surprisingly, although TC–2 and TC–5 clearly indicated the possibility of a three-burn mission to geosynchronous orbit, this capability was not implemented until the Titan Centaur IV, more than 20 yr later.

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Vented Tank Resupply Experiment

David J. Chato (GRC)

Executive Summary

The vented tank resupply experiment (VTRE) flight experiment on STS–77 confirmed the design approaches presently used in the development of vane-type propellant management devices (PMDs) for use in resupply and tank venting situations, and provided the first practical demonstration of an autonomous fluid transfer system. Transfers were more stable than drop tower testing would indicate, and show that rapid fills can be achieved. Liquid was retained successfully at the highest flow rate tested (2.73 gpm). Venting tests show that liquid free vents can be achieved. Liquid free vents were achieved for both tanks, although at a higher flow rate (0.1591 cfm) for the spherical tank than the tank with a short barrel section (0.0400 cfm). The liquid recovery test showed rewicking of liquid into the PMD after thruster firing was quicker than pretest predictions. Recovery from a thruster firing, which moved the liquid to the opposite end of the tank from the PMD, was achieved in 30 s. The objectives of VTRE were all achieved. The video provided great insight into the PMD behavior, and suggested new considerations for the design of future PMD that would not have been seen without this flight test.

Capability Description

Experiment description

The experiment was designed to fit within three modified Hitchhiker (HH) 5 ft^3 canisters. The center canister held the pressurization system and the experiment control electronics. The outer canisters held the test tanks and the video system.

The experiment hardware primarily consisted of two 0.8-ft^3 clear acrylic tanks with vane-type PMDs. The test fluid was a red-dyed Refrigerant 113. Two test tanks of equal volume were used. One tank was a 14-in. inner diameter sphere (test tank B) while the other was a 12.5-in. diameter by 16-in. long cylinder (test tank A).

The PMD consisted of 12 inner vanes that were mounted to a central standpipe as well as 12 outer vanes that follow the profile of the tank wall (fig. 1). The inner vanes are designed to locate the liquid over the inlet/outlet region and are shaped at the top to provide a centering force for the ullage bubble. The outer vanes provide an increase in the liquid orientation over the inlet/outlet. The outer vanes also quickly recover any liquid spilled out of the inner vanes back to the bulk liquid region. An inlet baffle of fine holes was used to spread the liquid evenly between the vanes.

Instrumentation

- Primary instrument: video camera
- Secondary instruments
- Liquid flowmeters
- Ultrasonic gas flowmeter (also used for GN_2/R113 measurement)
- Pressure sensors
- Thermocouples
- Capacitance type quality meters

The VTRE was launched on STS–77 on May 19, 1996 as part of a cross-bay HH bridge payload called the technology experiments for advancing missions in space (TEAMS). Most experiments were run during the crew sleep period to minimize any external disturbances during the testing. The only exceptions were the two sequences, which required STS thruster firings.

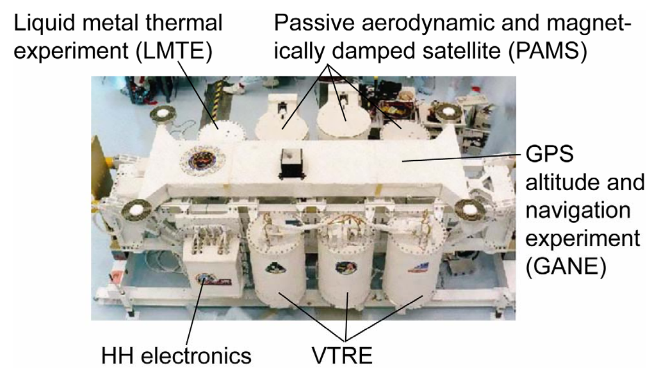

Figure 1.—VTRE (and other payloads) mounted on TEAMS hitchhiker bridge.

Key Cryogenic Refueling Technologies

- Liquid acquisition
  - Vane propellant management devices
- Transfer
  - Zero-g transfer
- Pressure Control
  - Noncondensable venting
  - Boiling vent
- Reorientation
  - Recovery of vaned PMD from spilling thrust

Key Findings

Transfer tests

The data showed that the eight empty-to-full transfers were successful and the critical Weber number is much higher than the preflight prediction. Liquid was retained successfully at the highest flow rate tested (2.73 gpm).

When filling an initially empty tank, a somewhat unstable geometry occurred when the tank was around 60 to 70 percent full. At this fill level, the vanes force the liquid into almost flat interface, lowering the surface tension. This made it easy for the inflow liquid to transfer from the inner vanes to the vent region. Video of tests 105, 107, and 108 show two-phase flow out the vent at this fill level (although not high enough percent liquid to fail our success criteria).

Further transfer tests were conducted to determine the difference in the inflow to a partially full tank (~20 percent fill level) versus the initially empty tank primary tests. In many of the partially full tank tests, the initial inflow surge would simply ride up the standpipe and would push the liquid out of the center vanes into the region of the vent tube, resulting in venting of the liquid. Tests 110, 112, and 115 fail because of this. Tests 109 and 113 vent two-phase flow at this point but continue on.

Vent tests

For test tank A, the critical point was found to be a vent rate corresponding to ~1.5 percent of the planned 5 percent ullage vol/s (~.025 cfm) while as for tank B a stable flowrate of 4 times this value was found in the testing. The primary reason for this disparity is the differences in tank ullage volumes between the tank A and the tank B vents. The vent tests for tank A had an ullage volume of ~6 to 7 percent while the ullage volume in the tank B testing was closer to 10 percent. As with the transfer testing, vent tests were conducted on tanks that were only 20 percent full. These tests showed no issues since the ullage volume was so large.

The last vent tests consisted of boiling vent tests. The boiling vent tests were not as successful as the previous nitrogen venting tests for two reasons. Firstly, the test tanks were designed to be thermally coupled to the HH canister environment. This caused the heat removal via venting to be much lower than the heat input from the environment, thereby resulting in a net boiling of the liquid without any actual pressure reduction. Secondly, the bubbles did not tend to coalesce in the boiling condition, and the tank simply filled up with a great amount of very small bubbles.

Liquid recovery tests

Two tests looked at the response of the system to a high thrust and a low thrust disturbance. For the high thrust acceleration a burn time of 15 s was chosen (using two of the orbiter primary reaction control system (RCS) jets). The fluid did indeed settle over the tank vent as predicted within this time and then rewicked back into the low-g orientation within 20 to 30 s. The pretest predictions were for a time of 2 to 3 min, therefore the wicking action of the vanes is much greater than previously thought. The second test showed similar thrust levels but for only 1 to 2 s. The fluid did slosh around the tank, and then quickly rewicked into the low-g orientation.

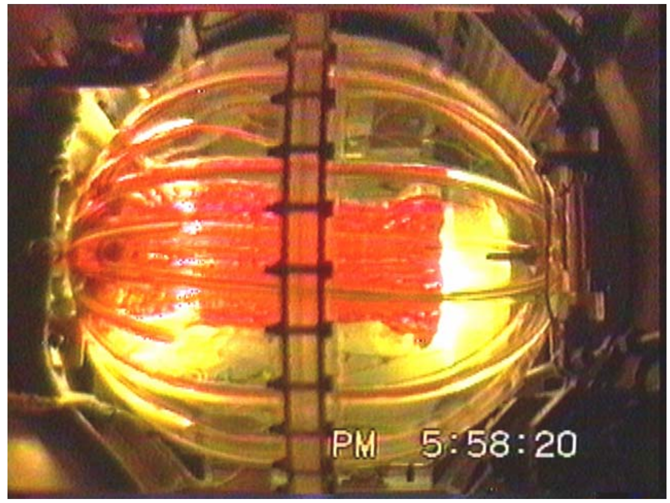

Figure 2.—Vanes turn back liquid inflow (Test 104).

Gap Analysis

VTRE demonstrated several successful approaches to fluid management. It showed that vane devices indeed act to stabilize the flow during transfer and that reasonable transfer rates could be achieved. Cautionary areas in terms of centerpost issues for partially full tanks and low retention at 60 to 70 percent were also uncovered. Liquid recovery was also successfully demonstrated and represents unique data that could not be obtained without flight test. Venting tests were also valuable although it is clear more research is required. The noncondensable venting tests were reasonably successful, but the boiling vent tests, which are more important to cryogenic designs, are not as successful. Both vent rates are dependent on bubble coalescence—a phenomenon unlikely to scale to larger sizes.

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Tank Pressure Control Experiment

David J. Chato (GRC)

Executive Summary

The tank pressure control experiment (TPCE) has flown three times. The first flight focused on the mixing studies of Aydelott. Improvements included actual heat transfer data by using a condensing fluid (Refrigerant 113) and longer duration low gravity. Bentz was able to confirm the geysering and circulating regimes of Aydelott, but encountered an asymmetric regime between the two that was even more catastrophic to heat transfer than aft collection. The second flight of TPCE focused mostly on rapid boiling phenomena, but contains some further tests on mixing. Hasan confirms the findings of Bentz. The third flight was done at a lower fill level but confirms the results of the other flights.

Capability Description

The TPCE hardware consists of a 7- by 9-in. Plexiglas (Degussa AG) tank partially filled with Refrigerant 113. Fluid is removed from the tank by a channel liquid acquisition device and reinjected as a jet. The main instrument is the video camera. Secondary instruments include pressure gauge and seven thermistors. The camera data is recorded on videotape which removed from the cameras post-flight. Secondary instruments are recorded on flight computer. The entire assembly fits in a GAS container. However, the experiment was usually flown as a complex autonomous payload to request specific shuttle attitudes during the experiment. The hardware was proof tested on Learjet (Bombardier Learjet), but no meaningful technology was generated. There was not enough time for heat-up on the Learjet, and the low-gravity environment induced excessive fluid motion.

Key Cryogenic Refueling Technologies

- Long-term storage
- Low-gravity mixing behavior
- Boiling onset in low gravity

Key Findings

The first flight was on STS–43 August 1991. In 26 hr of flight time, 38 tests were completed. Typical experiment included 10 min of heater-on time followed by 15 min of mixing. The first flight was able to confirm the geysering and circulating regimes of Aydelott, but encountered an asymmetric regime between the two.

Objectives

- Characterize the fluid dynamics of axial jet induced mixing in low gravity
- Validate empirical models of jet mixing
- Provide data for computational modeling

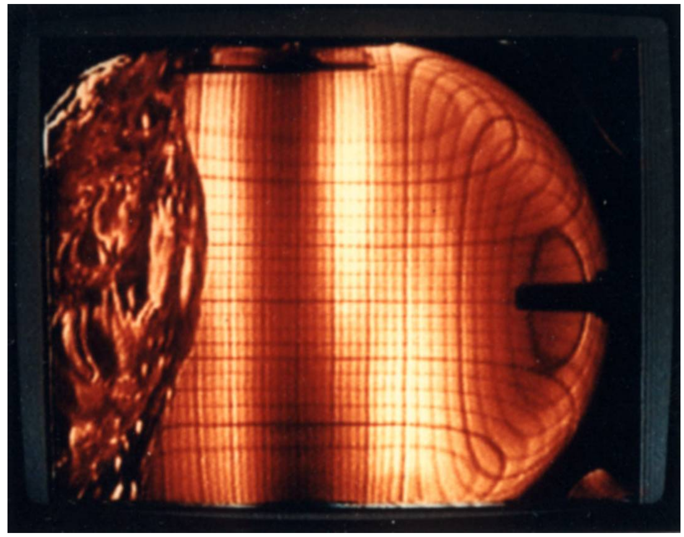

Figure 1.—View of the test tank during STS–52 flight.

Outcome

- The 38 experiments completed included: 9 flow rates range from 0.38 to 3.35 l/min and three 3-heater configurations
- Three-flow patterns observed nonpenetrating (we <1.4), Asymmetric and (we >4.8) penetrating mixing times inferred from pressure decay curves. Mixing time estimated from 75 percent pressure decay. Decay exponent models and 95 percent decay were unsuccessful due to sensor noise.

The second flight was on STS–52 in October 1992.

Objectives

- Observe liquid superheat and pool boiling at heat fluxes from 0.2 to 1.1 kW/m^2
- Observe explosive boiling phenomena
- Observe pressure decay for low flow rate jet mixing
- Characterize flow pattern and liquid-vapor interface response to various jet flow rates

Outcome

Of the 21 experiments completed, 16 were with full video. Four fluid motion tests without heating, six 10-min heating tests with either heater A or B, six 18-min heating tests with either heater A, heater B, or both. Five unvideoed 40-min heater tests contained various heater combinations.

Low heat fluxes combined with low gravity resulted in obtaining high levels of liquid superheat. However, when boiling occurred, all superheated liquid flashed quickly to vapor resulting in explosive boiling. This phenomena was observed in six of the heating tests (five with heater A, one with heater B). The majority of tests with heater B showed steady nucleate boiling within 2 to 4 min of the start of test. Two tests, one videoed and one not, showed rapid pressure rise right at the start of test. For this condition, the videoed test showed the relevant heater touching the ullage bubble rather than being immersed in the bulk liquid. Because the total power was controlled when both heaters were turned, it resulted in a lower heat flux per unit area for the two videoed 18-min runs. The heat flux was adsorbed in liquid superheat, and no boiling was observed. A longer 40-min two-heater run showed a sharp spike at 38 min similar to the explosive boiling, but no video data was available to confirm its occurrence. Mixing times and pressure collapse times were found comparable to the first flight. Four runs were performed without heating, but just jet mixing (test cases not performed on the first flight). Each of these tests were almost identical, starting from quiescent liquid and ramping flow rate up in 0.19 liter/min steps every 30 s for 6 min. Video shows a breakdown from stable geyser to asymmetric flows at Weber number of 1.5 and penetration of the ullage at Weber number of 5.

The third flight was on STS–77 in May 1996.

Objective

- To study TPCE response at a different fill level

Outcome

The test matrix run was identical to flight 1. However liquid fill-level was reduced to 39 percent. Low nozzle submergence resulted in some ullage penetration for all tests. The two lowest Weber number tests (Weber numbers of 1.25 and 1.42) resulted in jet alternating between penetrating and nonpenetration flows. Pressure reduction times were on average 1.8 times longer than flight 1. This was attributed to the 3.8 times larger ullage volume.

Gap Analysis

Prior drop tower testing laid the flow pattern groundwork but was too short a time to measure heat transfer rates. The first flight was able to confirm the geysering and circulating regimes of Aydelott, but encountered an asymmetric regime between the two. The first flight encountered pressure spikes characteristic of explosive boiling but could not confirm the phenomena, because no video was available during the time period when the pressure spikes. The second flight proved the value of being able to re-fly experiments. It co-corroborated the findings of the first flight and shed light on the explosive boiling phenomena. The third flight added some additional information. However, a cost-saving decision to use the flight software from the first flight, led to running tests in regimes other than those of primary interest.

Overall TPCE showed the value of actual low-gravity test by uncovering several phenomena not predicted by either ground or drop tower test. Of particular interest to cryogenic fluid management is the liquid superheat/explosive boiling issue, as this allows for a tremendous buildup in stored energy with little indication on temperature and pressure sensors.

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Storable Fluid Management Demonstration/Fluid Acquisition and Resupply Experiment Flight Experiments

David J. Chato (GRC)

Executive Summary

Storable fluid management demonstration/fluid acquisition and resupply experiment (SMFD/FARE) hardware flew in the shuttle mid-deck three times. It consists of two plastic spheres about 12.5 in. in diameter filled with air and water. One of the tanks had an elastomeric membrane that ensured positive expulsion. The second tank was filled with different test articles dependent on the flight. SFMD flew on STS–51G in January of 1985. The bottom of SFMD second tank was filled with a four-channel screened liquid acquisition device. The top half contained a series of baffle plates (four horizontal and six radial perforated plates). A maximum fill of about 85 percent was achieved at a maximum flow rate of 1 gpm. FARE I replaced the half-tank screen channel with a full-tank one and added an inlet with a small baffle plate over it. FARE I demonstrated fill up to the 70 percent level without liquid venting and a stable inlet Weber number of 2.3. FARE II replaced both of these devices with a vane fluid management that served both as a liquid acquisition device and an inlet baffle. FARE II demonstrated fill up to 95 percent without liquid venting at a maximum flow rate of 0.35 gpm. The low vapor pressure of water at room temperature meant that none of these have to face the issues of boiling and pressurant evolution found in many propellants. Using a surfactant to lower the contact angle of water and wet the walls resulted in foaming problems that are also unrepresentative of propellants.

Capability Description

SFMD/FARE was a mid-deck locker experiment locker experiment designed to look at liquid acquisition and transfer. It was flown three times.

Hardware

- Two modules that take the place of two mid-deck lockers
- Two Plexiglas (Degussa AG) tanks, 12.5-in. inner diameter
- Lower tank contains an elastomeric bladder
- Upper tank contains the liquid acquisition device of interest
- The bottom of SFMD's upper tank was filled with a four-channel screened liquid acquisition device. The top half contained a series of baffle plates (four horizontal and six radial perforated plates).
- FARE I replaced the half-tank screen channel with a full-tank one and added an inlet with a small baffle plate over it.
- FARE II replaced both of these devices with a vane fluid management that served both as a liquid acquisition device and an inlet baffle.
- Test fluid is water with blue food coloring, Iodine, and Triton X–100 (a wetting agent to reduce the surface tension and make the contact angle 0.
- An air pressurization capable of pressuring either tank.

Instrumentation

- Video camera
- Pressure gauges
- Calibrated cylinder
- Sight flow indicator
- Thermometer in lower tank

Key Cryogenic Technologies

- Liquid acquisition
- Transfer

Key Findings

SFMD was flown in January 1985. Filling tests into evacuated tanks were successful. A maximum fill of about 85 percent was achieved at a maximum flow rate of 1 gpm. The baffles were not as successful as expected in preventing liquid from entering the vent line. Filling into a tank at cabin pressure reached the maximum tank pressure of 20 psig before complete fill was achieved. LAD system was able to drain 93 percent pf the liquid back out.

FARE I was flown in December 1992. Expulsion efficiencies of 97 to 98 percent were achieved. FARE I demonstrated fill up to the 70 percent level without liquid venting and a stable inlet Weber number of 2.3.

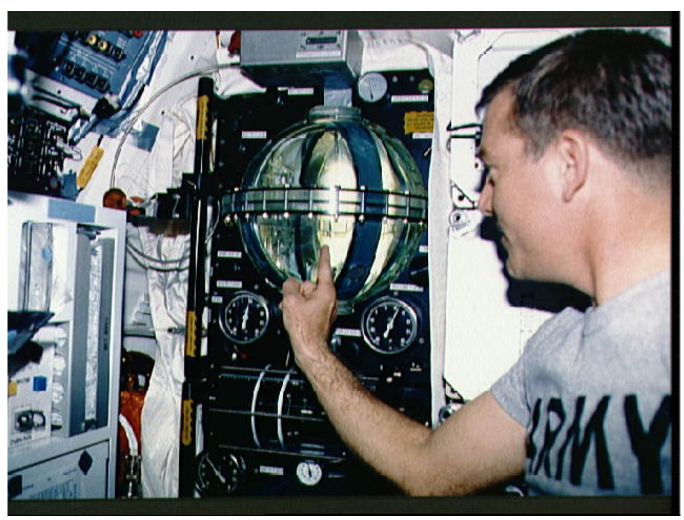

Figure 1.—FARE I experiment on orbit.

