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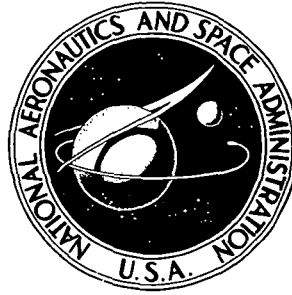
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AXIAL JET MIXING OF ETHANOL IN SPHERICAL CONTAINERS DURING WEIGHTLESSNESS

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16. Abstract

An experimental program was conducted to examine the liquid flow patterns that result from the axial jet mixing of ethanol in 10-centimeter-diameter spherical containers in weightlessness. Complete liquid circulation flow patterns were easily established in containers that were less than half full of liquid, while for higher liquid fill conditions, vapor was drawn into the inlet of the simulated mixer unit. Increasing the liquid-jet velocity or lowering the position at which the liquid jet entered the container caused increasing turbulence and bubble formation.

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AXIAL JET MIXING OF ETHANOL IN SPHERICAL

CONTAINERS DURING WEIGHTLESSNESS

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SUMMARY

An experimental program was conducted in the Lewis Research Center's 5-second zero gravity facility to examine the liquid flow patterns that result from the axial jet mixing of ethanol in 10-centimeter-diameter spherical containers in weightlessness. The effects of the volume of liquid in the tank, the position of the outlet for the liquid jet, and the liquid-jet velocity on the resulting liquid flow patterns were examined. At liquid fillings by volume of 50 percent or less, complete liquid circulation flow patterns were easily established. At liquid fillings by volume of 70 percent or more, vapor was drawn into the inlet of the simulated mixer unit. Increasing the liquid-jet velocity in an attempt to avoid the ingestion of vapor caused the tank contents to become highly turbulent with bubbles becoming entrained in the liquid bulk. Uniform liquid flow patterns were easier to achieve when the liquid jet exited at a position near the top rather than at the bottom of the container.

INTRODUCTION

The use of cryogenic propellants in the NASA space program has introduced problems of propellant management (ref. 1). During missions in space, cryogenic propellant tanks will require periodic venting, as the tank pressure increases due to various heat inputs, to allow the tank pressure to remain within acceptable limits. The current technique for venting orbital propellant tanks involves the use of settling rockets to position and maintain the liquid away from the vent, thus permitting the direct venting of only vapor from the tank.

Efforts to improve the performance of propulsive stages have introduced the concept of the thermodynamic vent system, a much lighter method of controlling tank pressure than the technique of liquid settling and direct venting (ref. 2). The basic operating concept of the thermodynamic vent system involves the sacrificial evaporation of a small

amount of the cryogenic propellant, which is then used to cool the remaining contents of the propellant tank. Cryogenic liquid is withdrawn from the tank and passed through a Joule-Thompson valve with a resultant pressure and temperature reduction. This fluid is then used as a coolant in a heat exchanger where evaporation takes place before the resulting vapor is vented overboard. The bulk of the cryogenic liquid and vapor in the propellant tank is the heat exchanger hot side fluid, which is cooled during the operation of the thermodynamic vent system, thus reducing the tank pressure.

Three options exist for locating the heat exchanger: within the tankage insulation, where most of the incoming heat can be intercepted before it reaches the propellant, on the tank wall, or inside the tank. The last option, commonly called a compact internal heat exchanger, promises to have the lowest weight, but it introduces the additional requirement of circulating the fluid in the tank so that effective cooling can take place.

The circulation or mixing of the bulk cryogenic liquid introduces additional orbital propellant management advantages. The rate of pressure rise in propellant tanks is reduced because temperature stratification of liquid and vapor does not develop, and problems associated with engine startup are reduced because uniform temperature fluid is delivered to the engine feed system.

Thermodynamic vent system concepts are particularly attractive when cryogenic payloads for the Space Shuttle are considered. Under many normal conditions and all abort modes, payloads cannot dictate Shuttle operations so that settling to relieve the payload tank pressure would be impossible; thermodynamic vent system concepts should impose no constraints on the Space Shuttle.

Thermodynamic vent systems employing internal compact heat exchangers and mixers have been designed, fabricated, and tested in cryogenic fluids under normal gravity conditions (ref. 3). The ability of these devices to control tank pressure at 1g has led to their general acceptance as the planned pressure control technique for the Tug and other future cryogenic tankage designed for weightless operation.

Although the technique for designing the heat exchanger for the thermodynamic vent system concept is well understood and should be little affected by gravity, the fluid dynamics associated with mixing the bulk fluid in a predictable manner is highly dependent on the level of acceleration. The difference between normal gravity and weightlessness will not only influence the liquid-vapor configuration before the initiation of mixer operation, but will be an important parameter in determining the liquid momentum or velocity required to establish the desired liquid flow pattern and degree of mixing of the tank contents.

The purpose of these experiments was to examine the flow patterns that resulted when an axial liquid jet (a circular liquid jet directed along the axis of the container) was used to mix the contents of a partially filled spherical container. The objective of the program was to define the jet characteristics required for effective circulation of the liquid without bubble formation or excessive turbulence. The desired mixing processes

will provide adequate interception of heat entering a cryogenic propellant tank and, thus, effective pressure control.

The experimental tank (fig. 1) used for the study was a 5-centimeter-inside-radius sphere containing a 0.2-centimeter radius jet exit tube. Liquid was withdrawn from the tank at the base of the jet exit tube, as liquid was forced into the tank through the tube as an axial jet. This process simulates the liquid flow pattern associated with a pump located in the bottom of the tank. Of equal importance with observation of the liquid flow patterns was examination of the motion of the ullage or main vapor region. Vapor encapsulation of the simulated pump (i.e., vapor ingested in the region of fluid withdrawal) would lead to failure of the liquid circulation concept. In addition to varying the liquid jet velocity, the effect on the liquid flow patterns of initial liquid filling and jet outlet position were examined at both normal and zero gravity.

BACKGROUND

Liquid-Jet Mixing of Fluids

Analytical studies, performed to determine the most desirable method of mixing the fluid contained in cryogenic tankage (ref. 4), have indicated that both radial and axial liquid jet pumps (see fig. 2) are the most promising devices. The liquid leaves an axial jet pump as a single stream of fluid generally flowing along the centerline of the tank while liquid is uniformly drawn into the pump around the base. The liquid flow pattern associated with a radial jet pump is directly opposite; liquid flows radially outward from the base of the pump and is returned to the pump from the center of the tank.

Either axial or radial liquid-jet pumps appear acceptable if only liquid mixing is desired in cylindrical tanks, where the bulk liquid has a preferred location due to surface tension forces, even under weightless conditions. However, mixing only the bulk liquid, which is desirable for minimizing the disturbing forces on the vehicle, may lead to inadequate pressure control since cooling of the vapor will depend on the heat and mass transfer taking place at the liquid-vapor interface. Therefore, it may be necessary to flow liquid over the entire cylindrical tank wall to provide cooling and the desired pressure response.

Mixing only the bulk liquid in a spherical tank under weightless conditions is impossible since the ullage will be spherical with no preferred location. Consequently, the required liquid circulation pattern involves totally wetting the tank walls as shown in figure 2.

An experimental study of the effect of gravity on forced liquid circulation patterns in spherical tanks was conducted at Lewis (ref. 5). The liquid flow pattern resulting from a radial jet was experimentally observed in three different tank sizes at acceleration

levels which ranged from normal to essentially zero gravity. For an initially empty tank and radial jet inlet velocities great enough to cause liquid flow up the walls and down the center of the tank, a great deal of turbulence, unsymmetric flow and bubble formation resulted. Bubble formation is undesirable because it defeats one of the advantages of the thermodynamic vent system concept: the delivery of uniform fluid to the tank outlet. Turbulent and unsymmetric liquid flow may add excessive demands to vehicle or space-craft attitude control systems.

