NASA Technical Memorandum 107498
AIAA–97–2815

Vented Tank Resupply Experiment—Flight Test Results

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Prepared for the
33rd Joint Propulsion Conference and Exhibit
cosponsored by AIAA, ASME, SAE, and ASEE
Seattle, Washington, July 6–9, 1997

National Aeronautics and
Space Administration

VENTED TANK RESUPPLY EXPERIMENT - FLIGHT TEST RESULTS

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Abstract

This paper reports the results of the Vented Tank Resupply Experiment (VTRE) which was flown as a payload on STS 77. VTRE looks at the ability of vane propellant management devices (PMD) to separate liquid and gas in low gravity. VTRE used two clear 0.8 cubic foot tanks one spherical and one with a short barrel section and transferred Refrigerant 113 between them as well as venting it to space. Tests included retention of liquid during transfer, liquid free venting, and recovery of liquid into the PMD after thruster firing. Liquid was retained successfully at the highest flow rate tested (2.73 gpm). Liquid free vents were achieved for both tanks, although at a higher flow rate (0.1591 cfm) for the spherical tank than the other (0.0400 cfm). Recovery from a thruster firing which moved the liquid to the opposite end of the tank from the PMD was achieved in 30 seconds.

Introduction

The process of resupply involves transferring liquid into either empty or partially full tanks. The resupply of tanks in low gravity poses several technical challenges. Chief among these are the uncertainty of liquid and vapor distributions in a tank in low gravity, and the need to keep tank operating pressure low to reduce tank mass. During a fill in a normal gravity environment, a top vent is kept open to vent the vapor generated during the fill process, thereby maintaining a low tank pressure. If the same approach is used in a low gravity environment, the ullage gas may not vent since the position of the vent opening relative to the ullage cannot be predicted. Instead of venting vapor, large amounts of liquid may be dumped overboard. Unbalanced torques produced by venting two-phase flow, may cause the spacecraft to tumble out of control (this occurred on Atlas Centaur 4[1]). One way to avoid these problems is to use a vane propellant management device (PMD) to separate liquid and gas. This PMD uses the capillary forces between the fluid and the vane device to control the fluid position inside the tank. If the PMD is designed such that the liquid is retained over the fluid inlet/outlet, and the gas is oriented around a vent tube, a tank may be directly vented to space even during resupply. The Vented Tank Resupply Experiment (VTRE) is designed to study such a design and determine its capabilities and limitations. Resupply issues studied by VTRE include the following. The first issue was retention of liquid during transfer over a possible range of 0.6 to 2.6 GPM in both spherical tanks and those with a cylindrical barrel section. Liquid retention was also tested with the tanks empty and partially full (20%) at the start of test. The next issue was liquid free venting of 90% and 20% full tanks over a gas flow range between 0.0101 cfm and 0.2520 cfm in the presence of dissolved gas and boiling in the liquid. The final issue was recovery of liquid into the PMD after thruster firing in excess of the PMD retention capability (estimated at 10^{-4} G acceleration).

Background

Vane type PMD's have been utilized in space applications for many years as a source of gas free liquid acquisition (anywhere from the Viking Orbiter[2] to current communications satellites[3,4]) and are planned for many more applications in the future (the authors personal knowledge includes, Mars Global Surveyor launched in 1996, the Mars Surveyor '98, and the Cassini space probes, although these designs are as yet unpublished). The tank draining aspects of the vane device have been extensively investigated in the past, and have been proven via a very successful history of use. After the Viking Orbiter PMD[2] was designed and verified via drop tower tests to provide a means of direct tank venting (which was not verified in-flight), a series of studies were begun to better understand and optimize this design approach. A priority of these tests were designs to vent a tank during resupply. Multiple series of tank PMD's were designed and tested in a drop tower to determine their effectiveness[4]. The best option was found to be a close variant of the Viking Orbiter PMD (a series of thin vanes around a central standpipe). A further advancement in the technology development was taken via a series of flights in 1988 on-board the NASA Johnson Space Flight Center (JSC) KC-135 test-bed[5]. Here a much larger scale system (12.5 inch

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diameter versus 3 inches in the drop tower tests) was tested over brief periods of low-g (5 to 10 seconds). The results showed that inflow would indeed scale between the two sizes, but the venting tests were of too short of a duration to provide meaningful data.

A much more significant step was taken in 1992 during the second flight of the Fluid Acquisition and Resupply Experiment (FARE II)[5] which flew on-board STS-57 as a mid-deck experiment. FARE II used a vane type PMD and showed that very high final fill levels (97%+ at an inflow rate of 0.25 GPM) could be achieved in the tank during a vented fill with water (the maximum stable inflow rate was found to be ~0.4 GPM). Because the vapor pressure of room temperature water is low and the water used in FARE did not contain large amounts of dissovled gas, the ability of the FARE vanes to move bubbles to the free surface during venting was not challenged.

The VTRE was developed as a part of the NASA IN-Space Technology Experiments Project (IN-STEP) to take this technology further. VTRE is a joint effort between the NASA Lewis Research Center (LeRC) and Lockheed Martin Astronautics (LMA). The objectives of VTRE were to study the resupply process from empty to full, see how volatile liquids and the presence of dissolved gasses affect the venting process, and see how quickly PMD devices recover liquid after it is spilled by thruster firings.