FARE II was flown in June of 1993. Expulsion efficiencies of 98 percent were achieved. FARE II demonstrated fill up to 95 percent without liquid venting at a maximum flow rate of 0.35 gpm.

Gap Analysis

The results of these experiments proved quite qualitatively useful while demonstrating the ability of screen channels to drain tanks effectively in low gravity, as well as showing a strong potential for vane devices. However, the low vapor pressure of water at room temperature meant that none of these experiments have to face the issues of boiling and pressurant evolution found in many propellants. The use of a surfactant to lower the contact angle of water and wet the walls resulted in problems with foaming that are also unrepresentative of propellants.

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Capillary Flow Experiment

David J. Chato (GRC)

Executive Summary

The capillary flow experiment (CFE) was designed as a rapid turnaround experiment, which would be simple and small enough to be launched as cargo on the Russian Progress module to the International Space Station (ISS). Tests are then conducted by space station crew and videotaped. Experiments consist of plastic tanks with internal geometry to elicit complex fluid behaviors in low gravity. Topics of investigation include internal corner flows, vane gap flows, and contact line behavior. Six tank sets were prepared—two for each topic. So far only one of the tank sets for contact line investigation has been tested, and final analysis of this test set is waiting delivery of high-resolution videotapes from the ISS.

Capability Description

The CFE was designed as a rapid turnaround experiment in response to the Columbia disaster. It was designed to the following constraints:

- Safe operation
- Mass < 2.5 kg
- Volume < 2 liters
- Minimal electrical interfaces
- Minimal power requirements
- Minimal to no crew training
- Short hardware delivery
- Low cost

These constraints enabled the experiment to be delivered to the space station on a Russian Progress module flight. Clear plastic modules were prepared to investigate several low-gravity capillary phenomena. The phenomena investigated include interior corner flows of interest to capillary vane designers. The second was the vane gap experiment designed to study the ability of liquid to bridge gaps between tank walls and vanes, which were also of interest to capillary vane designers. The third experiment examined contact line phenomena by studying the behavior of the liquid vapor contact line in both smooth cylinders and ones with lips designed to pin the contact line at a specific location. Each phenomenon was investigated with two sets of test tanks. All experiments were built out of clear plastic, and included a fluid reservoir and a test section of the required geometry, as well as a screw-driven piston to move the fluid from and to the reservoir in a controlled manner. All experiments used silicone oils of varying viscosities as their test fluid. Test data was be collected by color video camera.

Key Cryogenic Refueling Technologies

- Liquid acquisition
- Vane devices
- Wall-wetting phenomena

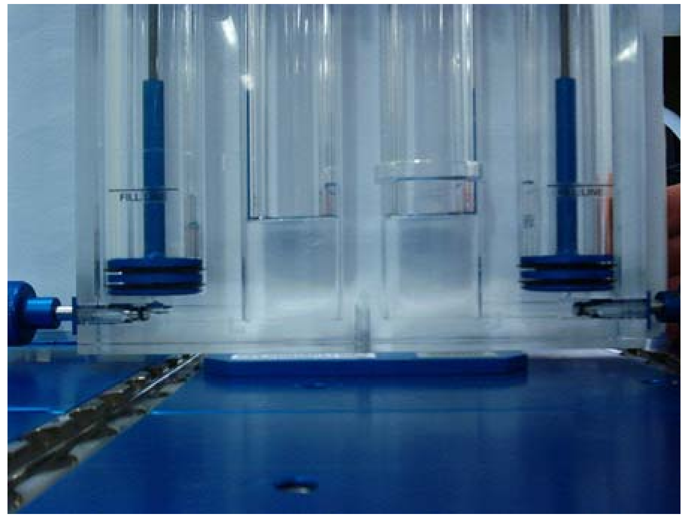

Figure 1.—CFE hardware successfully launched to the International Space Station on a Progress and tested in August 2004.

Key Findings

The CL–2 experiment was launched to ISS on Progress 13P January 29, 2004. The baseline experiment set was completed August 28, 2004. On September 18, 2004, several experiments from the baseline were repeated, and several new experiments were added based on the baseline results. A total of six 40-min ISS DVcam tapes were recorded, but have not yet been returned to Earth. Scientific analysis to date has been conducted with video downlink data recorded during the experiment, even though this data is significantly lower resolution than the tape data. Both the plain cylinder and the cylinder with the pinning lip were filled to the same level and observed against the background acceleration of the station. The test article was subject to a series of disturbances including tap, push, slide, multislide, swirl, displacement, and bubbles. (Detailed descriptions of these maneuvers can be found in the references.) Many of these maneuvers moved a significant portion of the bulk liquid above the equilibrium position in the unpinned tank. This fluid formed a nonequilibrium hourglass shape, which took significant time to drain back to an equilibrium shape. Eventually the astronaut developed a method to spin the container to centrifuge the liquid back to equilibrium, but several of the slide and push tests had to be repeated. Additional experiments were added for axial disturbances and different liquid fill levels. Liquid draining residuals were also examined by withdrawing as much liquid as possible back into the reservoir. From the smooth cylinder, 74 percent of the liquid was recovered, and 94 percent of the liquid was recovered from the cylinder with the pinning ring. Quantitative analysis of the oscillations observed during testing is still underway.

Gap Analysis

The CFE experience shows both great potential and disheartening reality. The CL experiments went from design concept to hardware in under 7 months. Four months after the build, the first flight was flown to ISS. However, after arriving on ISS it took almost 8 months for the crew to conduct 1 day of experiments, and the data from that experiment has not yet been returned to the researchers. Five out of six experiments still languish on the ground waiting for their chance to fly.

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Cryogenic Liquid Acquisition Storage and Supply Experiment

Eric Hurlbert (JSC)

Executive Summary

The cryogenic liquid acquisition storage and supply (CLASS) experiment was designed around proving technology readiness level for a space shuttle upgrade to a nontoxic OMS/RCS using LO_2 and ethanol as the propellant. It was presented as a good but not mandatory test (see paper on DTO approach) for a program to fly a cryogenic orbital maneuvering system (OMS)/RCS. However, CLASS would have provided excellent technology maturation for all cryogenic applications that would improve the performance of future system designs.

Capability Description

The CLASS experiment and the shuttle provided a unique capability. The shuttle power reactant storage and distribution (PRSD) tank was used to provide the LO_2 for transfer to the experiment.

The CLASS objectives were to

(1) Test two methods of pressure control axial jet mixer and spraybar
(2) Measure performance of liquid acquisition device (LAD) Determined that ground testing needed to be done first in order to make space test work properly
(3) Perform quantity gauging tests
(4) Perform cryogenic propellant transfer (as a fallout of using the shuttle PRSD to store LO_2 until getting on orbit

Gap Analysis

There were issues with the experiment that were being managed prior to being cancelled as a Shuttle Upgrade funded project.

- Measurement of thermal stratification under varying heat loads was the strongest objective and rationale for the experiment.
- Demonstration of pressure control (spraybar or axial jet) should provide useful data, but both are considered lower risk technologies with substantial ground and/or flight test history
- Mass gauging may provide useful data for pressure volume temperature (PVT); compression mass gauge (CMG) has significant technical issues
- CLASS–1 will not adequately address all the technology demonstration needs for the LO_2 tank
  - Liquid acquisition remains weakest point; also considered highest risk technology
  - An overall LO_2 tank technology program (Analysis + Ground Test + Flight Test) needs to be developed has not been fully developed due to emphasis on developing the CLASS experiment.

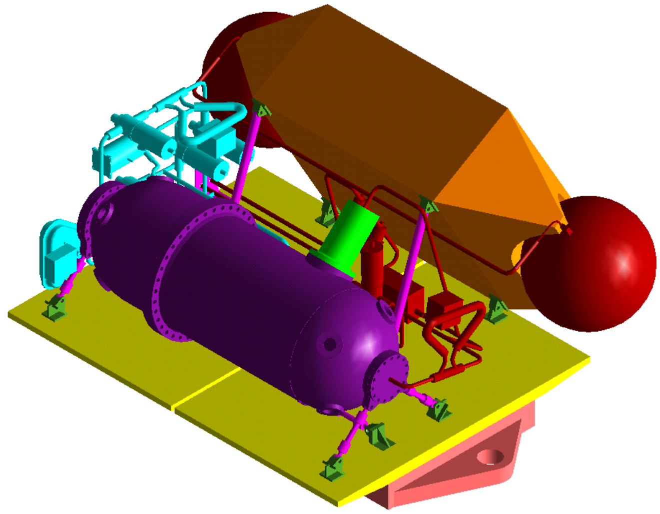

Figure 1.—CLASS experiment package shown on side wall mount.

- A descoped CLASS–1 with appropriate emphasis on ground testing (in process of being defined) and analysis should be pursued as an overall technology development program for the LO_2 tank.
- It needs to be determined where CLASS fits into the overall program, that is, what it can support technically and cost efficiently.
- Formal input from tank designers must be solicited to ensure all technology needs are identified, properly prioritized, and being addressed to best reduce technical and cost risk for the LO_2 tank.

Key Cryogenic Refueling Technologies

The CLASS objectives were to

(1) Test two methods of pressure control, axial jet mixer, and spraybar
(2) Measure performance of LAD
(3) Perform quantity gauging tests
(4) Propellant transfer and chilldown (PRSD to CLASS).

These are all related to key cryogenic refueling technologies

Key Findings/Issues With Experiment

- Go-NoGo technical issues remain open for the CLASS experiment
  - Dump/safing analysis and payload safety buy-in to extended overboard dump
    - Even if PRSD vent line meets flow/thermal requirements and use is negotiated with orbiter, CLASS will still require flexibility of venting

    outside of 30-min window dictated by NSTS 1700.7B
- Experiment chill and fill from the PRSD
  - Experiment success dependant on this initial operation
  - Planned PRSD outflow test (2/97) and analysis will address feasibility and reduce uncertainty
  - Orbiter integration/certification issues and cost have not been fully investigated
- Compatibility of CLASS with ISS missions and manifesting has not yet been evaluated
  - 2000+ flight opportunities on orbital vehicle (OV)–104 and OV–105 are ISS utilization flights
- OV–102 limitations not fully assessed: reduced heater power and reduced Bay 13 beam capability
  - OV–102 remains the only opportunity to fly CLASS without being tied to ISS restriction (to be determined)
  - Cryogenic valves for CLASS: 12 latching isolation valves, 3 relief valves, and 3 check valves
  - USA/BNA position is that PRSD and EDO hardware will not be available for use by CLASS
  - Cost and performance feasible candidates have not yet been identified for the Iso and RVs
- LO_2 centrifugal pump
  - LO_2 compatibility issues are being addressed
  - Conservative design and rigorous testing expected at a minimum to obtain buy-in for flying an LO_2 pump as part of a payload on the orbiter

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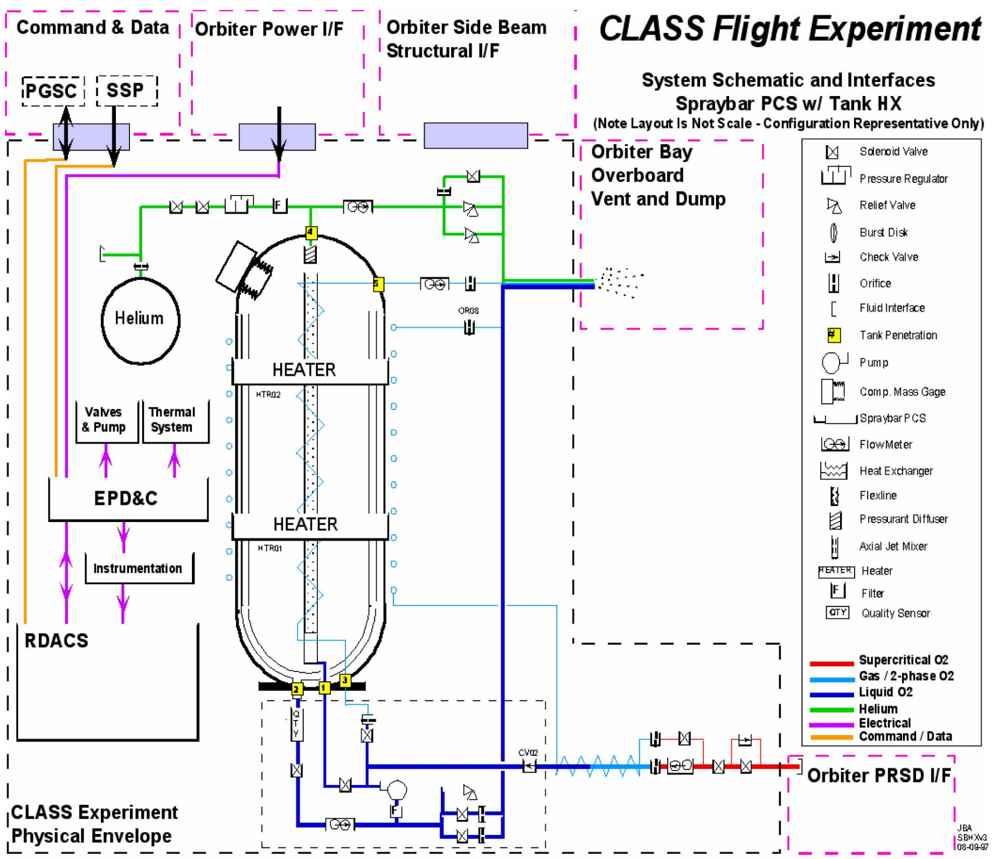

Figure 2.—CLASS experiment schematic.

Superfluid Helium On-Orbit Transfer Flight Demonstration

Michael DiPirro (GSFC)

Executive Summary

The Superfluid Helium On-Orbit Transfer (SHOOT) flew on STS–57 in June 1993. It demonstrated complete end-to-end superfluid helium handling and transfer in a low-gravity environment. SHOOT Flight Demonstration developed and proved the technology required to resupply superfluid helium dewars on orbit. In addition, a number of the components developed for SHOOT could be used on other liquid helium payloads as well as with other cryogenic systems. Six transfers were completed, and all pre-mission experimental goals were achieved. These were

- Pumpdown of normal liquid helium to superfluid on orbit
- Demonstration of high rate transfers
- Demonstration of an autonomous crew controlled transfer
- Demonstration of a warm dewar cooldown and fill
- Measuring the performance of two types of liquid acquisition device (LAD)
- Precision mass gauging and flow metering
- Liquid/vapor discrimination

Important differences between expected and actual on-orbit performance were identified and overcome. In addition, secondary objectives including observations of liquid helium sloshing and low-gravity stratification were also met.

SHOOT was designed for multiple flights. The experiment flight hardware is currently in storage. Some of the Hitchhiker (HH) carrier hardware is also in storage. The possibility of reflight of this hardware using normal liquid helium (4.5 > T > 2.2 K) as a simulant fluid for LH_2 is being studied.

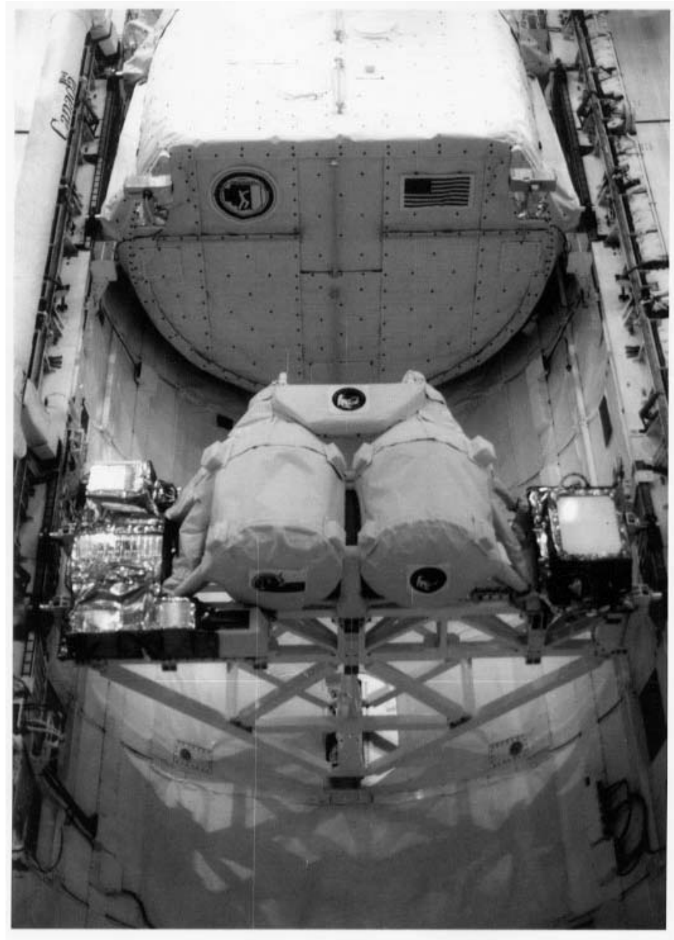

Figure 1.—SHOOT on its Hitchhiker cross-bay carrier in the shuttle payload bay.

Capability Description

Experiment description

The experiment utilized a cross-bay HH carrier system. It consisted of two 207-liter capacity liquid helium dewars joined by a transfer line. Either dewar could act as a supply or receiver dewar, differing only in the LADs in the tanks. The helium was transferred back and forth six times. The components and instrumentation within each dewar were removable using replaceable seals. This allows reconfiguration of the experiment space.

Instrumentation

See appendix C for white paper titled "Superfluid Helium On-Orbit Transfer Cryogenic Instrumentation Applicable to Cryogenic Depot."

Key Cryogenic Refueling Technologies

- Liquid acquisition
  - Vane LAD
  - Screened channel LAD
- Transfer
  - Zero-g transfer
  - Recovery from adverse acceleration
  - Precool and fill
- Instrumentation (See GSFC Cryo Instrumentation white paper in appendix C for more details.)
  - Precision thermometry
  - Liquid/vapor discriminators
  - Liquid/gas phase separator
  - Cryo valves and burst disks

Key Findings

Transfer tests

Transfers proceeded smoothly in each direction with rates up to 720 liters per hour. The vane LAD broke down at lower fill level (4 to 8 percent) than the screened channel LAD (5 to 10 percent). The screened channel LAD also required a gradual ramp up in transfer rate to prevent cavitation.

