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Fluid Acquisition and Resupply Experiments on Space Shuttle Flights STS-53 and STS-57

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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

ALFE	Advanced Liquid Feed Experiment
CFD	computational fluid dynamics
cg	center of gravity
FARE	Fluid Acquisition and Resupply Experiment
g	acceleration due Earth's gravity, 980 cm/s^2 (32.2 ft/s^2)
GRC	Glenn Research Center
ID	internal diameter
LAD	liquid acqusition device
LeRC	Lewis Research Center (now Glenn Research Center)
MGAMS	microgravity acceleration monitor system
MGS	Mars Global Surveyor
MMDA	Martin Marietta Denver Aerospace
MSFC	Marshall Space Flight Center
OD	outer diameter
OMS	orbital manuevering system
RCS	reaction control system
SFMD	Storable Fluid Management Demonstration

NOMENCLATURE

a	acceleration
Bo	Bond number
P_{BP}	bubble point pressure
P_D	dynamic pressure
P_{FR}	friction pressure
P_{FTS}	flow through screen pressure
P_H	head pressure
P_{total}	total pressure across screen
r	tank radius
V	feed line inflow velocity
We	Weber number
ρ	liquid density
σ	liquid surface tension

TECHNICAL PUBLICATION

FLUID ACQUISITION AND RESUPPLY EXPERIMENTS ON SPACE SHUTTLE FLIGHTS STS-53 AND STS-57

1. INTRODUCTION

1.1 General Background

Fluid management technologies, including depots for on-orbit resupply of fluids, are a key element of future space operations (fig. 1). Lunar and Mars exploration missions will require periodic resupply of liquids and gases for life support, propellants, reactants, and experiments. Simple, proven techniques for transferring a variety of different liquids, from hazardous propellants to cryogens, must be available, necessitating a more complete understanding of fluid acquisition and transfer technology.

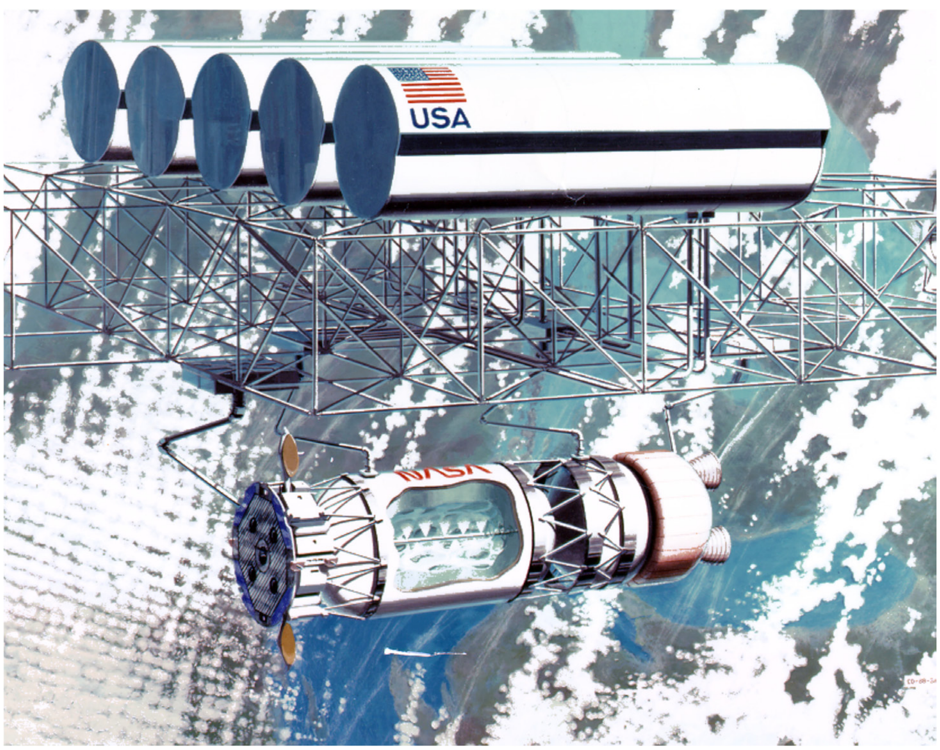

Figure 1. Cryogenic propellant depot for on-orbit storage and resupply.

Although cryogenic fluid transfer has been identified as a key technology, only a limited amount of orbital testing has been accomplished to date. Fluid transfered flight experiments have included the Martin Marietta Storable Fluid Management Demonstration (SFMD)[1] in 1985 (the same test bed hardware as the Fluid Acquisition and Resupply Experiment (FARE)), the NASA Glenn Research Center (GRC)/Boeing Aerospace Vented Tank Resupply Experiment,[2] and the Air Force/McDonnell Douglas Advanced Liquid Feed Experiment (ALFE). Of these, SFMD and ALFE were fluid transfer experiments but produced data with limited applicability due to hardware configurations designed for specific missions. Therefore, the basic objectives of the FARE were to provide orbital fluid acquisition, expulsion, refill, and pressure control data insofar as possible with a storable test liquid. To meet the space shuttle safety requirements and enable full visualization of fluid behavior without thermodynamic and heat transfer complexities,[3] the test fluid selected was water with additives. Furthermore, the experiment with its transparent acrylic tanks was designed to be 'middeck mounted' on the shuttle. Further experiment hardware details are presented in section 4.

The FARE program, managed by the Marshall Space Flight Center (MSFC) Space Propulsion Branch with Martin Marietta Civil Space and Communications as the contractor, consisted of two flights designated FARE I and FARE II. FARE I flew in December 1992 on STS-53 with a screen channel liquid acquisition device (LAD)[4] and FARE II flew in June 1993 on STS-57 with a vane LAD.[5] Please refer to appendix A for additional programmatic details.

1.2 Two Liquid Acquisition Device Approaches

The two LADs flown as FARE I and II represent the two basic LAD categories usually considered for in-space fluid management—screen channels and vanes. Screen channel LADs with fine mesh screens are designed to act as capillary barriers that allow gas-free liquid to be expelled regardless of the liquid's position within the tank. Screen channel LADs have been implemented extensively for orbital maneuvering and reaction control propulsion.[4] Vane devices are designed to take advantage of surface tension forces to favorably position both liquid and gas within a tank,[5] but historically have been used only in special cases with low acceleration forces and flow rates. Each of these LAD categories is described in sections 1.2.1 and 1.2.2.

1.2.1 Screen Channel Devices

Screen channel LAD implementation examples include communication satellites, spacecraft, and the space shuttle orbiter reaction control system (RCS). Although these devices have a mature flight history, design techniques are nevertheless conservative, particularly when estimating expulsion efficiency. This is because on-orbit propulsion operations cannot afford to jeopardize a mission by expelling propellants completely to depletion. Also, because screen channel LADs are routinely tested on the ground with referee fluids, data are widely available on screen performance with various fluids. Thus, the subject orbital testing with referee fluids provides useful data for a variety of propellants.

A representative screen channel concept is depicted in figure 2 and functions as follows:

- A solid plate barrier with a screen communication window divides the tank into two compartments such that a significant portion of the bulk propellants is always positioned in the lower compartment. The woven mesh screen communication window permits relatively unimpeded liquid flow between the compartments, but resists gas/vapor transfer.

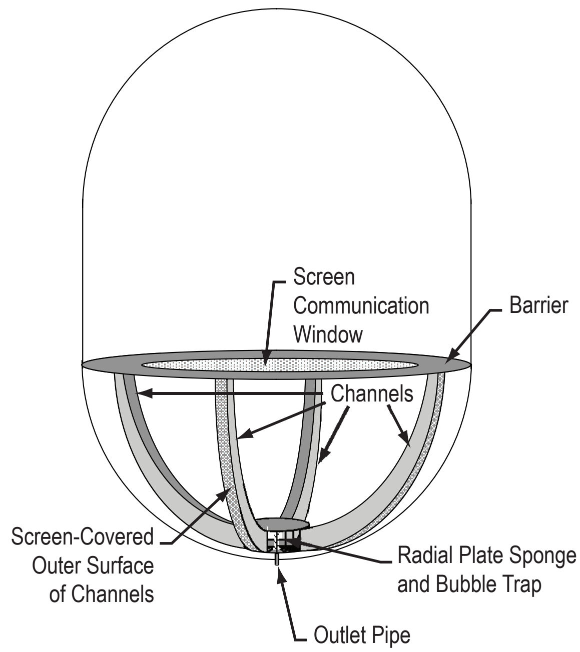

Figure 2. Representative screen channel LAD concept.

• The lower compartment contains screen-covered channels to ensure vapor-free expulsion independent of liquid position.

• The configuration is typical for both orbital maneuvering system (OMS) and RCS applications in which the acceleration vector could be either along the main axis and/or in random directions.

Specific design approach details regarding screen channels, presented in reference 6 are summarized herein, beginning with a description of the Dutch twill screen mesh in figure 3 typically used in screen channel LAD applications. A ‘325×2,300 screen mesh’ means that there are 325 wires per inch in the ‘warp’ direction and 2,300 wires per inch in the ‘shute’ direction. A 325×2,300 is the tightest mesh available, whereas a 160×800 screen is considered to be a very coarse mesh screen.

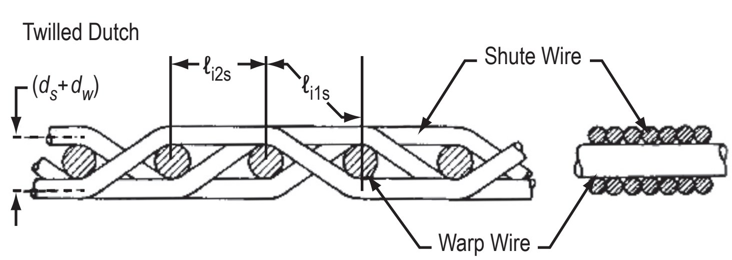

Figure 3. Twilled Dutch screen weave.

A designer's task is to optimize the appropriate number of channels and the best screen mesh, dimensions, and channel geometry selections; however, no 'best' screen exists for all LAD designs. Flow rate, percent fill, and acceleration are the most influential drivers for determining screen widths. High flow rates and a low percent fill drive the LAD width to large values regardless of screen choice. If accelerations are high, a screen with a high bubble point is desired. The total pressure drop of the LAD has four components: head pressure (P_H) losses, pressure losses due to flow through the screen (P_{FTS}), friction (P_{FR}) losses due to flow down the channel, and dynamic pressure (P_D) losses due to dynamic flow. Together, the summation of these four components (P_{total}) must be less than the bubble point pressure (P_{BP}) of the screen. Otherwise, the screen 'breaks down' and vapor is ingested.

$$P_{BP} > \Delta P_{\text{total}} = \Delta P_H + \Delta P_{FTS} + \Delta P_{FR} + \Delta P_D \,, \tag{1}$$

or (head + across screen + friction + dynamic losses).

Figure 4 shows each pressure drop component and the total pressure drop, P_{total}. Equations for each of the four pressure drop components and further details regarding analytical modeling are presented in reference 6.

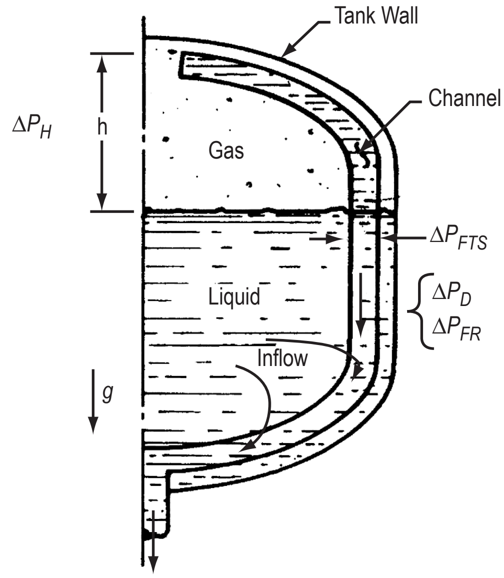

Figure 4. Screen channel individual pressure drop contributions.

1.2.2 Vane Devices

Vane devices are designed for the active orientation of both liquid and gas within a tank, thereby facilitating tank expulsion and filling. Vane devices typically consist of sheet metal structures that are attached either to the tank walls or to a support in the central volume of the tank. Although vane devices have a successful flight history, the sole validation source had been in drop-tower and aircraft testing in which low-gravity time is limited. Also, the ability of a vane device to orient liquid during tank filling, allowing the venting of only gas, had not been demonstrated before FARE. The capillary pressure difference that exists across a liquid-vapor interface causes a wetting liquid to wick into narrow openings, and a vane device uses this wicking phenomenon to position the liquid and/or gas and to refill itself. The vanes are designed to preferentially orient the liquid over the tank outlet and to control its motion during accelerations such as thruster firings. The unique design advantage of the vane device over other types of LADs is its ability to actively control the liquid and gas positions within the tank, providing control over the spacecraft's center of gravity and allowing venting of the tank in case of a pressurization system failure such as a leaking regulator.

However, because vane LADs rely solely on liquid surface tension, applications have been limited to special cases in which acceleration forces and flow rates have been low. The most prevalent of these applications are geostationary satellites and planetary spacecraft including the Viking mission[7] and, more recently, the Cassini mission[8] and Mars Global Surveyor (MGS).[9] The Viking Mars orbiter vane device performed well throughout the 4-yr mission. The MGS had a vane device almost identical to the Viking's that performed well for almost 10 yr in Mars orbit. The device was designed to provide propellant expulsion and center-of-gravity (cg) control during all mission phases and to have an expulsion efficiency of 99.5%. The aerobraking phase of the mission was the most challenging, wherein changes in the spacecraft's attitude due to the Mars atmosphere resulted in relatively large lateral accelerations. The device was required to retain enough fuel over the outlet under these conditions to provide for worst-case use of the attitude control thrusters.

Based on the preceding background (sec. 1.1), the flight experiment objectives described in section 2 were established.

2. FLIGHT EXPERIMENT OBJECTIVES

The FARE I fundamental test objectives were as follows: (1) To measure the effects of various flow rates and acceleration perturbations on the expulsion performance of a screen channel LAD, and (2) to achieve the on-orbit refill of a tank outfitted with a screen channel LAD. The FARE II fundamental objectives were as follows: (1) To measure vane device tank filling and expulsion performance, and (2) to evaluate the device's capability to control liquid motion in the tank under realistic conditions. Further details regarding these objectives are provided in the following subsections.

2.1 FARE I Screen Channel Device

The specific objectives of the FARE I flight were as follows:

(1) Characterize the performance of a screen channel LAD including expulsion efficiency and refill.

(2) Perform vented fills of the screen channel tank using only the surface tension force to orient the liquid over the tank outlet.

Basically, the availability of a long-duration, reduced-gravity environment made the above objectives achievable. For example, liquid could be expelled until vapor flowed out of the tank, thereby determining expulsion efficiency for the first time ever. The vented fill tests provided first-time data on the ability of surface tension to orient liquid within a tank during refill, especially the fill percentage that could be achieved without the loss of significant quantities of liquid overboard. Additionally, the Weber number (We) stability limits determined in previous drop-tower tests were used to successfully guide inflow rates specified in the FARE I test matrix. Finally, the orbiter RCS could be used to induce low-gravity bulk liquid dynamics data for anchoring analytical models.

2.2 FARE II Vane Device

The purpose of the FARE II flight was to establish vane device performance limits versus expulsion rate and acceleration environment. Additionally, orbital refill of tanks with vane devices had never been evaluated; i.e., specifically, the ability to evaluate whether or not surface tension orientation can be used to establish a liquid-vapor orientation that is favorable for venting. Thus, the specific objectives of the FARE II flight were as follows:

(1) Demonstrate low-gravity operation of a vane-type LAD during tank expulsion and quantify expulsion efficiency versus flow rate and acceleration perturbations.

(2) Evaluate the vane device's capability to orient the ullage bubble over the tank vent during the fill process.

(3) Demonstrate the static behavior of the liquid under ambient low-gravity conditions and its dynamic behavior with specifically applied accelerations and determine the ability of the vane device to keep the liquid and gas oriented during adverse accelerations.