Consequently, axial jets are preferred if it is desired to totally wet the walls of a spherical propellant tank under weightless conditions. The desired liquid flow patterns results when the liquid jet impinges on the top of the container; the liquid flows along the container walls to the interface between the bulk liquid and the vapor region, and liquid is drawn into the pump at the bottom of the tank.

Liquid-Jet Velocity Requirements

Determination of the minimum required axial liquid-jet velocity, for establishing the desired liquid flow pattern, was based on a Lewis study of liquid inflow to partially filled tanks (ref. 6). That program determined the maximum liquid inflow rate such that stable (minimum liquid-vapor interface distortion) filling of the container resulted. Since for the present study it was desired to have the incoming jet impinge on the top of the tank, the maximum stable inflow rate obtained from reference 6 was increased by approximately 50 percent to establish the lower limit on the presently desired flow rates. Based on this theory, stable zero-gravity filling of the 10-centimeter-diameter test container would result if the inflow rate was no greater than approximately 2.4 cubic centimeters per second.

An analysis developed in reference 7 predicts that complete mixing of the contents of the test container will occur if the liquid jet volumetric flow rate is at least 5.8 cubic centimeters per second, and a liquid jet volumetric flow rate of 58 cubic centimeters per second is recommended to insure mixing. Based on the results of both studies (refs. 6 and 7) a minimum liquid jet volumetric flow rate of approximately 4 cubic centimeters per second and a maximum liquid jet volumetric flow rate of approximately 60 cubic centimeters per second was chosen.

APPARATUS AND PROCEDURE

The Lewis zero gravity facility was used to obtain the experimental data for this investigation. A complete description of the facility, the experiment package, and the procedure for conducting the tests can be found in the appendix.

A schematic drawing of the liquid flow system is shown in figure 3. A piston pump, driven by an electric motor and gear mechanism, forces the ethanol test liquid out through the central tube, forming an axial liquid jet. Simultaneously, liquid is withdrawn from the bottom of the experiment tank and fills the region below the piston pump. Interchangeable liquid-jet exit tubes of different lengths could be fit into the opening at the top of the piston pump.

The speed of the piston pump, and thus the liquid-jet volumetric flow rate, is controlled by using various combinations of gear drives and applied voltage to the electric motor. As the piston moves, an electrical contact slides along a linear resistor mounted parallel to the piston pump. A 28-volt direct-current circuit, including the linear resistor that acts as a voltage divider, provides the input to a telemetry system which transmits to a receiver and strip chart recorder in the facility control room so that the position of the piston pump as a function of time can be determined. Because the piston drive mechanism occupies approximately 30 percent of the volume of the piston sleeve, the liquid volumetric withdrawal rate is only 70 percent of the liquid-jet volumetric flow rate.

During a test under weightless conditions, the first 2 seconds of test time are allocated for the bulk liquid to achieve a zero-gravity configuration; the liquid flow system is then activated by timers for the remaining test time of slightly more than 3 seconds. For simplicity, the identical sequence and timing of operations is used for the normal gravity tests.

A high-speed motion picture camera is used to photograph the bulk liquid motion during the first 2 seconds of test time and the liquid flow patterns within the spherical experiment tank (fig. 1) after activation of the piston pump. A digital clock is included in the camera field of view so that the elapsed time from the initiation of the test is also recorded.

EXPERIMENTAL RESULTS

The experimental conditions for the 8 normal gravity tests and 29 zero-gravity (less than 10^{-5} g's) tests, together with the characteristics of the axial liquid jet for each test, are presented in table I. In addition to gravity level, the experimental variables included initial experiment tank liquid fillings of 30, 50, 70, and 90 percent (by volume), two outlet positions for the axial liquid jet, and the piston pump velocity.

The axial jet exit tube lengths of 2 and 8 centimeters were measured from the hypothetical bottom of the 10-centimeter-diameter spherical experiment tank. For each test the average piston pump velocity was determined from the trace of position versus time obtained from the strip chart recorder. The average piston pump velocity was multiplied by the piston cross-sectional area to obtain the liquid-jet volumetric flow rate. This jet

volumetric flow rate was then divided by the tank volume to obtain the percentage of the tank volume that flows into the tank as a liquid jet each second. The liquid-jet volumetric flow rate was also divided by the cross-sectional area of the jet exit tube to yield the average liquid-jet velocity.

DISCUSSION OF EXPERIMENTAL RESULTS

The liquid-jet volumetric flow rate (table I), expressed as a percentage of the tank volume entering the container each second, is the most suitable parameter for describing the fluid flow phenomena to be discussed in this section. For simplicity, this liquid-jet volumetric flow rate will be referred to as the inflow rate and will be expressed in units of percent per second. The fact that the liquid withdrawal rate from the container was approximately 30 percent less than the inflow rate was not believed to significantly affect the experimental results or the general conclusions, since, for all test conditions that yielded nonturbulent, bubble free liquid flow conditions, the increase in the container liquid filling during the test was less than 5 percent.

Gravity Level

Eight tests were conducted under normal gravity conditions so that direct comparisons could be made with the zero-gravity results. Figure 4(a) shows the slight liquid-vapor interface disturbance caused by the liquid jet that was typical of test 3, 12, and 33. These tests show that similar results are obtained as the liquid filling and the inflow rates are increased. Test 3 was for a liquid filling of 30 percent and an inflow rate of 0.82 percent per second; test 12 was for a liquid filling of 50 percent and an inflow rate of 1.14 percent per second; test 33 was for a liquid filling of 90 percent and an inflow rate of 2.30 percent per second.

The effect of using a longer (8 cm) jet exit tube is shown in figures 4(b) and (c). The experimental results shown in figure 4(b) are for test 11, which had the same inflow rate and liquid filling as test 12 (fig. 4(a)). The liquid jet impinges on the top of the test container, but lacks enough inertia to wet the walls of the tank. Increasing the inflow rate to 1.64 percent per second, at the same 50 percent liquid filling (test 14, fig. 4(c)) yields the uniform liquid circulation patterns that were desirable (i.e., liquid-jet impinges on top of the container; liquid flows along the container walls and collects at the liquid-vapor interface; and the bulk liquid is withdrawn from the bottom of the tank simulating the flow into a mixer unit).

The liquid flow pattern shown in figure 4(c) is also typical of the results obtained in test 16 for an inflow rate of 4.60 percent per second at a liquid filling of 50 percent.

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Further increasing the liquid-jet velocity or inflow rate yielded the highly turbulent flow with entrained bubbles shown in figure 4(d). This flow condition was obtained with both the 2- and 8-centimeter jet exit tube lengths (tests 18 and 19) at inflow rates of approximately 11 percent per second.

Under zero-gravity conditions and for liquid fillings of 30 or 50 percent, the desired liquid flow patterns were easily established. Figure 5(a) shows the zero gravity liquid-vapor interface configuration that is typical for liquid fillings of 50 percent or less. The container walls are completely wetted by the liquid, but most of the liquid remains in the bottom of the tank over the simulated inlet to the mixer unit. When inflow from the liquid jet is initiated, the liquid flows along the tank walls and collects in the bottom of the container (fig. 5(b)) with a resulting liquid flow pattern very similar to the normal gravity results shown in figure 4(c).

The experimental data shown in figure 5 (test 9) are also typical of the results obtained in tests 1, 2, 4 to 8, 13, and 15. The desirable liquid flow patterns are achieved at both 30 and 50 percent liquid fillings over a range of inflow rates from 0.80 to 4.60 percent per second. The general conclusion to be drawn from these experimental data is that the desired liquid flow pattern could be established at lower liquid-jet velocities under weightless conditions than at normal gravity for liquid fillings of 50 percent or less.