Warm dewar cooldown test

One dewar was cooled to 2 K from 28 K and filled. The transition between chilldown, which required transitioning between an open vent valve and venting through a phase separator, and fill did not result in extra loss of liquid.

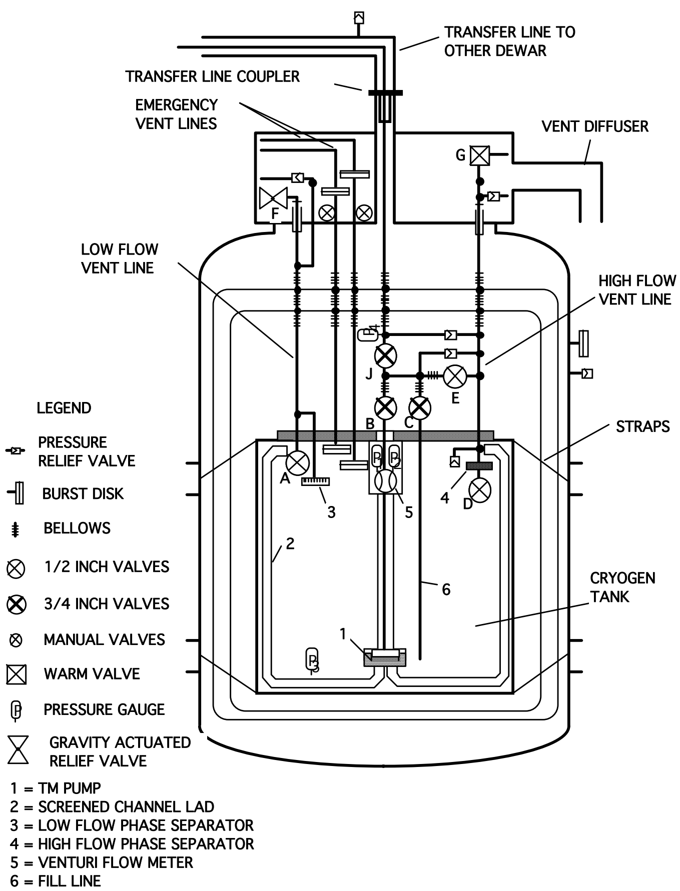

Figure 2.—Schematic of a SHOOT dewar.

Adverse Acceleration Liquid Recovery Tests

During two transfers, the shuttle was purposely accelerated in an adverse direction to move liquid away from the pump. Both transfers were interrupted by this process, but the vane LAD broke down at a higher acceleration and recovered more quickly than the screened channel LAD.

Gap Analysis

The system demonstration as a whole does not validate a transfer of normal cryogens, like hydrogen or even liquid helium in the normal state. SHOOT did, however, develop components and techniques that would be transferable to a cryodepot and resupply experiment or demonstration.

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Cryogenic Propellant Depots

Robert L. Christie (ZIN), David W. Plachta (GRC), and David J. Chato (GRC)

Executive Summary

Several cryogenic propellant depot concepts have been proposed and developed to a certain extent. The content and commonality of the concepts varies widely. The hydrogen tank sizes vary from 3.2 to 19 m in diameter. The length varies from 5 m to 29 m. LO_2 tank sizes vary from 2 to 8.5 m in diameter. Most of the concepts were located in the relatively warm low earth orbit environment at an altitude of approximately 400 km. Insulation varied from 20 to 100 layers of MLI (1 to 4 in.). All concepts were for refueling or for modular tank or stage replacement. Refueling concepts require fluid transfer.

Capability Description

As a part of the "In-Space Cryogenic Propellant Depot Project," a survey of existing depot concepts was made to highlight role and function of propellant depots. Table I summarizes the results of depot studies available in the open literature.

Depot capabilities

There are many functions of a depot. The primary purpose of it is to reuse spacecraft. Besides reusability, the historical depot concepts are multifunctional. These are as follows:

- Functions
  - Staging location
  - Maintenance
  - MMOD protection
  - EVA aid
  - Safe haven
  - Extend missions
  - ORU storage
  - Communication relay
  - Waste storage
  - OMV

With these functions in mind, the depot concepts have provided the following services:

- Services
  - Fluid storage and transfer
  - Fuel cell resupply
  - Power and recharging
  - Propulsion and attitude control
  - Communications
  - Propellant manufacturing
  - Shading and/or cooling
  - Vehicle servicing and storage
  - Cargo storage and transfer
  - Wireless power transmission

These functions and services are envisioned to be important to a long-term sustained human lunar and Mars mission architecture.

Depot technologies

Many technologies are required to support a depot development. Identified technologies in support of a depot are

- Transfer systems
  - LH_2, LO_2, He, and N_2H_4
  - Ar, Ne, Xe, or Kr
  - Water, N_2, and methane
    - Prechilling systems
    - Reliquifaction systems
    - Liquid acquisition device (LAD)
    - Vapor cooled shield (VCS)
    - Pumped cooled shields
    - Thermodynamic vent system (TVS)
    - Helium extraction
    - Vapor-vent liquid exclusion
    - Propellant settling techniques
    - Fluid transfer interface with autonomous connections and disconnects
    - Health monitoring
    - Robotics
    - Leak detection
    - Mass gauging
    - Para-to-ortho conversion
    - Heat shields
    - Foam thickness trades
    - PODS (large)
    - Active disconnect struts
    - Low thermal conductivity components (composite feed lines)
    - 20 K heat pipes
    - Pumped loops (circulators)
    - Line evacuation subsystems
    - Prechill bleed subsystems
    - MMOD protection
    - Environment compatibility
    - 20 K cryocoolers

Two representative depot concepts are shown in figures 1 and 2. Both were to be launched on the shuttle or a shuttle derivative and were SSF-supported. The long-term cryogenic storage facility (ref. 1) was substantially larger and serviced by a space tug and OTV. The Mini-Depot (ref. 16) was actually located at SSF. It serviced a vehicle called the space transport vehicle (STV). It had modular tanks that was assembled into and supported off a structure that was 12 ft in diameter.

TABLE I.—DEPOT CONCEPTS IN THE PUBLISHED LITERATURE

Reference	Description	Delivery	Propellant delivery	Customer	Platform	Services
15	Tank	Space shuttle	Modular tanks	STV	Space station	Refueling
10, 11, 14	Tank	Shuttle-C or advance launch vehicle (ALV) plus "kick" stage	Modular tanks	OTV	Space station	Refueling
1, 12	Tank	Heavy lift launch vehicle	Modular tanks	OTV	Propellant depot	Refueling
2	Demo depot		Transfer from Centaur		Free flyer	Refueling
17	Propellant module "combination depot/ drop tank"	Shuttle-class, e.g., Delta IV H	Launched full or partially full, then topped off in low earth orbit by ELV	L1 Gateway		Propellant supply for CTM and SEP
1	Commercial and military satellite servicing vehicle	ELV	Launched full or partially full, then topped off in low earth orbit by ELV	Satellites		Deployment, reboosting and repositioning. Xenon refueling.
1	Propellant processor	Space shuttle	Space shuttle	OTV	Shuttle ET	
9, 19	Propellant production depot	Delta IV Heavy	RLV and OMV 35 000 kg H_2O per launch	Mars Mission		Produces LH_2 and LO_2 at 500 000 kg per year from water
19	Depot using core stage of Delta IV Heavy	Delta IV Heavy	RLV and OMV			Cryogenic propellant storage
3	Reusable tanker	Self	Self			Delivers propellant in modular tank or transfers from own tanks
21	Superfluid helium tanker	Shuttle, et al.	Self	SIRTF, AXAF, et al.		Replenish superfluid helium at 2 K

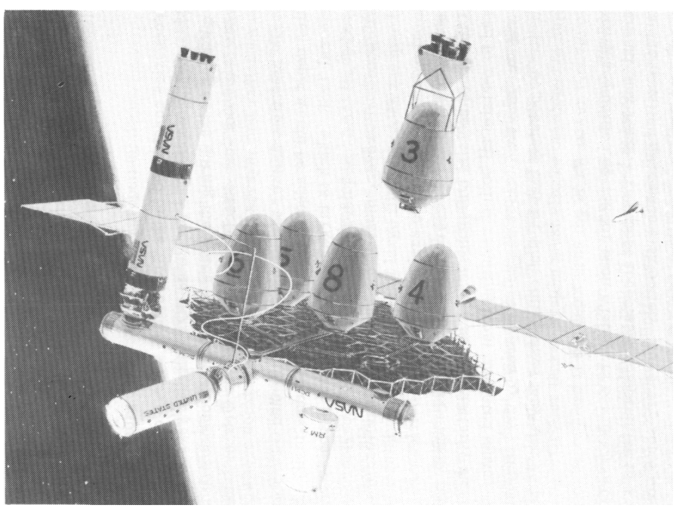

Figure 1.—Long-term cryogenic storage facility, General Dynamics Depot Concept, 1978.

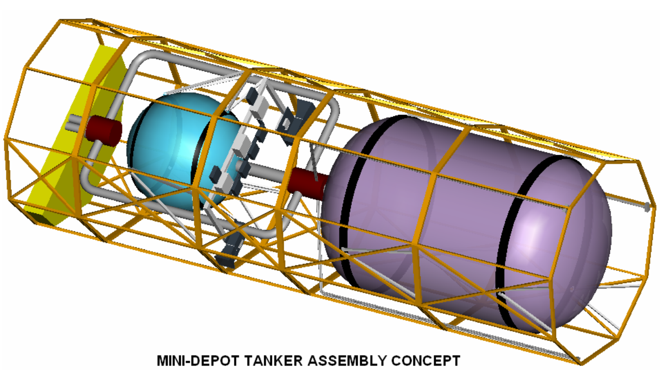

Figure 2.—MACDAC Mini-Depot Concept, 1992.

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Microgravity Science Support on the NASA Sounding Rocket Program

Brian Hall (GSFC)

Introduction

The NASA Sounding Rocket Program (SRPO) has historically supported the microgravity science community research in the United States. Sounding rockets offer a low-cost solution for providing short-duration exoatmospheric laboratories that allow experimentation in a low-g environment. The use of sounding rockets has been minimized in recent years due to the International Space Station (ISS) and its intended capability to support all the microgravity research.

A microgravity (µg) environment has historically been defined as the experiment having accelerations in the 10^{-6}g levels (g relates to the acceleration due to gravity). The µg environment is established via a reaction control system (RCS). This attitude control system effectively reduces the payload rates in the three payload body axes so the experiment bay will achieve the µg environment.

Historical SRPO Support of Micro-g Science

NASA's SRPO has supported the microgravity community for a number of years. Typically, the vehicle of choice for a µg mission is a BB IX vehicle (Terrier-boosted Black Brant), and the payload is recovered to allow an experiment evaluation post flight. Both land and water recoveries have successfully been used to retrieve the payloads.

Table I notes the recent history of microgravity mission supported by NASA's SRPO. All of the table I missions had dedicated vehicles planned to specifically support the science. There have also been multiple instances where piggyback µg experiments have been provided a ride when space was available.

TABLE I.—SRPO RECENT MICROGRAVITY LAUNCH HISTORY

Mission	Customer	Launch date	Launch site
36.103 NP	Ross/LeRC	11/22/1995	WSMR
36.138 NP	Ross/LeRC	8/28/1995	WSMR
36.145 NP	Ross/LeRC	2/23/1996	WSMR
36.119 NP	Olsen/LeRC	6/20/1996	WSMR
36.154 UM	Olsen/LeRC	10/16/1996	WSMR
36.161 NP	Olsen/LeRC	2/26/1997	WSMR
36.165 NP	Olsen/LeRC	9/10/1997	WSMR
36.169 NM	Olsen/LeRC	9/10/1997	WSMR
36.178 NM	Ross/LeRC	11/18/1998	WSMR
41.020 NM	Kim/Univ. of Maryland	12/17/1999	WFF
36.166 UM	McKinley/MIT	7/6/2000	WSMR
12.050 DP	NASA SRPO	12/19/2000	WFF
36.187 NM	Ross/GRC	2/12/2001	WSMR

Over the past 6 years, NASA Sounding Rocket Operations Contract (NSROC) has successfully launched four payloads that incorporated a rate control system for meeting the mission requirements with the goal of reducing accelerations to micro-gravity levels. The first three payloads used a space vector rate control system, while the third used a NSROC system. The NSROC system design is based on the Solar Pointing Altitude Control system (SPARCS) solar pointing altitude control system (ACS), which has a long successful history within the SRPO.

The early 1990s noted a significant amount of microgravity ongoing research at the University of Alabama in Huntsville (UAH). This institution used a separate commercial contract to acquire sounding rocket missions. The commercial contractor provided the same NASA vehicle (BB IX) for three microgravity missions for UAH. A mixed success rate caused the termination of the program along with funding issues at UAH.

TABLE 2.—SUMMARY OF NSROC SUPPORTED MICROGRAVITY MISSIONS

Mission	Launch vehicle	Diameter	Payload rates (lateral and at sensor)	µg level	µg duration
41.020 NM	Terrier/ImpOrion	14 in.		1.1×10^{-5}g	219 s
36.166 UM	BB IX	22 in.	0.17 °/s	2.7×10^{-7}g	300 s
12.050 DP	Terrier/Lynx	14 in.	0.36 °/s	1.1×10^{-7}g	190 s
36.187 NM	BB IX	22 in.		4.5×10^{-5}g	313 s

Mission 41.020, launched in December 1999 from Wallops Flight Facility (WFF), was a 14-in. diameter, 172-in. long, 448-lb recoverable payload containing an experiment to investigate basic mechanisms in bubble generation, detachment, and rewetting in pool boiling in micro-gravity. Requirements were to maintain acceleration levels of less than 1×10^{-3}g for 180 s. Flight results showed accelerations of between 1 and 11×10^{-6}g were maintained in the vicinity of the experiment for at least 219 s. Experiment data was successfully telemetered to the ground and the payload was successfully recovered.

Mission 36.166, launched in July 2000 from White Sands Missile Range (WSMR), was a 22-in. diameter, 304-in. long, 1448-lb recoverable payload containing an experiment to determine the transient extensional viscosity in uniaxial stretching flow for dilute polymer solutions and subsequent relaxation behavior after extensional deformation. Requirements were to maintain accelerations of less than 1×10^{-3}g during experiment operation (T+100 to T+370 s). Flight results showed rates between 0.4 and 4.5×10^{-5}g were maintained for that time period at a distance of almost 10 ft from the payload CG. Unfortunately, in-flight experiment malfunctions resulted in less than minimal data collection, but the payload was recovered in excellent condition.

Mission 12.050, launched in December 2000 from WFF, was a 14-in. diameter, 118-in. long, 354-lb nonrecoverable payload with the primary purpose of flight qualifying the new Terrier-Lynx vehicle configuration. A secondary objective was to flight qualify the NSROC RCS. The performance requirement set for the RCS was to reduce angular rates to less than 0.5 °/s in all three axes. Flight results showed rates were reduced to 0.5 °/s in 10 s. After switching to fine mode, rates were further reduced to 0.06 °/s resulting in accelerations of 3.2×10^{-7}g at approximately 3.4 ft from the payload CG.

Mission 36.187, launched in February 2001 from WSMR, was a 22-in. diameter, 290-in. long, 1234-lb recoverable payload containing an experiment to determine if pulsating flame spread in deep fuel trays will occur under the conditions that the existing model and short-duration drop tower tests predict it will occur. Requirements were to maintain rates of less than 5×10^{-4}g in all directions during time of experiment operation (T+90 to T+403 s). Flight results showed rates between 0.5 and 8×10^{-5}g were maintained for that time period at a distance greater than 8 ft from the payload CG. Fuel trays were located much closer to the CG so experienced much lower accelerations. Experiment data was successfully telemetered to the ground and the payload was successfully recovered.

Existing SRPO Stable of Vehicles Capable of Supporting Micro-g Science

The SRPO contains a stable of flight-proven vehicle configurations. While the majority of the vehicles can provide some amount of microgravity research time, typically there have been two vehicles that have supported the microgravity science discipline. The BB IX and the Terrier ImpOrion vehicle are the vehicles of choice for providing the µg laboratory. These vehicles are the mainstay of the program and have a long list of flight-qualified subsystems ready to support if needed. These vehicles have also been flown at most of the launch ranges including the primary ranges for SRPO missions including WFF, WSMR, and Poker Flat, Alaska.

Figure 1 shows the stable of SRPO vehicles that are currently flight qualified. Included in this picture is a graph the shows the vehicle performance as a function of payload apogee vs. payload weight. These performance values show relative performance. Any deviations in diameter, drag appendages, and/or launcher conditions will yield a slight variation in the values listed.

Potential vehicles in maximize micro-g science support

The SRPO is always looking at upgrading vehicle capabilities when a requirement is presented. Current evaluations of higher performing vehicles are underway. These trades include not only the performance enhancements, but also larger payload volume via a larger diameter and the costs involved. Some examples of higher performance vehicles include Terrier/ASAS, Terrier/ASA XL, Terrier/GEM–22, and Talos/ASAS XL. The use of the larger commercially available motors allow for a larger payload diameter, up to 30 in. in some instances.

Future Mission Planning

An excellent reference for determining the more detailed capabilities of the NASA SRPO can be found in the Sounding Rocket User's Handbook. This document not only describes the vehicle, system, subsystem, and component capabilities, but also there is a detailed discussion on how to work with the SRP and what data/requirements are required. A copy of this document is available at http://www.nsroc.com/front/what/SRHB.pdf.