3. HARDWARE AND OPERATIONS DESCRIPTION

3.1 Common Hardware and Operations

A previous 1984 test bed designed, built, and funded by Martin Marietta was used. The test bed was flown successfully in January 1985 on STS-51C under the name SFMD under a joint Martin Marietta/Air Force/NASA Johnson Space Center effort.[1] The SFMD experiment demonstrated a specific LAD design incorporating multiple slosh baffles and compartments as well as a partial screen channel LAD. However, the SFMD test bed was designed for a 'mission specific' set of requirements, thereby limiting data applicability to other missions. Therefore, the FARE flight experiment hardware was designed to address more general issues associated with reduced-gravity liquid acquisition and transfer. Although the FARE program consisted of two flight experiments, one flown on STS-53 and a second on STS-57, most of the test bed hardware and operations were the same on both flights. The most significant difference was the LAD design. The Cargo Systems Manual for each flight contains detailed information regarding the flight hardware and operations, including experiment physical description; orbiter/FARE interfaces; instrumentation, including photographic equipment; thermal, electrical, and structural/mechanical designs; and crew controls/procedures.[10,11] The common hardware and operations are summarized in subsections 3.1.1 through 3.1.3.

3.1.1 Experiment Modules and Supporting Equipment

FARE was composed of two modules mounted on the front wall of the middeck (figs. 5–9). Each module occupied two middeck lockers and was mounted on one standard double adapter plate supplied as government-furnished equipment by the space shuttle program. Each module contained a clear acrylic tank as well as other equipment such as lines, valves, regulators, and air storage bottles. The two modules were connected by three flex lines when installed in the ground support equipment cart or in the space shuttle orbiter.

The upper module contained the tank of interest, designated the LAD tank. The LAD tank could have been almost any shape provided it fit into the envelope of a 35.56-cm (14-in) outer diameter (OD) circular opening. In addition to the LAD tank, the upper module contained two pressurant air storage tanks, a relief valve and burst disk, valves, temperature and pressure gauges, a flowmeter, plumbing, and two light fixtures. A quick disconnect, located on the left side of the upper module, interfaced with the orbiter's wastewater crosstie and enabled FARE tank venting to space. The module was designed to ease tank and plumbing reconfiguration to support its use in future fluid management flight experiments.

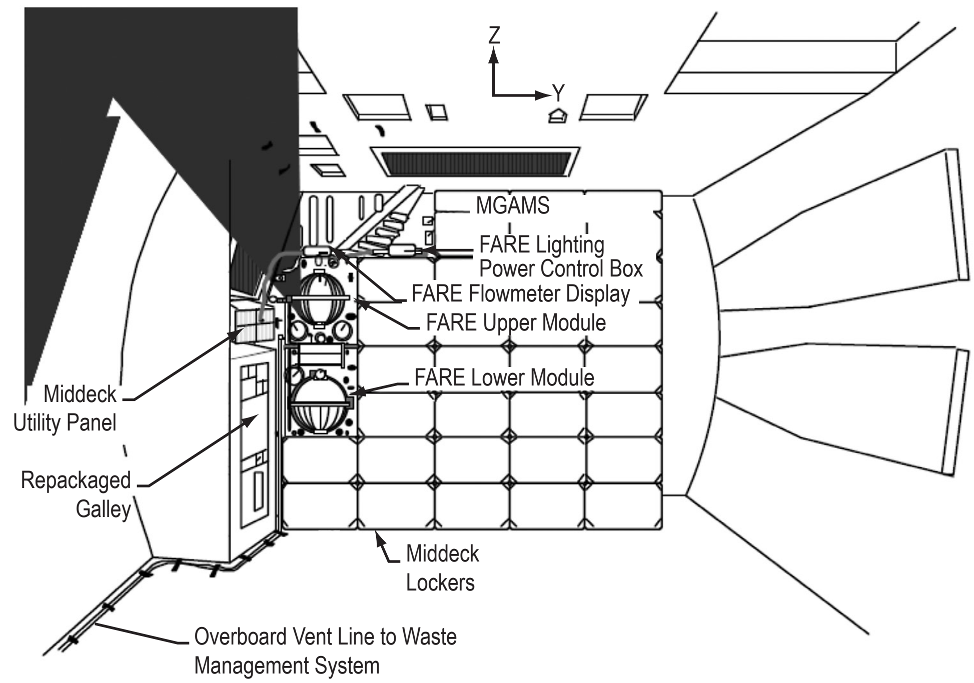

Figure 5. Drawing of FARE installation in orbiter middeck.

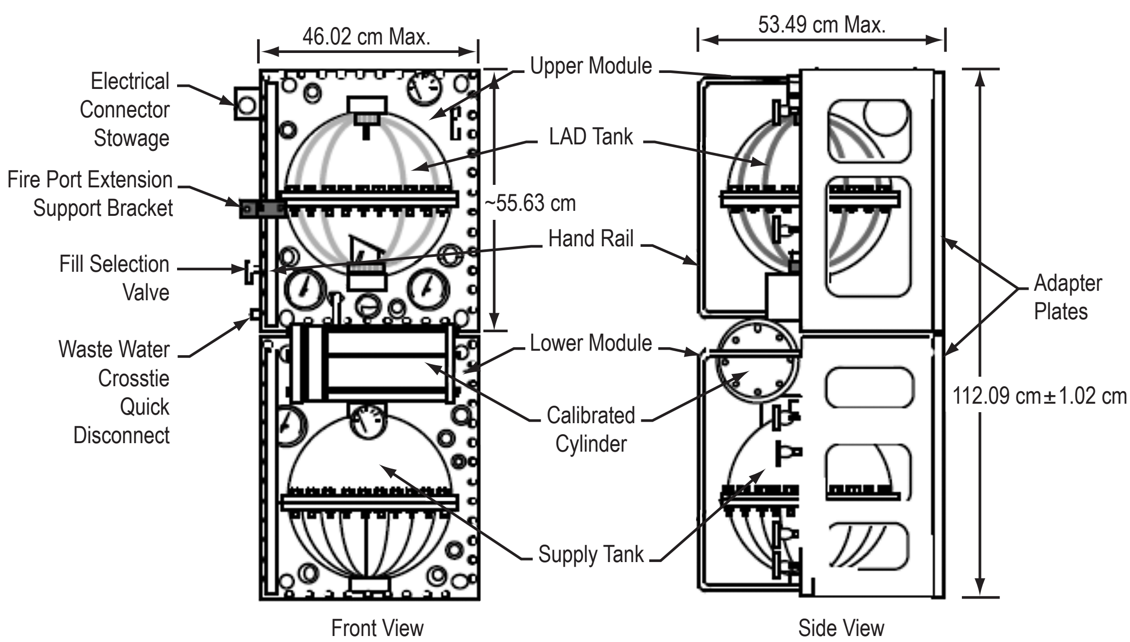

Figure 6. Drawing of FARE module arrangement.

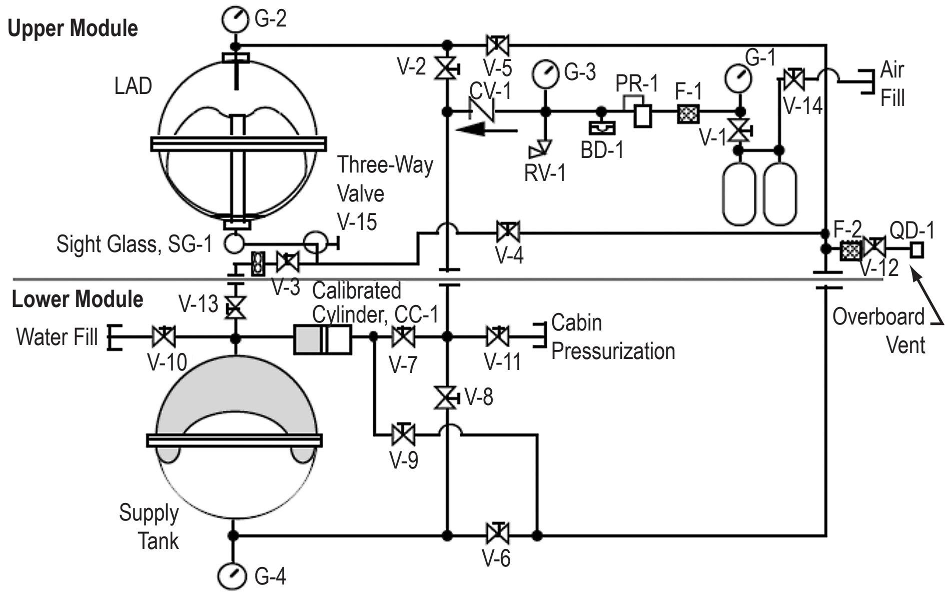

Figure 7. Fluid schematic.

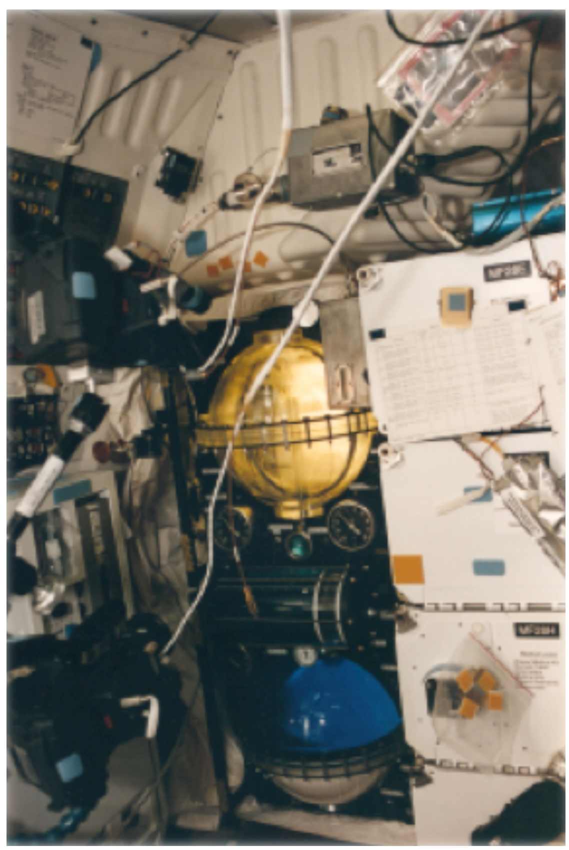

Figure 8. FARE module arrangement.

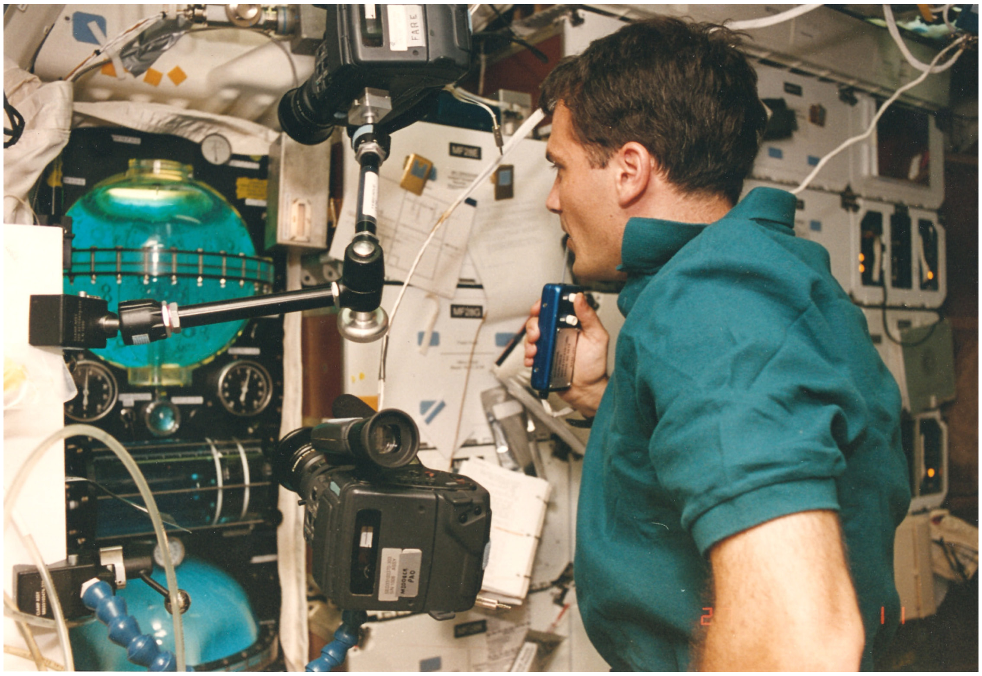

Figure 9. Astronaut observation of FARE module.

The lower module contained a spherical diaphragm tank that served as the supply tank. An acrylic calibrated cylinder provided both an additional fluid supply for the LAD tank test article and a means for measuring expulsion efficiency. During flight, a NASA-provided microgravity acceleration monitor system (MGAMS) recorded the acceleration environment. The MGAMS accelerometer measured acceleration levels ranging from 1.26×10^{-4} to 0.1 g in both the orbiter $\pm X_o$ and $\pm Z_o$ axis directions and was used to evaluate acceleration perturbations on liquid behavior. A temperature monitor positioned at the supply tank outlet provided liquid temperatures accurate to within 2%. The lower module also included valves, gauges, and plumbing.

The lighting system included two polycarbonate-enclosed fluorescent lamps and two power control boxes, one each for ac and dc power. Only one of the power control boxes, either ac or dc, was flown with the experiment on any given flight, based on orbiter power availability. The lamps were mounted above and below the tank mounting flange in the upper module, behind the LAD tank. During FARE operations, a cable connected to both fixtures extended from inside the upper module to the power control box, which in turn was plugged into the shuttle power system. During nonoperational periods, the cable was stored within the module, with the connector mated to a ‘dummy’ receptacle, and the power control box was stored in the FARE ancillary equipment middeck locker.

The bearingless flowmeter system provided a digital readout of the current liquid flow rate, in gallons per minute, while fluid was flowing from the LAD tank to the supply tank (the most significant testing phase). The system consisted of the flowmeter; a fiber optic cable; and an electronics box, or readout unit. The electronics box was powered by three alkaline-manganese dioxide batteries enclosed within the box itself. Except during experiment operations, the flowmeter box was stored in a separate middeck locker with other FARE ancillary equipment, and the cable was coiled within the unit. Further details regarding FARE equipment are provided in the STS-53 and STS-57 cargo systems manuals.[10,11]

3.1.2 Test Liquid

Filtered, deionized water with additives was used as the working fluid (table 1) for the experiment. Water was chosen because it is both practical and safe for use on the orbiter middeck and because it permitted the use of clear acrylic plastic, which was essential for viewing, understanding, and recording reduced-gravity liquid behavior.

Table 1. FARE I and II test fluid.

Deionized water
One part per million iodine
45-ppm Dow Corning FG-10 antifoaming agent
0.1% Triton – X-100 wetting agent
0.05% blue food coloring

Additives altered the water properties to more closely represent actual propellants. A wetting agent, Triton X-100, reduced the surface tension by approximately one-third (to 32 dynes/cm), and an antifoam emulsion counteracted foaming caused by the wetting agent. Small quantities of iodine retarded bacterial growth. A commercial blue food coloring was used as a dye for the liquid to enhance the data collection.

3.1.3 Orbital Operations

Fluid transfer operations were performed between the two tanks under the manual control of an astronaut trained in both the operation of the FARE and the physics of fluid phenomena. The pressurized transfer rate could be adjusted using the two high-pressure (71 kPa or 2,050 psig) air tanks and/or by the vacuum available from the shuttle's overboard vent system and cabin pressure. At various stages in the experiment, the astronaut coordinated the fluid transfers with shuttle RCS firings to simulate the effect of pertubations that would be experienced during full-scale operations. A transfer operation consisted first of reducing the LAD tank pressure to the required level via the interface with the shuttle's overboard vent system. (Both test tanks were designed to tolerate the negative pressure level associated with a hard vacuum.) Then, the supply tank was pressurized via the hand-loaded regulator and air bottles to the desired pressure, typically 69 kPa (10 psig). Flow was then initiated and controlled by opening the flow control metering valve and observing the flowmeter display. Filling continued until the supply and screen channel tank pressures were equalized or until the desired fill level was reached. Because the experiment was manually operated, it was possible—within mission constraints—to allow the crewmember to react to unusual test results and alter the test matrix in real time. Additionally, the verbal comments given by the crew proved to be invaluable in interpreting the video data. Often, the verbal observations helped explain fluid and/or bubble motion that was otherwise difficult to ascertain via the video and 35-mm still photographs.