Experiment Description

The experiment hardware primarily consisted of two 0.8 cubic foot acrylic tanks with vane type propellant management devices (PMD's) for fluid position control. The test fluid was a dyed Refrigerant-113 which provided the best simulant for both storable propellants and for cryogenic fluids (it has a much higher vapor pressure at room temperature than water). The red dye along with the clear tanks provided the capability to record video of the fluid motion during both the inflow and outflow of the fluid from the tanks. Two test tanks of equal volume were used. One tank was a 14 inch inner diameter sphere (test tank B) while the other was a 12.5 inch by 16 inch long cylinder (test tank A), thereby providing for the differences in these two common tank shapes.

The PMD consisted of twelve inner vanes that were mounted to a central standpipe as well as twelve outer vanes that follow the profile of the tank wall (Figure 1). The two sets of vanes were developed for two separate reasons. The inner vanes are designed (using approaches similar to reference 2) to locate the liquid over the inlet/outlet region and are shaped at the top to provide a centering force for the ullage bubble (if the center vanes did not incorporate the dip at the top the ullage bubble would be oriented in the vent end of the tank, but centering could not be guaranteed). The outer vanes (design similar to reference 3) provide an increase in the liquid orientation over the inlet/outlet (there are effectively twenty four vanes in that region of the tank) and also provide a means of recovering any liquid that happened to be upset out of the inner vanes (due to thruster firings or excessive inflow rate) back to the bulk liquid region in a timely manner. The outer vanes are certainly over designed for an operational system (there may be only 1 or 2 such vanes in an operational system) but the VTRE design was chosen to allow for a quick recovery after each test (time is a commodity on a Shuttle mission). An inlet baffle of fine holes was used to spread the liquid evenly between the vanes.

A key parameter in a vented transfer is the inflow rate at which liquid would not be captured by the vane device and would start to vent along with the vapors. This inflow rate can be then converted to a non-dimensional Weber number (the ratio of inertial to capillary forces) to allow scaling to other applications. To allow comparison to reference 4 the length scale was arbitrarily chosen as tank diameter divided by the number of vanes. The Weber number relationship is defined below

$$We = \frac{\rho V^2 D}{g_c \sigma N}$$

where, ρ is the liquid density (lbm/ft^3),
σ is the liquid surface tension (lbf/ft),
V is the average entering flow velocity (ft/sec) (calculated by dividing the volumetric flow rate by the area of the inlet pipe),
D is tank diameter (ft)
and N is the number of outer vanes.

For VTRE a series of drop tower tests were conducted using a 4 inch scale model of the VTRE tanks and the maximum stable Weber number for inflow was found to be at a Weber number of 4 to 5.
The system design of the VTRE Flight Experiment is shown schematically in Figure 2. The fluid transfers were driven by a pressure difference from tank to tank which was provided by a gaseous nitrogen (GN2)

pressurization system consisting of a 300 cubic inch, 3000 psia GN2 tank and dual regulators to reduce the pressurization system outlet pressure to 10 psig. The experiment was designed to fit within 3 modified Hitchhiker (HH) 5 cubic foot canisters. The lids were modified to provide for the required fluid and electrical connections between the center can (which included the pressurization system and the experiment control electronics) and the outer cans (containing the test tanks and the video system). During a transfer, one tank would be pressurized via the pressurization system and the other one vented to a lower pressure via a back pressure regulator in the vent plumbing. This use of regulators allowed nearly similar delta pressures between the test tanks over a wide range of transfer flowrates. The flowrate was controlled via the use of a stepper motor driven flow control valve in the center canister, which was programmed to provide 15 flowrate steps over the range of 0.6 to 2.6 GPM. This flowrate range resulted in a tank Weber number range of 0.5 to 9.4. Fifteen discrete flow rates were chosen to provide equally ratioed Weber numbers with a gap of 11% between each value. A bisectioning search algorithm was used to pick flowrates based on the results of the previous test. After four tests the stable flowrate would be bounded between two points of the fifteen point range. To gain additional data the tests were repeated, but instead of starting with an empty tank and filling to more than 90% full, these tests were started with the tank 20% full and ended when the tank reached 80% full. The first test was at the highest stable flow rate of the previous tests. Then the bisectioning search algorithm used to pick two more flowrates (three tests total).

The presence of liquid in the vent line was indicated by capacitance type quality meters consisting of an acrylic tube with two copper plates bonded to the exterior. These meters measured the change in dielectric constant between the vapor and the liquid phase, and produced a voltage which could be correlated to the percent of liquid by volume. A sensors was placed in each tank vent line as well as in the liquid inlet tubing for each tank (to indicate if a tank had completely drained of liquid). Each meter was individually calibrated for all gas and all liquid voltages and the voltage assumed to vary linearly with percent liquid in-between. VTRE ground testing of this approach showed an accuracy of $\pm$ 10% liquid volume. These quality meters along with a turbine flowmeter and the video record of the fluid transfers, defined the core set of instrumentation for the transfer testing.