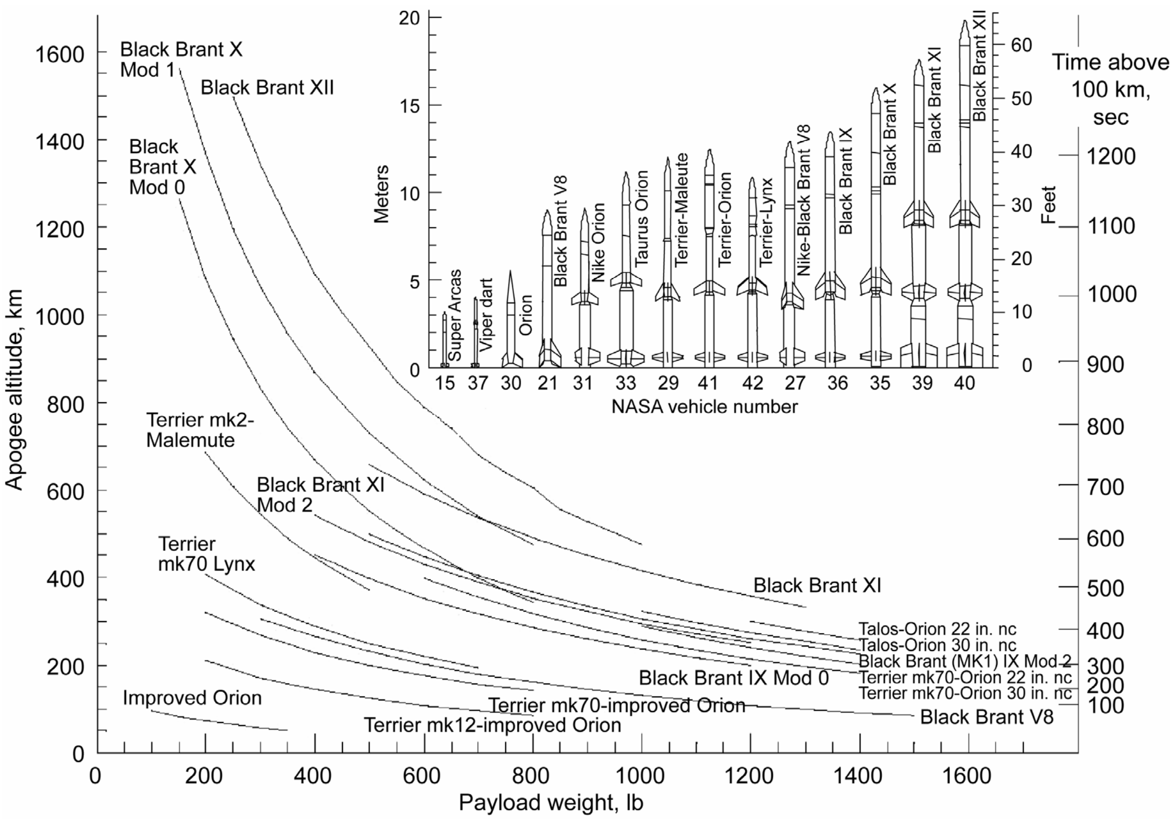

Figure 1.—NSRP launch vehicle performance.

Appendix C—Instrumentation

Cryogenic Flowmeters

Eric Hurlbert (JSC) and David Chato (GRC)

Executive Summary

Different types of flowmeters were evaluated for on-orbit refueling applications in 1988 in ground testing and on the KC–135 in simulated zero gravity. The flowmeters were evaluated for performance, maintenance, operating conditions, operating environment, and packaging. For cryogenic refueling systems, the selection of a flowmeter will depend on the detailed requirements for performance, operating conditions, maintenance, and operating environment.

Capability Description

A flowmeter provides the capability to measure the amount of propellant transferred. There are two techniques: mass flow and volumetric flow. It is possible a hybrid combination of these techniques, such as turbine and venturi or turbine and coriolis, may work the best. For cryogenics, the ability to measure two-phase flow, or to estimate void fraction is an important issue, although for Earth storables, helium coming out of solution due to pressure drop is a similar issue.

The capability clearly exists for a flight flowmeter for a single-phase cryogenic. If sufficient subcooling exists, then the two-phase flow becomes an issue. The quantity of propellant transferred during chilldown, which is two-phase, may be unknown. This unknown may be small enough to be manageable, if the receiver tank is vented.

Key Cryogenic Refueling Technologies

The flowmeter is a key component of refueling systems. It is likely to be used along with tank gauging to measure the quantity transferred and to detect gas flow.

Gap Analysis

Additional flight testing of flowmeters is needed for further development; however, simulated zero-g testing should be sufficient. In general, there is a need to develop flight weight versions of these flowmeters.

Key Findings

The results of the 1988 NASA Technical Memorandum 100465 are shown in table I. These results for these flowmeters are listed specifically by model number. The user should be cautious in the use of the data. The user needs to balance turndown ratio requirements, accuracy, fluid types, two-phase flow measurement needs, vibration sensitivity, and maintenance/life issues.

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TABLE I—FLOWMETER ASSESSMENT

	Perform SS 1-phase flow error	Perform SS 1 phase linearity	Perform SS 1phase repeat	Perform zero-g linearity	Perform zero-g repeat	Perform pulse flow linearity	Perform. Pulse flow repeat	Perform two-phase linearity	Perform two-phase repeat	Accel. vib. insens.	Cryo LO_2 temp	Cryo LH_2 temp[1]	Packaging mass[2]	Mainten. in-line replace	Mainten. least moving parts[3]
Clamp-On Ultrasonic Controlotron 48-MP[4]	±1% for 0 to 16 turndown	1% error from 0 to 16 turndown	Good			Work required	Work required	Work required	Work required	Good	Work required	Not Good	Good	Good	Good
Area averaging flowmeter ultrasonic Panametrics 0.04 meter	Good	±3.7 to 16% over 1.2 to 35 TD	0.15 to 22% over 1.2 to 35 TD			Electronics not designed for transients	Electronics not designed for transients	–2.5 to –28%	Work required	Good	Work required	Not Good	Good	Good	Good
Offset Ultrasonic Panametrics		±2.4 to 8.5% over 1 to 25 TD	±1.06 to 12.15%			Electronics not designed for transients	Electronics not designed for transients	–42.33 to 61%		Good	Good	Not Good	Work required		
Coriolis Micro Motion D1505[5,6]	Good	Good 0.1% to 0.2% over 1 to 60 TD	Good	5 to 19 turndown range	5 to 19 turndown range	>2 s pulses	> 2 s pulses	0.2 to 2% over 1 to 35 TD	Work required	Requires work around[7]	Good		Work required		
Vortex shedding[8]	Good	0.08 to 0.77% over 0 to 25 TD	0.13 to 3.4% over 0 to 25 TD			> 2 s pulses	> 2 s pulses	<1% error with up to 3% gas by vol.	Good	Work required	Good		Work required		Good
Venturi - Delta-P		0.5 to 2% over 1 to 10 TD range	0.05 to .35% over 1 to 10 TD range			4.5 to 17.6%	<0.16%	<–2.2% error for up to 10% gas by vol	<0.12%	Good	Good	Good	Good		Good
ITT 7186-0006A[9]	Good	<0.36% from 1 to 10	<0.16% from 1 to 10	<2% from 0 to 44 TD	<1% from 0 to 44 TD	<0.6% error for pulses 1 to 5 s	Good	<10% error for up to 10% by vol gas in zero-g	<0.15% error in 1g and zero-g	Work required	Work required	Work required	Work required		
Bearingless Flow systems E100		Sensitive to orientation in 1g @ > 15 TD	< 0.8%	<2% from 0 to 44 TD	<1% from 0 to 44 TD	Work required	Work required	<1% error for up to 3% by vol gas in zero-g	<0.15% error in 1g and zero-g	Work required	Work required	Work required	Work required		
Turbine/Delta-P Hybrid ITT 718 mod with Pt[10]		<6%	<.0.4% up to 9 TD	<3% up to 3 TD ratio		Work required	Work required			Work required	Good	Good	Work required		
Drag body										Work required	Good		Good		
Drag Body/ Turbine Hybrid		Good		Good						Work required	Good		Work required		

[1]In 1988, ultrasonic transducer crystal limitations.
[2]Units were ground test units and not optimized for flight use.
[3]Hydrodynamic bearings may improve life.
[4]Measures Doppler shift across flow.
[5]Measures mass flow—U-shaped tube.
[6]Coriolis has a new design with triangular shaped tube.
[7]Coriolis can be used during zero-g transfer.
[8]Cyclic cooling measured by thermistor.
[9]Hydrodynamic bearing.
[10]Hydrodynamic bearing turbine and venturi.

Superfluid Helium On-Orbit Transfer (SHOOT) Cryogenic Instrumentation Applicable to Cryogenic Depot

Michael DiPirro (GSFC)

Executive Summary

The SHOOT Flight Demonstration flew on STS–57 in June 1993. It demonstrated complete end-to-end superfluid helium handling and transfer in a low-gravity environment. A number of components and techniques developed for SHOOT are applicable for other cryogenic payloads.

Capability Description

Experiment Description

See white paper on SHOOT page.

Instrumentation

Instrumentation and components developed for SHOOT include superfluid helium pumps, a vane liquid acquisition device, a screen-channel liquid acquisition device, liquid/vapor discriminators, venturi flowmeter, heat pulse mass gauging using high-resolution thermometry, absolutely leak-tight cryogenic stepper valves, cryogenic burst disks, and liquid/gas phase separators (ref. 1).

Key Cryogenic Refueling Technologies

Liquid acquisition
- Vane LAD
- Screened channel LAD

Transfer
- Venturi flowmeter
- Zero leakage cryovalves

Storage
- High-resolution thermometry
- Cryogenic burst disks
- Liquid/gas phase separators

Reorientation
- Liquid/vapor discriminators

Key Findings

The LADs used in SHOOT were demonstrated successfully. The vanes provided much better performance both under steady state flow conditions, and in recovery from a disturbing acceleration (refs. 2 and 3). The low-flow phase separator completed separated liquid from vapor (refs. 4 and 5). The flowmeters and mass gauging systems were accurate to better than 3 percent across a wide range (refs. 6 and 7). The liquid/vapor discriminators were shown to work with both normal and superfluid helium on orbit (ref. 8), and with LH_2 and LN_2 in ground tests (ref. 9). Ground tests of the cryogenic valves and cryogenic burst disks showed excellent, repeatable performance (ref. 10). For representative performance figures on these components refer to table I.

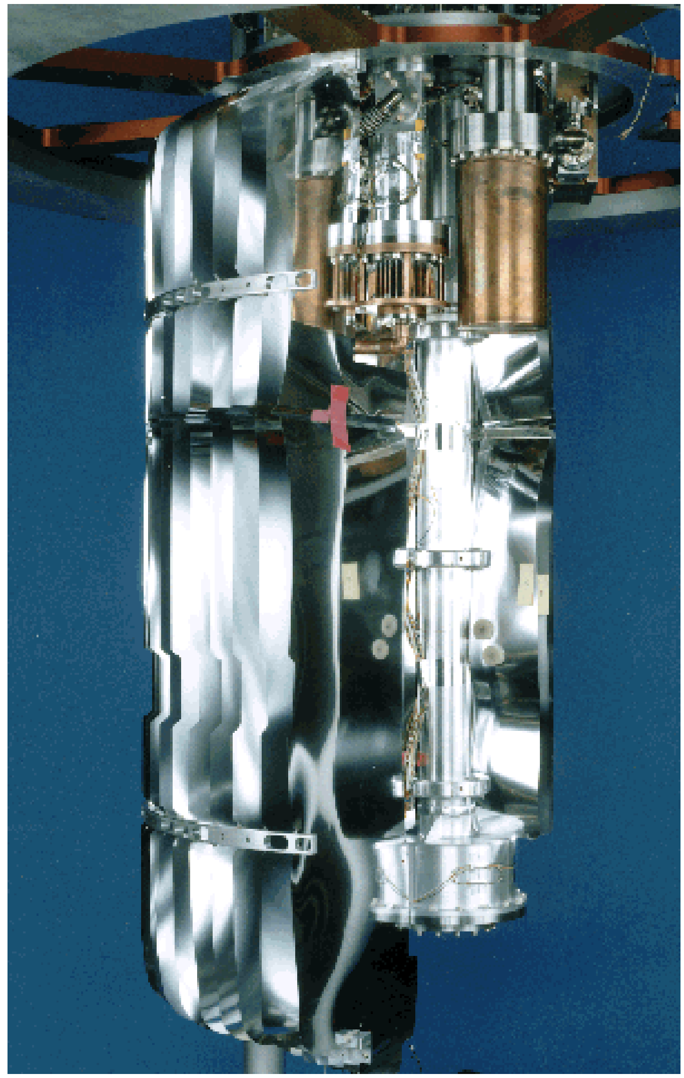

Figure 1.—The partial vane LAD in one of the SHOOT dewars. The vanes consisted of double aluminized mylar. Also shown are tow types of liquid/gas phase separators (top) and the pump housing (bottom). The vanes connected to a porous silica sponge, which fed the pump during transfers.

Gap Analysis

The pump used in SHOOT relies on the unique properties of superfluid helium, so would not be applicable to normal cryogenic liquids. The heat-pulse mass-gauging technique relies on the uniquely high thermal conductivity of superfluid helium, so would not be directly applicable to other cryogens. Because superfluid helium does not stratify, SHOOT did not require a mixer or any other means of destratification.

TABLE I.—COMPONENT RESULTS SUMMARY

Component	Results	Ref.
Thermomechanical pump	Nearly ideal fountain effect, flows over 800 liters/hr	1
LAD-screen channel	Easily cavitated, more delay in restarting than vane/sponge	2, 3
LAD-vane/sponge	More reliable, predictable operation than screen channel	2, 3
Low-flow phase separator	Complete liquid/gas phase separation up to pressures >1.2 MPa and T >4.3 K	4, 5
Flowmeters	1 to 2 percent accuracy for both venturi and TM pump flowmeter	6
Mass gauging	1 to 3 percent accuracy, up to 11 W (0.11 W/cm^2) could be applied without bubble formation	7
Liquid/vapor detectors	Response time <150 ms, power <200 μW, useful for LHe, LH_2, and LN_2	8, 9
Cryogenic valves	>50 open/close cold cycles per valve, no leak through seat	10
Cryo burst disks	Predictable, repeatable actuation to 5 percent	10

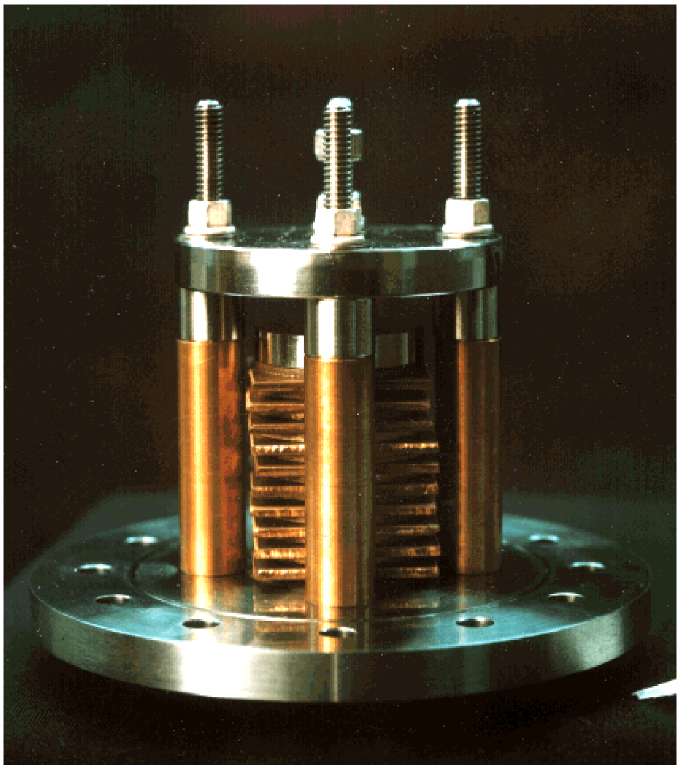

Figure 2.—Liquid/gas phase separator consisting of several plates of copper with square holes in the center, separated by 6 μm gaps. The total height of the copper plates is 30 mm.

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Appendix D—Experiments Proposed

The Zero Boil-Off Tank Experiment

Mohammad Kassemi (NCSER) and David J. Chato (GRC)

Research Approach

The overall objective of the zero boil-off tank (ZBOT) is to investigate the effectiveness of the zero boil-off strategy as an innovative means for eliminating self-pressurization and mass loss in space cryogenic storage tanks based on an optimized and synergetic application of active heat removal and forced mixing. The objectives of this research will be realized using an experimental/numerical approach involving hand-in-hand, ground-based, and microgravity experiments with a model fluid together with two-phase computational fluid dynamics (CFD) simulations based on a comprehensive model of the system. The project involves performing a small-scale International Space Station (ISS) experiment to study tank pressurization and pressure control in microgravity. Motivations include

- Deriving engineering correlations for pressurization, cooling, and mixing rates (time constants) in microgravity as functions of the key system design parameters.
- Validating and verifying the tank pressurization and pressure control models.
- Elucidating important phenomena such as effect of noncondensable gases and local superheats that will be more prevalent in microgravity.

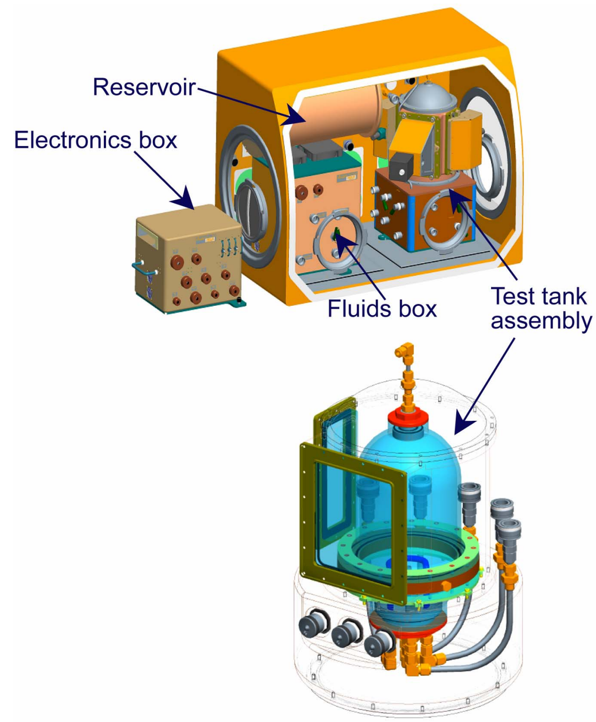

Figure 1.—ZBOT design concept.

Experimental Setup

Figure 1 shows the experiment fitted in the ISS glove box facility.

Test cell

The test cell is a tank with a diameter to length aspect ratio of 1:2 with hemispherical end caps. The tank is 4 in. diameter by 8 in. long. The internal tank volume is about 80 in^3. The tank material will be a clear plastic to provide optical quality transparency for ullage bubble positioning determination, field view velocimetry (particle imaging velocimetry (PIV)), and thermal imaging (liquid crystal thermography (LCT)). A solid model of the tank is shown in figure 2.

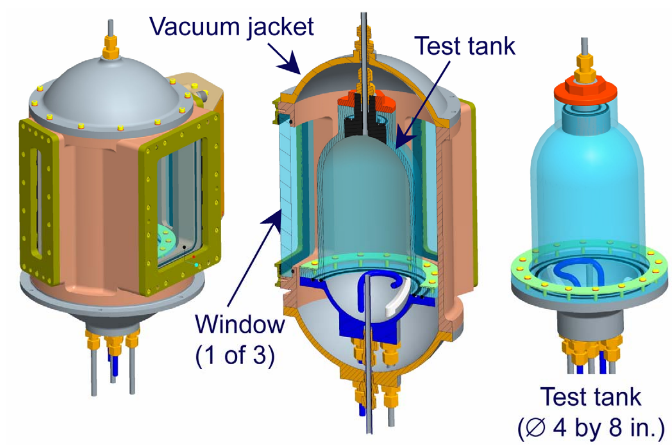

Figure 2.—Test cell design details.