3.2 FARE I Screen Channel Tank

FARE I was configured with a screen channel LAD as shown in figure 10. The tank had a 31.75-cm (12.5-in) internal diameter (ID) with a total internal volume of 16.8 L (1,022 in^3 or about 4.4 gal) without the LAD. The LAD screen was a 325×2,300 stainless steel mesh installed in two circular channels that were 3.81 cm (1.5 in) wide. Additionally, to accommodate vented fill testing, a second inlet at the tank bottom along with a circular, perforated baffle (to diffuse the incoming liquid momentum) were installed. The baffled inlet consisted of a 0.953-cm (0.375-in) ID acrylic tube located just slightly off center due to the screen channel manifold. This off-center location was necessary because the preexisting screen channel manifold could not be easily modified to incorporate an in-line nozzle. The baffle itself was 7.62 cm (3 in) in diameter with a 50% open area. The baffle center was solid, however, to better control liquid geysering during inflow. The original acrylic tank domes, previously used on SFMD, were replaced and retested to eliminate any concerns about material age.

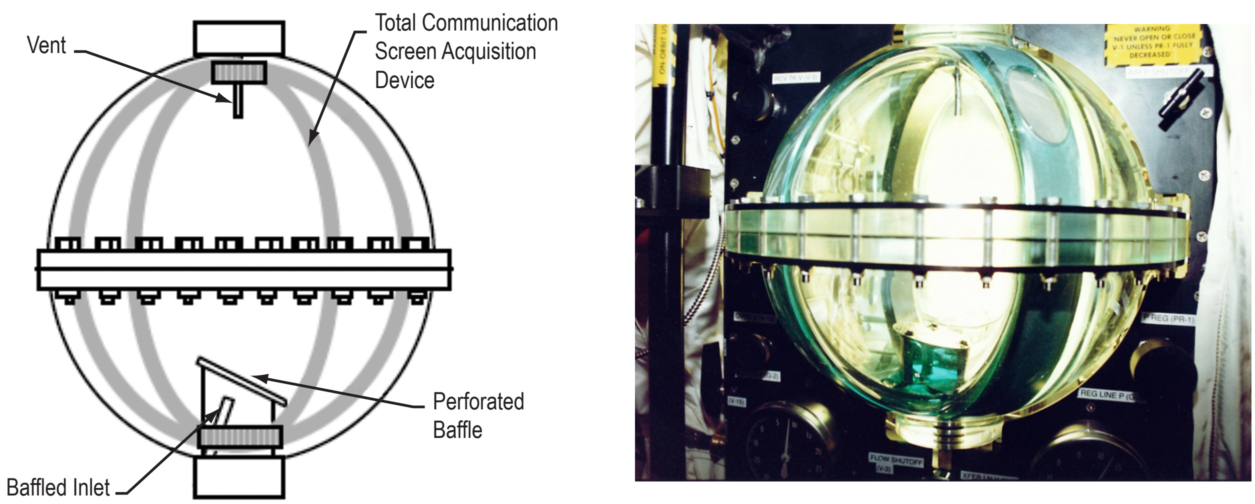

Figure 10. FARE I screen channel tank configuration.

3.3 FARE II Vane Tank

As mentioned earlier (sec. 2.2), the FARE II LAD tank was configured with a vane device (fig. 11) similar to those successfully used in the Viking 1975 orbiter, the Cassini spacecraft propulsion system, and the MGS propulsion system.[7–9] It consisted of a central standpipe with eight vanes radiating from it. Because the standpipe diameter was small (fig. 12), it had a much greater capillary stability than the vanes; therefore, it could hold liquid under higher adverse accelerations. Located within the standpipe was a triangular vane. This vane was tapered so that its width decreased from the bottom of the standpipe to the top. This tapering caused any gas bubble that became trapped in the standpipe to be forced to the top of the standpipe and purged out, which helped keep the standpipe full of liquid. On Cassini, the standpipe acted as a reservoir to supply a propulsion system with enough propellant to start the engines even if the bulk liquid had been forced to the top of the tank.

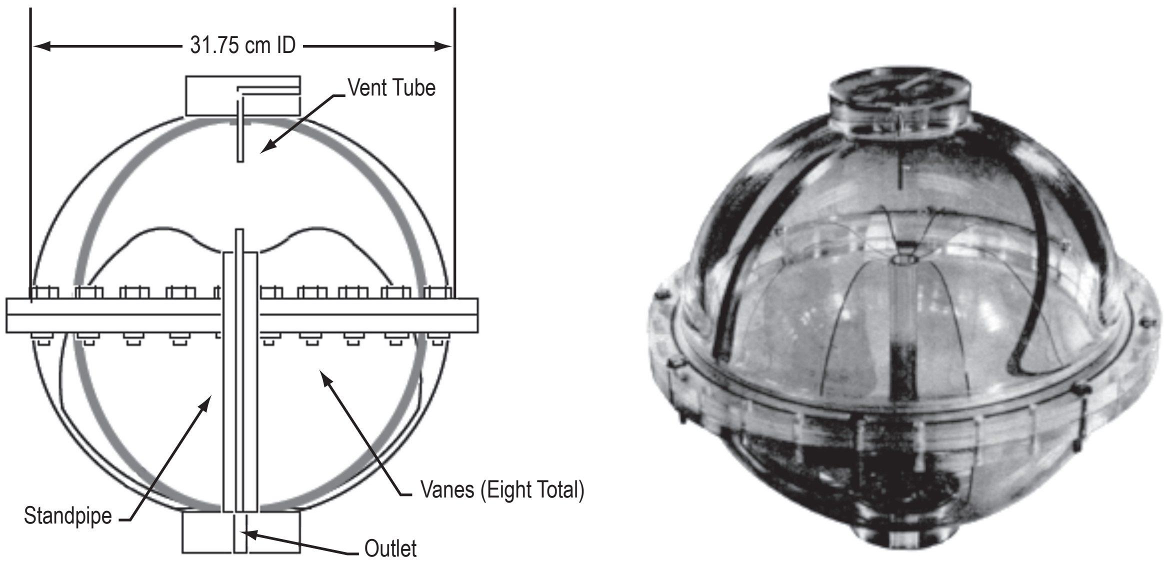

Figure 11. FARE II vane tank configuration.

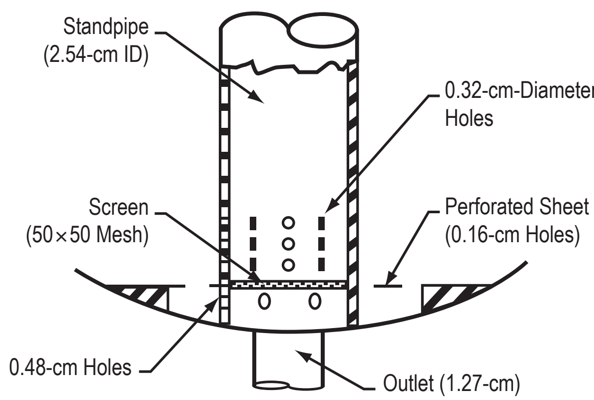

Figure 12. FARE II tank outlet with standpipe configuration.

The wicking channel was a stainless steel ring with a ‘T’ cross section that completely encircled the tank. This type of wicking channel, used in the Viking orbiter, provided a capillary wicking path to the tank outlet for any liquid located outside the vanes. The liquid wicked along the channel back to the bottom of the tank. Because this wicking used capillary pressure as the driving force, the rate was rather small and was heavily influenced by the acceleration environment and liquid orientation.

The vane device profile and height were designed to allow the tank to be filled to the 95% full level with the bubble positioned over the vent port.

4. FARE I AND FARE II TESTING

FARE I testing was conducted in December 1992 on STS-53 with a screen channel LAD. A total of eight tests were performed over the course of the 7-day mission by three crewmembers: Rich Clifford, Guy Bluford, and Jim Voss. FARE II testing was conducted in June 1993 on STS-57 with a vane LAD. A total of six tests were performed during a 2-day period. During both missions, data were recorded on two orbiter-supplied 8-mm camcorders, one each for the upper and lower screen channel tank areas. In addition, 35-mm still photographs were taken following each fill and expulsion. Background acceleration data were recorded on the MGAMS for later correlation with the fluid motion. Additionally, verbal commentary was provided by the crew with regard to the fluid motion, and general observations during the tests as well as written notes (pressures, fill levels, etc.) and sketches of the liquid and gas within the supply and screen channel tanks were recorded. The FARE I and II test conditions and results are summarized in the following sections.

4.1 FARE I Screen Channel Testing and Results

FARE I testing addressed vented fill and expulsion efficiency as indicated by the preflight test matrix shown in table 2. The actual test conditions and results are discussed in the following sections. Further technical details are presented in reference 12.

Table 2. FARE I test matrix.

		LAD Initial Pressure			Flow Rate	
		Fill,	Expulsion,		Inflow,	Outflow,
Test	Description	kPa (psig)	kPa (in Hg)	(psig)	lpm (gpm)	lpm (gpm)
1	Evacuated fill/expulsion	–98.5 (–29)	69 (20.4)	(10)	4.5 (1.2)	4.5 (1.2)
2	Evacuated fill/expulsion with pulsed flow	–98.5 (–29)	69 (20.4)	(10)	4.5 (1.2)	4.5 (1.2)
3	Evacuated fill/expulsion	–98.5 (–29)	69 (20.4)	(10)	4.5 (1.2)	4.5 (1.2)
4	Evacuated fill/expulsion with accelerations	–98.5 (–29)	69 (20.4)	(10)	2.6 (0.7)	4.5 (1.2)
5	Evacuated fill/expulsion to 5%	–98.5 (–29)	69 (20.4)	(10)	4.5 (1.2)	2.6 (0.7)
6	Vented fill/expulsion to 5%	0	69 (20.4)	(10)	0.4 (0.1)	2.6 (0.7)
7	Vented fill/expulsion to 5%	0	69 (20.4)	(10)	0.8 (0.2)	2.6 (0.7)
8	Vented fill/expulsion to gas ingestion	0	69 (20.4)	(10)	1.1 (0.3)	2.6 (0.7)

4.1.1 Evacuated Fill

To assure gas-free expulsion, screen channel devices must first be completely filled with liquid. On the ground, this is accomplished via provisions for an overflow vent within the channel or through vacuum loading. For FARE tests 1–5, the screen channel tank was filled using the vacuum technique, in which the tank was vented to space through the orbiter vent system. However, instead of the expected –98 kPa (–29 in Hg), only about –94 kPa (–28 in Hg) could be achieved due to the relatively high flow impedance of the orbiter's vent system and because a small amount of residual water remained after the functional testing performed before installation in the orbiter. During the initial portions of the fill process, the incoming liquid entered through the screen channels and had a milky appearance due to the vapor coming out of the solution at the low tank pressures (figs. 13 and 14). Additionally, the wetting agent inhibited bubble coalesence until the tank appeared to be filled with a bubbly mixture. As the fill process continued and tank pressures increased, however, the bubbles dramatically cleared except for one bubble about 5 cm in diameter and about nine smaller ones. The crew estimated the fill level to be 98%.

4.1.2 Vented Fill

During tests 6–8, the LAD tank was filled through the baffled inlet located at the tank bottom while the tank was vented to space. The crew vented the LAD tank to near-zero pressure and then periodically opened and closed the overboard vent to maintain a constant backpressure and, hence, a constant flow rate into the tank. The procedure continued until the vent was closed, when liquid venting was observed. Three different inflow rates were selected to produce three Weber numbers (table 3) that spanned the stability regime given by Martin Marietta and the NASA Lewis Research Center (LeRC) (now GRC)[13,14] An integrated summary of applicable drop-tower testing at LeRC and Martin Marietta is presented in appendix B. Additionally, all the vented fills were performed with the orbiter in free drift to eliminate disturbances during the fill process.

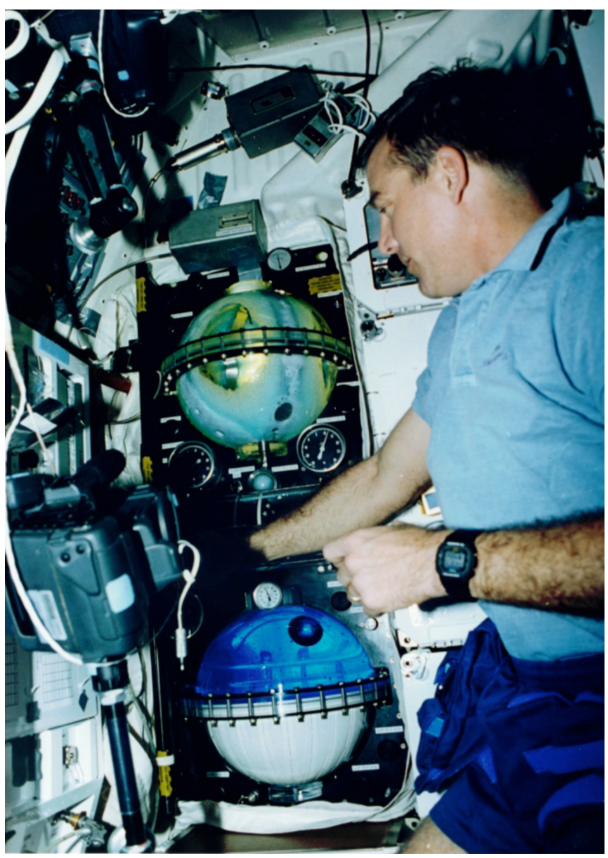

Figure 13. Overview of liquid condition during evacuated tank screen channel tank fill.

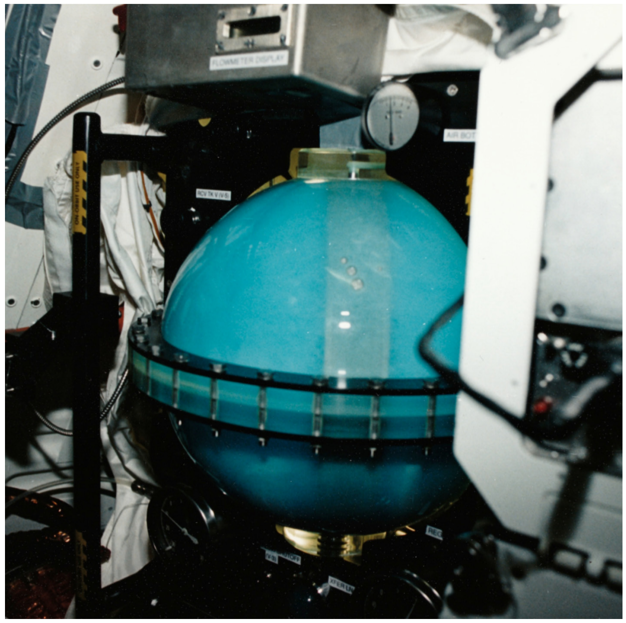

Figure 14. Close-up of liquid condition during evacuated screen channel tank fill.

Table 3. FARE I fill rate versus Weber number (based on nozzle inlet diameter) for vented fill testing.

Test No.	Flow Rate, lpm (gpm)	Weber No.
6	0.38 (0.1)	0.6
7	0.76 (0.2)	2.3
8	1.14 (0.3)	5.2

4.1.2.1 Test 6. Test 6 was performed using the minimum fill rate of 0.38 lpm (0.1 gpm). In preparation for test 6, the crew expelled the screen channel tank down to a level of 5% during test 5 to avoid gas ingestion into the screen channels. Although some residuals collected between the channel and tank walls, and around the baffle, the test 6 initial flow was unaffected, and the liquid collected around the inlet nozzle and was stable as expected. The liquid began to quickly climb the tank walls and form the low-gravity spherical interface shape. The incoming liquid never appeared to fill the region of the tank between the nozzle and the baffle.

At the flow rates tested, the incoming liquid never penetrated the holes in the baffle and, therefore, flowed over the baffle. The flow appeared to bias itself toward flowing along the left tank wall rather than toward the middle. This may have been because the LAD manifold, positioned directly to the right of the inlet nozzle, biased the initial wicking toward the left.

Tank fill continued until the liquid began to cover the vent tube at the top of the tank (fig. 15). At this point, the crew observed liquid escaping, closed the LAD tank vent valve, and continued to fill until the supply and LAD tank pressures equalized. The fill volume, when the LAD tank vent was closed, was estimated to be 60%. The crew commented that, had the vent tube extended down toward the center of the screen channel tank, filling could have been more complete.