The direct tank vent testing was accomplished by first pressurizing one test tank via the regulator and then maintaining the pressure for up to one hour in an attempt to force nitrogen gas into solution in the liquid. The non-dimensional parameter used to range the flowrates was the % of the ullage volume per second of flow (at the minimum ullage volume of 5% of the tank volume). There was no data available to use to determine test parameters, so a nominal value of 1.0% per second was used. The tests were started at the fill level achieved by the previous transfer (nominally between 90 and 95% liquid)

The methodology used to select a flowrate for the liquid tests was repeated for the vent testing. 15 different discrete flowrates were available for test., with the flowrates being chosen so that a range of vent rates of 0.4% to 10% per second could be achieved in testing. The vent flowrate was measured by an ultrasonic flowmeter that utilized the difference in the transport time for an ultrasonic pulse between the upstream (against the flow) and the downstream (with the flow) directions to gauge the flowrate. One side benefit of this sensor is that the speed of sound of the vent gas mixture (Refrigerant-113 vapors and GN2) could also be measured, thereby providing a measurement of the mixture mole fractions. This sensor along with tank pressures and the video record of the vent testing, provided the main set of test instrumentation for the vent tests. Again three additional tests were run to study the effect of starting fill level. These tests were conducted at a 20% fill level.

In addition to the venting tests described above, a series of boiling tests were conducted in one tank. The same procedure as described above applied. However, the tank was vented to a low enough pressure that bubbles in the fluid were generated due to the boiling of the liquid itself.

Finally, one other series of tests were conducted where the STS thrusters were used to impose accelerations on the fluid. The video system was used to record the resulting fluid motions and the rewicking of the fluid into the steady-state low-g fluid interface shape. Due to the conflicting requirements for the tank orientations these tests were conducted in tank B only at a fill level of 20%.

Flight-test Results

The VTRE was launched on STS-77 on May 19, 1996 as part of a cross bay Hitchhiker bridge payload called the Technology Experiments for Advancing Missions in Space (TEAMS). The test matrix is shown in table 1. The experiments were run during the crew sleep period (except for the two sequences which required STS thruster firings) to minimize any external disturbances during the testing. Success for all transfers and vents was defined by the output of the test tank vent quality meter. Exceeding a % liquid reading of 50% for two seconds or 80% for one second would indicate failure and result in termination of the test.

Transfer Tests

The data showed that the eight primary (empty to full) transfers were successful and the critical Weber number is much higher than the preflight prediction. Video stills from a typical transfer are shown in figure 3. In figure 3a the transfer is just starting but already a column-of-liquid is evident around the central vane support. This area fills first. In figure 3b the liquid is beginning to fill along the outer vanes as well. In figure 3c the inner and outer vanes are at about the same level of fill. This corresponds to roughly 60% to 70% full. Figure 3d is at the very end of the test (90% full). Note the bubbles flowing into the tank at this point. These are caused by a suction dip that occurred in the supply tank resulting in an ingestion of gas into the inlet of the receiving tank. The outflow characteristics of the vane devices were known to be somewhat suspect at the high flowrates, but the receiver tank was thought to be less stable and therefore to provide the limit to the transfer rates. The video showed that, as expected, the region of greatest capillary forces is at the liquid inlet/outlet and at the root of the vanes along the standpipe.

The pressure traces for the two tanks are shown in figure 4. As can be seen the supply tank holds pressure fairly well with flow. The small drop off in supply tank pressure is due to the operation of the system close to the regulator overpressure maximum setpoint of 28 psia at which point the software closed the pressurant valve for a period of time (the HH canister was pressurized to 18 psia rather than the expected 15 psia, causing the regulators which are referenced to can pressure to shift three psi as well). The receiver tank pressure increases during the transfer as the vent flow increases(shown in figure 5). This is due to the backpressure regulator whose ΔP increases slightly with the increased flowrate.

The flowmeter data for test 101, a typical transfer, is provided in Figure 5. The Figure shows the output of the liquid turbine flowmeter and the output of the ultrasonic flowmeter in the gas system (converted so that the two readings are in the same units). As can be seen in this plot, the two readings move toward the steady state flowrate point as the tank pressures reach steady-state (the supply tank decreases in the pressure and the receiver tank increases). Both of these flowrates fluctuate with the pressure transients seen in figure 4. Also included on this plot is the measured speed of sound of the vent gas mixture. The speed of sound is correlated to a mole fraction of GN2 variation. The speed of sound is higher at the start due to the relatively Refrigerant-113 free GN2 in the receiver tank entering the vent flowmeter at the start, and then drops as some of the liquid vaporizes to establish a local vapor pressure of Refrigerant-113 in the ullage.