Test fluid

The test fluid shall be a transparent model fluid. The candidate test fluid is HFE–7000 (3M). This fluid was chosen due to its low normal boiling point, its nominally nontoxic and environmentally friendly properties, and its relatively steep saturation curve. It still needs to be approved by NASA's stringent ISS safety review.

Test cell heaters

Two heaters adjustable between 0.125 to 0.5 W per heater (0.25 to 1 W of total heat entering the system) will be installed. To maximize the field of view, the heaters shall be axially located where the hemispherical caps mate with the
axially located where the hemispherical caps mate with the
test cell body. For the heater closest to the jet, placement shall be biased towards the end cap.

Liquid jet mixing

Liquid mixing will be accomplished by drawing the working fluid from the test cell, through the flow loop, and pumping it back into the tank via a jet flow nozzle. It is planned to keep the outlet of the jet nozzle projecting one-half diameter (equal with the hemisphere's end) into the test cell. In this fashion, the jet flow and spread angle will be completely in the field of view (FOV) for flow visualization and PIV velocimetry. Several different jet flow rates will be used during the test runs in order to span both laminar, turbulent, and interface breakup regimes. The ability of the jet to counter the effects of thermal stratification and natural convection driven by residual gravity will be quantified. The temperature of the jet can be controlled via the jet cooling system described below. During most of the test runs, the jet flow rate will be kept constant. However, a set of intermittent jet flow studies are also planned. These test runs are undertaken in order to mimic the actual future scaled-up cryogenic storage tank operation in space where the pump is cycled on and off to save power and minimize the undesirable heat generated by the pump that may end up leaking into the tank.

Heat removal mechanisms

There will be two independent mechanisms for heat removal from the tank during the pressure control studies. These are the jet cooling and the cold finger systems. Figure 3 shows the design concept for the jet inlet, liquid acquisition device, and cold finger.

Jet cooling

During the jet cooling test runs, heat removal from the tank will be accomplished via the mixing jet. That is, when the liquid is pumped out of the tank, it will pass through a heat exchanger connected to the fluid loop. Several jet cooling case studies are planned. In the first set of cases, pressure in the tank shall be controlled by keeping the temperature of the jet at a prescribed subcooled set point equal to the initial tank fluid temperature. In these cases, the flow rate of the jet shall be varied. In the second set of cases, the jet shall have a fixed flow rate and the temperature of the liquid entering the tank will vary. The position of the ullage in microgravity is unknown. In order to prevent withdrawal of vapor from the tank into the fluid loop, a simple liquid acquisition device (LAD) shall be designed and implemented at the nozzle's fluid loop inlet inside the test cell.

During the mixing-only cases, the jet temperature shall be within 0.25 K of the tank outlet temperature within the first L/U seconds of mixing operation and remain within 0.25 K. L is the length of the nozzle interior to the tank, and U is the average jet speed.

Cold finger

It is also of interest to determine the efficacy of using a cold finger with or without liquid mixing to control tank pressure. Unlike the jet cooling cases, where cooling and mixing are accomplished simultaneously via the liquid jet loop, in the cold finger test runs, heat removal will be accomplished by a cold finger that is totally independent of the mixing provided by the liquid jet loop. The cold finger shall be located entirely in the fluid and shall consist of a material with a high thermal conductivity. The exact shape of the cold finger is not yet determined. It is envisioned that its end will have a closed circular-ring configuration mounted on a longitudinal stem.

Noncondensable Gas Injection

Gas injection studies will be performed to determine the effect of a noncondensable gas on the evaporation/condensation process and the overall tank pressurization and pressure control characteristics. It is envisioned that 95 percent nitrogen will be used as the pressurant gas. The injection of gas shall be directly into the existing ullage volume and shall result in mole fractions of 15, 30, 45, 60 ± 2 percent (moles of gas/moles of vapor). To minimize heat transfer in the ullage during injection the inert gas shall be injected at a temperature of T_o ±0.25 °C. Pressurization tests with the noncondensable shall be terminated whenever the tank maximum operating pressure (MOP) is reached.

Experimental Measurements

- Tank pressure
- Heat powers
- Fill ratio
- Temperature at all locations (inside and outside)
  - Ten temperature measurements on the wall
  - Inlet jet temperature
  - Tank outlet temperature
  - Cold finger temperature
  - Two transversely located in the ullage volume
  - Three in different locations in the cylindrical section and bottom dome
  - Ullage position
  - Jet flow rate
  - Noncondensable mole fraction
  - Flow rate, temperature, and pressure of the noncondensable at injection
  - Gravitational acceleration data
  - Temperature field visualization—LCT
  - Velocity field visualization—PIV

Figure 4 shows the design layout for the LCT and PIV.

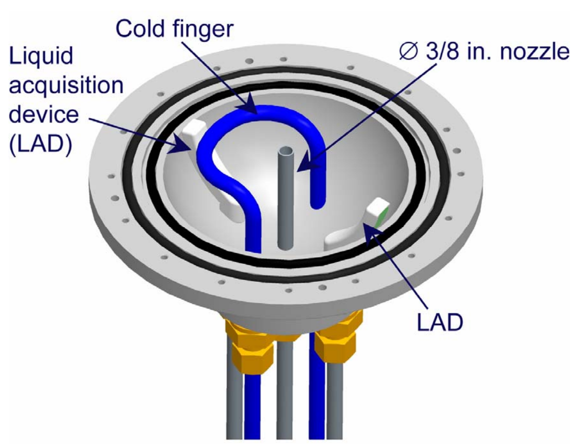

Figure 3.—Closeup of tank bottom showing tank internals important for heat removal.

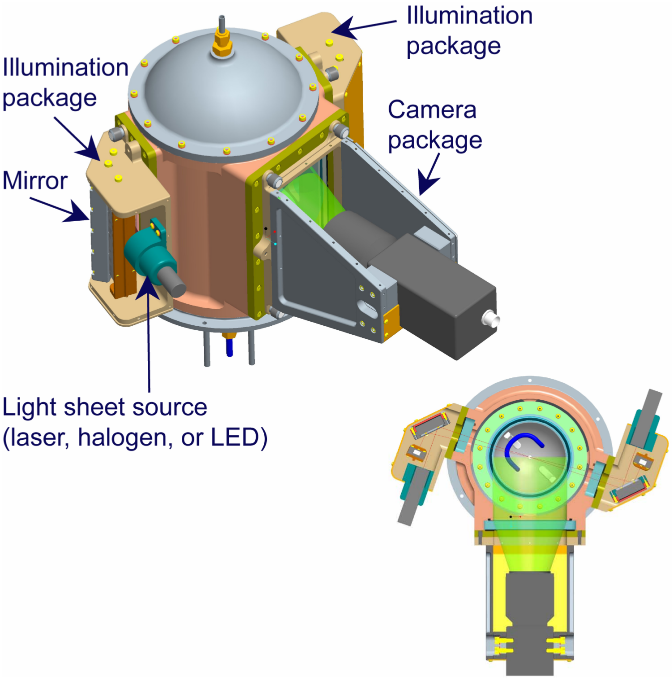

Figure 4.—Visualization system layout.

Matrix of Tests and Test Parameters

The matrix of tests is shown in table I. Typical duration for one run is 12 hr.

TABLE I.—TESTS AND TEST PARAMETERS

Type of test	Runs	Parameters to vary
Self-pressurization	5	Fill ratio Heater power
Mixing only tests	10	Jet speed (laminar and turbulent) Heater power Fill ratio
Subcooled jet mixing	19	Jet speed Jet temperatures Simultaneous and initial pressurization tests Heater power Fill ratio
Cold finger cooling only	9	Cold finger temperatures Simultaneous and initial pressurization tests
Heat power intermittency tests	14	Mixer duty cycle Fill ratio Heater powers
Noncondensable tests	12	Mole fraction Self-pressurization cases Subcooled jet cases Cold-finger-only cases

Centaur Test Bed for Cryogenic Fluid Management

Steven Salka (Lockheed Martin)

Executive Summary

NASA's Space Exploration Vision will require significant increases in the understanding and knowledge of space-based cryogenic fluid management (CFM), including the transfer and storage of cryogenic fluids. Existing CFM capabilities are based on flight of upper-stage cryogenic vehicles, scientific dewars, a few dedicated flight demonstrations, and ground testing. This current capability is inadequate to support development of the crew exploration vehicle (CEV) cryogenic propulsion system and other aspects of robust space exploration with reasonable risk.

The Centaur upper-stage vehicle can provide a low-cost test platform for performing numerous flight demonstrations of the full breadth of required CFM technologies in a schedule supporting CEV development.

Centaur Test Bed

The Centaur Test Bed (CTB) concept is composed of the addition of a "receiver" bottle to the Centaur aft bulkhead, a control panel, and plumbing connecting the bottle to the LO_2 or LH_2 tanks, as seen in figure 1. This receiver bottle would enable the transfer of LO_2 or LH_2 from the Centaur to the CTB, storage of the cryogens on the CTB, transfer of the cryogens back to the Centaur tanks and the venting of the cryogens overboard.

The Centaur cryogens are accessed via the installation of tubing connected to the LO_2 or LH_2 feedlines. During the nominal mission, a redundant valve isolates the CTB system from the Centaur's propulsion hardware to minimize risk to the primary payload. Following spacecraft separation these valves are opened allowing the controlled transfer of cryogens to the CTB.

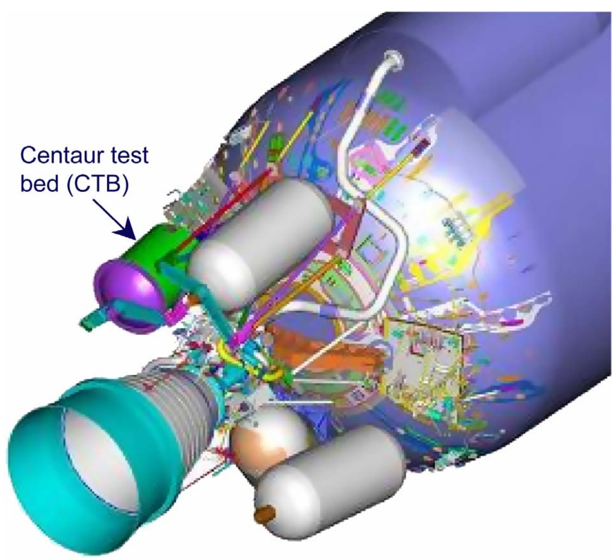

Figure 1.—CTB concept offers affordable, flexible CFM demonstration satisfying NASA's near-term CFM requirements.

The Centaur aft bulkhead contains sufficient space for the installation of a CTB as large as 48 by 30 by 30 in. A CTB of this scale is large enough to adequately test most CFM requirements. Existing flight hardware of similar size is already integrated on Centaur.

For missions requiring the demonstration of alternative cryogens, (e.g., LCH_4), another bottle containing the cryogen could be added to the Centaur aft bulkhead. This additional bottle would be connected to the CTB, providing the source cryogen for orbital demonstration.

CTB Benefits

The CTB is designed to advance all manner of CFM and cryotransfer technologies under zero-g or definable low acceleration. The technologies that CTB can address include

- Liquid acquisition and propellant management devices
- Mass gauging
- Cryotransfer efficiency
- Fluid stratification and mixing
- Liquid inflow geysering
- System chilldown
- No vent fill
- Transfer coupling control
- System operation
- Long-duration storage technologies
- Pressure control
- Active and passive cooling

Large Scale Demonstrations

The Centaur team has taken advantage of the unparalleled recent cryoflight experience (fig. 2) including 100 flights since 1990, to refine the teams CFM understanding and the operation of cryogenic systems. This learning has benefited from the numerous unique mission profiles and augmented by dozens of post mission demonstrations. A partial list of the broad range of Centaur flight CFM experience is shown in table I. These demonstrations are used to evolve Atlas and Centaur's capabilities in a pragmatic, minimal-risk manner.

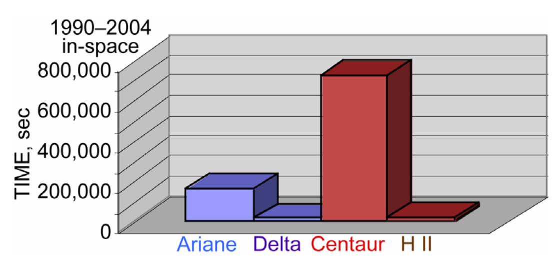

Figure 2.—Centaur's long history, high-flight rate, and long-duration-mission capability results in unparalleled cryofluid management experience.

For CFM technologies requiring large-scale demonstration, the Centaur provides an ideal platform. CFM technologies, such as circulation, spray bars, insulation systems, and liquid acquisition (fig. 3) can be integrated directly to the Centaur and demonstrated as a ride share, or on dedicated mission. System interaction in particular will benefit from the large scale the Centaur has to offer.

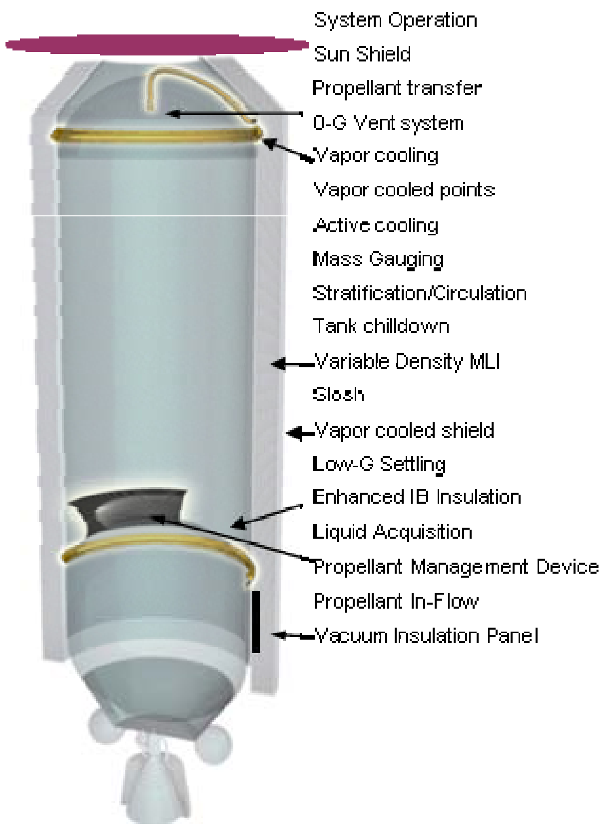

Figure 3.—Centaur can provide basis for large-scale CFM demonstration.

TABLE I.—CENTAUR'S NUMEROUS FLIGHT DEMONSTRATIONS OF CFM RELEVANT TO CRYOTRANSFER

Liquid control (10^{-5} to 6g)	Long coast impact (17 hr)
Feed system warming and chilldown	Pressurization sequencing
Propellant pullthrough	Slosh characterization
Ullage/wall thermal effect	Vent sequencing
Ullage and liquid stratification	Pressure collapse
Propellant utilization	Bubbler vs. ullage pressurant
Mass gauging	Unbalanced venting

Centaur Propellant Excess

Most Atlas/Centaur missions have excess propellants, ranging from hundreds to thousands of pounds. This excess LH_2 or LO_2 propellant can provide large quantities of working fluid for CFM demonstrations. This ability to utilize excess propellant rather than providing dedicated cryodewars enables the Centaur to enact cost-effective CFM demonstrations with minimal performance impact to the primary mission. Implementing the CTB on the LO_2 aft bulkhead separates the cryo-demonstration from the primary payload, easing integration.

Key Exploration Vision Technologies

CFM technologies are an integral part of all aspects of the Space Exploration Vision. In the immediate future, the CEV will require CFM technologies such as liquid acquisition, long-term storage with improved passive and active insulation systems, thermodynamic vent system, cryofluid recirculation to minimize stratification, and zero-g mass gauging. These examples of near-term technologies requirements directly benefit from on-orbit flight demonstration testing. The CTB provides a cost-effective solution to demonstrate all of the required technologies in time to support CEV development.

Maturation Strategies—Settled Cryogenic Transfer

Bernard Kutter (Lockheed Martin)

Executive Summary

For the space exploration initiative to be able to realize the huge benefit of cryogenic propellant transfer, one must ensure the reliability and robustness of the transfer process. To implement cryotransfer starting with the first lunar exploration mission requires the use of existing or nearly existing technology to maintain a reasonable development risk. Utilizing low acceleration during the cryotransfer operation significantly simplifies the entire operation, 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 Centaur and the Delta IV upper stage. The key remaining technology—rendezvous and docking—is required regardless of the use of propellant transfer.

Capability Description

Low acceleration settling

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. Settled fluid transfer becomes attractive at accelerations below ~10^{-4}g (fig. 1). Over the last 15 years Centaur has spearheaded the development of low settling CFM to enhance performance. Centaur utilizes 2×10^{-4}g for short coast missions and 8×10^{-5}g for longer missions to maintain propellant aft during coast phases of flight. In the quest for even more performance, Centaur has demonstrated effective propellant control at accelerations down to 1×10^{-5}g (fig. 2). In the 1960s Saturn also demonstrated effective settling at 2×10^{-5}g.

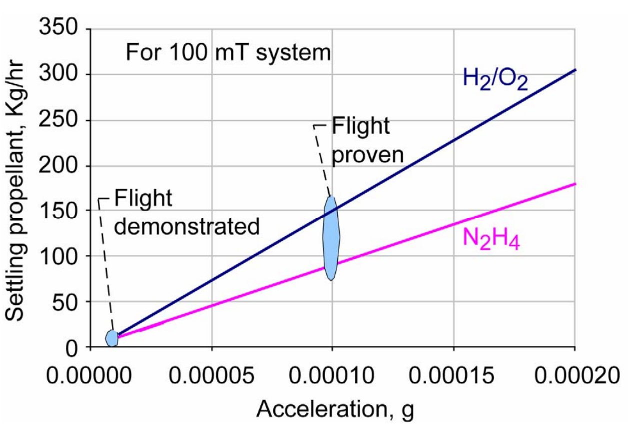

Figure 1.—With low acceleration, propellant consumption for settled cryotransfer is reasonable.

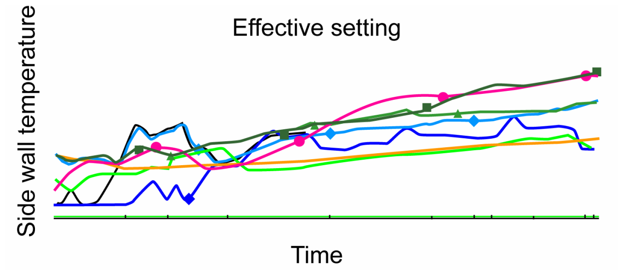

Figure 2.—Centaur has demonstrated effective propellant control at 10^{-5}g, well below the acceleration required to make settled propellant transfer attractive.