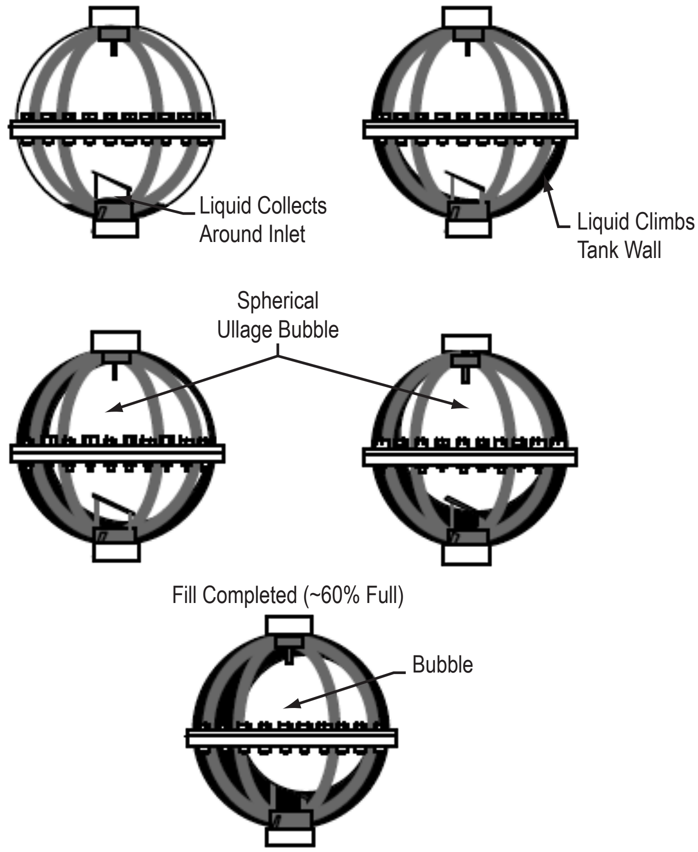

Figure 15. FARE I test 6, liquid-vapor behavior during vented fill with a Weber number of 0.6.

4.1.2.2 Test 7. The inflow rate (0.76 lpm or 0.2 gpm) during test 7 represented the stability limit based on the Weber number. At the initiation of inflow, the liquid appeared to move upward toward the baffle along the baffle support posts, causing the area under the baffle to fill more quickly (fig. 16) than was previously observed in test 6. Also, the liquid appeared to fill more symmetrically and above the baffle. As a result, the estimated fill percentage (80%) was much better than in test 6. Again, the crew commented that, had the vent tube extended down toward the center of the screen channel tank, filling could have been more complete. Overall, however, the faster fill rate (a factor of 2 over test 6) proved much more effective at filling the tank.

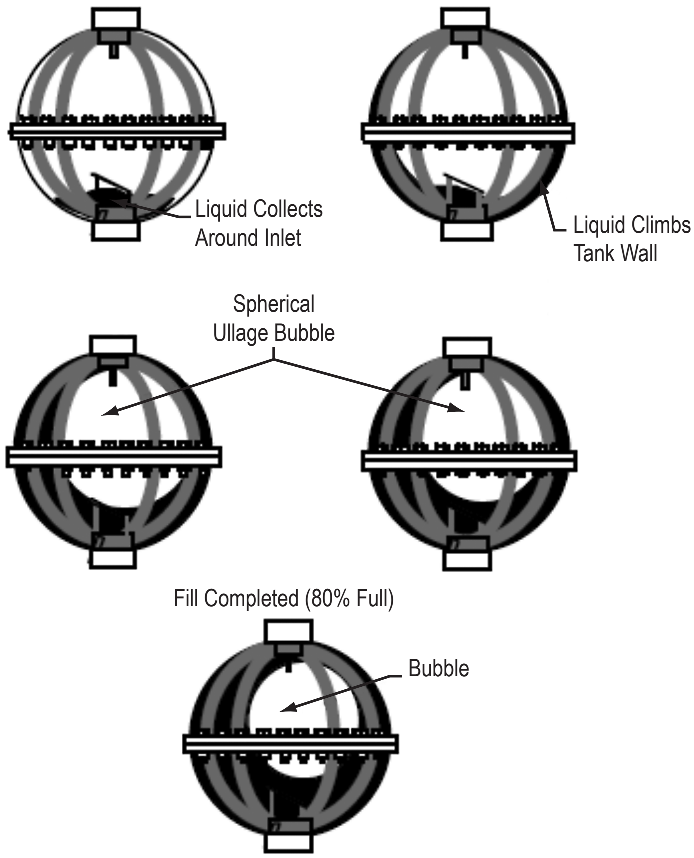

Figure 16. FARE I test 7, liquid-vapor behavior during vented fill with a Weber number of 2.3.

4.1.2.3 Test 8. Test 8 was selected to produce unstable inflow. The flow rate of 1.1 lpm (0.3 gpm) produced a Weber number of 5.2, and indeed, the incoming liquid was unstable, forming a geyser that impacted the baffle. The liquid was deflected by the baffle and began to fill the area underneath the baffle and along the tank walls. Unlike the previous test, rhythmic undulations or capillary waves in the liquid surface were very apparent in the video (fig. 17). This was most likely due to the continual disturbance of the liquid-vapor interface as the equilibrium shape was forming. Once the area under the baffle was filled with liquid, the flow predominantly moved up the tank walls in a relatively uniform condition, although as on the previous tests, the flow seemed biased toward the left side of the tank. The procedure used by the crew was the same as in tests 6 and 7 in that the LAD tank vent valve was closed when liquid covered the vent holes. The final fill was estimated from the video and crew comments to be ~70%.

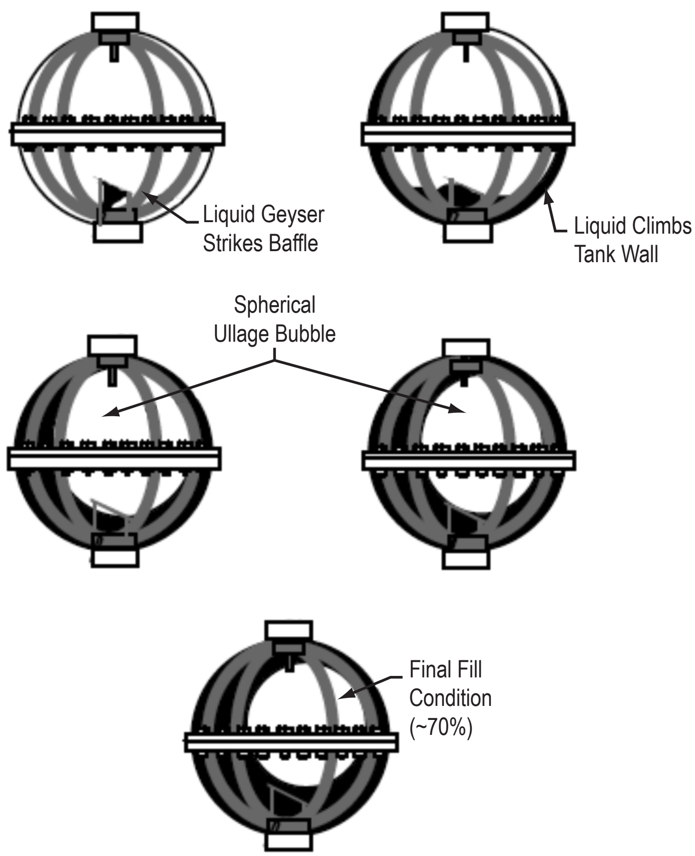

Figure 17. FARE I test 8, liquid-vapor behavior during vented fill with a Weber number of 5.2.

4.1.3 Vented Fill Test Evaluation

The FARE I vented fill tests, the first ever performed on-orbit, showed that, even with no active positioning of the ullage, it was possible to fill the tank to levels averaging 70%. This result was somewhat surprising because it was thought that these fill levels would not be possible without some type of active positioning of the liquid and gas within the tank. As noted by the crew, had the screen channel tank vent tube been approximately 2.54 cm (1 in) longer (extended more toward the tank center), much higher fill levels could have been achieved. Also a surprise was the relative fill levels with respect to flow rate. The lowest flow rate produced the poorest fill level. Capillary forces appeared to dominate the test 6 fill, and the low-gravity interface shape formation was not impacted significantly by the incoming liquid. The liquid penetrated and filled the area above the baffle. This appeared to delay ullage bubble movement away from the vent tube, thereby assisting the fill process. Test 8 produced an unstable initial inflow as expected, and the liquid appeared to be biased toward flow along the wall more so than in test 7 (although not as much as in test 6). In all the vented fill tests, however, the ullage bubble appeared to be located in the same position. This positioning was most probably caused by the incoming flow (which, from crew comments, was more or less symmetrical), with some possible influence from the vent tube and baffle as well. However, more testing is required to determine whether the results of the three vented fill tests are indeed repeatable before a definitive conclusion regarding the effect of incoming flow rate on fill level can be established. Finally, it should be noted that the spherical geometry of the FARE I LAD tank represents the worst case for vented fill operations. A cylindrical tank is better suited to vented fill, because the low-gravity interface shape formation does not transport liquid as quickly to the top of the tank near the tank vent.[15]

The results showed that the vented fill method can be feasible for storable propellants without active ullage positioning devices (such as vanes) for fill levels of ~70%. However, much more experimental testing is required to fully characterize the effects of flow rate, baffle configuration, and vent tube orientation on the final fill level. The 70% average fill level reached during the FARE tests was, however, quite typical of systems in which blowdown pressurization is used. Therefore, the filling efficiencies achieved for FARE could be adequate for storable blowdown systems with the proper configuration and orientation of the vent tube. For example, applying the results of the FARE I vented fill tests to actual systems can be accomplished by scaling the Weber number. For a 106.68-cm-diameter (42-in-diameter) tank containing hydrazine and a 2.54-cm (1-in) inlet line, the tank could be filled to the 70% level in <2 hr using a Weber number of 2.3 as a guide.

4.1.4 Expulsion Test Conditions and Results

In each of the eight pressurized expulsions of the screen channel LAD tank, as described in the following sections, multiple bubbles formed around the submerged vent/pressurization port at the top of the tank. Additionally, the wetting agent did not allow bubbles to coalesce as quickly as in an actual propellant (figs. 18 and 19). Therefore, the bubbles gradually coalesced as the expulsion progressed, but persisted throughout the expulsion. Eventually, after gas ingestion and shutoff of the flow, the remaining bubbles coalesced and the residual liquid wicked into the gap between the channel and the tank wall, positioning the final tank residual (figs. 20 and 21). The liquid-vapor behavior during an evacuated fill and expulsion to depletion process (a complete cycle) is depicted in figure 22.

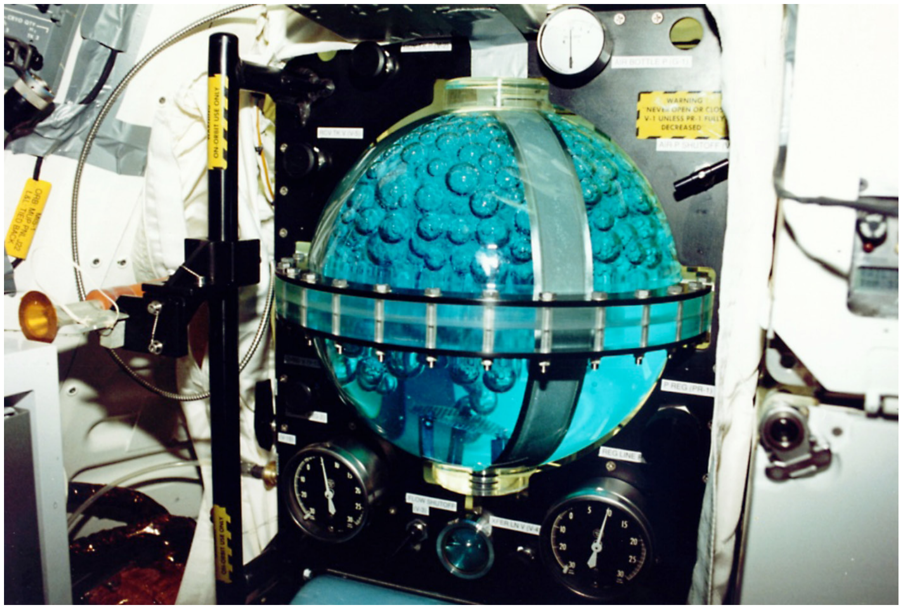

Figure 18. FARE I overview of expulsion efficiency test
with the shuttle in free-drift mode.

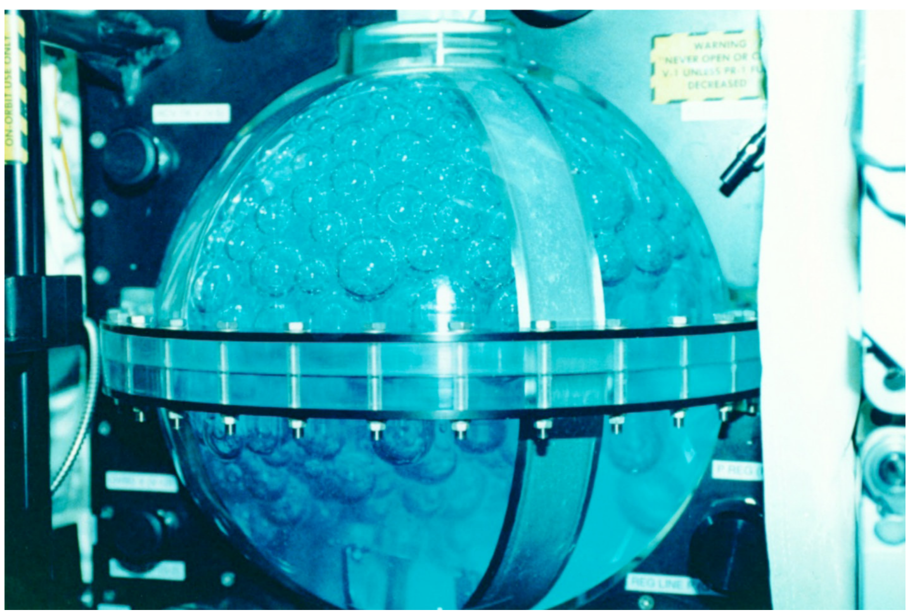

Figure 19. FARE I close-up of expulsion efficiency test
with the shuttle in free-drift mode.

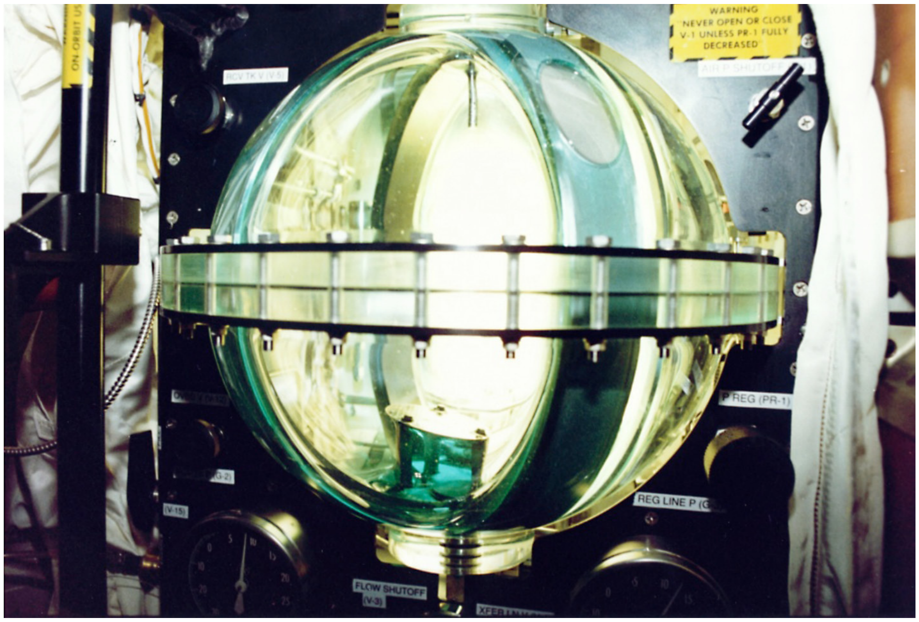

Figure 20. FARE I overview of liquid-vapor distribution at end of expulsion.

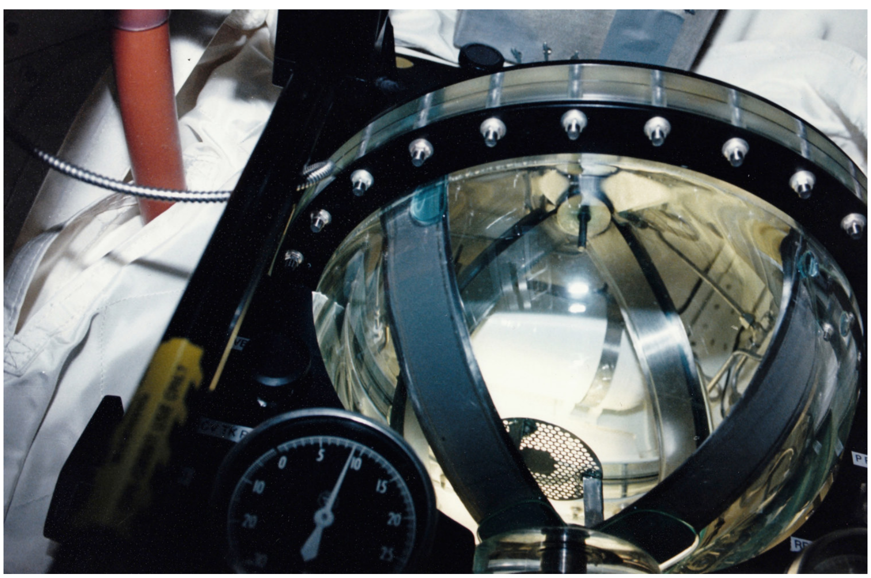

Figure 21. FARE I top view of liquid-vapor distribution at end of expulsion.