Percent Liquid Filling

Increasing the percentage of liquid in the test tanks demonstrates that the location of the vapor bubble when liquid inflow from the jet is initiated may be the dominant factor controlling the achievement of a desirable liquid flow pattern. Figures 6(a) and (c) show typical zero gravity liquid-vapor interface configurations for containers that are 70 and 90 percent full. The significant point to observe is that not only are the tank walls completely wetted, but also the vapor bubble is no longer at the preferred location near the top of the tank.

Figure 6(b) shows the steady liquid flow pattern that is typical of tests 20 and 21 (liquid filling, 70 percent; inflow rate, approx. 1.15 percent/sec). The bulk liquid collects on the sides of the container; the liquid from the jet impinges on the top of the tank and flows along the bulk-liquid - vapor interface; and the vapor bubble is elongated and approaches the region of the inlet to the simulated mixer unit.

At liquid fillings of 90 percent no liquid flow can be observed for liquid jet inflow rates ranging from 1.14 to 1.72 percent per second. The liquid from the jet collects at the top of the tank, and the vapor bubble moves downward and is drawn into the outlet. This fluid flow phenomena, which would lead to failure of the liquid circulation concept, is shown in figure 6(d) and is typical of the results obtained in tests 28 to 30.

The results of the 70 and 90 percent liquid filling tests suggest that difficulties may also exist at lower liquid fillings. It is important to realize that, by starting the tests with the liquid in the bottom of the test container, the resulting zero gravity liquid-vapor configuration was such that the inlet to the simulated mixer unit was always initially covered with liquid. Under actual orbital operating conditions, very low accelerations that would result from drag forces would be enough to adversely position the vapor bubble in spherical propellant tanks. Careful choice of the location of a mixer unit may be necessary even at liquid fillings of less than 50 percent to insure complete circulation of the tank contents without vapor being ingested into the mixer unit.

Liquid Jet Velocity

In an attempt to establish the desired liquid flow patterns in tanks more than 70 percent full of liquid, several tests were run at increasing liquid-jet velocities. The range of inflow rates examined was from approximately 1 percent per second, which yielded the undesirable flow patterns shown in figure 6, to more than 4 percent per second.

The experimental results shown in figures 7(a) to (c) are typical of tests 22 to 24, 31, 34, and 35. At both 70 and 90 percent liquid fillings, desirable liquid flow patterns could be established, but in each case there is a transition period during which the vapor bubble is located in the region of the inlet to the simulated mixer unit. In a real propellant tank mixer unit the vapor would probably be ingested into the mixer and forced out through the jet exit tube thus causing failure of the liquid-jet mixing concept.

It is interesting to note that, if the inlet to the simulated mixer unit could be designed so that vapor would not be ingested, increasing liquid-jet velocities are required to establish the desired liquid flow pattern as the percentage of liquid in the tank increases. For container liquid fillings of 50 percent or less, the desired liquid flow patterns were established at inflow rates that were less than 1 percent per second. The desired liquid flow pattern was first observed at an inflow rate of 1.64 percent per second for the 70 percent filled container (test 22) and at an inflow rate of 2.25 percent per second for the 90 percent filled container (test 31). Consequently, propellant mixing devices will have to be designed for the highest liquid fill condition anticipated.

In an attempt to completely eliminate the transition period when vapor is ingested into the tank outlet, liquid-jet velocities were further increased. Figures 7(d) and (e) show experimental results typical of test 25 to 27, 36, and 37. At the high liquid filling conditions and inflow rates ranging from approximately 4.5 to 9 percent per second, the ullage bubble is pulled into the region of the simulated mixer unit and the tank contents become highly turbulent with bubbles entrained in the liquid bulk; this condition also resulted during test 17 at a tank liquid filling of 50 percent and an inflow rate of 9.43 percent per second.

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At the high liquid filling conditions it is possible that actual orbital operating conditions, with the resulting drag forces, could be beneficial. If the very low acceleration that results from orbital drag can be used to initially position the vapor bubble away from the mixer unit, relatively low liquid-jet velocities would be sufficient to provide the desired liquid flow pattern.

Position of Jet Outlet

Most of the zero gravity data discussed thus far were obtained with the exit for the liquid jet located 8 centimeters above the bottom of the spherical tank. Obviously, it would be desirable to keep a propellant mixing unit as compact as possible, and, thus, locate the exit for the liquid jet near the bottom of the tank. Several tests were conducted using a liquid jet exit tube 2 centimeters long. The experimental data shown in figure 8 are from test 10. The axial liquid jet leaving the 2-centimeter-long jet exit tube tended to form into globules before striking the top of the container. For tests 2 and 5 (30 percent liquid filling), the jet breakup had little effect on the resulting liquid flow patterns. For the 50 percent liquid filling condition shown in figure 8, some bubbles were formed. At the 90 percent liquid filling (test 32) the liquid-jet breakup caused turbulence and bubble formation at the relatively low inflow rate of 2.30 percent per second (fig. 9).

SUMMARY OF RESULTS

An experimental program was conducted in the Lewis 5-second zero gravity facility to examine the liquid flow patterns that result from the axial jet mixing of ethanol in spherical (10-cm diam) containers in weightlessness. The effects of the volume of liquid in the tank, the length of the 0.4-centimeter-diameter tube from which the liquid jet exited, and the liquid-jet volumetric flow rate or jet velocity on the resulting liquid flow patterns were examined.

Several tests were also conducted under normal gravity conditions for comparison. Higher liquid-jet velocities were required in normal gravity to achieve the uniform liquid circulation patterns that were considered to be desirable (i.e., liquid-jet impinges on the top of the container; the liquid flows along the container walls and collects at the liquid-vapor interface; and the bulk liquid is withdrawn from the bottom of the tank simulating the flow into a mixer unit).

A qualitative summary of the zero gravity experimental test results is presented in the following sketch:
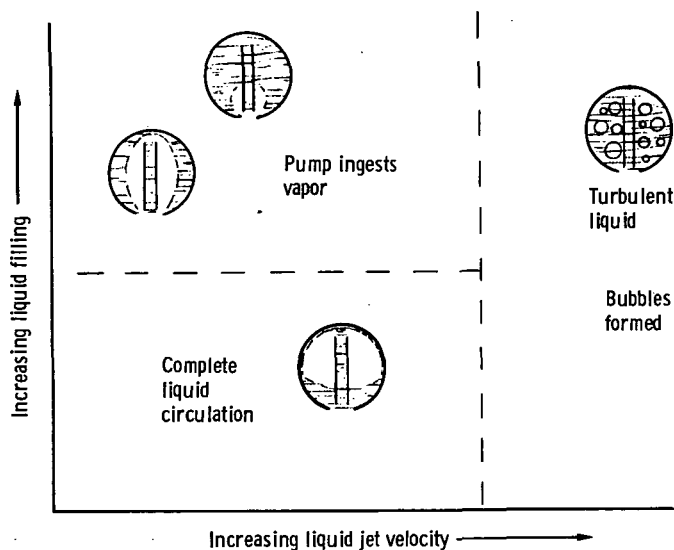
Under weightless conditions the amount of liquid in the container and the resulting liquid-vapor configuration at the initiation of liquid flow from the axial jet was the dominant factors affecting the resulting liquid flow patterns. At liquid fillings by volume of 50 percent or less, the desired liquid flow patterns were easily established.