The drop tower tests showed that the point of least stability in the inflow process would be at the initiation of the inflow where there is the least amount of liquid in the tank to diffuse the inflow velocity of the liquid. This was found to occur for the tests started at an initial fill level of 20%, but not for the tests started with the tank empty. It is believed that when the tank is initially empty, the inflow velocity is dissipated by wetting and filling the columnar region around the central vane support. When filling an initially empty tank a somewhat unstable geometry occurred when the tank was around 60 to 70% 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 % liquid to fail our success criteria). Figure 6a shows test 105 at this stage. Liquid has escaped from the inner vanes and wet the vent. After several seconds of inflow the interface shape again made the situation less likely to occur. Figure 6b shows test 105 at the end. Liquid no longer wets the vent. Quality meter data for test 105 is shown in Figure 7. . Here the inlet and vent quality meter outputs are shown. As can be seen in the plot, the inlet meter ,after an initial transient, provides an indication of 100% liquid during the entire transfer, while the vent sensor varies with the amount of liquid in the vent This figure shows a brief spike of two phase flow, but does not exceed the 50% liquid threshold

Further transfer tests were conducted to determine the difference in the inflow to a partially full tank (~20% fill level) versus the initially empty tank primary tests. The drop tower testing indicated that the critical inflow rate should be greater for a partially full tank since there would be fluid over the tank inlet to diffuse the flow at the initiation of the transfer (the inflow rate at the start

of the transfer is the greatest since the tank ΔP is also the greatest). The inflight data showed the reverse to be true. 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 as shown in figure 8. Tests 110, 112, and 115 fail because of this. Tests 109 and 113 vent two phase flow at this point but continue on. Figure 9 shows a similar time during test 104 (a test starting from empty). Here the inflow surge is captured by the vanes and the inflow could continue as planned.

The response of the quality meters to the venting of liquid during the partially full transfer is shown in Figure 10. The vent meter shows all gas then subsequently venting of liquid shortly after the transfer begins returning to all gas at the end. The percent liquid volume value was not high enough to terminate the transfer but liquid venting can be seen in the video data.

Vent Tests

Of the 8 primary(90% Full) vent tests conducted 6 of them were successful. Figure 11 shows the test tank at the end of a typical successful vent test. For test tank A the critical point was found to be a vent rate corresponding to ~1.5% of the planned 5% ullage volume per second (~.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 ~6-7% while the ullage volume in the tank B testing was closer to 10% (This is confirmed by a slower pressure reduction for the tank B than tank A, in tests with same the vent flow rate). The vent tests did show that a non-settled tank can be vented without risk of liquid venting using a vane type PMD. The video record of the venting showed very little bubble formation until the tank pressure dropped to the pressure corresponding to the saturation level of the dissolved pressurant, at which point nitrogen bubbles would begin to evolve. The key to being able to sustain a vent using a vane type PMD is that these bubbles must grow to a size large enough for the vane device to effectively pump the bubbles to the ullage region (as opposed to what occurs in a one-g environment where numerous small bubbles form and are then transported to the gas region via buoyancy). In low-g a bubble will not be pumped in any direction unless a pressure gradient is established across the surface. Once the bubbles contacts two or more vanes, the bubble is deformed from the low energy spherical shape to a tapered shape with a preference to move in the direction where the taper is wider. The VTRE PMD is designed to pump a minimum size bubble of 0.5 inch in diameter (this will only occur in the region of the tank inlet/outlet) up to a maximum size of 4.2 inch diameter in the vent region (corresponding to a volume of 2.5% of the tank).

The video record showed that the bubbles did indeed grow to a size large enough to be pumped by the PMD. This process occurred via vapor generation inside the bubbles causing them to grow in size, and via two bubbles coalescencing into one larger bubble. The bubble coalescence method appeared to be the predominate one. Any time two bubbles would contact for more than an instant, the two would grow into one bubble (which is supported by a free surface energy analysis showing one large bubble being a lower energy state than two smaller ones). The time for the combination roughly correlated with the time for the very thin remaining liquid film between the two bubbles to vaporize, which would occur within one second or so. This observation also applied when the individual bubbles contacted the main tank ullage. Sometimes very large bubbles would contact the ullage resulting in an off centered ullage volume once the two volumes joined. The PMD would simply re-center this volume over the standpipe. This re-centering occurred very quickly (within 4 to 5 seconds), which was much faster than predicted.

The pressure data during one vent is provided in Figure 12. Here the tank pressure can be seen to drop very rapidly at the start with the pressure reduction rate gradually decreasing. The decrease in the pressure reduction rate is due to the reduction in flowrate with decreasing tank pressure (the vent flow control valve was choked during these vents) and was also due to the nitrogen bubbles coming out of solution, resulting in an increase in gas volume that must be vented from the tank to achieve a net pressure reduction. Figure 13 provides the output of the ultrasonic flowmeter during this test. The flowrate shows a nearly constant flowrate range of 0.025 to 0.030 cfm, while the mole fraction (as calculated from the measured speed of sound) showed a decrease from 0.8 initially to a value of 0.5 at the end. This data matches the pre-test predictions for the mole fraction (simply based on the partial pressures of the two gases). This model correlation confirms the assumption that the ullage gases are a well mixed homogenous mixture, with the Refrigerant-113 partial pressure corresponding to the saturation pressure of the liquid.

As with the transfer testing, vent tests were conducted on tanks that were only 20% full. These tests showed no issues since the ullage volume was so large. Considerably higher vent flowrates than were possible with the VTRE system would have been required to obtain an unstable vent for these fill levels.