The screen channel LAD expulsion efficiency was determined using the FARE calibrated cylinder and visual estimates of the liquid residual from both the video and 35-mm still photographs. The expulsion efficiency was measured at two flow rates: (1) 4.5 lpm (1.2 gpm), which is near the maximum capability, and (2) an intermediate flow rate of 2.625 lpm (0.7 gpm). Expulsions were performed until gas ingestion occurred, as indicated by bubbles in the sight glass located adjacent to the screen channel tank outlet. When these bubbles were seen, the crewmember manually terminated the flow via a toggle valve.

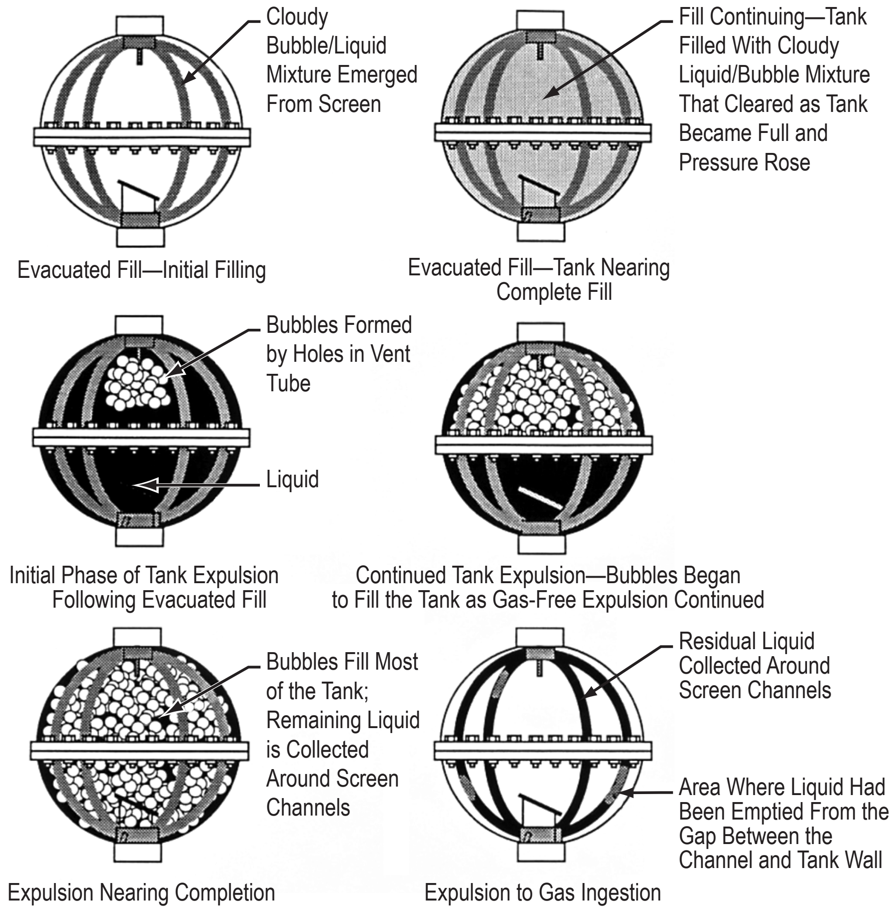

Figure 22. FARE I diagrams of liquid-vapor behavior during evacuated fill and outflow test results summary.

Specific expulsion tests with the shuttle in free drift and with specified perturbation or acceleration levels are discussed in the following subsections.

4.1.4.1 Free-Drift Mode—Tests 1–3. The first three outflow tests (tests 1–3) were performed with the orbiter in the free-drift mode with an ambient acceleration of about 10^{-4} *g* and an expulsion rate of 4.5 lpm (1.2 gpm). Bubbles generated at the pressurization port persisted throughout the expulsion sequence, although coalescence was also present. It was not until gas ingestion was detected in the sight glass and outflow was terminated that coalescence was complete. Details specific to each of the three tests are presented below.

4.1.4.1.1 Test 1. Upon nearing depletion at 4.5 lpm, most of the liquid appeared to be in the gap between the channels and tank wall. Then, as the gap began to empty, the flow area decreased until the pressure losses became greater than the bubble point and gas ingestion occurred. Some refill of the gap occurred after expulsion termination due to wicking of the residual liquid and continued coalescence. The crew-estimated residual was 1%.

4.1.4.1.2 Test 2. Most communications satellites are required to perform station-keeping operations that necessitate small attitude-control firings with low fill levels. Therefore, whether or not multiple pressure pulses would cause premature gas ingestion within the screen channels was the question addressed during test 2. In preparation for test 2, the crewmember drained the LAD tank to the 5% fill level and then momentarily stopped the flow via the toggle valve, V-3. At that point, the toggle valve was pulsed open and closed at 1-s intervals until bubbles were observed in the sight glass. Eighteen cycles were obtained before gas ingestion occurred, with an estimated residual of 3%. Compared with test 1, an increase in residual occurred.

4.1.4.1.3 Test 3. Test 3 was identical to test 1 except that an orbiter exercise machine produced a sinusoidal acceleration disturbance that caused a shift in the liquid-vapor interface of about 0.63 cm (0.25 in) during the expulsion process. The residual was estimated to be ~3%.

Based on the calibrated cylinder readings and visual estimates, the expulsion efficiency of approximately 97%–99% for all three tests was repeatable. The residual liquid was primarily contained in the internal volume of the screen device, which was 2.2% of the total tank volume of 16.6 l (1,022 in^3) without the LAD. However, the amount of liquid that could be observed in the gap between the channel and the tank wall varied from test to test. For example, the channel/tank wall gap had almost no liquid left during the test 8 expulsion, whereas the gap was nearly full during the test 2 expulsion. However, the gap volume was negligible compared to the total tank volume (~0.8%). Pretest residual modeling techniques used in actual screen LAD applications indicated expulsion efficiencies in the range of 97% to 98%. Therefore, no major effects due to flow rate variations and pulsed outflow were observed and the expulsion efficiencies matched the pretest predictions. These tests, therefore, demonstrated the validity of current design techniques for screen LAD gas-free liquid expulsion under a variety of conditions.

4.1.4.2 Acceleration Effects—Test 4.

4.1.4.2.1 Bulk Liquid Dynamics. To obtain data on bulk liquid dynamics, discreet accelerations were applied with tank fill levels of 50% and 5%. The accelerations produced by the orbiter's primary RCS thrusters were applied along the Y, –Y, and Z axes. Each acceleration level was applied for 4 s, followed by 1 min of free drift, after which the orbiter maneuvered back to its primary attitude. These maneuvers applied acceleration levels estimated at $7.3\times10^{-3}\,g$ along the Y axis (two primary jets) and $1\times10^{-2}\,g$ along the Z axis (three primary jets). The response of the bulk liquid to these low acceleration levels can be estimated using the nondimensional parameter, Bond number (Bo), which is the ratio of acceleration to surface tension forces:

$$\mathrm{Bo} = \rho a r^2/\sigma \ , \tag{2}$$

where ρ is the liquid density, a is the acceleration, r is the tank radius, and σ is the liquid surface tension. Previous drop-tower testing has shown that different flow regimes occur depending on the Bond number for a given tank size, propellant, and acceleration.[16] Generally, for Bond numbers >20, the liquid forms a jet (Rayleigh–Taylor instability) that grows along the tank centerline or tank wall until the opposite end of the tank is reached. For Bond numbers of ~5 or lower, the liquid tends to flow along the tank walls.

During test 4 at the 50% fill level, a series of 27 distinct accelerations were applied, three of which were planned along the Y , –Y, and Z axes, and 24 of which were during the orbiter return to its prescribed attitude after the prescribed accelerations. For the FARE I case, under quiescent conditions (background acceleration level of 1×10^{-4} *g*), the Bond number was 0.7. The orbiter's jet firings produced Bond number values in the 50–70 range. Consequently, when an acceleration was applied, a geyser continued to grow until the tank wall was impacted and liquid recirculation began. Although significant motion occurred after each thruster firing, there was no spray or liquid breakup. However, the circulation pattern damped out approximately 10–15 s after the acceleration initiation, indicating that the screen channels and the baffle were significant in damping out the fluid motion (see sec. 5, Data Correlations With Analytical Modeling). Within 20 s after each adverse acceleration, the ullage bubble returned to an equilibrium position resting on the baffle. After the 50% fill level testing was completed, expulsion to the 5% level was resumed.

4.1.4.2.2 Worst-Case Expulsion. The final expulsion to gas ingestion began within 3 s after the final Z adverse acceleration was applied to move the remaining liquid into a position opposite the tank drain at the tank top. This represented a worst-case expulsion because the liquid was positioned at the top of the tank, opposite the drain at the tank bottom, and expulsion occurred immediately following an adverse acceleration. A residual of ~3% was estimated.

4.1.4.3 Expulsion at 2.6 lpm—Tests 5–8. Conditions for tests 5–7 were designed primarily to provide initial conditions for the vented fill testing and were therefore drained at 2.6 lpm (0.7 gpm) to 5%, which did not represent a challenge for the screen channel LAD. Test 8 represented the only expulsion to gas ingestion at 2.6 lpm (0.7 gpm). Although a large number of bubbles occurred during pressurization, the expulsion appeared to be the most efficient with an estimated residual of 1% or less.

4.2 FARE II Vane Device

4.2.1 Vane Tank Vented Fill Testing

The FARE II test matrix (table 4) specified that the vented fill tests be performed at three flow rates: one at a low flow rate (predicted to produce stable inflow) of 0.76 lpm (0.2 gpm), one at a medium flow rate (predicted to be at the theoretical limit of stable inflow) of 1.51 lpm (0.4 gpm), and one at a high flow rate (predicted to be unstable) of 2.25 lpm (0.6 gpm). The three flow rates were chosen based on analysis and drop-tower tests performed by Martin Marietta that traversed the LAD stability zone[9] and had corresponding Weber numbers of 0.9, 3.6, and 8.2 based on the inlet radius and the assumption that the flow rates did not vary during the fill process. All the fill tests were to be performed with the orbiter in free-drift mode, which prevented thruster firings from disturbing the liquid during the test.

Vented fill of the LAD tank was performed in tests 1, 8, and 2–4, in that order. Test 5 vented fill was not performed due to problems with test 8 expulsion. Each test began with filling from the supply tank with the vane tank vent valve open. Based on flow calibration tests performed before the flight, the LAD tank initial pressure was set at 35 kPa (5 psig) to assure a flow rate in the desired range. During the filling process, a crewmember manually adjusted the LAD tank vent valve to maintain a constant pressure and flow rate as the ullage was compressed by the incoming liquid.

Table 4. FARE II test matrix.

Test	Procedure	Flow Rate	Comments
1	Fill	Low	Fill until liquid is vented
	Expel	Low	Expel until gas ingestion
2	Fill	Medium	Fill until liquid is vented
	Expel	Medium	Expel until gas ingestion
3	Fill	High	Fill until liquid is vented
	Expel	High	Expel until gas ingestion
4	Fill	Selected	Fill until liquid is vented
	Expel, incr.	Medium	Stop flow at various levels to vent and repressurize
5	Fill	Selected	Fill until liquid is vented
	Expel, incr.	Medium	Stop flow at various levels to apply low-level accelerations (10^{-4} *g*)
6	Fill	Selected	Continue based on tests 1–3 looking for maximum stable flow rate
	Expel	Selected	–
7	Fill	Selected	Same as test 6
	Expel	Selected	–
8	Fill	Selected	Verify repeatability of best of either test 6 or 7
	Expel, incr.	Medium	Stop flow at various levels to apply high-level accelerations to demonstrate stability and recovery from unstable condition (10^{-3}–10^{-2} *g*)

Although the general fill process was similar for all the vented fill tests, differences arose due to varying flow rates. The lowest flow rate of 0.76 lpm (0.2 gpm) produced the aforementioned stable inflow. The flow rate in test 1 began at 0.76 lpm but was ramped up to 1.32 lpm (0.35 gpm) and remained stable (fig. 23). The next vented fill test performed was test 8, with a target flow rate of 0.6 gpm. In the first few seconds, the crewmember ramped up the flow rate to 1.82 lpm (0.48 gpm) and quickly noticed unstable flow. The momentum of the liquid entering the standpipe dominated surface tension, resulting in a geyser that traveled out of the top of the standpipe and up the vent tube, creating a loss of liquid overboard (fig. 24). The flow was stopped and restarted with a lower, stable flow rate of 1.32 lpm (0.35 gpm). In the remaining portion of test 8 and the final three vented fill tests (tests 2–4), the crewmember adjusted the flow to locate the critical flow rate. At a flow rate of 1.12 lpm (0.3 gpm), the flow was stable and a small protrusion could be seen at the top of the standpipe. As the flow rate was ramped up to 1.21 lpm (0.32 gpm), the flow remained stable and the protrusion grew. When the flow rate was increased to 1.32–1.36 lpm (0.35–0.36 gpm), the protrusion extended, almost touching the vent tube. It began to fluctuate from side to side but remained at a constant height. Because unstable geysering occurred at 1.44 lpm (0.38 gpm), it was decided that 1.32–1.36 lpm (0.35–0.36 gpm) was the critical flow rate (We = 2.9).

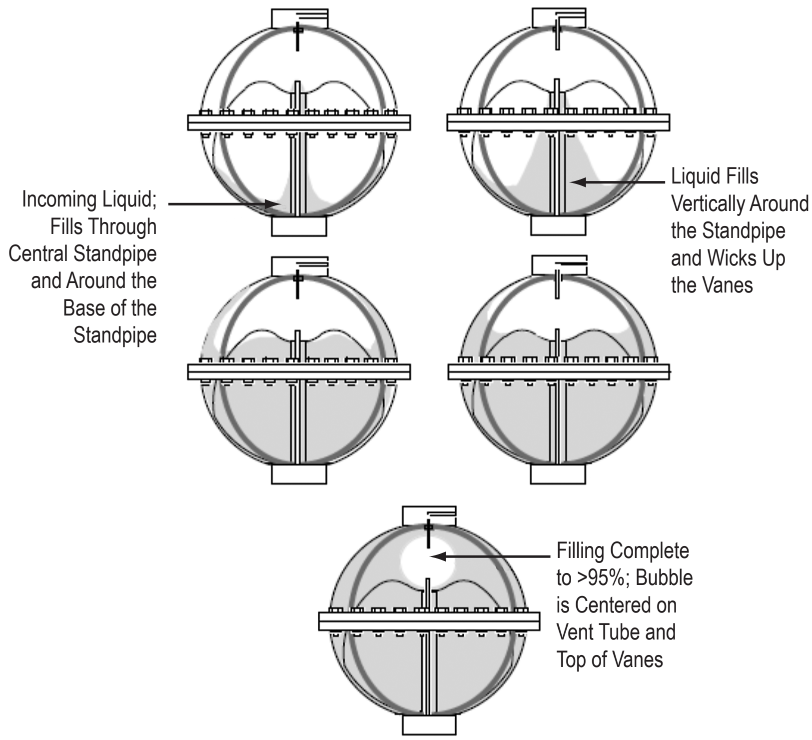

Figure 23. FARE II, test 1, stable liquid inflow during vented fill with a Weber number of <2.9.