For the 70 percent liquid filling and relatively low liquid jet velocity, when the liquid jet flow was initiated, the bulk liquid collected on the sides of the container and the jet liquid flow was through the central portion of the container, on the bulk liquid-vapor interface, to the bottom of the tank. For the 90 percent liquid filling and relatively low liquid jet velocity, the initiation of the liquid flow from the axial jet caused the bulk liquid to collect at the top of the tank and the vapor bubble to move to the bottom where it was drawn into the container outlet.

At both 70 and 90 percent liquid fillings, the desired uniform flow patterns could be established by increasing the liquid-jet velocity; however, there is a transition from the initial liquid-vapor configuration to the steady flow situation that includes a period of time when the vapor bubble is located over the tank outlet. In a real tank mixer unit, the vapor would probably be ingested into the pump and forced out through the exit tube, thus causing failure of the liquid-jet mixing concept.

In an attempt to eliminate the transition period when vapor is ingested into the tank outlet, much higher liquid-jet velocities were examined. This proved to be ineffective because higher jet velocities caused the tank contents to become highly turbulent with bubbles becoming entrained in the bulk liquid.

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Uniform liquid flow patterns were easier to achieve when the liquid jet exited from the tube at a position 8 centimeters above the bottom of the container. Axial liquid jets leaving the tube that was only 2 centimeters above the bottom of the tank tended to form into globules before striking the top of the container causing a great deal of turbulence and bubble formation.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, January 16, 1976,
            506-21.

APPENDIX - DATA ACQUISITION

Test Facility

The experiment data for this study were obtained in the 5- to 10-second zero-gravity facility at Lewis. A schematic diagram of this facility is shown in figure 10. The facility consists of a concrete-lined 8.5-meter-diameter shaft that extends 155 meters below ground level. A steel vacuum chamber, 6.1 meters in diameter and 143 meters high, is contained within the concrete shaft. The pressure in this vacuum chamber is reduced to 13.3 newtons per square meter by using the Center's wind tunnel exhaust system and an exhauster system located in the facility.

The ground-level service building has, as its major elements, a shop area, a control room, and a clean room. Assembly, servicing, and balancing of the experiment vehicle are accomplished in the shop area. Tests are conducted from the control room (see fig. 11), which contains the exhauster control system, the experiment vehicle pre-drop checkout and control system, and the data retrieval system.

Mode of operation. - The zero-gravity facility has two modes of operation. One is to allow the experiment vehicle to free-fall from the top of the vacuum chamber, which results in nominally 5 seconds of free-fall time. The second mode is to project the experiment vehicle upwards from the bottom of the vacuum chamber by a high-pressure pneumatic accelerator located on the vertical axis of the chamber. The total up-and-down trajectory of the experiment vehicle results in nominally 10 seconds of free-fall time. The 5-second mode of operation was used for this experimental study.

In either mode of operation the experiment vehicle falls freely; that is, no guide wires, electrical lines, and so forth are connected to the vehicle. Therefore, the only force (aside from gravity) acting on the freely falling experiment vehicle is due to residual air drag. This results in an equivalent gravitational acceleration acting on the experiment which is estimated to be no greater than 10^{-5} g.

Recovery system. - After the experiment vehicle has traversed the total length of the vacuum chamber, it is decelerated in a 3.6-meter-diameter, 6.1-meter-deep container which is located on the vertical axis of the chamber and filled with small pellets of expanded polystyrene. The deceleration rate (averaging 32 g's) is controlled by the flow of pellets through the area between the experiment vehicle and the wall of the deceleration container. This deceleration container is mounted on a cart that can be retracted when using the 10-second mode of operation. In this mode of operation the cart is deployed after the experiment vehicle is projected upward by the pneumatic accelerator. The deceleration container mounted on the cart is shown in figure 12.

Experiment Vehicle

The experiment vehicle consisted of two basic sections (see fig. 13). An experiment section, which is housed in a cylindrical midsection, and a telemetry section, which is contained in the top fairing.

Experiment. - The experiment section consisted of the test container tray plus electrical power and control system equipment mounted in the cylindrical section of the experiment vehicle (fig. 14). The test container tray included the test container, camera, and lighting and timing systems. The liquid flow system, which included an electric drive motor, speed reducing gears, and the piston pump, was mounted below the test container. During the test drop, electric power activated the drive motor and piston pump. The ensuing liquid flow pattern was recorded by a high-speed motion-picture camera. Elapsed time was obtained from a digital clock.

Telemetry system. - The on-board telemetry system is an FM/FM system with 18 continuous channels. During a test drop, telemetry is used to continuously record the position of the piston pump, two low-gravity accelerometers, and other parameters pertinent to the experiment operation.

Test Procedure

The test containers were cleaned in the facility's clean room (fig. 15). The test cylinders were cleaned ultrasonically in a detergent-water solution, rinsed with a distilled-water-methanol solution and dried in a warm air dryer. The test cylinders were then mounted on the test container tray and filled to the desired liquid depth. Contamination of the liquid and cylinder, which could alter the surface tension and contact angle, was carefully avoided. During the test, a predetermined time increment was allowed so that the liquid-vapor interface could approach its low-gravity equilibrium shape. After the formation time, the piston pump was activated, by electric timers, for approximately 3 seconds.

The experiment vehicle is balanced about its vertical axis to ensure an accurate drop trajectory. The vehicle is then positioned at the top of the vacuum chamber as shown in figure 16. It is suspended by the support shaft on a hinged-plate release mechanism. During vacuum chamber pumpdown and before release, monitoring of experiment vehicle systems is accomplished through an umbilical cable attached to the top of the support shaft. Electrical power is supplied from ground equipment. The system is then switched to internal power a few minutes before release. The umbilical cable is remotely pulled from the support shaft 0.5 second before release. The vehicle is released by pneumatically shearing a bolt that holds the hinged plate in the closed position. No

measurable disturbances are imparted to the experiment vehicle by this release procedure.

The total free-fall test time obtained in this mode of operation is 5.16 seconds. During the drop, the vehicle's trajectory and deceleration are monitored on closed-circuit television. After the drop, the vacuum chamber is vented to the atmosphere and the experiment vehicle is returned to ground level.

REFERENCES

1. Lacovic, Raymond F.; et al.: Management of Cryogenic Propellants in a Full-Scale Orbiting Space Vehicle. NASA TN D-4571, 1968.

2. Stark, J. A.; and Blatt, M. H.: Cryogenic Zero Gravity Prototype Vent System. (GDC-DDB67-006, General Dynamics Convair; NAS8-20146) NASA CR-98079, 1967.

3. Bullard, B. R.: Liquid Propellant Thermal Conditioning System Test Program. (LMSC-D159262, Lockheed Missiles and Space Co.; NAS3-12033 (NASA CR-72971, 1972.

4. Poth, Louis J.; and Van Hook, James R.: Control of the Thermodynamic State of Space-Stored Cryogens by Jet Mixing. J. Spacecraft, vol. 9, no. 5, May 1972, pp. 332-336.

5. Berenyi, Steven G.; Nussle, Ralph C.; and Abdalla, Kaleel L.: An Experimental Investigation of the Effect of Gravity on a Forced Circulation Pattern in Spherical Tanks. NASA TN D-4409, 1968.

6. Symons, Eugene P.; and Staskus, John V.: Interface Stability During Liquid Inflow to Partially Full, Hemispherical Ended Cylinders During Weightlessness. NASA TM X-2348, 1971.

7. Sterbenz, W. H.: Liquid Propellant Thermal Conditioning System. (LMSC-K-07-68-2, Lockheed Missiles and Space Co.; NAS3-7942) NASA CR-72365, 1968.