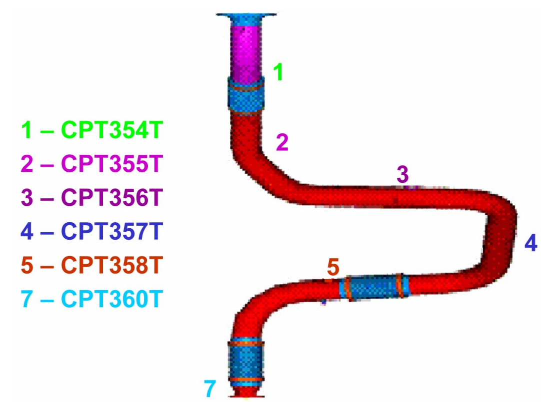

Figure 3.—Centaur has demonstrated numerous effective chilldown methods, including full flow, trickle flow, and pulse flow.

Propellant Acquisition

Propellant acquisition through settling has been reliably used for all large-scale cryostages. Expulsion efficiencies well in excess of 99 percent are achieved on Centaur, even at the relatively low accelerations encountered during blowdown. Expulsion efficiency at 10^{-5}g is yet to be demonstrated.

Chilldown

The Centaur upper stage has demonstrated high capacity, rapid-chill ducting, and associated procedures to enable efficient propellant transfer (fig. 3).

The 12 Titan Centaur missions have demonstrated the complete chilldown of the LH_2 and LO_2 tank walls during the transition from engine burn to zero-g. Unique settling/venting logic has been incorporated to avoid venting liquid.

Mass gauging

With settling, accurate mass gauging can be accomplished using numerous accurate and reliable techniques. Low vehicle acceleration provides a simple method that can accurately gauge total system mass. Thermal couples and liquid sensors have proven very effective in defining the liquid/gas interface. The cryotracker (ref. 1) 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 on Centaur, ensuring 99.9 percent propellant expulsion efficiency.

Pressure control

Settling provides a reliable method to segregate liquid and gas. This enables heat rejection via venting for long coasts, or to maintain pressure in the receiver tank during fluid transfer. With extremely low acceleration, propellant entering the receiver tank may geyser. To prevent liquid venting, the propellant transfer process can be accomplished in pulse mode, where propellant transfer and venting are conducted sequentially.

Cryofluid coupling

Although numerous couplings have been proposed, the Centaur LO_2 feedline slip duct is a flight proven component that provides the required cryogenic sealing, coupling/decoupling, and high-flow capacity with minimal thermal mass.

A partial list of relevant CFM capabilities that have been demonstrated on Centaur is provided in table I.

Key Findings

Cryotransfer utilizing low-level settling enables the use of flight proven CFM techniques. Through the use of settling, near term missions can immediately reap the benefits of propellant transfer. For example, the delivered performance of the ESAS baseline exploration architecture can be greatly increased. LM modeling shows that the ESAS architecture currently requires the Earth Departure Stage (EDS) to burn ~101 mT of its propellants (~58 percent) simply to attain low Earth orbit. “Topping off” the EDS with ~20 mT in LEO, using cryotransfer, doubles the useful, lunar-delivered payload (everything beyond the lunar service access module). Entirely filling the EDS in low Earth orbit with 101 mT increases the delivered payload by a factor of 6. Encouraging competitive commercial delivery of the propellants could significantly reduce launch cost.

TABLE I.—CENTAUR HAS CONDUCTED NUMEROUS FLIGHT DEMONSTRATIONS OF CFM RELEVANT TO CRYOGENIC FLUID TRANSFER

Liquid control (10^{-5} to 6g)	Long coast (to 17 hr)
System warming chilldown	Pressurization sequencing
Propellant acquisition	Slosh characterization
System thermal interaction	Vent sequencing
Ullage and liquid stratification	Pressure collapse
Propellant utilization	Bubbler vs. ullage pressurant
Mass gauging	Unbalanced venting

Gap Analysis

With settled cryogenic propellant transfer, the primary outstanding technology requirement is a reliable fluid coupling and system operation. Rendezvous and docking is required for all exploration missions, and is thus not considered an additional gap. 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 can be used to demonstrate the system functionality of cryotransfer.

Work Cited

1. Daniel J. Schieb, “Cryo Tracker Mass Gauging System Testing in a Launch Vehicle Simulation”

Computational Opportunities for Cryogenic and Low-g Fluid Systems

Gary Grayson (Boeing)

Executive Summary

Computational modeling tools for the design of cryogenic and low-gravity fluid space systems offer both development cost savings and improved designs. However, the tools and approaches employed must be quantitatively verified in relevant environments. It is recommended to develop and experimentally validate computational capabilities in several thermodynamic and fluid-dynamic areas of spacecraft propulsion design to reap the performance and financial benefits of these advanced modeling technologies.

Introduction

Many spacecraft subsystems require fluids to operate and perform their mission functions. Propulsion, thermal, environmental controls, and life support subsystems all have fluid components that must be designed to operate in space environments. A given mission scenario may require that the vehicle subsystems perform in dynamic environments that include varying acceleration and heat transfer. Development and qualification of such systems often requires testing in relevant environments and at actual scale. Testing can become expensive if the relevant environments are hazardous or impossible to simulate on Earth. The processing of toxic propellants such as hydrazine or dinitrogen tetroxide requires careful precautions to prevent human exposure. Here, significant equipment and training are needed, which adds to the cost of each test. Testing with cryogenic fluids also incurs additional costs due to the hazards associated with liquefied gases and the costs of the refrigeration hardware. In the low-gravity environments of orbit and interplanetary coast, the thermal and fluid dynamic behavior of spacecraft hardware can be greatly different from that in normal gravity. Earth-based experimentation, such as parabolic trajectory aircraft and drop towers, typically do not provide long enough simulated low-gravity time to verify spacecraft hardware and frequently cannot use actual scales or fluids.

Space experiments are needed in several areas such as propellant delivery and storage systems to provide useful verification due to the scales, fluids, and durations needed to simulate mission conditions. Since large-scale space experiments are prohibitively expensive, vehicle designers typically avoid space testing and add severe design conservatism or ignore a promising technology altogether. To avoid such technical and financial penalties in future space exploration vehicles, a means to reduce or eliminate expensive testing is needed that also allows infusion of new technology into the development of advanced space fluids systems. Computational modeling offers this benefit but only after careful validation of the models employed. Quantitative verification of modeling approaches is particularly important if computer simulations are included as part of a design process. A high-fidelity computer model that has proven accuracy in relevant environments with actual fluids and scales could replace testing on future fluid system designs as long as the system is not too different from the validating experiment. Furthermore, conditions and design features that are not practical to test, even in a space experiment such as failure scenarios, can be simulated by model to improve device performance and reliability in off-nominal environments. Rapid design iterations and evaluations are also possible with computational fluid dynamics (CFD) while they are not possible in a test-based approach that requires remanufacturing of hardware for a design change. Accordingly, a CFD approach to spacecraft fluid system design offers both performance and financial benefits. However, the models and methods must be developed and proven first.

Capability Description

Recent advances in computational modeling software and computer processor speeds have permitted the simulation of many spacecraft liquid and gas systems. Several fluid design areas are described below where a CFD-based design approach would applicable.

Slosh: Liquids stored in containers move about in response to the net acceleration as well as effects from buoyancy, viscosity, and surface tension. It is important to understand the expected force and moment histories from slosh to design the spacecraft flight control system.

Liquid acquisition: The draining of a liquid in a particular mission environment can be difficult if the liquid is moving about the tank. Internal tank devices such as capillary enclosures are frequently used to ensure single-phase liquid removal from the tank. The conditions when screen devices break down, the collecting of gas bubbles in traps, and liquid acquisition device channel fill-fractions are all important parameters that must be characterized in the design and optimization of screen liquid acquisition devices.

Small-scale capillary: The effect of surface tension in normal gravity is frequently ignored since very small scales are typically required. In low-gravity conditions, surface tension can be the dominant force that drives a fluids motion or position at larger. The design of fluid devices, such as wetting vanes or low-gravity mass gauge sensors, requires characterization of capillary flows with complex geometries.

Antivortexing and vapor ingestion: In draining-tank problems, buoyancy typically prevents liquid-gas interface deformation by holding the liquid against the outlet, while inertia and viscosity serve to deform the interface by pulling it downward towards the tank outlet. Vortices in the container can further increase this deformation by centrifuging liquid away from the drain. In spacecraft fluid systems where a liquid is removed, it is important to know how much suction dip can be expected since it directly influences the residual or unusable liquid.

Two-phase cryogenic: Containers that hold a cryogenic liquid and ullage gas are in a special class of fluid systems since the liquids are frequently near boiling. Here, heat transfer and phase change also influence the tank dynamics in addition to acceleration, buoyancy, viscosity, and surface tension. Special hardware is also frequently used for thermal as well as fluid-dynamic conditioning. For any space vehicle using cryogenic fluids, it is important to understand the tank thermodynamics and how it couples with the fluid dynamics and mission environments. This is important for both normal boiling point and densified cryogenic liquids.

Valve flow: Most fluid systems contain one or more valves that can start or stop the flow. In the design of complex valves, the pressure drop characteristics for a given geometry must be understood. In flowing liquids that are near saturation, cavitation within the valve can occur. Cavitation for many systems can lead to failure, and so the ability to characterize and predict cavitation in fluid devices is important.

Gap Analysis

The degree of existing model validation and suitability for hardware design varies across the applications; some have detailed quantitative verification while some are only qualitatively proven.

Slosh: Liquid slosh has been quantitatively validated in several design applications; it is considered a mature developed capability for storable fluids and cryogenic fluids in short-duration missions where heat transfer is not important. Previous quantitative validation includes large-scale water motion, low-gravity drop tower tests, variable aircraft experiments, and design application on rockets. In the case of cryogenic fluids, heat transfer can cause large liquid movements. Similarly, draining tanks transitioning from high gravity to low gravity can also exhibit surprisingly severe motion; this occurs after main engine shutdown on a launch vehicle. It is recommended to further characterize liquid slosh in cryogenic and dynamic low-gravity environments to provide a robust analysis slosh simulation capability that includes all heat transfer and dynamic effects.

Liquid acquisition: Liquid acquisition in aircraft and launch vehicle tanks is basically a slosh problem. However, in low-gravity applications screen surface tension devices are common, and thus an accurate method is needed to simulate flow through such complex devices. Currently, screen devices are analyzed with a slosh model to determine the wetted screen area versus time, which is then input into separate pressure drop and bubble point calculations. The ability to predict a devices bubble point pressure characteristics using solid obstacle models within the CFD simulation is recommended to allow end-to-end liquid acquisition simulation and in turn improved designs.

Small-scale capillary: Flows along vanes and level sensors has been previously simulated, and appear to be qualitatively correct. However, no quantitative validation of small-scale capillary flows in aerospace applications has been performed. Important low-gravity device performance characteristics such as wicking, droplet adhesion, and capillary pumping are all modelable and beneficial to the design of many low-gravity fluid devices on smaller scales. This applies to propulsion but also other subsystems such as life support that have typically smaller scale devices. It is recommended to quantitatively verify select small-scale capillary models so that the developed methods can be applied with confidence for the design of fluid hardware. It is important to validate with cases that are widely applicable in their dynamic characteristics.

Antivortexing and vapor ingestion: Antivortexing that reduces swirling motion and vapor ingestion has been previously modeled with CFD for draining tanks. Several coarse mesh models have been run that appear to be qualitatively accurate with and without various antivortex and/or vapor ingestion suppression devices. Comparison with test data is required to establish the accuracy of the draining models. Since many future exploration vehicles will have tanks that drain, and since residual, undrainable liquids are not usable, it is recommended to determine the accuracy and capabilities of vapor ingestion and antivortex simulation by comparison of model predictions to measured test data.

Two-phase cryogenics*:* A recent contract with MSFC has established the first successful CFD models of a two-phase cryogenic tank containing a cryogenic liquid and its vapor. Models have been developed and compared to test data from the Multipurpose Hydrogen Test Bed experiments and from the Saturn SIV–B flight test conducted in 1966. Both tank pressurization from propellant boiling and tank depressurization during cooling and thermodynamic vent system (TVS) operation have been demonstrated. The pressurization results are in general agreement with the measured data and typically match within 30 percent. Depressurization during cooling and TVS operation is slower with current models due to the inability to simulate actual surface area in spray flows. Low-gravity pressurization simulations of the Saturn experiment are also in good agreement with the test data within 10 percent. The recent cryogenic modeling developments are encouraging but additional features are required in order for the model to be most useful as a design tool. Current models employ similar gas and liquid velocities and temperatures inside computational cells containing the free surface. This limitation prevents simulation of large temperature gradients near the interface and decreases the accuracy of the predictions. An upgraded two-phase model is recommended in order to improve tool robustness and applicability to more complex fluid systems than the MHTB and Saturn tanks. Similarly, modeling of low-gravity surface tension effects and how they interact with buoyancy and heat transfer can be improved to yield more accurate low-gravity mission solutions. Furthermore, verification of cryogenic tank models with multi-component ullages is needed to accurately represent the effects of noncondensable helium gas.

Valve flow: Flow of storable liquids through complex cavities such as valves is a mature capability with extensive quantitative validation. For example, the CFD model of the Space Launch Initiative crossfeed check valve was within 11 percent of the measured test data. However, valve flow models with cryogenic liquids or other conditions where heat transfer is important have not been verified. Liquid cavitation has been previously simulated with CFD, but the results have not been verified quantitatively. It is recommended to quantitatively establish the accuracy of flow through complex devices with and without cavitation for simulation of flowing cryogenic liquids in spacecraft subsystems.

Recommendations

The overall recommendation is to improve and quantitatively verify the accuracy of computational modeling tools for internal flows in dynamic environments that include both energy and momentum effects. Much of the validation work requires the consideration of cryogenic fluids and low-gravity effects. This quantitative verification can be achieved to some degree with existing ground- and flight-test data. However, the greatest benefits for the design and operation of future spacecraft fluid devices can only be achieved if the tools are proven accurate with actual environments, scales, and fluid types. Therefore, any future space experiments or vehicles should be designed to collect the necessary data to validate computational fluid methods. Use of the described CFD-based design philosophies, once proven, will lead to development cost savings and higher performing spacecraft designs than possible with test-only-based development approaches.

On-Orbit Cryogenic Fluid Management Technologies

Albert Olsen (Boeing)

Executive Summary

On-orbit cryogenic fluid management (CFM) technologies enable the zero-g storage and transfer of cryogenic propellants from supply tanks to engines or receiver tanks without excessive pressure or propellant losses. Current NASA exploration initiatives will require the on-orbit storage and use of liquid hydrogen (LH_2), liquid oxygen (LO_2), and liquid methane (LCH_4) as cryogenic propellants. The basic elements and functions of these propulsion systems include liquid storage, supply and transfer, as well as fluid handling, instrumentation, and tank structures and materials.

Many technology gaps can be addressed through ground testing, but several (e.g., liquid acquisition and transfer) will require flight testing in an on-orbit (low-g) environment to adequately demonstrate a high technology readiness level (TRL).

Capability Description

Liquid storage has two main components, thermal and pressure control. Combinations of active (refrigeration) and passive (multilayer insulation (MLI), vapor cooled shields (VCS), etc.) ensure that cryogenic propellants can be stored for extended periods of time with little or zero boil-off (ZBO) loss. Multiple VCS and advanced insulation have been demonstrated to show high boil-off reduction in ground demonstrations. Pressure control enables the use of the cryogenic propellants without the use of an engine burn to settle the propellants. Liquid supply involves the use of pressurization (gaseous helium (GHe), gaseous nitrogen (GN_2), or autogenous), pumps and liquid acquisition devices (LADs) for acquiring and supplying liquid. LADs have been successfully tested on the ground in LH_2 and LN_2. Liquid transfer includes the phenomena associated with line and tank chilldown and conditioning followed by tank filling. This process may or may not involve venting cryogens overboard. Fluid handling involves the important issue of fluid dynamics and slosh along with fluid dumping and tank inerting. Considerable analytical work has been done using computational fluid dynamics (CFD) codes to model cryogenic tanks in a ground (1-g) environment and the codes have been validated with low-g data obtained from flight experiments using water and storable propellants. Instrumentation includes quantity (mass) gauging, liquid and/or vapor sensors, mass flow and quality metering, as well as leak detection to support integrated vehicle health management. Considerable advancement has been done in the area of mass gauging for on-orbit cryogenic applications using compression mass gauges and optical approaches. Tank structure and material relates directly to tank mass and building extremely lightweight tanks with low thermal conductivity (low-k) components (supports, penetrations, etc.).

Capability Benefits

On-orbit CFM technology applications will be used in all human exploration missions, orbit transfer vehicles, and other in-space stages. Current studies are looking at cryogenic stages with 6-month hold times in low Earth orbit. Spin-off benefits include deep space missions (2+ year duration) using high Isp cryogenic propellants, the in situ planetary production and storage of cryogens and low-pressure storage of cryogens for life support applications such as fuel cells and breathing atmosphere.

Gap Analysis

Many of the on-orbit CFM technologies have been tested on the ground (1g) over the last 40 years using LH_2 and LN_2 as a safer alternative to LO_2. However, with the current emphasis of the NASA exploration initiative on the use of LO_2/LCH_4 propellants, LCH_4 must be demonstrated both on the ground and on orbit with all of the CFM technologies. This is a large technology gap.

Thermal control of on-orbit cryogenic tanks is affected by several technologies. The use of subcooled/densified cryogenic propellants, advanced MLI, VCS, and cryocoolers offer the potential for high boil-off reduction and even ZBO systems. Advanced MLI has been demonstrated to provide a 50 percent reduction in boil-off while a single VCS provides a 65 percent reduction. Also, aerogels are showing promise as cryogenic tank insulation with equivalent performance to MLI. Reusability and damage during reentry are technology gaps for MLI. Also, micrometeoroid and orbital debris (MMOD) protection will be integrated with the use of MLI/VCS. Cryocoolers, as active components, provide 100 percent reduction in boil-off but require power and radiators to dissipate heat. ZBO systems using commercial cryocoolers have been successfully demonstrated on the ground. However, the development of flight-type cryocoolers specifically designed for integration into a large space system is a technology gap. Other technologies such as surface coatings, MLI penetration and seam techniques, vehicle configuration and orientation, and sunshades offer low boil-off reduction. The designer of cryogenic tanks will take advantage of several of these technologies in a single design to fully optimize his tank for the system requirements. Current upper stages perform pressure control by settling propellant using auxiliary propulsion systems prior to venting of firing of main engines. Large-scale and small-scale pressure control has been demonstrated on the ground using LH_2 and LN_2 with an integrated thermodynamic vent system (TVS). LADs used with storable propellants on the space shuttle, and many satellites are state of the art. Zero-g thermodynamics and heat transfer significantly complicate LAD design and performance and coupled with the lack of on-orbit LO_2, LH_2, and LCH_4 data, will require a flight demonstration. Also, availability of LO_2 and LCH_4 LAD data on the ground is a technology gap. Cryogen transfer has been well developed on the ground and is considered state of the art. This encompasses line and tank chilldown by venting cryogen gases and tank filling. For the on-orbit application of cryogen transfer, the designer wants to minimize the amount of cryogen vented overboard due to line and tank chilldown. No vent fill of cryogen tanks has been successfully demonstrated on the ground but is a technology gap on orbit. Fluid dynamics and slosh control represent another technology gap for cryogens on orbit. Cryogenic test data for ground tests is available and matches CFD predictions extremely well. Most of the data used to validate these tools for on-orbit applications is water or ammonia. On-orbit test data will be required to validate CFD codes and this means carrying additional instrumentation during test flights. Quantity and/or mass gauging for cryogens on orbit is another technology gap. Optical and capacitance mass gauges have been demonstrated on the ground with cryogens and appear to have good results. Compression mass gauges have been built and subjected to small-scale testing with good results. As part of an integrated vehicle management system, good lightweight leak detectors for cryogens are a must for on-orbit applications. This is another technology gap. Lightweight tankage can be demonstrated on the ground as can low-k components. Table I shows the current TRL of many of the CFM technologies discussed above and the increased TRL after flight testing.