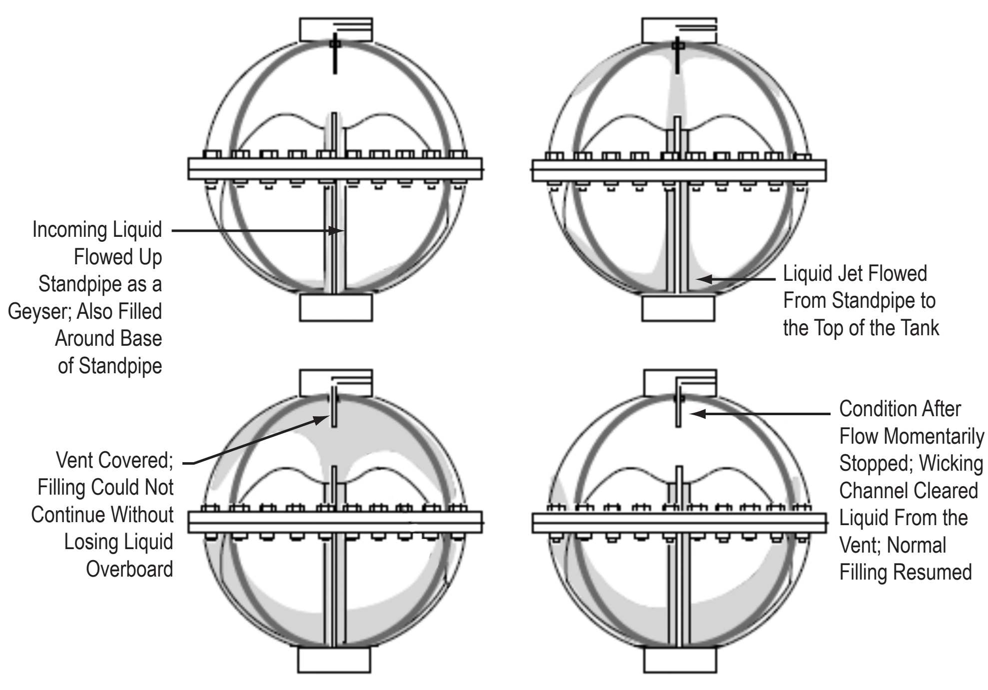

Figure 24. FARE II, test 8, vented fill with a Weber number of 8.2.

All five vented fill tests produced the same results once the unstable flow rates were avoided. Test 1 proved the ability of the vane to reach its design fill level of 95% and beyond. The four remaining vented fill tests demonstrated repeatability to a 90% fill level. If the conservative approach had not been taken, it appears that a 95% fill level could have been consistently achieved.

4.2.2 Vane Tank Vented Fill Evaluation

Based on analysis and previous work in drop towers, the low fill rate did produce a stable liquid-vapor interface. The liquid initially flowed into the tank through the standpipe and around the base of the vanes. Test 1, the first vented fill test, was initiated with the minimum flow rate of 0.76 lpm (0.2 gpm), but was ramped up to 1.32 lpm (0.35 gpm) and remained stable. The fill process was typical of all vented fill tests. The standpipe filled first while liquid entered through the perforated sheet over the outlet and then began to rise up the outside of the standpipe, filling in between the vanes. At this point, the liquid started to collect at the bottom of the tank. As filling continued, the liquid climbed the tank wall and filled in the spaces between the vanes. Filling stopped at the design limit of the vanes, that is 95% fill, at which a 5% ullage bubble rested on top of the vanes and surrounded the vent tube. This was to ensure a stable liquid-vapor interface to which the bubble would return if adverse accelerations were experienced. The final fill level on test 1, however, went a little further than planned, roughly 98%. At this point, the ullage bubble was quite small and detached from the vanes. Subsequent thruster firings could be seen moving the ullage bubble away from the tank vent. This caused the LAD tank to fill with bubbles during the expulsion. Consequently, the following four vented fill tests were stopped prematurely, at around 90%–92% full, to avoid submerging the vent tube again.

Unstable inflow occurred when the incoming liquid momentum was so high that the vane device was unable to diffuse it enough to allow the liquid to collect at the bottom of the tank. During unstable inflow, the liquid formed a geyser that flowed vertically up the standpipe to the top of the tank. Again, as in the stable inflow case, close monitoring of the vent was required along with the quick closure of valve V-5 to prevent liquid from going overboard.

Calculating a corresponding Weber number to the instability point required knowledge of the amount of the inflowing liquid coming through the standpipe and the amount coming through the screen/perforated plate area at the base of the standpipe. Because only qualitative methods (such as visual) were possible to measure this flow split, it was difficult to make any definitive conclusions as to the Weber number of the unstable liquid flowing up the standpipe. However, the tests proved dramatically that a very distinct and abrupt transition between stable and unstable flow occurred and could be easily repeated.

To summarize, the vented fills all were performed to levels of at least 95% without the loss of any liquid. The stability of the liquid was clearly demonstrated at a flow rate of 1.32 lpm (0.35 gpm). The tests showed that a vane device can provide liquid-free venting during vented tank fills to levels of 95% or greater, provided the flow rate of the incoming liquid is kept stable.

4.2.3 Vane Tank Expulsion Testing

The FARE II vane data indicated an expulsion efficiency of 90%–98%. The main objective of the expulsion testing was to demonstrate vapor-free liquid expulsion to 90% or better at flow rates of 0.75, 1.5, and 2.25 lpm (0.2, 0.4, and 0.6 gpm). Expulsion was to cease when the crewmember observed gas exiting through the tank outlet. As the tank drained, however, momentum forces of the liquid induced premature gas ingestion as the liquid-gas interface approached the outlet.

The test 1 expulsion began by pressurizing through the vent/pressurant tube. Under ideal conditions, an ullage bubble of 5% would surround the vent tube as the result of the previous vented fill. However, the ullage was closer to 3% and moved to one side, submerging the pressurant tube. When the pressurant gas entered the tank, many bubbles formed. This was also typical of the FARE I expulsions, wherein the screen channel device accommodated multiple bubbles. The vane device, however, was not designed for this. Test 1 continued as more bubbles formed (fig. 25) until expulsion was terminated at a fill level of ~50% because too many bubbles were passing through the outlet. The expulsion for test 8 had the same problems, and only a small amount of liquid could be drained.

The expulsion portion of test 5 was much improved relative to the first two tests, tests 1 and 8, primarily because the bubbles coalesced until only a small number of medium-to-large-sized bubbles remained (fig. 26). Ignoring the small bubbles remaining and treating them as part of the bulk liquid led to a very successful expulsion of 98%. The expulsions in tests 2–4 were conducted the same way, ignoring the very small bubbles trapped in the bulk liquid. The fact that these tests were run on the following day improved the situation. Overnight, the bubbles had coalesced even more, bringing the test fluid closer to its original condition. The expulsion characteristics during the last three tests appeared to perform much like the vented fills in reverse and produced expulsion efficiencies of 90%–95%. When the crewmember noticed medium-to-large-sized bubbles of 1.27–2.54 cm (0.5–1 in) in diameter exiting the tank, the expulsions were stopped. Some liquid remained in the standpipe, some was trapped outside the standpipe between the vanes, and varying amounts were left on the tank bottom between the vanes and the tank walls (fig. 27).

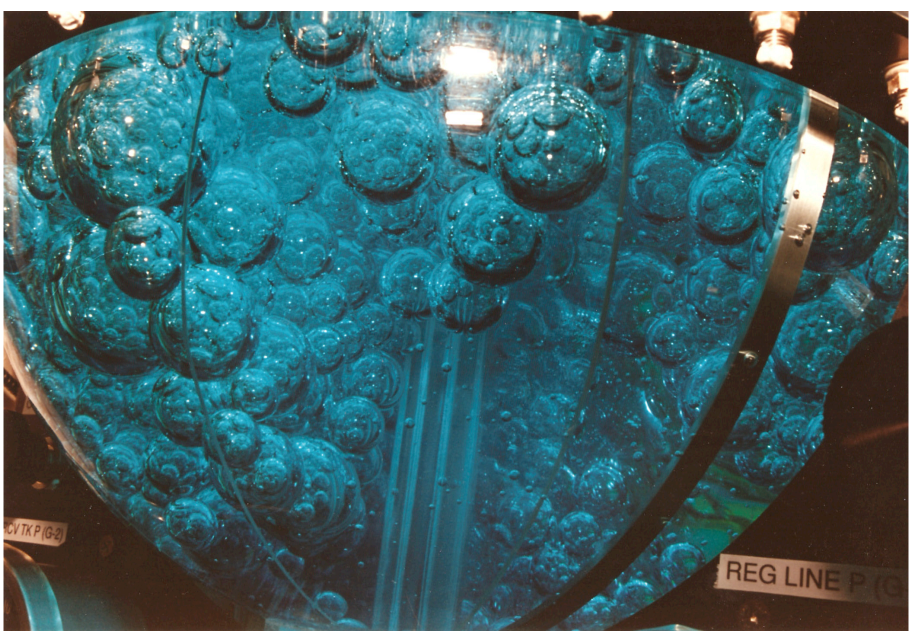

Figure 25. Vane tank expulsion with high bubble density.

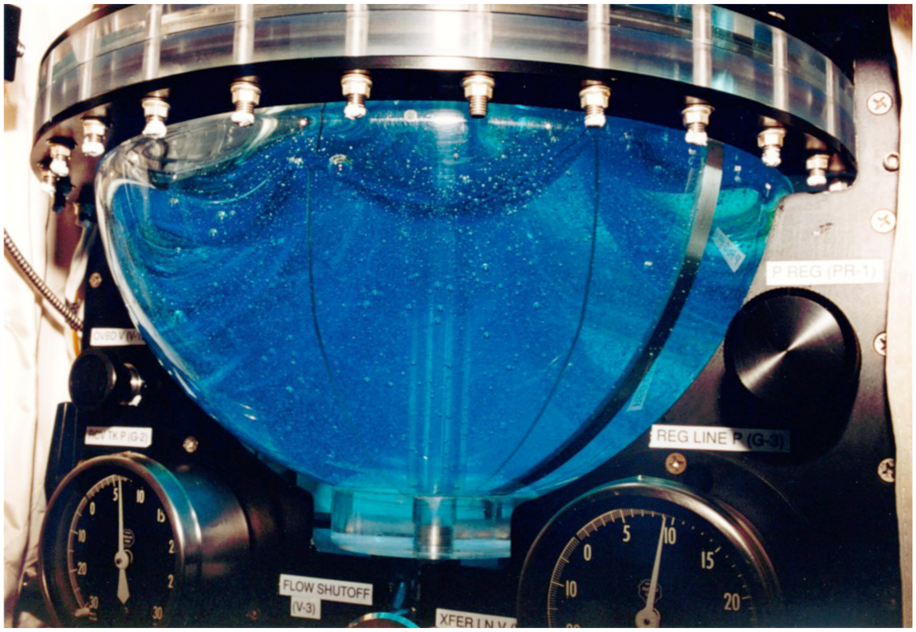

Figure 26. Liquid-vapor distribution during vane tank expulsion to 50% fill.

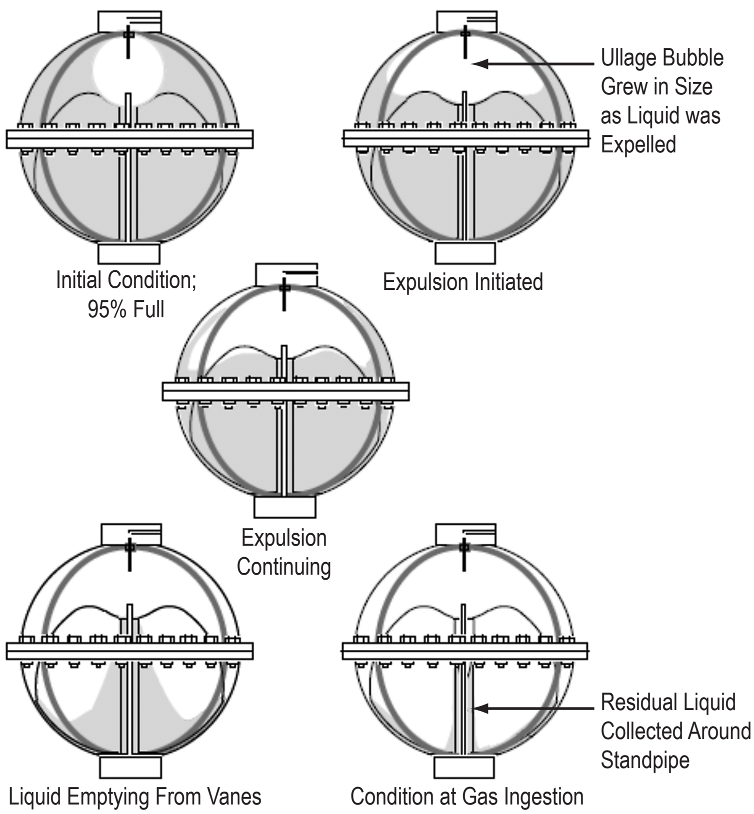

Figure 27. Liquid-vapor distribution during vane tank expulsion to near depletion.

Once the large bubbles started to coalesce and the very small bubbles were evenly distributed throughout the bulk fluid, the expulsion tests performed as predicted. The flow rates were varied from 0.75 to 2.25 lpm (0.2 to 0.6 gpm), and in all cases, the momentum of the draining fluid was controlled by the vane device. It was not until the residual liquid in the tank approached 10% that gas ingestion at the outlet started to occur. The last four tests demonstrated the ability of this vane device to efficiently drain a tank at various flow rates, unless it was overwhelmed by a large number of small bubbles.

4.2.3.1 Vane LAD Explusion Evaluation. The normal tank expulsion process began with pressurization through the tank vent/pressurization tube. It resembled the reverse of a stable vented fill in that the liquid drained more or less symmetrically from the tank until near-terminal expulsion. Some vanes tended to preferentially empty first in the sequence for an as-yet unknown reason as terminal expulsion neared; however, the final conditions were similar in all expulsions. As the tank neared the empty condition, the remaining liquid positioned itself around the standpipe in the form of a liquid column. The standpipe was always full of liquid when gas ingestion was first seen. The expulsions were fairly repeatable, with the standpipe full and some liquid located outside of the standpipe and its intersection with the vanes at the final condition. Expulsion efficiencies ranging from 90 to 98% were estimated.

4.2.4 Vane Tank Venting/Repressurization Testing

The last test run for FARE II, test 4, was selected to demonstrate the ability of the vane device to control the dynamic liquid-vapor interface during tank venting at various fill levels. The approach was to drain it to a specified fill level, then open the vent valve and monitor the response of the liquid surface. The vent valve was then closed and the tank repressurized to continue the expulsion to the next level.

The crewmember drained the tank to 60% for the first vent. As the tank pressure reduction began at 98 kPa (29 in Hg), bubbles began to form in the liquid. When the tank pressure reached –25.3 kPa (–7.5 in Hg), the bulk liquid began to foam. As the pressure reached –77.7 kPa (–23 in Hg), the bulk liquid began to move up the tank walls at a quick pace. As the tank pressure reduction continued, air bubbles came out of the solution and water vapor bubbles formed. The liquid, as a result, turned cloudy and opaque, but at no time was any liquid seen leaving the tank vent. The pressure leveled off at –84.4 kPa (–25 in Hg). At this point, the liquid had moved up to the top of the tank but never reached the vent; therefore, it was not lost. The tank was then pressurized back to 98 kPa (29 in Hg). When the pressurant air first entered, the bulk liquid quickly traveled down the tank walls. As the pressure increased, the tiny bubbles collapsed back into the liquid and the final state was almost identical to the initial state. The tank was then drained to 30%. Because of a time shortage, the pressure was reduced to only 49 kPa (14.5 in Hg) and little movement was observed. The final venting was then performed at a fill level of 10%. As the tank pressure began to decrease, tiny bubbles began to form, as was observed in the 60% fill level case, at around –25.3 kPa (–7.5 in Hg). By the time the pressure reached –77.7 kPa (–23 in Hg), the bulk liquid foamed and was traveling up the tank walls. The pressure leveled off at –87.8 kPa (–26 in Hg). The final condition of the liquid and vapor was similar to the final condition at the 60% level except that the liquid did not rise as much. Again, there was no liquid lost through the vent. As the tank was pressurized back to 98 kPa (29 in Hg), the bulk liquid traveled down the walls and the bubbles collapsed into the liquid. The final state was almost identical to the initial state. Test 4 clearly demonstrated the ability of this vane device to handle rapid venting of this particular test liquid at fill levels equal to or less than 60%.

4.2.4.1 Vane Tank Vent/Repressurization Evaluation. Although the tank pressure reduction caused air bubbles to come out of the solution and water vapor bubbles to form, at no time was any liquid seen leaving the tank vent. As repressurization progressed, the air and water bubbles collapsed and the liquid returned to the original clear condition. It was very difficult to see any discernible differences in the liquid between the pre- and post-test conditions. This test showed the ability of the vane device to allow on-orbit venting without the loss of the test liquid. It is cautioned that these results should not be directly applied to venting in a cryogenic tank without similar testing with that specific cryogen.