The last vent tests consisted of boiling vent tests. Since at ambient temperature (which was the design environment for VTRE) the saturation pressure of Refrigerant-113 is ~5 psia, test tank B was first vented to this pressure to begin the testing. The boiling vent tests were not as successful as the previous nitrogen venting tests for two reasons. First, the test tanks were designed to be thermally coupled to the HH canister environment to ensure the Refrigerant-113 would not freeze, resulting in a net boiling of the liquid without any actual pressure reduction (the heat removal via venting was much lower than the heat input from the environment). Second, 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 (thereby resulting in liquid venting due to the swelling of the liquid volume). The differences between the nitrogen and the boiling vents tests are still being analyzed, with the bubble nucleation phenomena being investigated.

Liquid Recovery Tests

Two tests looked at the response of the system to a high thrust and a low thrust disturbance. Since the burns that were used to generate these acceleration were not dedicated to VTRE (i.e. VTRE piggybacked off another planned maneuver) the thrust levels were not controllable, only the duration. For the high thrust acceleration a burn time of 15 seconds was chosen [using two of the Orbiter primary Reaction Control system (RCS) jets] since that represented a factor of four on the predicted settling time for the liquid (thereby providing enough time to damp out any residual oscillations in the fluid). 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 seconds. Figure 14 shows the liquid during the high thrust period. Liquid position before and after thrust is similar to figure 3b. The pre-test predictions were for a time of 2 to 3 minutes, therefore the wicking action of the vanes is much greater than previously thought. Accelerometers were flown to record the acceleration levels of the firing, with the planned acceleration to be in the low 10^{-4} g range. The accelerometer output saturated at the maximum reading of 7×10^{-4} g's during the firing meaning that the thrust level was much higher than originally planned (the planning was based on use of one RCS jet only). This test showed the total robustness of a vane device system (the fluid was upset out of the vane device for a total time of less than one minute after a very high level acceleration event of a fairly long duration). The second test showed similar thrust levels but for only 1 to 2 seconds. The fluid did slosh around the tank and then quickly rewicked into the low-g orientation.

Summary

The VTRE flight experiment on STS-77 confirmed the design approaches presently used in the development of vane type PMD's 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 pre-test predictions. Recovery from a thruster firing which moved the liquid to the opposite end of the tank from the PMD was achieved in 30 seconds. The objectives of VTRE were all achieved. The video provided great insight into the PMD behavior, and suggest new considerations for the design of future PMD that would not have been seen without this flight test.

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Table 1 Test matrix

Mission time	Test Seq.	Type	Flowrate	Success	Comments
0:21:11:26	105	Transfer AB	1.28gpm	Y	
0:21:39:57	101	Transfer BA	1.27gpm	Y	
0:22:06:58	106	Transfer AB	1.95gpm	Y	
0:22:32:17	102	Transfer BA	1.93gpm	Y	Gas in inflow
0:22:57:28	107	Transfer AB	2.40gpm	Y	Gas in inflow
0:23:22:13	103	Transfer BA	2.43gpm	Y	Gas in inflow
1:00:22:04	201	Vent A	0.0504 cfm	N	
1:00:32:58	202	Vent A	0.0201 cfm	Y	
1:00:49:30	203	Vent A	0.0318 cfm	Y	
1:01:18:47	204	Vent A	0.0400 cfm	Y	
1:01:47:35	108	Transfer AB	2.73 gpm	Y	Gas in inflow
1:21:30:46	205	Vent B	0.0504 cfm	Y	
1:21:42:28	206	Vent B	0.1264 cfm	Y	
1:22:18:35	207	Vent B	0.2002 cfm	N	
1:22:36:24	208	Vent B	0.1591 cfm	Y	
1:22:54:54	104	Transfer BA	2.60 gpm	Y	Gas in inflow
1:23:24:26	112	Transfer AB	2.73 gpm	N	20% full
1:23:32:45	213	Vent A	0.0504 cfm	Y	20% full
1:23:47:38	109	Transfer BA	2.60 gpm	Y	20% full
1:23:55:05	216	Vent B	0.2002 cfm	Y	20% full
2:20:00:47	110	Transfer AB	2.73 gpm	N	20% full Gas in inflow
2:20:02:19	214	Vent A	0.0798 cfm	Y	20% full
2:20:12:03	113	Transfer BA	2.60 gpm	Y	20% full
2:20:18:44	217	Vent B	0.1005 cfm	Y	20% full
2:20:25:50	115	Transfer AB	2.73 gpm	Y	20% full
2:20:26:56	215	Vent A	0.1264 cfm	Y	20% full
2:20:34:35	114	Transfer BA	2.60 gpm	Y	20% full
2:20:42:13	218	Vent B	0.2002 cfm		20% full
3:11:33:49	150	Upset		Y	>7e-4G
3:16:57:47	151	Upset		N	G level not achieved
3:20:20:47	209	Boiling Vent A	0.1591 cfm	N	