TABLE I. – SUMMARY OF TEST PARAMETERS

Test	Gravity level, g's	Liquid filling, percent by volume	Jet exit tube length, cm	Jet volumetric flow rate		Jet velocity, cm/sec
				cc/sec	Percent of tank volume/sec	
1	0	30	8	4.2	0.80	33.4
2	0		2	4.3	.82	34.2
3	1		2	4.3	.82	34.2
4	0		8	6.1	1.16	48.6
5			2	6.1	1.16	48.6
6			8	8.4	1.60	66.9
7				24.0	4.58	191.0
8		50		4.2	.80	33.4
9				6.4	1.22	51.0
10			2	6.0	1.14	47.8
11	1		8	6.0	1.14	47.8
12	1		2	6.0	1.14	47.8
13	0		8	8.5	1.62	67.7
14	1			8.6	1.64	68.5
15	0			24.1	4.60	191.0
16	1			24.1	4.60	191.0
17	0			49.3	9.43	393.0
18	1			60.5	11.55	482.0
19	1		2	56.5	10.80	450.0
20	0	70	8	6.0	1.14	47.8
21			2	6.1	1.16	48.6
22			8	8.6	1.64	68.5
23				12.3	2.35	98.0
24				17.2	3.29	137.0
25				24.2	4.62	192.0
26				34.0	6.50	271.0
27				42.7	8.15	340.0
28		90		6.0	1.14	47.8
29			2	6.2	1.18	49.4
30			8	9.0	1.72	71.6
31			8	11.8	2.25	94.1
32			2	12.0	2.30	95.7
33	1		2	12.0	2.30	95.7
34	0		8	16.9	3.23	135.0
35				24.2	4.62	192.0
36				33.9	6.48	270.0
37				48.2	9.20	384.0
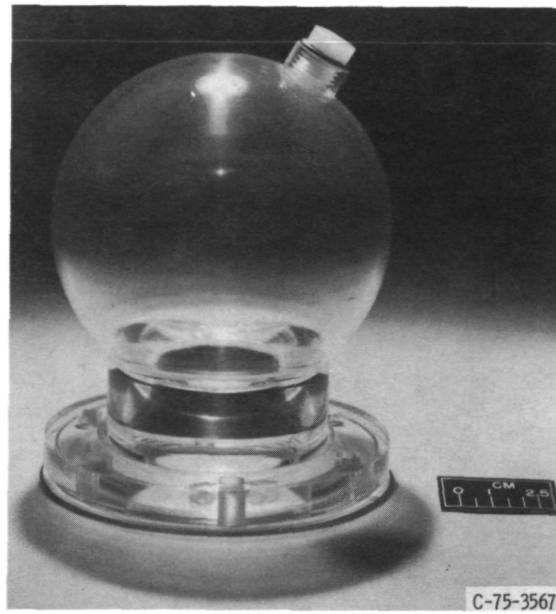
Figure 1. - Spherical experimental tank.

Axial jet   Radial jet
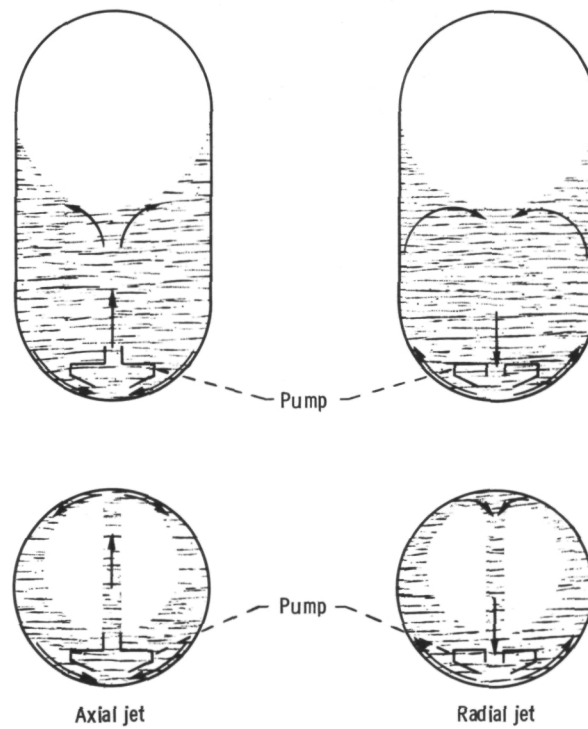
Figure 2. - Liquid-jet pump flow patterns.
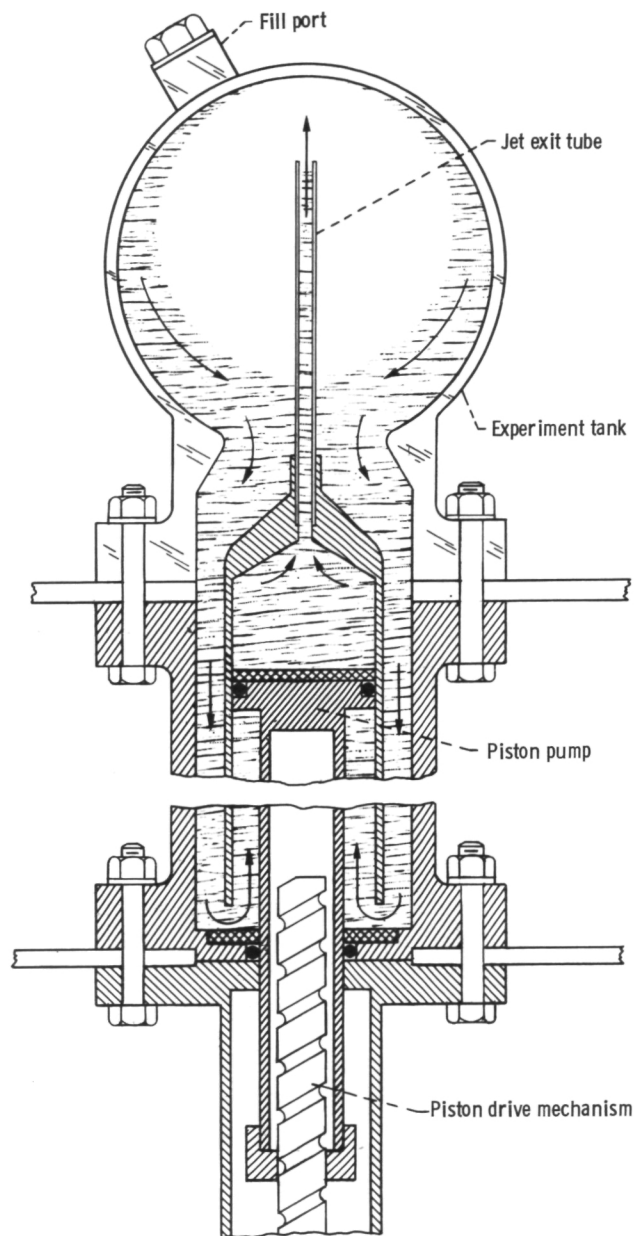
Figure 3. - Liquid flow system.
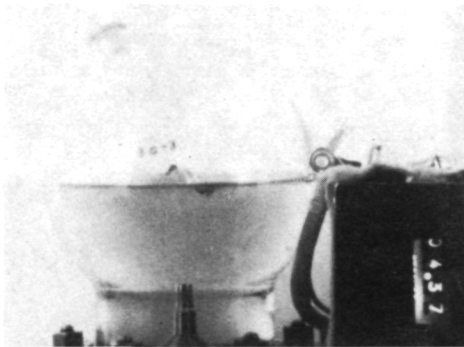
(a) Exit tube length 2 centimeters; liquid-jet inflow rate, 1.14 percent per second.
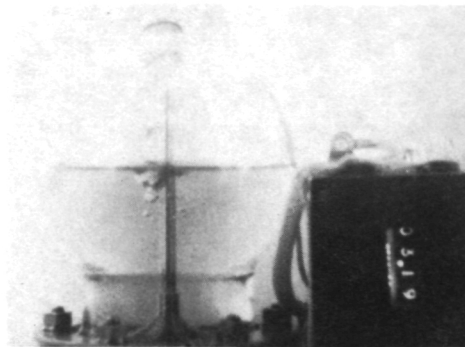
(b) Exit tube length, 8 centimeters; liquid-jet inflow rate, 1.14 percent per second.
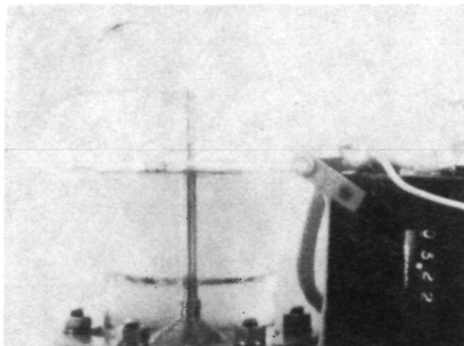
(c) Exit tube length, 8 centimeters; liquid-jet inflow rate, 1.64 percent per second.