4.2.4.2 Vane Device Acceleration Tests. Tests 5 and 8 were run to demonstrate the ability of the vane LAD to control the liquid-vapor interface under specific adverse accelerations and to reposition detached liquid over the outlet. Test 8 was performed first with the objective of testing under very high accelerations to evaluate vane liquid retention. The accelerations were produced by the orbiter RCS thrusters and were in the Z and –Z directions, resulting in a Z acceleration of 2.5×10^{-3} *g* and a –Z acceleration of 1.6×10^{-2} *g*. The accelerations were applied for 5 s followed by a 1-min, free-drift period to observe the liquid response and attempt an expulsion. The initial tank level was 90% with one large ullage bubble at the tank top. The first acceleration was in the Z direction, forcing the liquid to the top and the ullage bubble to the bottom. As the ullage bubble came into contact with the vanes, it was sliced into six or seven smaller bubbles. Movement of the liquid damped out within the minute; however, the bubbles located in different sections of the vane device could not coalesce. Then the vanes had little influence on the bubble orientation; therefore, the center of mass control was lost. The second Z acceleration produced the same liquid/ullage bubble movement in the tank, with motion damping out within 1 min. The last acceleration performed in test 8 was the –Z maneuver during which the ullage bubble was forced to the top of the tank and the liquid to the bottom. Many of the larger bubbles coalesced upon contacting at the top. Once again, the liquid movement was damped out within the minute. The final fill level was 75%, and no further draining of the tank was attempted.

Test 5 was performed next to determine if the vane LAD, under low-level accelerations, could keep the ullage bubble positioned at the top and the liquid near the tank outlet at different fill levels. Orbiter pitch maneuvers were started until a constant rotation rate was achieved. The first scheduled rotation rate was 0.95 deg/s, resulting in an acceleration level of 4×10^{-4} *g*. The second was 0.47 deg/s, with an acceleration level of 1×10^{-4} *g*. Actual rotation rates generated were 0.988 and 0.425 deg/s, respectively. When these rotation rates were applied, the ullage bubble moved toward the front of the tank but the vanes stopped the motion and maintained the liquid over the outlet. Once the maneuver stopped, the ullage bubble moved back to its initial position at the top of the tank within 15 s.

5. DATA CORRELATIONS WITH ANALYTICAL MODELING

5.1 FARE I

A computational fluid dynamics (CFD) model using FLOW-3D from Flow Science, Inc. was developed for analytical correlations of liquid orientation during test 4. As described earlier (sec. 4.1.4.2, Acceleration Effects), discrete accelerations were applied with screen channel tank fill levels of 50% and 5%. Accelerations applied for 4 s, followed by 1 min of free drift, were estimated to be 7.3×10^{-3} *g* along the Y and –Y axes and 1×10^{-2} *g* along the Z axis. Further details are presented in the FARE I Final Report.[12]

The CFD analytical modeling focused on the 50% fill condition. It was determined that the experimental data were best correlated by a model that included the inflow baffle, flow channels, and surface tension. The experimental data are shown in figures 28, 30, and 31 for accelerations applied in the –Y, Y, and Z directions, respectively. The corresponding analytical results are shown in figures 29, 31, and 33. In each case, the data are presented at 2-s intervals. The –Y test data were difficult to correlate due to the presence of numerous bubbles, which may have influenced the energy dissipation; however, the basic fluid motion correlates favorably with the modeling. The bubbles coalesced in the Y test case, and the analytical model correlated very well. Within 16 s, a liquid wave formed, moved halfway across the tank, swirled along the wall, and returned to the initial orientation. The Z model also closely correlated with the experimental data. Because of the larger acceleration level (1×10^{-2} *g*), a liquid jet formed, traveled across the tank, and interacted with the inflow baffle. The fluid motion transitioned to flow along the wall and returned to its original position within 20 s, indicating that both the screen channeling and the baffle were significant in damping out the fluid motion.

In all cases, capillary forces dominated liquid orientation after the bulk liquid motion subsided. Liquid flowed slowly from the tank top toward the bottom and accumulated around the inflow baffle. The analytical modeling reflected some of this capillary motion, although the modeling indicated more liquid near the tank top than was actually observed in the video.

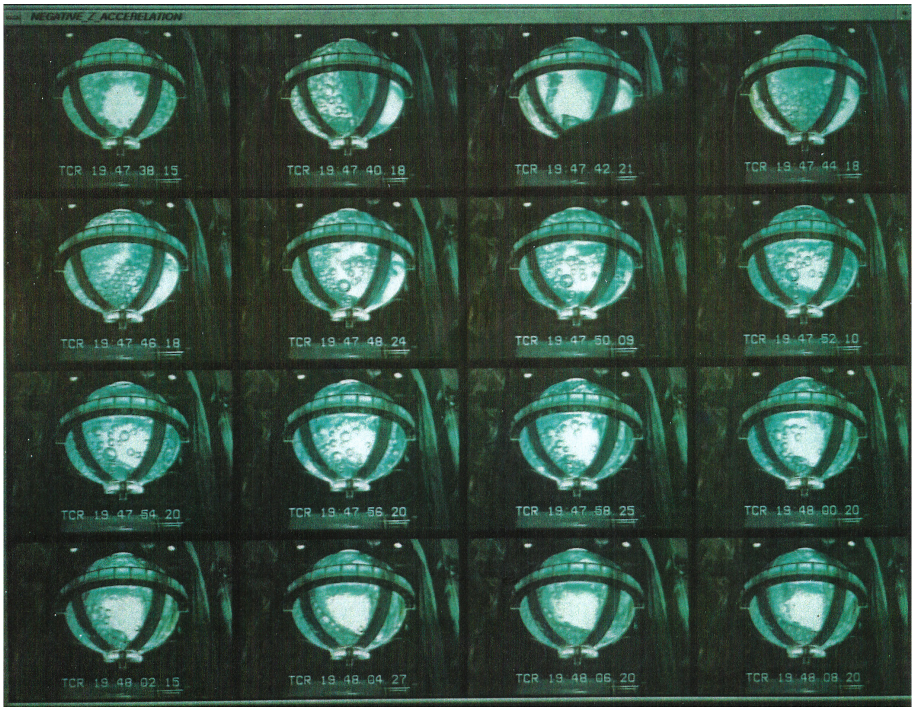

Figure 28. –Y acceleration, 50% fill.

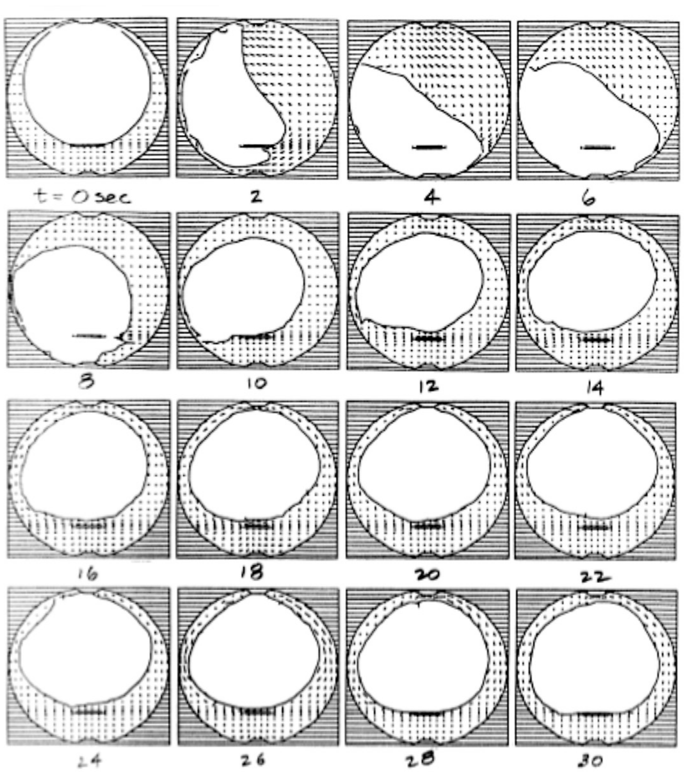

Figure 29. FLOW-3D analysis (–Y, 50% fill).

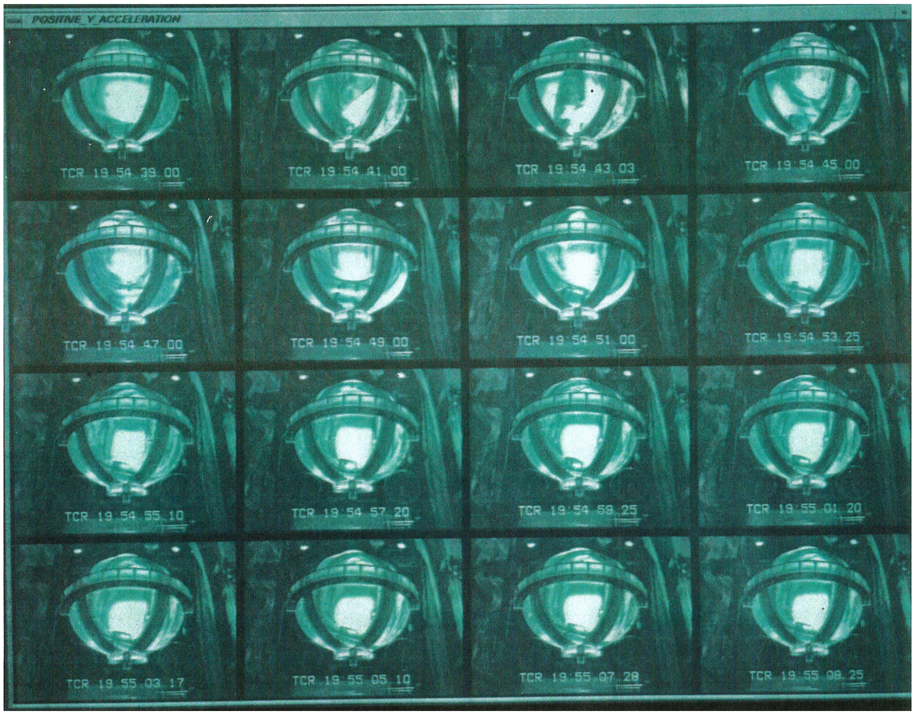

Figure 30. Y acceleration, 50% fill.

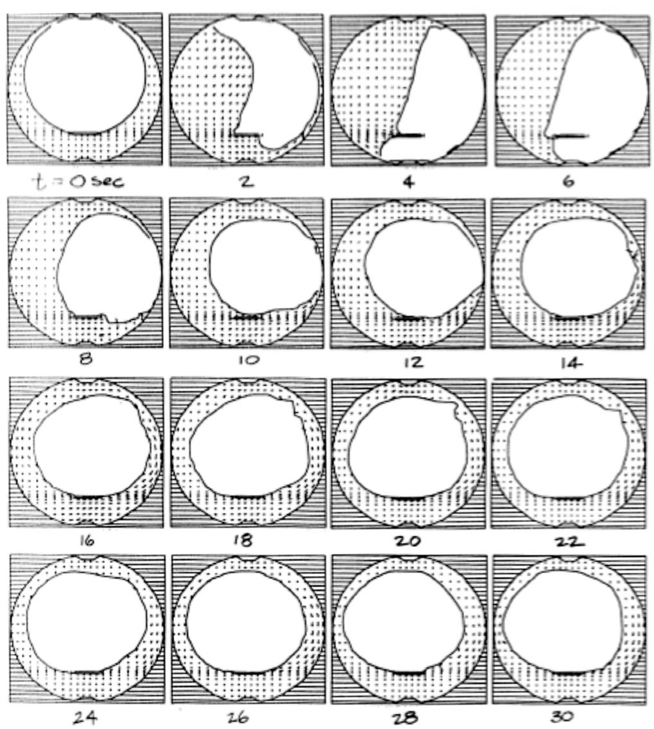

Figure 31. FLOW-3D analysis (Y, 50% fill).

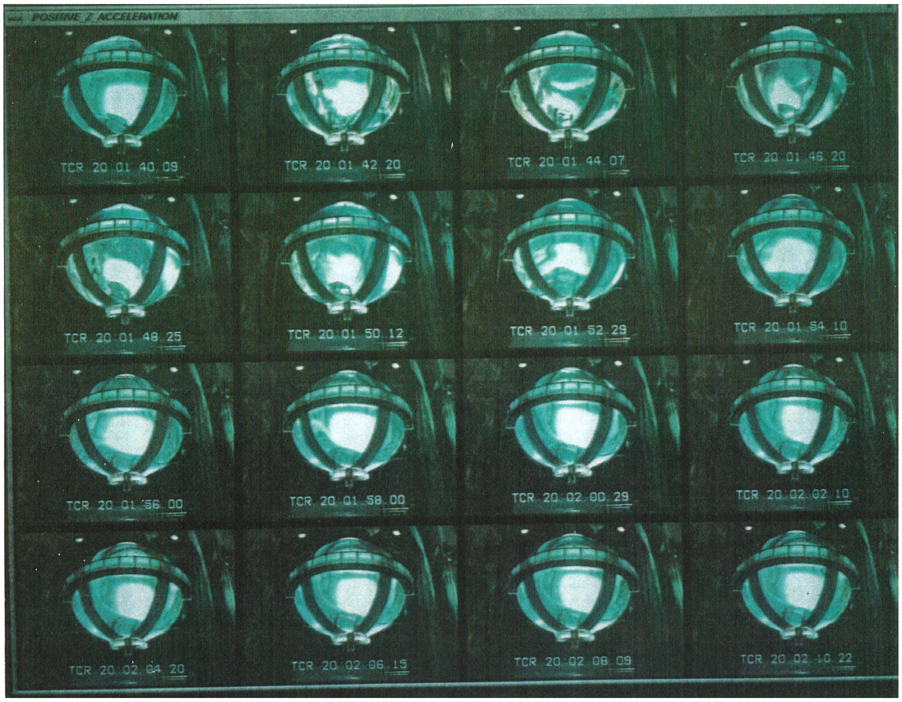

Figure 32. Z acceleration, 50% fill.

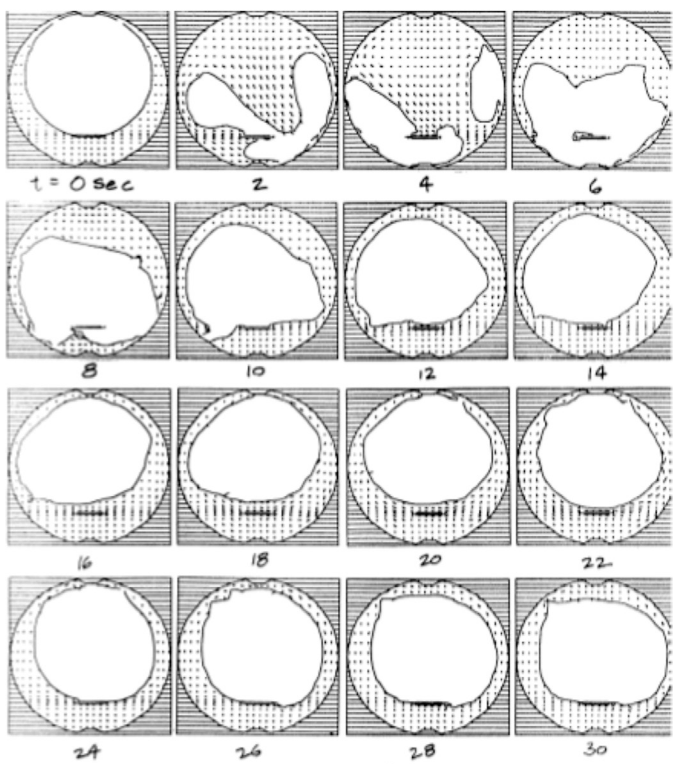

Figure 33. FLOW-3D analysis (Z, 50% fill).

5.2 FARE II

A key aspect of predicting the cg control capabilities of a vane device is the shape of the three-dimensional, liquid-gas interface within the vanes at various fill levels and under varying accelerations. The shape of the liquid-gas interface within the vanes can be very complex, and for a time, methods of analytically modeling this interface did not readily exist. However, codes were eventually developed that modeled complex surface shapes, and the FARE II data offered a unique opportunity to anchor analytical modeling with flight data. The analytical model used to correlate the FARE II data was Surface Evolver, a development of the Geometry Center at the University of Minnesota. It is an interactive program capable of calculating fully three-dimensional surfaces shaped by surface tension and an acceleration in any direction relative to the surface. Solid surfaces, such as the tank, and internal structures, such as a vane-type propellant management device, are input to the model along with contact angle and tank geometry.