TABLE I.—ON-ORBIT CFM TECHNOLOGY (TRL)

Technologies	NASA GRC[a]	Boeing/NASA MSFC[b]	Post-flight test TRL
MLI	5	5 (insulation thermal performance) 4 (insulation degradation in launch) 5 (atomic oxygen and contamination)	7
VCS	5	5 (performance) 5 (thermal performance)	7
MMOD	N/A	3 (material and thickness) 3 (performance)	7
Instrumentation	N/A	N/A	7
Low-k penetrations	N/A	5	7
TVS	4	5 (thermal performance) 3 (micro-g heat transfer from fluid)	7
Mass gauging	3	4 (performance) 3 (micro-g performance)	7
Cryocoolers	4 (LO_2/CH_4) 3 (LH_2)	4 (thermodynamic efficiency and life) 3 (micro-g performance)	7
Umbilicals	3 (fluid transfer)	3 (fluid leakage, pressure drop) 3 (force and alignment requirements) 3 (thermal performance)	7
PMD	3	3 (residual fraction; flow vs. percent liquid) 4 (pressure drop, long-term use)	7

[a]Chato, D.J., “Low Gravity Issues of Deep Space Refueling,” AIAA Paper 2005–1148, 43rd AIAA Aerospace Sciences Meeting, Jan. 2005.
[b]“Space Solar Power and Platform Technologies for In-Space Propellant Depots,” Boeing/NASA MSFC Final Report for Contract NAS8–99140, Mod. 2, Task 3, 14 Nov 2000.

Recommendations

Flight testing of CFM technologies on orbit is a very expensive task as is any dedicated space flight. Because of the large cost of a dedicated flight experiment, it may be necessary to accept higher risk and make the first flight of a new cryogenic fueled vehicle the flight test required for the on-orbit CFM technologies. Alternate methods to simulate the necessary low-g environment include secondary payloads on a Delta or Atlas launch vehicle, sounding rockets, and low-g airplanes used by NASA. However, there may be restrictions on the use of cryogens with these alternate methods.

Flight Development Test Objectives Approach for In-Space Propulsion Elements

Eric Hurlbert (JSC)

Executive Summary

Certain aspects of a cryogenic propellant system design can only be fully tested in zero-g. However, flying an in-space experiment for zero-g testing of propellant acquisition, gauging, and transfer is an expensive proposition. The experiment becomes in itself a spacecraft with propulsion, avionics, launch vehicle interfaces, analysis, and ground test, etc. Another approach is basically to do analysis, tests in 1g, and limited simulated zero-g environment, and then to build and fly the full-scale spacecraft. The mission is flown in a manner as to not jeopardize vehicle or crew, but such that data on performance is gathered to accomplish specific development test objectives (DTO). This DTO data on performance is then used to expand the flight envelope. This paper describes the approach used to design and qualify the space shuttle propulsion system and how this could be applicable to a cryogenic system. The conclusion is that the zero-g thermal environment would be the primary focus of in-space DTOs. This however can be flown in a manner to minimize effects by either mixing the system using pumps or by virtue of the maneuvers. Acquisition, gauging, and transfer can be certified for flight on the ground, and operational data gathered with DTOs.

Capability Description—Flight Development Test Objectives

The shuttle is unique in that it was flown manned on its maiden voyage, STS–1. STS–1 and the following three flights are engineering test flights to prove out the shuttle system in launch, orbital, and landing operations. A lengthy list of flight test objectives, detailed test objectives, and two categories of supplementary objectives spell out what information is sought from STS–1, ranging from thermal responses to systems performance. As the first manned orbital flight, STS–l's flight profile has been designed to minimize structural and operational loads on the spacecraft and its boosters. Orbiter Columbia's cargo bay was bare for this first test flight except for a data collection and recording package called developmental flight instrumentation (DFI). The data collection package consisted of three magnetic tape recorders, wideband frequency division multiplexers, a pulse code modulation master unit, and signal conditioners. This package was removed after STS–4 from Columbia's cargo bay, where it was mounted at fuselage station 1069. A major portion of the flight and detailed test objectives is aimed toward wringing out orbiter hardware systems and their operating computer software, and toward measuring the overall orbiter thermal response while in orbit with payload doors opened and closed. Still other test objectives evaluate orbiter's attitude and maneuvering thruster systems and the spacecraft's guidance and navigation system performance. The office of Aeronautics and Space Technology, through its orbiter experiments program, is providing research-dedicated experiments onboard the shuttle orbiter to record specific, research-quality data. This data will be used to verify the accuracy of wind tunnel and other ground-based simulations made prior to flight; to verify ground-to-flight extrapolation methods; and to verify theoretical computational methods. The data gathered through these development test objectives allowed the orbiter to further certify the shuttle and to expand its operational capability.

Key Cryogenic Refueling Technologies

- Storage in zero-g and the thermal effects
- Acquisition
- Transfer/distribution
- Gauging

Gap Analysis

Storage: Thermal effects that can take hours or days require on-orbit testing. For the principle investigators, this has been a significant objective of many flight experiments. For the spacecraft designer, the brute force solution to thermal stratification is to mix the tank, which can be done with a pump, mixer, or thruster firings. From a risk perspective, thruster firings are sufficient for most if not all missions, especially if the tank is highly subcooled pressure-fed system. A thermodynamic vent system can then passively cool the tank and thermal stratification minimized to acceptable levels. DTO would then be performed to turn off mixers or stop firings jets to determine thermal stratification. (Check PRSD tank data).

Acquisition: Propellant acquisition can be evaluated in ground testing and KC–135 simulated zero-g. The Shuttle orbital maneuvering system (OMS) propellant tank was tested in this manner. The OMS tank is a compartmented tank with zero-g acquisition capability for the RCS engine interconnect. The simulated zero-g tests were performed on the KC–135 with a full scale lower compartment and tank diameter as shown in figure 1. The acquisition was qualified for OMS engine starts and bulkhead screen rewetting after dryout on STS–1 DTOs. The OMS-to-RCS interconnect operation deviated from the preplanned procedure. All the RCS test firings were conducted while interconnected to the left OMS; whereas it was planned that only the first RCS test would use left OMS propellant. The OMS-fed propellants to the RCS for approximately 22 hr during the 54-hr mission, and during that period, propellant usage was 709 lbm (5.5 percent) from the left pod and 725 lbm (5.6 percent) from the right pod. The propellant acquisition system operation was excellent. Five zero-g starts and both left and right OMS-to-RCS interconnect operations were performed with no gas ingestion by the engines. The system operated in accordance with the design and within

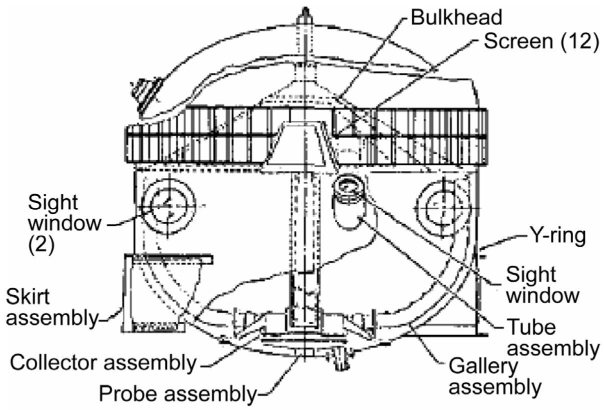

Figure 1.—Full-scale lower compartment in KC–135 test container.

the limits expected while performing several planned maneuvers, both in a single axis and in multiple axes. The system configuration for launch had both pressurization paths open (legs A and B) in the forward and two aft modules, with the propellant tanks in the forward module full and in the aft modules "overfilled" (no gas ullage in the tank). The purpose of the overfill was to prevent gas ingestion prior to and during external tank separation, and flight data confirm that the initial firings of the engines were gas free.

Gauging: On initial flights gauging techniques such as burn time integration, level sensor under +X acceleration, and PVT can be used. A DTO can be added to qualify a zero-g quantity gauge. On STS–1, the OMS propellant quantity gauging system did not perform to design requirements during STS–1. After a 15-s gauging lockout period at the beginning of OMS–1 maneuver, the OMS fuel gauging quantities were erratic for the rest of the mission. The specific anomaly was that the left and right indicated total fuel quantities were erroneous and behaved in an unpredictable fashion during the mission. Both left and right total fuel quantity outputs did not decrease in the manner observed during ground test and maneuver, the right pod oxidizer total quantity showed an initial response lag similar to, but smaller than, the fuel side. The oxidizer readings did show an oscillation of about 0.7 percent. The oscillation frequency of about 1 cycle every 5 s could have been slosh induced. The aft probe readouts for both oxidizer and fuel operated properly.

Transfer: Although no specific transfer application in the shuttle existed. Thermal effects on cryogenic propellants for transfer or distribution to engines would be the focus of DTOs.

Key Findings

The conclusion is that the zero-g thermal environment would be the primary focus of in-space DTOs. The spacecraft can be flown in a manner to minimize effects by either mixing the system using pumps or by virtue of the maneuvers. Acquisition, gauging, and transfer can be certified for flight on the ground, and operational data gathered with DTOs.

Appendix E—Summary Evaluation Sheets

Prior to the final review team members were asked to complete the evaluation form shown in table III for each white paper in the "Experiments Proposed" and "Maturation Strategies." To preserve the reviews summarized results are presented as tabular representations in this appendix (results from individual reviewers are combined to preserve reviewer anonymity). A table was prepared for each evaluated white paper as follows. Question 1 was used only to confirm the placement of the white paper under its grouping and is not reproduced here. For the multiple choice questions (2, 6, 7, 8, 9, and 10) the number under each response is the number of reviewers that picked that choice. Team members were asked to not review white papers their organization had submitted so not all white papers had the same number of reviews. Also not reviewers answered all questions so it is possible to have different total responses for each question. For the essay questions (3, 4, 5, 11, and 12) all comments received are reproduced (each comment from each review is a separate bullet). Again, not all reviewers provided responses. To understand question 11 better, the rating the reviewer gave in question 10 has been added in front of the comment. A total of six tables have been prepared. Table order is the same as white paper order in the document as follows:

Table I.—Review of zero boil-off technologies experiment
Table II.—Review of centaur test bed for cryogenic fluid management
Table III.—Review of computational opportunities for cryogenic and low-g fluid systems
Table IV.—Review of settled cryogenic transfer
Table V.—Review of on-orbit cryogenic fluid management technologies
Table VI.—Review of flight development test objective approach for in-space propulsion elements

Evaluation Questions for MDSCR White Papers

Evaluator

Name of white paper

Type of white paper (from grouping)

1. Is the paper categorized correctly? If not where would you group it?

2. What Cryogenic Fluid Technologies can be addressed by the approach proposed (circle all that apply)
   a) Passive Storage
   b) Active Storage
   c) Pressure Control
   d) Liquid Acquisition
   e) Fluid Transfer
   f) Other ________________________

3. What are the strengths of the proposed approach?

4. What are the weaknesses of the proposed approach?

5. Is the proposed approach capable of significantly advancing cryogenic fluid technologies? Explain your answer.

6. Estimate the cost to prepare experimental hardware for this approach (circle one).
   a) Less than $1 million
   b) $1 to $5 million
   c) $5 to 20 million
   d) More than $20 million

7. Estimate the cost to integrate and fly experimental hardware on the proposed carrier for this approach (circle one).
   a) Less than $1 million
   b) $1 to $5 million
   c) $5 to $20 million
   d) More than $20 million

8. Estimate the time to prepare experimental hardware for this approach (circle one).
   a) Less than 1 year
   b) 1 to 2 years
   c) 3 to 5 years
   d) More than 5 years

9. Estimate the time to integrate and fly experimental hardware on the proposed carrier for this approach (circle one).
   a) Less than 1 year
   b) 1 to 2 years
   c) 3 to 5 years
   d) More than 5 years

10. Compared to the other white papers rate the return on investment of this approach
    a) Below average
    b) Average
    c) Above average
    d) Cannot tell

11. Explain your rating for question 10.

12. If you were conducting a preliminary design for this approach, what issues would you focus on first?

TABLE I.—REVIEW OF ZERO BOIL-OFF TECHNOLOGIES EXPERIMENT

Question 2		Question 6	
Cryogenic Fluid Technologies address by the proposed approach	No. of evaluators selecting	Estimated cost to prepare experimental hardware	No. of evaluators selecting
Passive storage	3	Less than $1 million	
Active storage	3	$1 to $5 million	3
Pressure control	5	$5 to $20 million	2
Liquid acquisition	3	More than $20 million	
Fluid transfer	1		
Other	1 (Gauging)		

Question 7		Question 8	
Estimated cost to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Estimated time to prepare experimental hardware	No. of evaluators selecting
Less than $1 million	1	Less than 1 year	
$1 to $5 million	3	1 to 2 years	3
$5 to $20 million		3 to 5 years	2
More than $20 million	1	More than 5 years	

Question 9		Question 10	
Estimated time to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Return on investment of this approach compared to other white papers	No. of evaluators selecting
Less than 1 year	1	Below average	3
1 to 2 years	2	Average	1
3 to 5 years	2	Above average	1
More than 5 years		Can't tell	

Strengths of the approach

- Simple, low cost
- Capable of testing a board range of Fluid Management technologies. Can be used validate and verify CFD models.
- Potential for low cost. Possibility for numerous repeated tests.
- Long term on-orbit operations are available so tests could be repeated if necessary
- Proposed experiment uses a clear storage vessel aboard the ISS to allow for visual observation of test fluid in a low-g environment using concepts for jet mixing.

Weaknesses of the approach proposed?

- Makes a big leap in size and fluid properties to the final application, although some scaling factors work out quite well. Thermal issues that are specific to cryogens will not be addressed, for instance, MLI, low heat of vaporization, etc.
- Not cryo—uses a refrigerant. Very small scale, will be difficult to scale to CFM size tanks
- It is hard to believe that testing at the 4 by 8" scale with ambient temperature fluids will be representative of large scale cryo fluid management. The gas ingestion testing is proposed to be done with common temperatures. Centaur flight experience indicates a huge pressure control impact due to temperature variation
- The proposed experiment utilizes ISS. This appears to be fairly high risk as the future of ISS is currently being debated within NASA and the U.S. Government.
- The proposed experiment uses a simulated fluid. It does not address cryogenic issues. They will have to be addressed by analysis
- Test fluid is not a cryogenic fluid. Requires correlation of test fluid to actual cryo propellant fluids that would be used for CEV propulsion system (i.e., LH_2, LO_2 or LCH_4). Experiment is also required to be conducted aboard the ISS which significantly increases development and recurring costs by including launch services and ISS integration costs. Experimental hardware will also require human safety rating which adds more complexity and cost to proposed experiment.

Is the approach proposed capable of significantly advancing Cryogenic Fluid Technologies? Explain your answer.

- The experiment allows many tests of different types and configurations to be performed in a relatively short time. The fluid properties will be able to be extrapolated to those of hydrogen. The modeling will cover this extrapolation as well as be verified by the data taken during these tests.
- Unclear. The test tanks are so small, scaling to real propellant tanks will be difficult. But, can be used to validate and verify CFD models.
- No. The emphasis of the concept is on demonstrating fluid circulation and mixing in micro-g. The small scale

and use of HFE–7000 for the test fluid are not representative of a cryo system.
- No, since it involves the use of a simulated fluid and the use of ISS as the test vehicle.
- Experiment may provide significant advances in CFM technologies but still requires a correlation between the test fluid and cryogenic fluids which will be used in real world, space exploration missions.

Explain your rating for return on investment

- Above average. A large quantity of data may be obtained for a relatively low cost. The modeling accuracy and capabilities can be verified and tested with such a low cost experiment.
- Average. The test tanks are so small, scaling to real propellant tanks will be difficult. But, can be used validate and verify CFD models.
- Below average. It is unclear how this proposal advances CFM TRL.
- Below average. The proposed use of ISS and a simulated fluid diminish the value of this investment
- Below average. Nonrecurring and recurring costs for this experiment are expected to be high due to launch costs, ISS integration cost and added costs for human rating test hardware to fly aboard ISS. The technological benefits are expected to be low since actual test fluid is not a cryogen.

If you were conducting a preliminary design for this approach what issues would you focus on first?

- Instrumentation
- Can fluid properties be varied to address scaling issues?
- How could the experiment be done without depending on ISS?
- Human rating and safety requirements to fly aboard ISS with astronauts onboard.

TABLE II.—REVIEW OF CENTAUR TEST BED FOR CRYOGENIC FLUID MANAGEMENT

Question 2		Question 6	
Cryogenic Fluid Technologies address by the proposed approach	No. of evaluators selecting	Estimated cost to prepare experimental hardware	No. of evaluators selecting
Passive storage	4	Less than $1 million	
Active storage	4	$1 to $5 million	2
Pressure control	4	$5 to $20 million	2
Liquid acquisition	4	More than $20 million	
Fluid transfer	4		
Other	Gauging		

Question 7		Question 8	
Estimated cost to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Estimated time to prepare experimental hardware	No. of evaluators selecting
Less than $1 million	1	Less than 1 year	
$1 to $5 million	1	1 to 2 years	3
$5 to $20 million	2	3 to 5 years	1
More than $20 million		More than 5 years	

Question 9		Question 10	
Estimated time to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Return on investment of this approach compared to other white papers	No. of evaluators selecting
Less than 1 year	2	Below average	
1 to 2 years	2	Average	
3 to 5 years		Above average	4
More than 5 years		Can't tell	

Strengths of the approach

- Eliminates ground handling issues of loading cryogens
- Allows test with either hydrogen or oxygen
- Very attractive relatively low cost access to space by using the "secondary" capability of the Atlas Centaur. The Centaur upper stage can provide spacecraft functions as well as left over LO_2 and LH_2 and gaseous helium.
- Capable of supporting a broad range of CFM experiments at low cost, with many flight opportunities each year. Flights of opportunity as secondary payload on Centaur missions. Can validate and verify CFD codes.
- Considerable on-orbit/low-g testing can be conducted using the residual launch vehicle propellants.
- Flying as a secondary payload on an existing launch vehicle and conduction on-orbit/low-g CFM experiments greatly reduces the total cost of the experiment
- This technology could reduce the weight of crew exploration vehicles by allowing them to be launched empty and fueled on-orbit.