(d) Exit tube length, 2 centimeters; liquid-jet inflow rate, 10.80 percent per second.

Figure 4. - Normal gravity liquid flow patterns, 50 percent liquid filling.
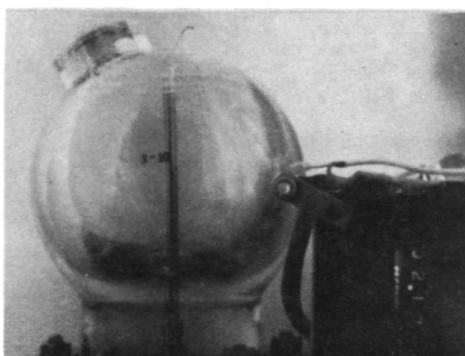
(a) Zero-gravity liquid-vapor interface configuration at initiation of flow.
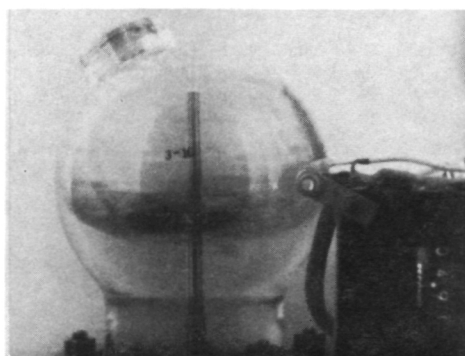
(b) Steady liquid flow pattern; liquid-jet inflow rate, 1.22 percent per second.

Figure 5. - Liquid flow pattern during weightlessness, 50 percent liquid filling.
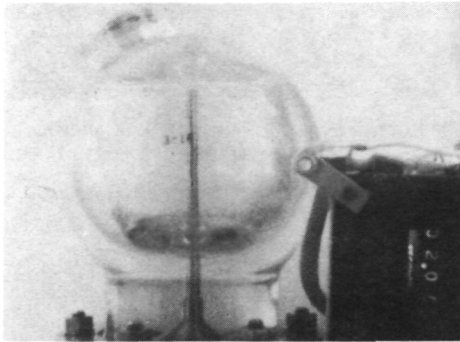
(a) Zero-gravity liquid-vapor interface configuration at initiation of flow; 70 percent liquid filling.
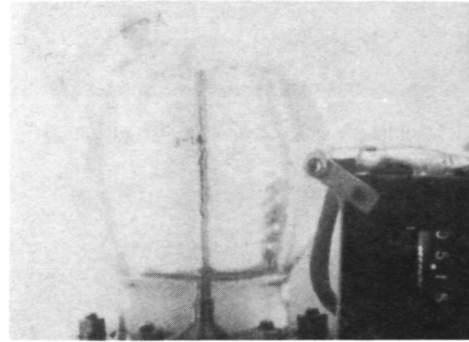
(b) Steady liquid flow pattern for 70 percent filling; liquid-jet inflow rate, 1.14 percent per second.
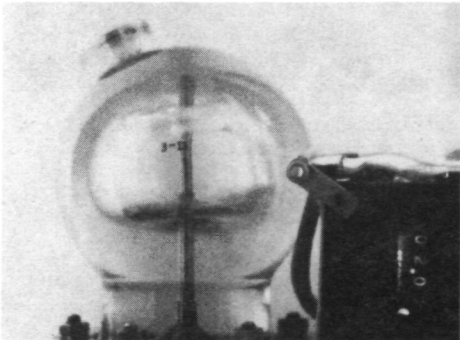
(c) Zero-gravity liquid-vapor interface configuration at initiation of flow; 90 percent liquid filling.
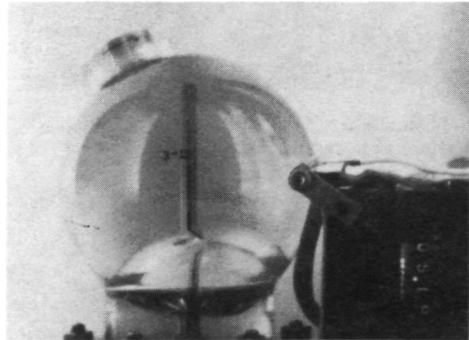
(d) Liquid-vapor interface configuration for 90 percent filling after 3 seconds. Liquid jet inflow rate, 1.14 percent per second.

Figure 6. - Effect of liquid filling.
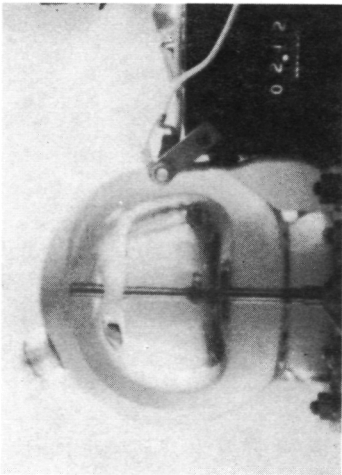
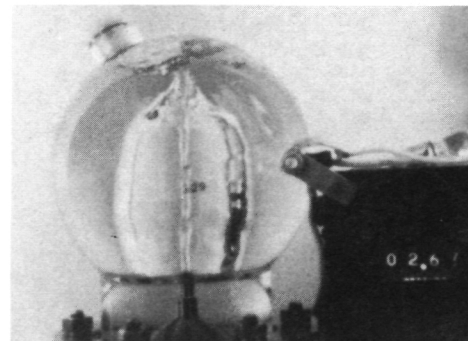(a) Zero-gravity liquid-vapor interface configuration at initiation of flow.
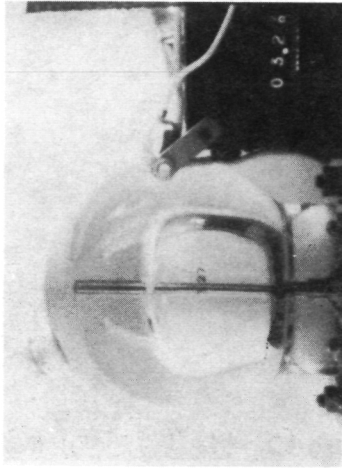
(b) Liquid-vapor interface configuration after 1 second. Liquid-jet inflow rate, 2.25 percent per second.
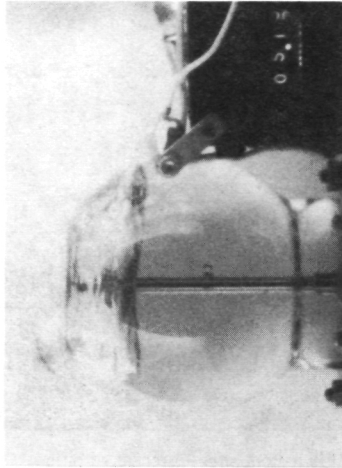
(c) Steady liquid flow pattern; liquid-jet inflow rate, 2.25 percent per second.
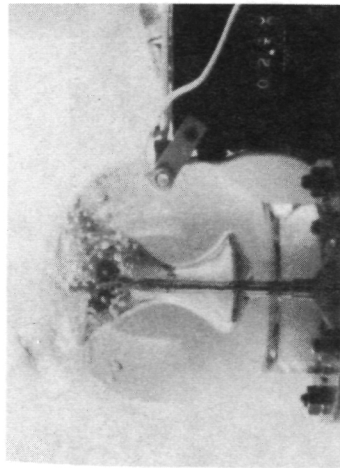
(d) Liquid-vapor interface configuration after 0.4 second. Liquid-jet inflow rate, 6.48 per second.
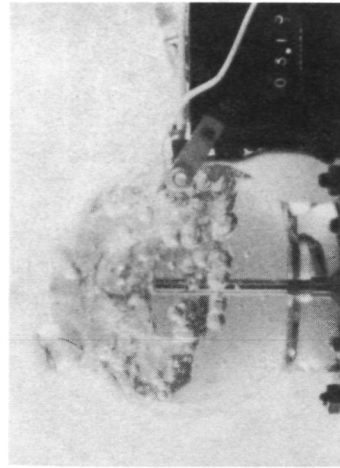
(e) Highly turbulent flow pattern. Liquid-jet inflow rate, 6.48 percent per second.