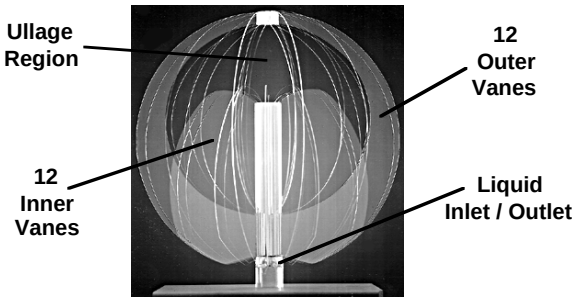


Figure 1 - VTRE Vane Type PMD

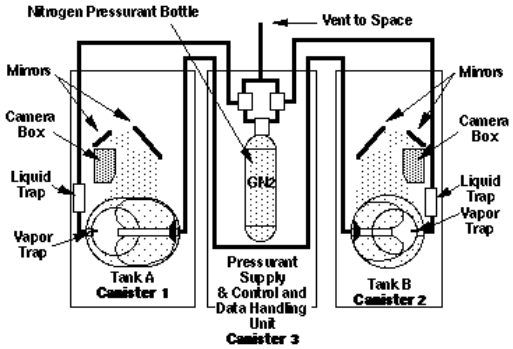
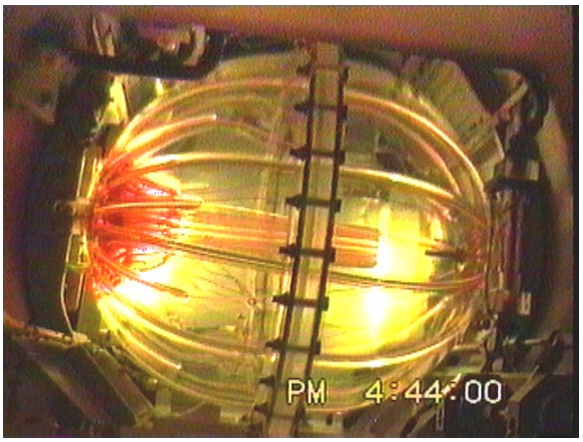
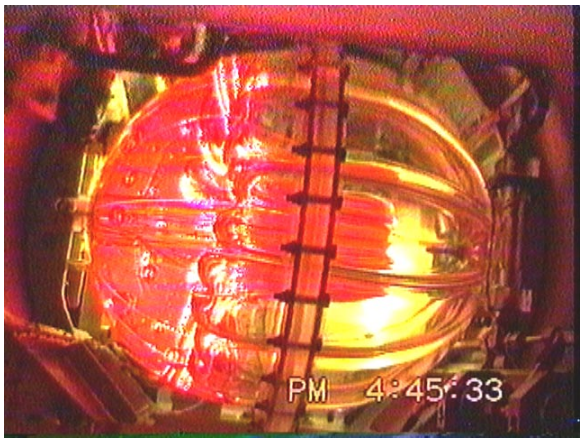


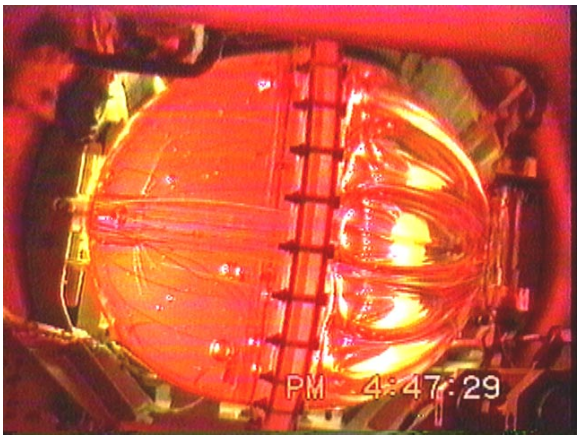
Figure 2 - VTRE Experiment Layout



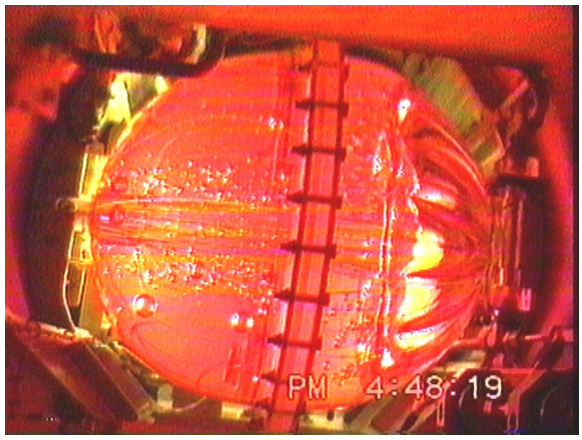
a) Start of Transfer



b) Part way Full



c) Nearing End of Fill



d) End Of Fill (Note Bubbles from Inflow)

Figure 3 - Typical Fill (Test Sequence 101)

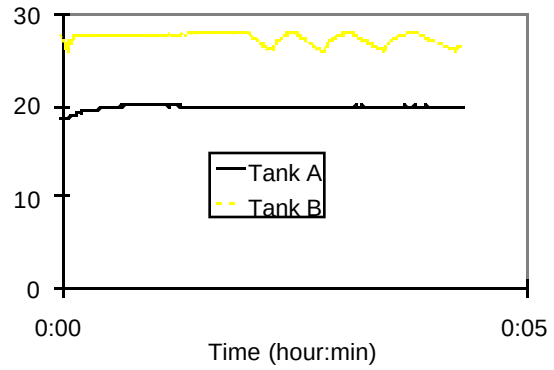


Figure 4 - System Pressures During a Typical Transfer (Test 101)