Weaknesses of the approach proposed?

- High reliability required to tap into engine feedlines
- Secondary payload status imposes additional constraints on experiment
- No commanding capability. This, then does not permit interacting with the payload, which will limit the possibilities in a single flight. This platform also is limited in duration to approximately one day.
- All operations must be preprogrammed; there is no data uplink. Experiment tank is ~ $1m^3$. There are scaling issues.
- Since the CTB is tied to a launch vehicle (Atlas) the following would have to be demonstrated prior to the CTB being allowed on the launch vehicle:
  - Permission/approval would need to be obtained from the launch vehicle manufacturer by demonstrating that the CTB will not impact/affect the launch vehicle. This could involve considerable analysis by the CTB program up to two years in advance of the launch date, approximately the same time the payload customer begins to supply documentation to the launch vehicle provider.
  - How the CTB impacts the launch vehicle would require considerable work by the launch vehicle team which would need to be paid by the CTB program. These costs could be expensive.
  - Permission/Approval would need to be obtained from the launch vehicle payload owner by demonstrating that the CTB will not impact/affect the payload. Again, considerable analysis could be involved.
- A large quantity of helium gas may be required to purge tanks prior to conducting CTB experiments. Analyses would need to be conducted to determine launch vehicle remaining helium versus needed helium for experiments. Large quantities could be needed if purging of Atlas tanks is required.

- To obtain engineering data for validation of analytical codes, considerable instrumentation would need to be added to the launch vehicle tanks/lines. This again would need to be approved by the launch vehicle provider and could involve considerable analysis by the CTB program.

Is the approach proposed capable of significantly advancing Cryogenic Fluid Technologies? Explain your answer

- Yes, this experiment will allow testing in low-g with cryogens.
- The opportunities allowed by this approach are many. It allows a tank of roughly 350 liters which is significant. Various devices for test could be placed within this experimental space. The experimental volume concept allows full and easy access. Both LO_2 and LH_2 may be tested, as well as the possibility of a separately contained LCH_4 tank.
- Yes, all CFM technologies can be tested and results used to validate and verify CFM codes.
- Yes, this approach has the capability of raising the TRL to 6–7 for all CFM technologies requiring a relevant environment of low-g. Technologies like cryogenic fluid transfer, autonomous fluid couplings, no vent fills, etc.

Rating for return on investment and explanation

- Above average, this approach allows significant testing in low gravity with the fluid of interest at a reasonable cost
- Above average, low cost and high capability. This technique also allows rapid experiment design to flight. Multiple flight opportunities are also attractive.
- Above average, capable of demonstrating all CFM technologies at low cost and with multiple opportunities per year.
- Above average, this approach has the capability of raising the TRL to 6–7 for all CFM technologies requiring a relevant environment of low-g with only one launch into space. Technologies like cryogenic fluid transfer, autonomous fluid couplings, no vent fills, etc.

If you were conducting a preliminary design for this approach what issues would you focus on first?

- Integration with the upper stage
- Acceleration environment
- Prioritization of CFM technologies based on date of need, risk that can be retired, and flight readiness
- Coordination with the launch vehicle team to resolve impacts that the CTB would have on the launch vehicle

TABLE III.—REVIEW OF COMPUTATIONAL OPPORTUNITIES FOR CRYOGENIC AND LOW-G FLUID SYSTEMS

Question 2		Question 6	
Cryogenic Fluid Technologies address by the proposed approach	No. of evaluators selecting	Estimated cost to prepare experimental hardware	No. of evaluators selecting
Passive storage	3	Less than $1 million	1
Active storage	3	$1 to $5 million	
Pressure control	5	$5 to $20 million	2
Liquid acquisition	5	More than $20 million	1
Fluid transfer	5		
Other	Valves		

Question 7		Question 8	
Estimated cost to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Estimated time to prepare experimental hardware	No. of evaluators selecting
Less than $1 million		Less than 1 year	
$1 to $5 million	1	1 to 2 years	
$5 to $20 million	2	3 to 5 years	3
More than $20 million		More than 5 years	

Question 9		Question 10	
Estimated time to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Return on investment of this approach compared to other white papers	No. of evaluators selecting
Less than 1 year		Below average	
1 to 2 years	2	Average	
3 to 5 years	2	Above average	3
More than 5 years		Can't tell	2

Strengths of the approach

- Good summary of modeling state of the art
- Covers most of the technologies required for cryogenic fluids
- Modeling is key to demonstrated understanding of the system.
- A fully developed cryo CFD code will be a very useful design tool, allowing rapid evaluation of design options.
- Development of flight anchored tools to help in the design, development and operation of any CFM system. Centaur sidewall temperature patches have been used to anchor Flow–3D CFD slosh modeling, significantly increasing confidence in modeling results.
- Approach recommends developing CFD codes that are anchored to flight data to provide significant advances in CFM technologies.

Weaknesses of the approach proposed?

- Experiments to validate models only addressed in general
- No specific tests are proposed to test the models. The design of a test must take this into account, in some cases over emphasizing a characteristic in order to fully measure it.
- Validation and verification could be very difficult and expensive.
- Acquiring sufficient data to anchor CFD models across a relevant range of fluid conditions and geometries could prove expensive and difficult. The paper does not suggest specific data that will be required to anchor the CFD models, nor how to acquire this data.
- CFD code is limited in its ability to accurately predict cryogenic fluid behavior in a zero-g environment for the complex missions that are planned for NASA space exploration initiatives. Two-phase flow will also be a significant challenge

Is the approach proposed capable of significantly advancing Cryogenic Fluid Technologies? Explain your answer

- Possibly, however it must be combined with a strong experimental effort
- Modeling is key to demonstrated understanding of the system.
- Yes, a fully developed cryo CFD code would significantly reduce design cost, reduce risk, and reduce system mass by not having to over engineer systems.
- Approach will provide significant advances in CFM technologies, but needs to provide details of how to implement the proposed experiments and anchor test data to CFD code.
- The flight tests required to anchor CFD models, and the CFD models themselves will significantly increase the understanding of all aspects of CFM.

Rating for return on investment and explanation

- Can’t tell; this white paper only addresses one piece of the puzzle.
- Can’t tell; It is tough to evaluate without proposing a specific experiment.
- Above average; A fully developed cryo CFD code promises significant reduction in the life cycle costs of future systems by allowing risk reduction, mass reduction, reduction in development time, and rapid evaluation of design options.
- Above average; Anchored CFD modeling would be extremely useful in the development on any stage requiring CFM, short duration upper stages, long duration in-space stages as well as cryo depots.
- Above average; Anchoring of flight data to CFD code can significantly advance CFM technologies by reducing future development risk involving mission rqmt’s of increasing complexity. Although development costs are similar to other proposals, development of accurate CFD code can provide a significant investment for future space exploration missions.

If you were conducting a preliminary design for this approach what issues would you focus on first?

- Make the model of a test item, then perform a detailed design in order to emphasize model validation. In other words, design the test system to be sensitive to those parameters in the model that need validation.
- Prioritization of validation and verification experiments to concentrate on risk reduction in near term missions.
- Existing anchored CFD modeling.
- What data is required to anchor CFD models, modeling various aspects of CFM: Slosh, thermal gradients and heat transfer, liquid acquisition, circulation, geysering, etc.
- What data exists to validate CFD models (ground, flight, etc).
- Capabilities and limitations of the various existing CFD codes on the market, and what enhancements would be beneficial.
- Strategies to develop required data in relevant environment
- Development of initial CFD modeling for various CFM aspects. Assess ballpark validity based on sanity and any existing data.

TABLE IV.—REVIEW OF SETTLED CRYOGENIC TRANSFER

Question 2		Question 6	
Cryogenic Fluid Technologies address by the proposed approach	No. of evaluators selecting	Estimated cost to prepare experimental hardware	No. of evaluators selecting
Passive storage		Less than $1 million	
Active storage		$1 to $5 million	3
Pressure control	3	$5 to $20 million	
Liquid acquisition	4	More than $20 million	
Fluid transfer	4		
Other	Couplings, chilldown, gauging		

Question 7		Question 8	
Estimated cost to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Estimated time to prepare experimental hardware	No. of evaluators selecting
Less than $1 million		Less than 1 year	1
$1 to $5 million	2	1 to 2 years	2
$5 to $20 million	1	3 to 5 years	
More than $20 million		More than 5 years	

Question 9		Question 10	
Estimated time to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Return on investment of this approach compared to other white papers	No. of evaluators selecting
Less than 1 year		Below average	2
1 to 2 years	2	Average	2
3 to 5 years	1	Above average	
More than 5 years		Can't tell	

Strengths of the approach

- Uses existing hardware.
- The likelihood of success is great because this just builds on techniques for acquisition that are currently in use.
- Using settling avoids the uncertainty of 0g transfers. It is a significant risk reduction as no new technologies are needed.
- Data obtained from previous Centaur flights provides a good data base.
- Approach is fairly simple.

Weaknesses of the approach proposed?

- Although the concept addresses several key parts of transfer it does not actually conduct a transfer.
- There are some inefficiencies of this approach. Long duration passive and active control are not addressed.
- Eliminates the option of 0-g transfers, which may be required for some missions. Does not significantly advance CFM technologies. Requires settling burns from the vehicle/depot to transfer cryogenic fluids.
- Complexity of ACS firings if a vehicle is docked to a depot and transferring cryogens. Which vehicle should do the firing? Added software to accomplish complex firing.
- Have to ensure that complex ACS firings for docked vehicles transferring cryogens do not cause either vehicle to tumble or go out of control.
- This creates an architecture decision resulting in only one method of cryogen transfer on-orbit.

Is the approach proposed capable of significantly advancing Cryogenic Fluid Technologies? Explain your answer

- No, Although this approach can demonstrate several key concepts, additional experiments are required for a technology breakthrough.
- This is a solid approach to solving the liquid acquisition issues.
- No, no new CFM technologies required.
- This approach would advance CFM Technologies in the low to medium range due to the dependence on propellant settling which involves firing the ACS. This could be complicated during a docked maneuver involving cryogen transfer.

Rating for return on investment and explanation

- Average, experiment is reasonably low-cost but also low return
- Average, provides a high reliability approach to "getting there," but does not address long-term storage.

- Below Average, does not significantly advance CFM.
- Below Average, the proposed approach ties the CFM technologies to a settling burn to create artificial gravity to force a liquid/gas interface in the cryogen to be utilized. This creates a single architecture which restricts development of future concepts.

If you were conducting a preliminary design for this approach what issues would you focus on first?

- How much experimentation can be conducted in a settled environment?
- What are the impacts of settling on mission architecture?
- Modeling of the low-g environment and model verification.
- Prioritization of CFM technologies based on date of need, risk that can be retired, and flight readiness
- Focus on interactions when two vehicles or a single vehicle and depot are docked and transferring cryogens and what impact this has on ACS and stability requirements

Additional Comments

- I think that this is one solution, but not the solution. More research needs to be done before a solution for transferring cryogens on-orbit can become routing and architecture decisions are made too far in advance.

TABLE V.—REVIEW OF ON-ORBIT CRYOGENIC FLUID MANAGEMENT TECHNOLOGIES

Question 2		Question 6	
Cryogenic Fluid Technologies address by the proposed approach	No. of evaluators selecting	Estimated cost to prepare experimental hardware	No. of evaluators selecting
Passive storage	3	Less than $1 million	
Active storage	3	$1 to $5 million	1
Pressure control	4	$5 to $20 million	2
Liquid acquisition	4	More than $20 million	
Fluid transfer	4		
Other	gauging		

Question 7		Question 8	
Estimated cost to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Estimated time to prepare experimental hardware	No. of evaluators selecting
Less than $1 million		Less than 1 year	
$1 to $5 million	1	1 to 2 years	1
$5 to $20 million		3 to 5 years	1
More than $20 million	2	More than 5 years	1

Question 9		Question 10	
Estimated time to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Return on investment of this approach compared to other white papers	No. of evaluators selecting
Less than 1 year		Below average	1
1 to 2 years	1	Average	1
3 to 5 years	1	Above average	
More than 5 years	1	Can't tell	1

Strengths of the approach

- Good summary of the state of the-art.
- Emphasis is on liquid methane properties which is in line with the current CEV design.
- Well-considered evaluation of TRL of current state of the art and evaluation of TRL after flight demonstration
- Approach attempts to address all risk items associated with near-term applications related to NAS space exploration initiatives. White paper does an excellent job of identifying risk items and required maturation strategies to reduce development risk.

Weaknesses of the approach proposed?

- No specific experiment proposed
- Flying the experiment on the same flight and with the same hardware as the operational system takes risks or reduces the usefulness of the data. In other words, an operational system is more robust and takes fewer risks than an experiment.
- Does[n't] describe how one should accomplish the demonstration(s).
- Recommendation is to accept higher risk due to large cost of dedicated launch and make first flight of new vehicle a development flight. Dedicated launches are not necessarily required for CFM testing. Cost of a dedicated development flight for a new vehicle will likely be higher than flying experiment module on an expendable vehicle.

Is the approach proposed capable of significantly advancing Cryogenic Fluid Technologies? Explain your answer

- Possibly, white paper clearly explains the need for flight testing, however it will have to be combined with flight experiments to advance cryogenic fluid technologies
- Yes. Any data is better than none.
- No, it is a list of what needs development, not how to do it.
- Approach will provide significant advances in CFM technologies, but needs to provide details of how to implement the proposed experiments.

Rating for return on investment and explanation

- Average, advocates standard approaches to flight testing
- Below average, this has a limited scope and will not result in data on a short time scale.
- Can't tell, it is a list of what needs development, not how to do it.
- Average, the proposed approach will likely yield large advances in CFM technologies but at a high cost if a new vehicle uses the first few flights for development of critical CFM technologies.

If you were conducting a preliminary design for this approach what issues would you focus on first?

- Define flight experiment options
- Schedules
- Investigation of how all of the listed technologies could be demonstrated.
- Implementation of proposed test requirements and integration onto launch vehicle. Test data correlation to CFD codes will also be an important issue to address early in the program.

TABLE VI.— REVIEW OF FLIGHT DEVELOPMENT TEST OBJECTIVE APPROACH FOR IN-SPACE PROPULSION ELEMENTS

Question 2		Question 6	
Cryogenic Fluid Technologies address by the proposed approach	No. of evaluators selecting	Estimated cost to prepare experimental hardware	No. of evaluators selecting
Passive storage	3	Less than $1 million	1
Active storage	2	$1 to $5 million	
Pressure control	3	$5 to $20 million	1
Liquid acquisition	3	More than $20 million	1
Fluid transfer	2		
Other	Gauging, chilldown		

Question 7		Question 8	
Estimated cost to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Estimated time to prepare experimental hardware	No. of evaluators selecting
Less than $1 million	2	Less than 1 year	1
$1 to $5 million		1 to 2 years	1
$5 to $20 million		3 to 5 years	
More than $20 million	1	More than 5 years	1

Question 9		Question 10	
Estimated time to integrate and fly experimental hardware on the proposed carrier	No. of evaluators selecting	Return on investment of this approach compared to other white papers	No. of evaluators selecting
Less than 1 year	1	Below average	1
1 to 2 years	1	Average	
3 to 5 years		Above average	2
More than 5 years	1	Can't tell	

Strengths of the approach

- Approach takes a low-risk, evolutionary approach to advancing CFM technology by starting with analysis and moving to suborbital or parabolic flight testing, and finally on-orbit testing. Each step in the development program attempts to expand the envelope of data and knowledge.
- Allows the immediate development of cryo stages and systems
- Capable of supporting CFM experiments at low cost, with several flight opportunities each year. Uses current shuttle hardware

Weaknesses of the approach proposed?

- Approach may require a significant investment in time which may not support CEV development cycle. Near term application will require significant advances in a relatively short time period.
- By avoiding initial CFM technology/component testing and development, one relies on the real article to learn from. This requires early missions to be very benign, or take on excessive risk. These early, limited missions may or may not provide useful functions. For example, the CEV may be launched to orbit as a demo, stay in orbit for a day and return. This is a benign environment that will not overly stress existing CFM capabilities. However, at hundreds of millions of dollars (or much more) this is a very expensive demonstration of CFM. If surprises develop, correction activities may result in serious schedule delay.
- Transfer not addressed. Scope limited to current shuttle hardware, not likely to change configuration to test scaling.

Is the approach proposed capable of significantly advancing Cryogenic Fluid Technologies? Explain your answer

- Approach will provide significant advances in CFM technologies by incrementally advancing the technology and increasing on-orbit CFM knowledge.
- TRL will remain low until actual flight of the final article, at which point TRL will climb with each successive flight and expansion of the envelope.
- Unclear—not sure how wide of a range of testing can actually be done.

Rating for return on investment and explanation

- Above average, low risk approach ensure high yield in technology advancement with minimal risk and cost by using all available resources for advancing CFM technology (analysis, suborbital and orbital testing) in an evolutionary approach.
- Below average, only limited capability and only limited range of parameters can be varied.

If you were conducting a preliminary design for this approach what issues would you focus on first?

- Risk reduction plan for using analysis followed by ground testing, followed by suborbital and orbital testing. In other words, defining the evolutionary plan from analysis to orbital flight testing.
- Determine limits of what testing can be done.

Additional comments

- I had trouble understanding whether this paper proposed using the shuttle system itself for these investigations or was going to do experiments on a future operational system. If the latter then this seems to be the same approach as the On-Orbit CFM paper.

References

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14. ABSTRACT
This report describes the results of the “Experimentation for the Maturation of Deep Space Cryogenic Refueling Technology” study. This study identifies cryogenic fluid management technologies that require low-gravity flight experiments bring technology readiness levels to 5 to 6; examines many possible flight experiment options; and develops near-term low-cost flight experiment concepts to mature the core technologies. A total of 25 white papers were prepared by members of the project team in the course of this study. The full text of each white paper is included and 89 relevant references are cited. The team reviewed the white papers that provided information on new or active concepts of experiments to pursue and assessed them on the basis of technical need, cost, return on investment, and flight platform. Based on on this assessment the “Centaur Test Bed for Cryogenic Fluid Management” was rated the highest. “Computational Opportunities for Cryogenics for Cryogenic and Low-g Fluid Systems” was ranked second, based on its high scores in state of the art and return on investment, even though scores in cost and time were second to last. “Flight Development Test Objective Approach for In-space Propulsion Elements” was ranked third.

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