Figure 7. - Effect of inflow rate at 90 percent liquid filling.

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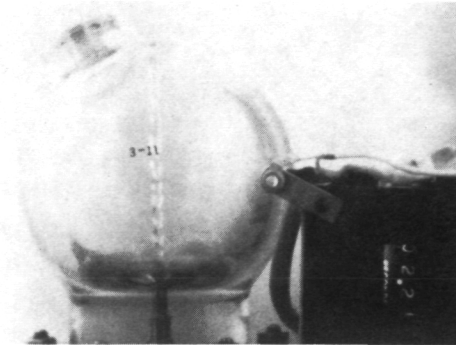
(a) Zero-gravity liquid-vapor interface configuration at initiation of flow.
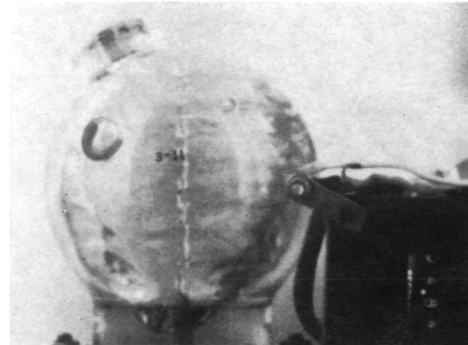
(b) Final flow pattern after 3 seconds of inflow.

Figure 8. - Effect of liquid-jet outlet position at 50 percent liquid filling; liquid-jet inflow rate, 1.14 percent per second.
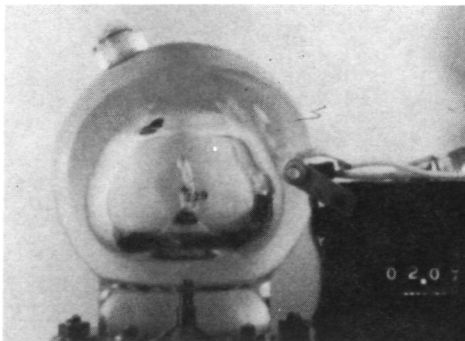
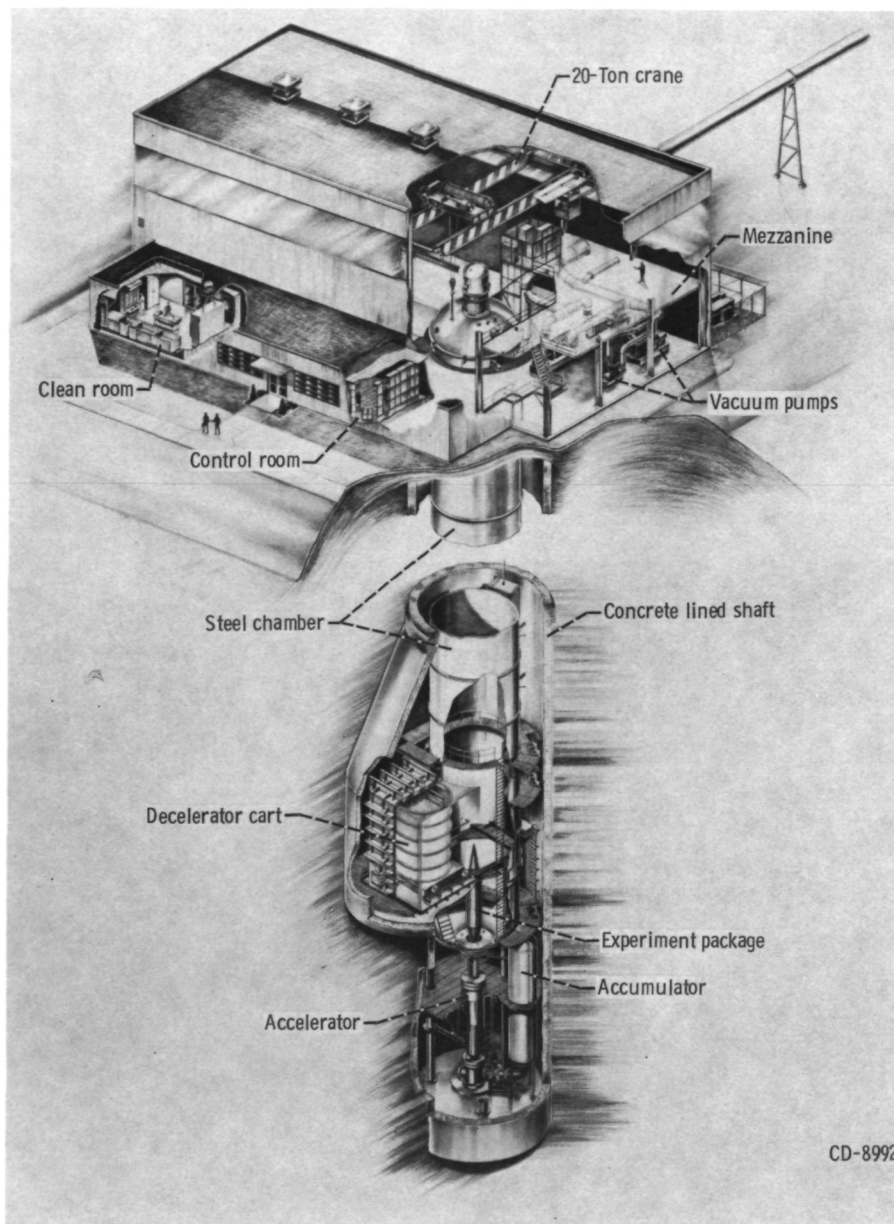(a) Zero-gravity liquid-vapor interface configuration at initiation of flow.

(b) Liquid-vapor interface configuration after 0.6 second of inflow.
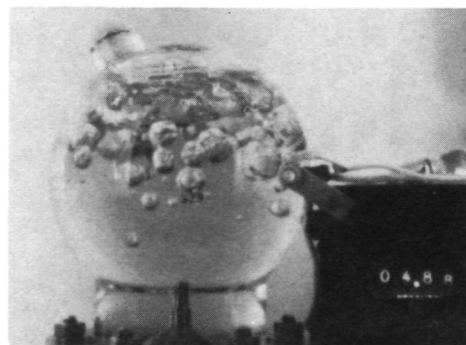
(c) Final highly turbulent flow pattern.