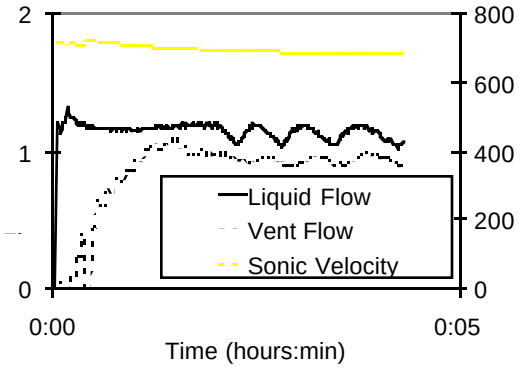


Figure 5 - Flowmeter Comparisons During a Typical Transfer(Test 101)

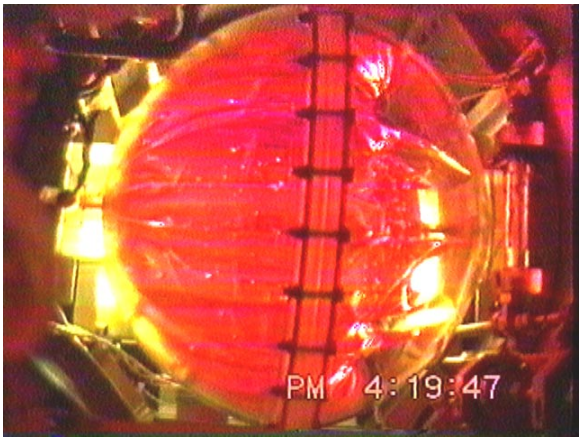


Figure 6a - Test 105 liquid wicks over vent

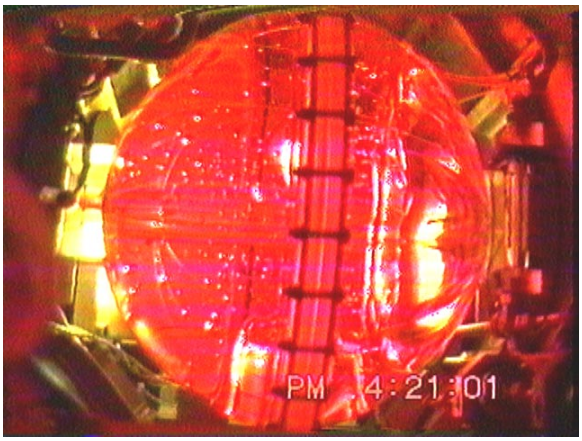


Figure 6b - Test 105 end of test

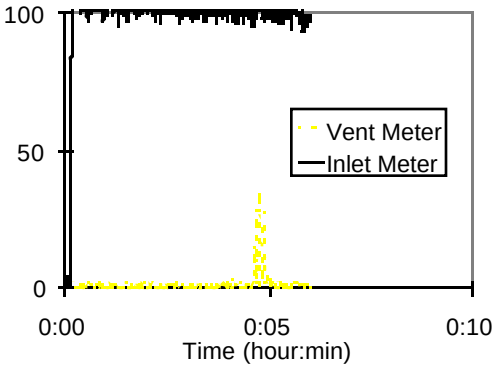


Figure 7 - Quality Meter response during test 105

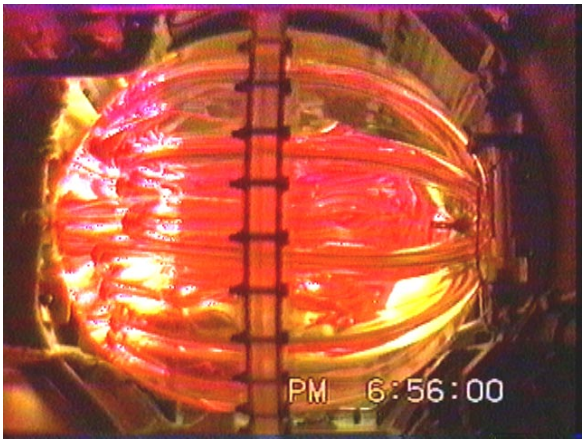


Figure 8 - Liquid Inflow escapes from top (test 109)

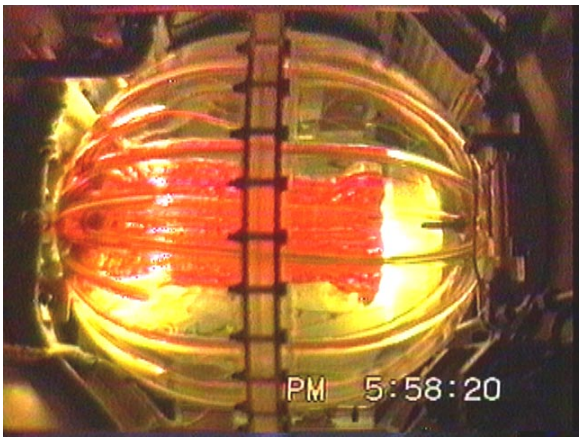


Figure 9 - Vanes Turn Back Liquid Inflow (Test 104)