By defining the surface with a union of triangles, the surface evolves toward minimal energy by a gradient descent method. Through a process of iteration and refinement of the surface, while controlling the shape and size of the triangles, an equilibrium interface shape is defined. The size of the triangles determines the resolution accuracy of the contact intersection between the liquid and solid.

The computed or modeled interface shapes matched very well with those observed on the videos over the full range of tank fill volumes. To provide 'a frame of reference,' a video picture of liquid-vapor interface shapes (with expulsion about 45% complete) is presented in figure 34. Two examples, for which two photos are available, were at lower fill volumes of 2.5% and 10%, at which the liquid filled the junction of the vanes at the standpipe and oriented within the vanes at the tank bottom to cover the outlet (figs. 35–36). The analytical model calculated the ullage as a single bubble that wetted the wall and the vanes. These figures do not begin to present the three-dimensional detail that was available from the graphic output of the computer model, which allowed the interface to be examined with a selected resolution and viewing angle. Likewise, the photos lack the perception of the interface shape provided by the video. Nevertheless, the ability of the model to predict the fluid distribution was verified, making it a useful tool in the design of future vane LADs.

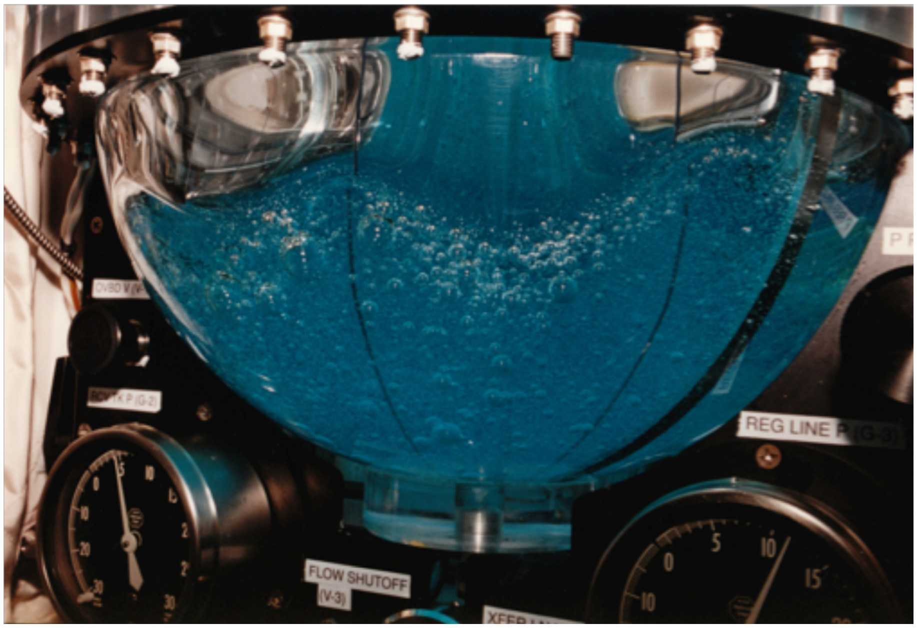

Figure 34. Picture of vane tank with expulsion about 45% complete.

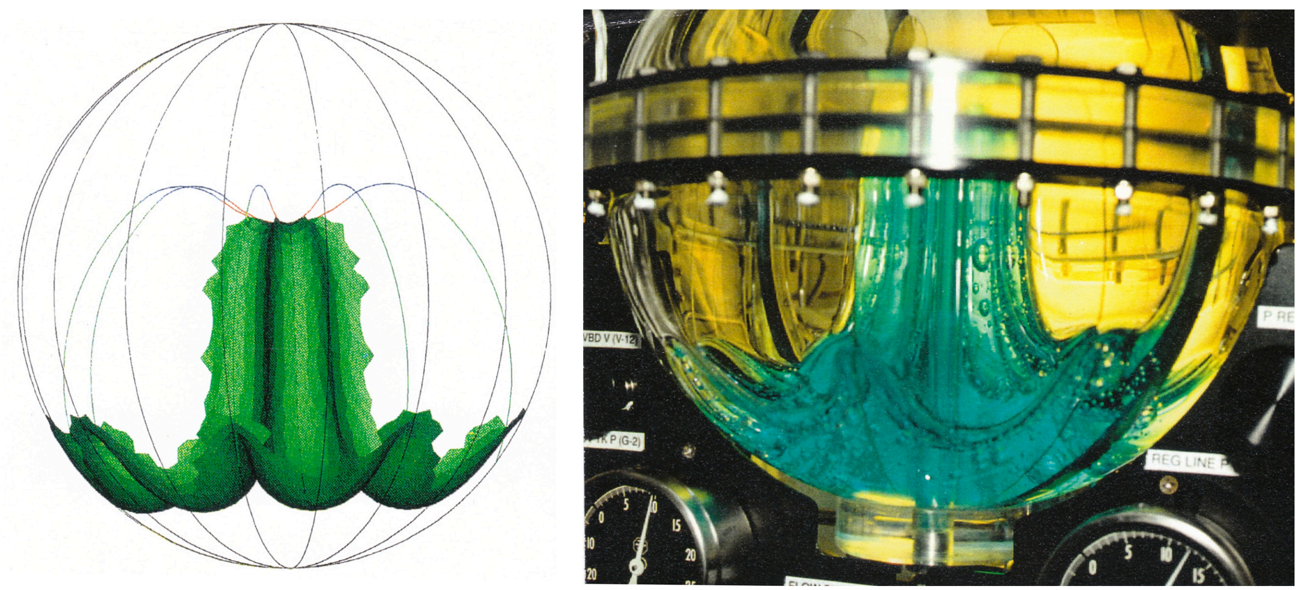

Figure 35. Schematic and picture of vane tank with expulsion at 10% fill.

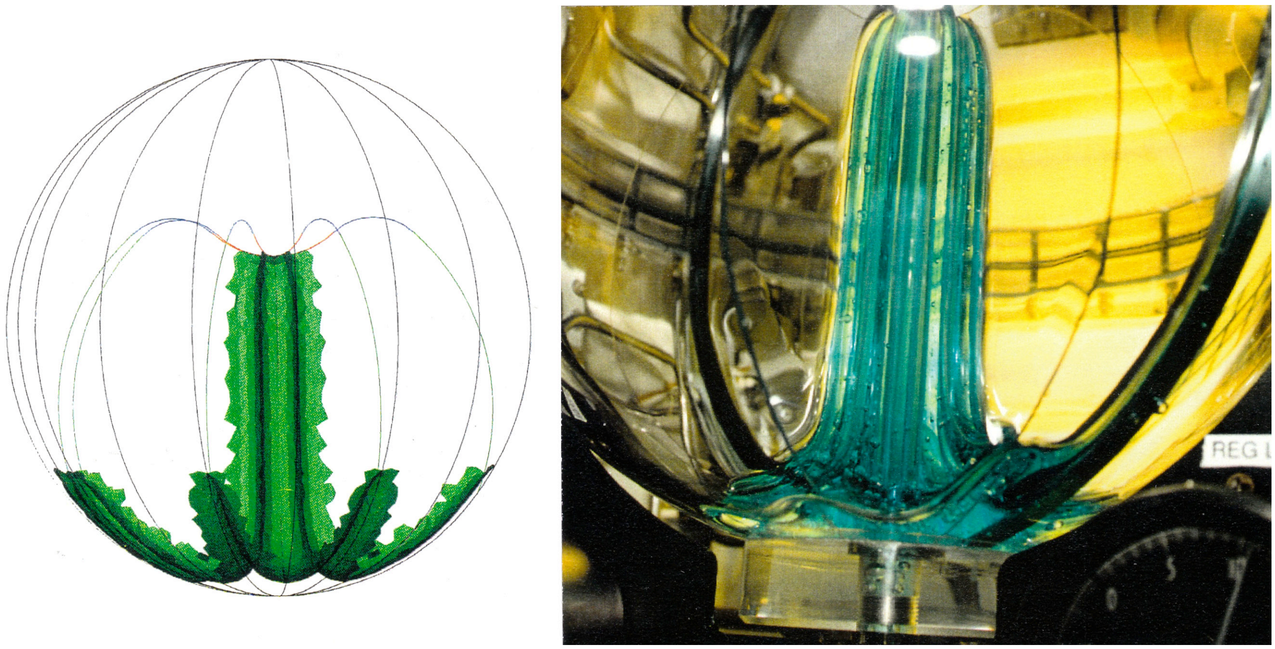

Figure 36. Schematic and picture of vane tank with expulsion at 2.5% fill.

6. CONCLUSIONS

An overall conclusion was that the astronauts' ability to observe and react was a substantial benefit on both FARE I and II, significantly improving the understanding of how capillary LADs actually function and what can affect design margins. Conclusions specific to FARE I and II are given in sections 6.1 and 6.2, respectively.

6.1 FARE I Screen Channel Liquid Acquisition Device

The FARE I flight on STS-53 achieved all of its objectives. Screen channel LAD performance during refill and expulsion was demonstrated, and the results matched those of the pretest predictions. Expulsion efficiencies of 97%–98% were demonstrated, even during and following liquid motions to the top of the tank. Additionally, it was demonstrated that even large-scale liquid motions damp out in a relatively short period of time. The final expulsion to gas ingestion began within 3 s after the final Z adverse acceleration was applied to move the remaining liquid into a position opposite the tank drain at the tank top. This represented a worst-case expulsion because the liquid was positioned at the top of the tank, opposite the drain at the tank bottom, during an adverse acceleration. A residual of ~3% was estimated.

Other conclusions regarding the FARE I screen channel device are as follows:

- When an OMS acceleration was applied, a geyser formed that impacted the tank wall and recirculation began. However, the circulation pattern damped out approximately 10–15 s after the acceleration initiation and surface tension dominated liquid positioning. Post-flight analysis indicated that the screen channels and the baffle were significant factors in fluid damping.

- Liquid expulsion testing revealed the significance of the gap between the tank wall and screen channel. In all expulsion-to-depletion cases, the gap was almost empty when gas ingestion occurred. This indicated that liquid was being withdrawn from the gap faster than the wicking of the liquid from elsewhere could refill the gap. The gap refilled upon termination of draining in most cases. Also, bubbles generated during the pressurization process can enter the gap and, driven by capillary forces, accumulate at one end of the channel. Gap geometry is an important factor in expulsion efficiency.

- The on-orbit evacuated fill process functioned very well with the screen channel LAD. It should be noted, however, that extra purge/vent cycles probably would be required in situations where a noncondensable pressurant such as helium was present.

- The vented fill tests produced maximum and minimum fills of 80% and 60%, respectively. The tests indicated that a longer vent tube and better vent tube/inlet tube alignment would have improved the fill efficiencies for the hardware setup tested. However, that is not necessarily true in other propellant transfer situations since ullage position transients are dependent on tank hardware geometry, inflow rates, propellant properties, and acceleration environment.

6.2 FARE II Vane Device

The FARE II tests on STS-57 provided a first-time demonstration of a vane device in operation during extended low-gravity periods and achieved 85% of its goals. The ability of the vane device to control the liquid cg was demonstrated successfully. Control of the liquid and vapor motion by this device was demonstrated under low-level accelerations on the order of 10^{-4} g. The vane device, however, could only expel gas-free liquid to these levels when the fluid had no small bubbles dispersed throughout. In such situations, expulsion was better handled by screen channel LADs. The vane LAD was successful in the vented fill testing, repeatedly filling the tank to at least 90% and up to 98%. The critical flow rate was found to be 1.32–1.36 lpm (0.35–0.36 gpm), corresponding to a Weber number of 2.9, above which the inflowing liquid became unstable and geysered to the top of the tank, resulting in liquid loss through the vent tube. Expulsion efficiencies of 90%–98% were consistently obtained at the various flow rates tested.

The vent/repressurization tests performed demonstrated the capability of the vane device to vent liquid-free gas with various fill levels to a final pressure of –87.8 kPa (–26 in Hg). It is cautioned, however, that such data may not be directly applied to cryogens. Control of the liquid and vapor motion by this device was demonstrated under low-level accelerations on the order of 10^{-4} g. The tests also provided data that could be used to ‘anchor’ analytical tools and techniques that may be applied to designing vane devices for flight applications.

The FLOW-3D modeling correlated very well with the liquid behavior during the acceleration perturbations purposely imposed by the obiter auxiliary propulsion system. Such correlations represent substantial steps in ‘anchoring’ CFD modeling techniques for propellant dynamics during reduced gravity environments.

Compared with FARE I, the FARE II LAD was expected to enable much higher inflow rates and levels before liquid would be seen entering the tank vent. However, although only the liquid surface tension was available to orient the incoming liquid and prevent vent entry, the FARE I flight demonstrated vented fill to ~70% with an inflow Weber number of 2.3.

APPENDIX A—PROGRAMMATICS HISTORICAL NOTE

Leon Hastings and George Schmidt, Space Propulsion Branch (EP53) in the MSFC Propulsion Laboratory, proposed the FARE project in response to a NASA Headquarters' Code M 'Call for Flight Experiments' in December 1988. FARE was listed as MSFC's top priority submittal and became the only experiment selected by Code M. Based on already existing flight hardware at Martin Marietta Denver Aerospace (MMDA), Technical Directive 15, under contract NAS8–37856, was negotiated with MMDA in June 1990. George Levin represented Headquarters (Code MD), James Sledd (EJ21) served as MSFC's Project Engineer, and Susan Driscoll (ER63) was the Project Manager/Principal Investigator. At MMDA, the Program Manager was Sam Dominick and the Lead Analyst was James Tegart; at the Johnson Space Center, the Payload Integration Manager was Frank Moreno; and at the Kennedy Space Center, the Launch Site Support Manager was Beth Cerrato.

APPENDIX B—DROP TOWER TESTING ON LIQUID ACQUISITION DEVICES REFILL AND VENTING

A generally accepted refill method is the ‘no-vent’ fill approach in which a screen channel LAD tank is vented to a vacuum; then the vent is closed, preventing the escape of the incoming liquid. This method is especially attractive for tankage containing screen channel devices because it assures complete channel refill. ‘Vented fill,’ the primary subject of this appendix, is similar to the method of filling tanks on the ground; the liquid is preferentially located to one end of the tank, allowing liquid-free vapor or gas to be vented from the tank.

Various drop-tower tests have been performed by both NASA and Martin Marietta to examine the stability limits of the liquid-vapor interface during low-gravity inflow into cylindrical and spherical tanks. Liquid-vapor interface stability with tank inflow is defined by the dimensionless Weber number (We), which is the momentum divided by the surface tension force:

$$\mathrm{We} = \rho V^2 r / 2\sigma \ , \tag{3}$$

where ρ is the liquid density, V is the feed line inflow velocity, r is the feed line radius, and σ is the liquid surface tension. Under low-gravity conditions with no flow, surface tension forces act to form a curved liquid-vapor interface. Surface tension forces can support the formation of a stable liquid-vapor interface during tank fill without venting liquid if the inflow conditions are low enough. Increased flow rates can be accommodated with the addition of inlet baffling.

Testing indicated the ‘critical’ Weber number, the value at which an interface becomes unstable, to be 1.5 and higher as initial liquid depth increased. Testing performed with cylindrical tanks containing baffles over the inlet line indicated that the critical Weber number ranged from 6 to 180, depending on the baffling geometry. This allowed significant increases in the inflow rate, substantially reducing the overall fill time.

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14. ABSTRACT
The Fluid Acquisition and Resupply Experiment (FARE) program, managed by the Marshall Space Flight Center Space Propulsion Branch with Martin Marietta Civil Space and Communications as the contractor, consisted of two flights designated FARE I and FARE II. FARE I flew in December 1992 on STS-53 with a screen channel liquid acquisition device (LAD) and FARE II flew in June 1993 on STS-57 with a vane-type LAD. Thus, the FARE I and II flights represent the two basic LAD categories usually considered for in-space fluid management. Although both LAD types have been used extensively, the usefulness of the on-orbit data has been constrained by the lack of experimentation beyond predicted performance limits, including both propellant fill and expulsion. Therefore, the FARE tests were designed to obtain data that would satisfy two primary objectives: (1) Demonstrate the performance of the two types of LADs, screen channel and vane, and (2) support the anchoring of analytical models. Both flights were considered highly successful in meeting these two primary objectives.

15. SUBJECT TERMS
on-orbit propellant resupply, liquid acquisition devices (LADs), low gravity fluid management, on-orbit liquid transfer flight experiment

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