Figure 9. - Effect of liquid-jet outlet position at 90 percent liquid filling; liquid-jet inflow rate, 2.30 percent per second.

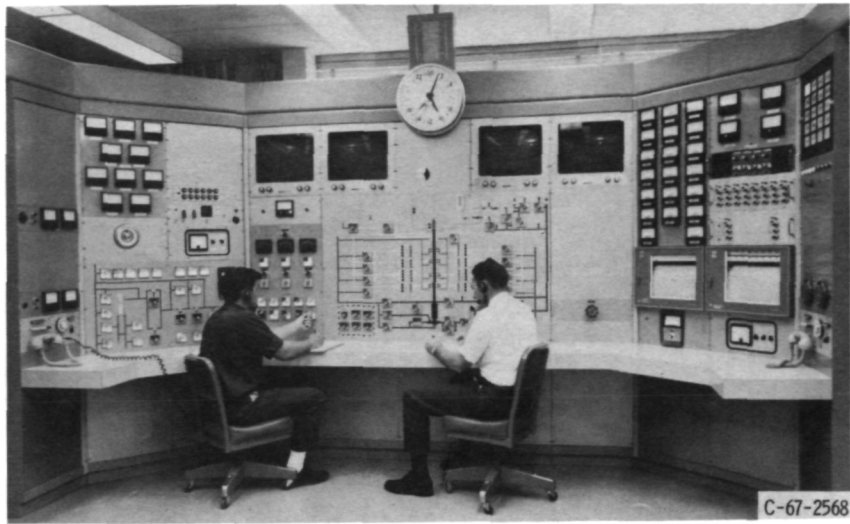Figure 10. - 5- To 10-second zero-gravity facility.

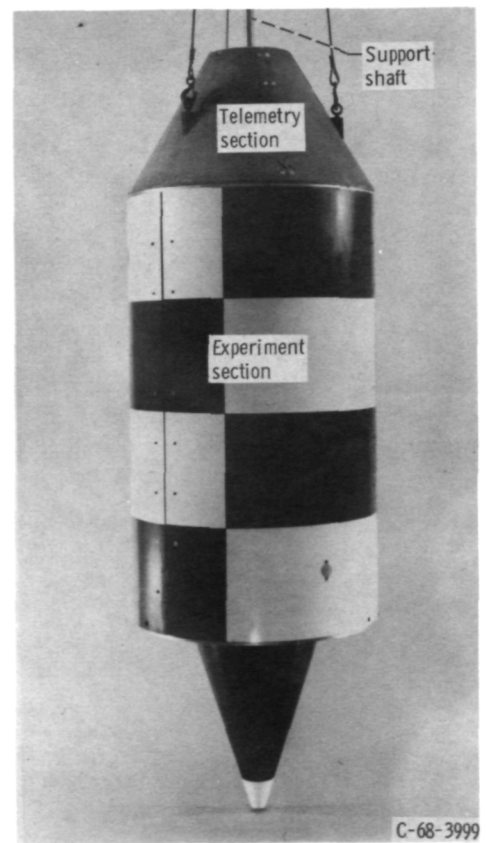Figure 11. - Control room.

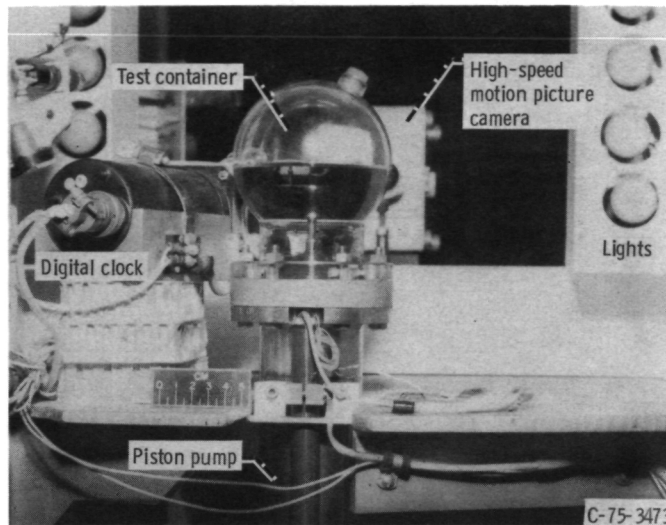Figure 12. - Deceleration system.

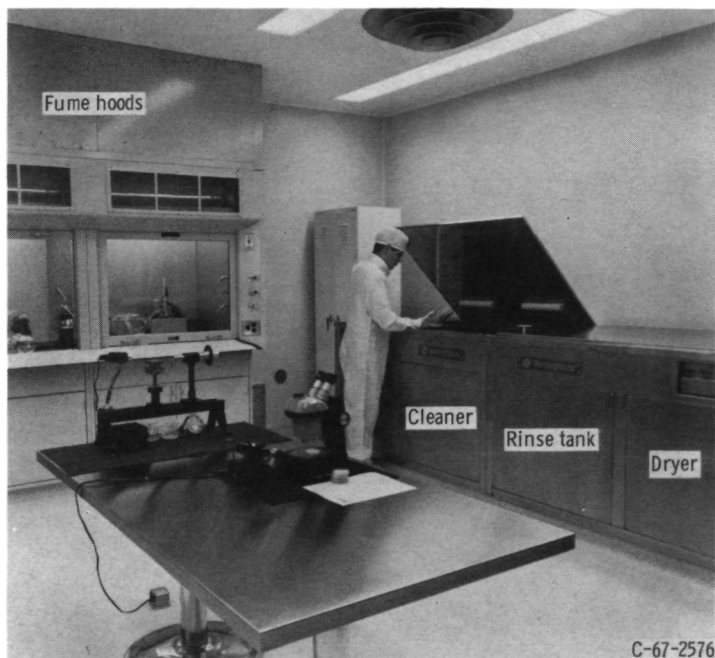Figure 13. - Experiment vehicle.

Figure 14. - Experiment section.

Figure 15. - Facility clean room.
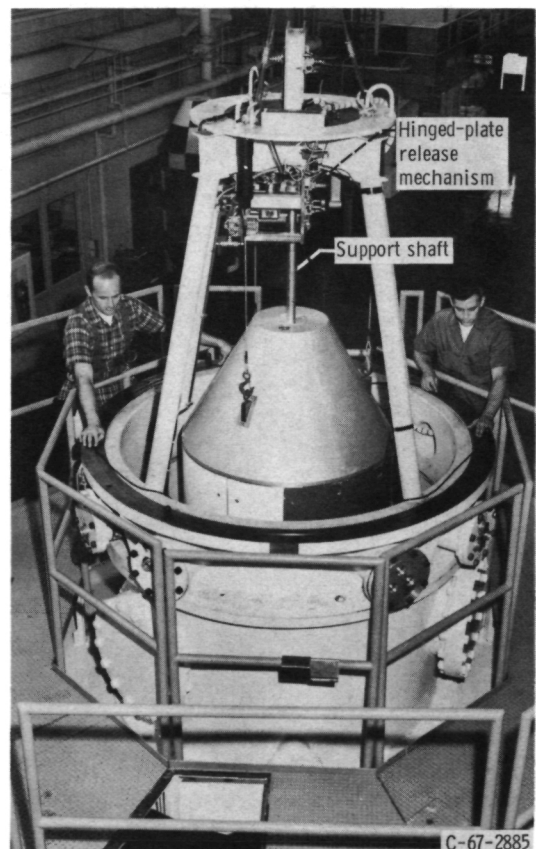

Figure 16. - Vehicle position before release.

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