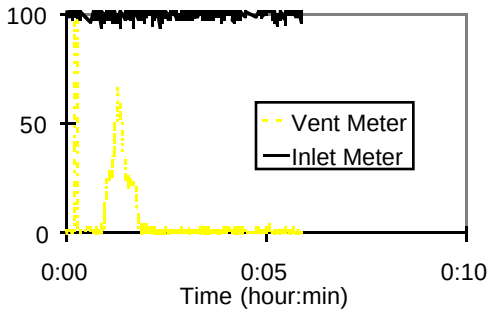


Figure 10 - Quality Meter Response to Liquid Venting during Test 109

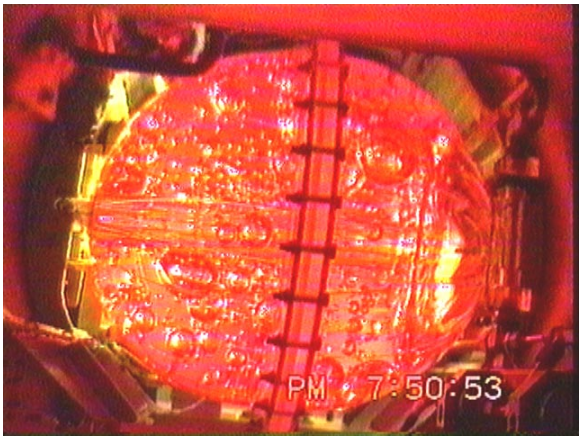


Figure 11 - Typical Vent (Test 204)

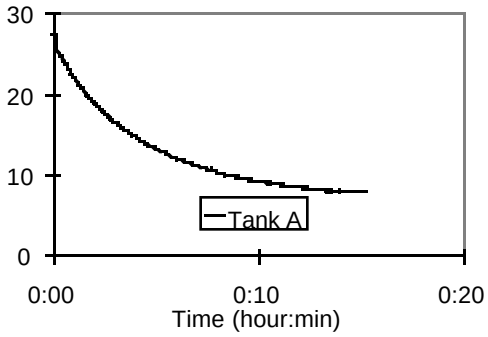


Figure 12 - Tank Pressure During a Tank Vent

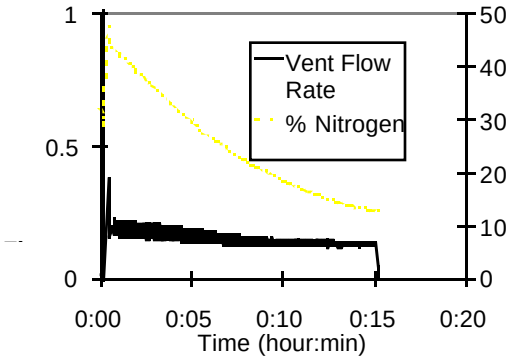


Figure 13 - Measured Flowrate and Mole Fraction During a Tank Vent

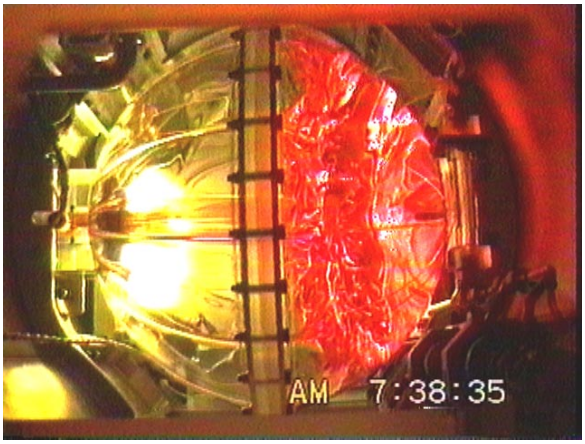


Figure 14 - Fluid Position during Shuttle Thruster Firing

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
July 1997

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Vented Tank Resupply Experiment—Flight Test Results

5. FUNDING NUMBERS
WU–632–1C–1A

6. AUTHOR(S)
David J. Chato and Timothy A. Martin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–10797

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

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107498
AIAA–97–2815

11. SUPPLEMENTARY NOTES
Prepared for the 33rd Joint Propulsion Conference and Exhibit cosponsored by AIAA, ASME, SAE, and ASEE, Seattle, Washington, July 6–9, 1997. David J. Chato, NASA Lewis Research Center and Timothy A. Martin, Lockheed Martin Astronautics, Denver, Colorado. Responsible person, David Chato, organization code 5870, (216) 977–7488.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 20

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This paper reports the results of the Vented Tank Resupply Experiment (VTRE) which was flown as a payload on STS 77. VTRE looks at the ability of vane propellant management devices (PMD) to separate liquid and gas in low gravity. VTRE used two clear 0.8 cubic foot tanks one spherical and one with a short barrel section and transferred Refrigerant 113 between them as well as venting it to space. Tests included retention of liquid during transfer, liquid free venting, and recovery of liquid into the PMD after thruster firing. Liquid was retained successfully at the highest flow rate tested (2.73 gpm). Liquid free vents were achieved for both tanks, although at a higher flow rate (0.1591 cfm) for the spherical tank than the other (0.0400 cfm). Recovery from a thruster firing which moved the liquid to the opposite end of the tank from the PMD was achieved in 30 seconds.

14. SUBJECT TERMS
Low gravity; Propellant management; Liquid transfer

15. NUMBER OF PAGES
12

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT