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ZERO-GRAVITY LIQUID-VAPOR
INTERFACE CONFIGURATIONS
IN CONICAL TANKS

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Cleveland, Ohio 44135

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SUMMARY

An experimental investigation was conducted to determine the isothermal liquid-vapor interface configuration in weightlessness for several conical tanks varying in tank cone angle and oriented at various angles to the gravity vector before entering weightlessness. The tank cone angles investigated ranged from 26.6° to 81.0° . The orientation tests ranged from 0° (the apex of the cone located "down") to and including 180° . The liquid used in the tests had a 0° static contact angle with the tank wall. The results obtained give the liquid volumes required to enclose the vapor space (totally wet walls) as a function of tank cone angle and orientation angle.

INTRODUCTION

NASA's Lewis Research Center has been involved in extensive programs studying the liquid-vapor interface configuration in various tank geometries during weightlessness. These studies have been limited primarily to cylindrical and spherical geometries (refs. 1 to 5) because of their applicability to present day vehicles. With the advent of more ambitious space travel, such as an orbiting space station, a space shuttle, and interplanetary missions, the efficient packaging of propellants and other liquid supply systems is becoming increasingly important. For these applications, other tank geometries such as toroids and cones have received renewed emphasis. Recently, the interface configuration in toroidal tanks in weightlessness has been documented in detail (refs. 6 and 7).

The only known information describing the liquid-vapor interface shape in conical tanks in weightlessness is that of reference 8. In that experimental study, the basic interface shape for a conical tank was photographed for a range of liquid fillings and for

liquids which were wetting and nonwetting on the container walls. The orientation before entering weightlessness was restricted such that the tank's axis of rotation was parallel relative to the gravity vector with the apex located "down" and the liquid initially positioned in the apex of the cone (0° orientation). The results for a wetting liquid (0° contact angle), which would be representative of typical propellant and tank combinations, indicate that for low fillings the bulk liquid remained in the same location in the tank with the interface forming a surface of constant curvature intersecting the tank wall at the contact angle of the liquid. For a sufficiently high filling, end effects were reported, for which the gas bubble was located in the interior of the liquid.

For a tank to be efficiently used in a low gravity environment, the position of the liquid and vapor must be predictable, so that operations such as draining liquid and venting vapor can be accomplished successfully. Because accelerations to maneuver a spacecraft may be oriented at various angles to the tank, the configuration of the liquid-vapor interface in a conical tank that enters a weightless state at different orientations must be known. This report, therefore, presents the results of an experimental investigation to determine the isothermal liquid-vapor interface configuration in weightlessness for several conical tanks varying in tank cone angles and oriented at various angles to the gravity vector before entering weightlessness. The angle or orientation tests ranged from 0° as described earlier to and including 180° and simulated the effect the nonaxial maneuvers would have on repositioning the liquid-vapor interface. Results are presented giving liquid volumes required to enclose the vapor space (totally wet walls) as a function of orientation and cone angle. The liquid used in the tests had a 0° contact angle with the tank wall.

APPARATUS AND PROCEDURE

The experimental vehicle and the test facility used in this study together with their operating procedure are described in detail in the appendix.

The test tanks used were cone-shaped glass containers with truncated apex and ellipsoidal base. Four tanks were selected as shown in figure 1 varying in cone angles from 26.6° to 81.0° and with base shapes generated so that the total volume for each tank was nearly equal. The table accompanying figure 1 gives the pertinent dimensions of the tanks.

In order to determine the effect of initial conditions on the final equilibrium liquid-vapor interface configuration, the conical tanks were initially mounted at various angles relative to the gravity vector before entering weightlessness (see fig. 2). These mounting angles or orientation angles included 0° , 45° , 90° , 135° , and 180° .

The liquid used in the tests was anhydrous ethanol which had a 0° static contact angle with the glass. A small amount of dye was added to the liquid to improve photographic quality and had no measurable effect on the fluid properties. The density and surface tension of ethanol are 0.789 gram per cubic centimeter and 22.3 dynes per centimeter at 20° C, respectively.

RESULTS AND DISCUSSION

Effect of Tank Geometry

For a tank oriented at 0° relative to the gravity vector prior to entering weightlessness, the liquid is initially positioned in the apex of the cone. After entering weightlessness, the liquid will either partly wet the walls or completely wet the tank enclosing the vapor, depending on the amount of liquid in the tank. Figure 3 shows the interface configurations for both partly wet and completely wet walls in a 39.8° cone angle tank. The interface configurations are typical of the ones that formed in all the tanks. For the case when the walls were partly wet, the bulk of the liquid remained in the apex of the cone and the interface formed a surface of constant curvature intersecting the tank wall at the contact angle of the liquid (0°), as reported in reference 8. When the walls were totally wetted, a thin layer of liquid covered the base of the tank with the bulk of the liquid remaining in the apex.

The delineation between partly wetted and totally wetted tank walls for various tank cone angles for the 0° tank orientation is shown in figure 4. The theoretical points on the figure were determined by assuming the liquid-vapor interface was a surface of constant curvature intersecting the walls at the contact angle of the liquid and the breaking point between partly wetted and totally wetted walls was the top of the frustum of the cone. If the liquid went above the top of the frustum of the cone, the ellipsoidal end of the tank would cause the liquid to enclose the vapor. A line drawn through the theoretical points delineates the regions of partly wetted and totally wetted walls. The area to the left of the line in figure 4 is the region where the walls are partly wetted, and the area to the right of the line is the region where the vapor is completely enclosed by the liquid. Figure 4 shows that the experimental results do fall into the theoretical predicted regions of partly wetted walls or enclosed vapor. The figure also shows that as the tank cone angle is increased the percent filling by volume required to enclose the vapor space decreases.

Effect of Tank Orientation

For tanks oriented at angles relative to the gravity vector before entering weightlessness, the resulting zero-gravity liquid-vapor interface configurations which formed were functions of both the orientation and percent filling. Interface configurations in a 39.8° cone angle tank which are representative of the ones that formed in the other tanks are shown in figure 5. Again, the interface configurations shown are for a filling low enough to cause a partly wetted condition and for filling sufficient to enclose the vapor. For the partly wetted wall condition the interface configurations were similar to the 0° orientation interface configuration in that the bulk of the liquid was retained in the tank end in which it was initially positioned before entering weightlessness. However, depending on the tank orientation angle, some liquid moved toward the opposite end of the tank. At a 45° orientation, some liquid moved along the lower portion of the tank reaching and covering part of the ellipsoidal base. At a 90° orientation, a layer of liquid covered part of the base and part of the lower conical wall. At a 135° orientation, a thin layer of liquid moved along the lower conical wall toward the apex and came to rest before reaching that end of the tank. At 180° orientation, the bulk of the liquid remained in its normal gravity position with the interface forming a surface of constant curvature and intersecting the wall at the contact angle of the liquid.

In most cases for the totally wetted wall condition, as the photographs in figure 5 show, only a small amount or a thin layer of liquid reached the opposite end of the tank. An exception is noted for the 135° orientation, in which a considerable amount of liquid collected in the apex. It is also interesting to note that, at a 90° orientation, a relatively low liquid filling was sufficient to totally wet the wall, and at a 180° orientation, a very high filling was required.

The photographs in figure 5 clearly indicate that, regardless of whether the liquid partly covers or totally covers the wall, effective positioning of drains and vents will be difficult. In-flight maneuvers or other spacecraft motions which could cause the liquid in the tank to be repositioned could result in either totally wetted walls or undesirable relocation of the liquid. As the photographs show, locating the vent and drain at either tank "end" may result in a liquid covered vent or a vapor covered drain, or both.

The delineation between the regions of partly wetted and totally wetted tank walls is illustrated graphically in figures 6, 7, and 8 for three of the cone angles investigated. In figure 6 the data for the 26.6° cone angle tank are presented. For a tank oriented at 0° , the percent filling required to enclose the vapor was approximately 43 percent and remained relatively unchanged up to the 45° orientation. At a 90° orientation, there was a significant decrease to approximately 10 percent in the percent filling required to enclose the vapor. The probable reason for the decrease was the relatively small cone angle. For small cone angles, a relatively large portion of the conical section of the

tank is covered with liquid for small percent fillings. For both the 135° and 180° orientations, the vapor was not completely enclosed even at fillings up to 98 percent. Again, the probable reason for the high filling without the liquid enclosing the vapor was the small cone angle. At these orientations for small cone angles, the distance from the top of the cone to the highly curved liquid-vapor interface is relatively large.

Figure 7 presents the data for the 39.8° cone angle tank. For a tank oriented at 0° , the percent filling required to enclose the vapor was approximately 34 percent and remained relatively unchanged up to a 45° orientation. At a 90° orientation, the percent filling required to enclose the vapor decreased significantly to 10 percent. The probable reason for this decrease is the same as for the 26.6° cone angle tank, namely, the small cone angle. At orientations greater than 90° , the percent filling required to enclose the vapor increased with increasing tank orientation. At a 135° orientation, a filling of approximately 51 percent was required to enclose the vapor and at 180° this filling increased to approximately 95 percent.

Figure 8 presents the data for the 50.6° cone angle tank. For this tank oriented at 0° the percent filling required to enclose the vapor was approximately 34 percent and remained relatively unchanged up to a 90° orientation. The probable reason for the higher percent filling required to enclose the vapor at a 90° orientation in this tank was the larger cone angle which resulted in the liquid covering a smaller portion of the lower surface of this tank than it did in the other two tanks. For orientations greater than 90° the percent filling required to enclose the vapor increased with increasing tank orientation reaching approximately 80 percent at a 180° orientation.

A comparison of the lines delineating partly wetted and totally wetted walls for the 26.6° , 39.8° , and 50.6° cone angle tanks is made in figure 9. For orientations of 0° and 45° , the percent filling required to enclose the vapor in the 26.6° cone angle tank was approximately 10 percent greater than that required for the 39.8° and 50.6° cone angle tanks. At a 90° orientation, the percent filling required to enclose the vapor decreased to approximately 10 percent in the 26.6° and 39.8° cone angle tanks while in the 50.6° cone angle tank it remained relatively unchanged from its 0° and 45° orientation requirements. At orientations greater than 90° , the percent filling required to enclose the vapor increased with increasing orientation for all the tanks. At orientations of 135° and 180° the vapor in the 26.6° cone angle tank was not enclosed even at fillings up to 98 percent. At 180° orientation, the percent filling required to enclose the vapor decreased with increasing tank cone angle. From figure 9, it can be seen that increasing the tank cone angle smooths out the line delineating partly wetted and totally wetted walls. This means that the effect of tank orientation on percent filling required to enclose the vapor was reduced as the tank cone angle was increased.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the isothermal liquid-vapor interface configuration in weightlessness for several conical tanks varying in tank cone angle and oriented at various angles to the gravity vector before entering weightlessness. The angle or orientation tests ranged from 0° (the apex of the cone located "down") to and including 180° . The liquid used in the tests had a 0° static contact angle with the tank wall. The following results were obtained:

1. For tanks oriented at a 0° angle relative to the gravity vector prior to entering weightlessness, the liquid-vapor interface for partly wetted walls was a surface of constant curvature intersecting the wall at the contact angle of the liquid as was reported in TN D-2075. Furthermore, the percent fill required to enclose the vapor decreased with increasing tank cone angle.

2. The percent filling required to enclose the vapor was a function of initial tank orientation and tank geometry (cone angle). Generally, the percent filling required to enclose the vapor was relatively unchanged up to the 45° orientation. At the 90° orientation, the percent filling required to enclose the vapor either reached a minimum or remained relatively unchanged from its 45° orientation requirement depending on the tank cone angle. At orientation greater than 90° , the percent filling required to enclose the vapor increased with increasing orientation. At a 180° orientation, the percent filling required to enclose the vapor decreased with increasing tank cone angle.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 14, 1971,
113-31.

APPENDIX - APPARATUS AND PROCEDURE

Test Facility

The experiment data for this study were obtained in the Lewis Research Center's 5- to 10-Second Zero-Gravity Facility. A schematic diagram of this facility is shown in figure 10. The facility consists of a concrete-lined 8.5-meter (28-ft) diameter shaft that extends 155 meters (510 ft) below ground level. A steel vacuum chamber, 6.1 meters (20 ft) in diameter and 143 meters (470 ft) high, is contained within the concrete shaft. The pressure in this vacuum chamber is reduced to 13.3 newtons per square meter (1.3×10^{-4} atm) by utilizing the Center's wind tunnel exhaust system and an exhaust 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 exhaust control system, the experiment vehicle predrop checkout and control system, and the data retrieval system. Those components of the experiment which are in contact with the test fluid are prepared in the facility's class 10 000 clean room. The major elements of the clean room are an ultrasonic cleaning system (fig. 12(a)) and a class 100 laminar flow work station (fig. 12(b)) for preparing those experiments requiring more than normal cleanliness.

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 falls freely. That is, no guide wires, electrical lines, etc., 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 of the order of 10^{-5} g maximum.

Recovery system. - After the experiment vehicle has traversed the total length of the vacuum chamber, it is decelerated in a 3.6-meter (12-ft) diameter, 6.1-meter (20-ft) 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

which can be retracted prior to utilizing 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 13.

Experiment Vehicle

The experiment vehicle used to obtain the data for this study is shown in figure 14. The overall vehicle height (exclusive of the support shaft) is 1.74 meters (5.58 ft), the length is 1.52 meters (5 ft) and the width is 0.51 meter (1.68 ft). The vehicle consists of a telemetry system and an experiment section which is housed in the rectangular mid-section.

Telemetry system. - The on-board telemetry system which is used to collect data is a standard Inter-Range Instrumentation Group (IRIG) FM/FM 2200-megahertz tele-meter. It is used during a test drop to record as many as 18 channels of continuous data. The system frequency range extends to 2100 hertz. The telemetered data are recorded on two high-response recording oscillographs located in the control room.

Experiment section. - The experiment section consists of the test tank, a photographic and lighting system, a digital clock, and an electrical system to operate the various components. The test tank is indirectly illuminated by means of a backlighting system contained in the experiment housing which provides sufficient light so that the behavior of the liquid-vapor interface can be recorded by a high-speed 16-millimeter camera. A clock having a calibrated accuracy of ± 0.01 second is positioned within the field of view of the camera to give an indication of the elapsed time during the weightless drop. The electrical components onboard the package were operated through a control box and received their power from rechargeable nickel cadmium cells.

Test preparation. - The test preparation included ultrasonic cleaning, filling, and mounting of the tank in the experiment housing at the desired tank mounting angle.

The tank was cleaned in the ultrasonic cleaner with a mild aqueous detergent solution, rinsed with distilled water and dried in a warm-air dryer so that the wetting characteristics of the liquid would not be affected by contaminants. The tank was then filled with the required volume of test liquid in the clean room area and mounted in the experiment housing.

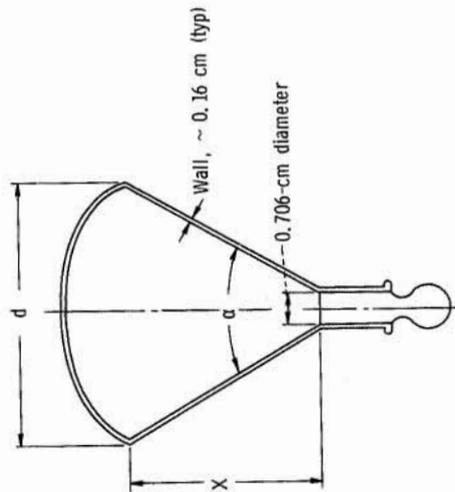
Test procedure. - The vehicle was then positioned at the top of the vacuum chamber, as shown in figure 15. It was suspended by the support shaft on a hinged-plate release mechanism. During vacuum chamber pumpdown and prior to release, monitoring of the experiment vehicle system was accomplished through an umbilical cable attached to the top of the support shaft. Electrical power was supplied from ground equipment. The

system was switched to internal power a few minutes before release. The umbilical cable was remotely pulled from the shaft 0.5 second prior to release. The experiment vehicle was released by pneumatically shearing a bolt that was holding the hinged plate in the closed position. No measurable disturbances were imparted to the experiment by this release procedure.

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

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Frustum height, X, cm	Diameter, d, cm	Tank cone angle, α , deg	Volume, cc
8.56	4.75	26.6	91.8
6.63	5.54	39.8	94.2
5.72	6.19	50.6	92.6
3.81	7.53	81.0	84.5

Figure 1. - Conical tanks.

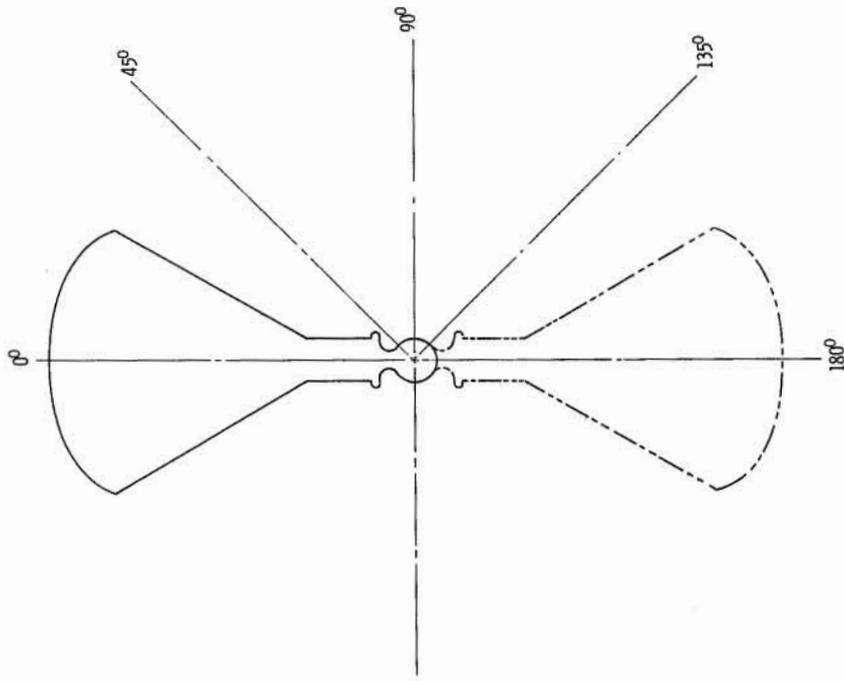
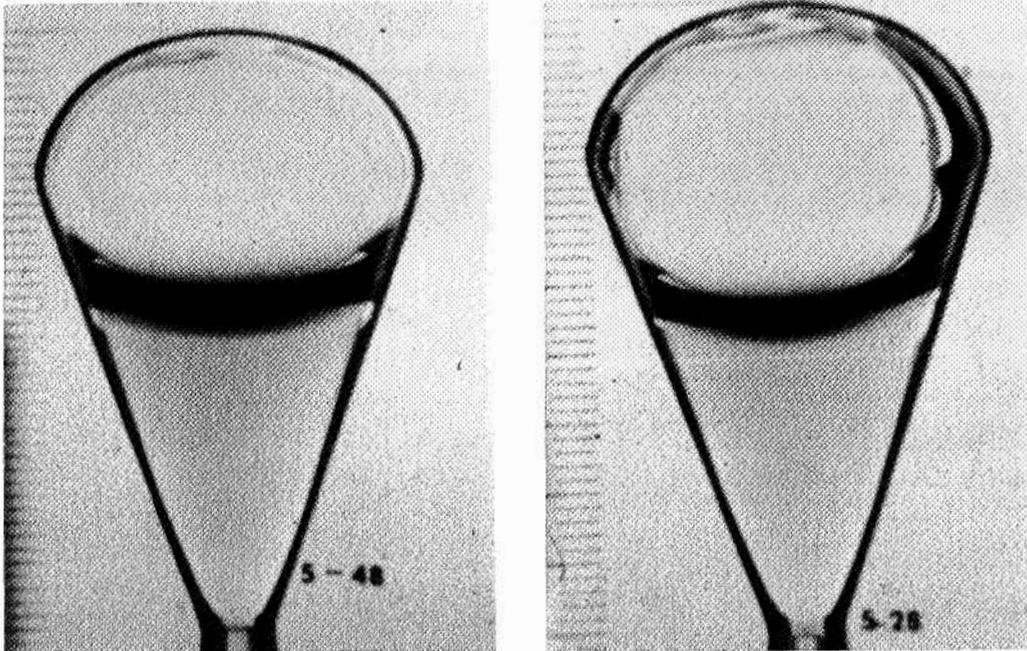


Figure 2. - Tank mounting angles.



(a) Partly wet; 29.6 percent filling.

(b) Wet; 37.2 percent filling.

Figure 3. - Interface configurations for 0° tank orientation and 39.8° cone angle tank.

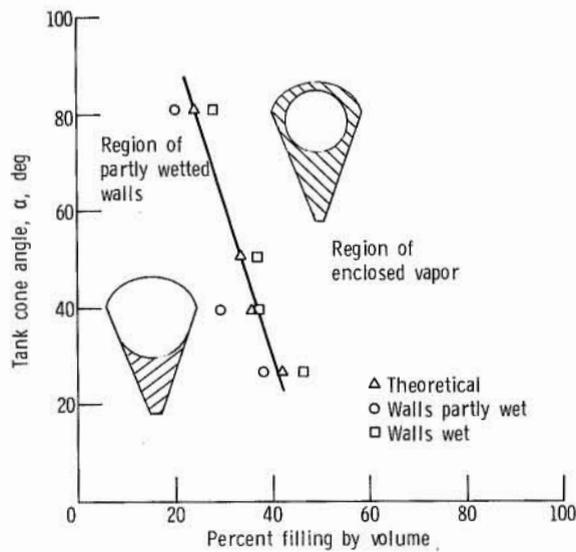


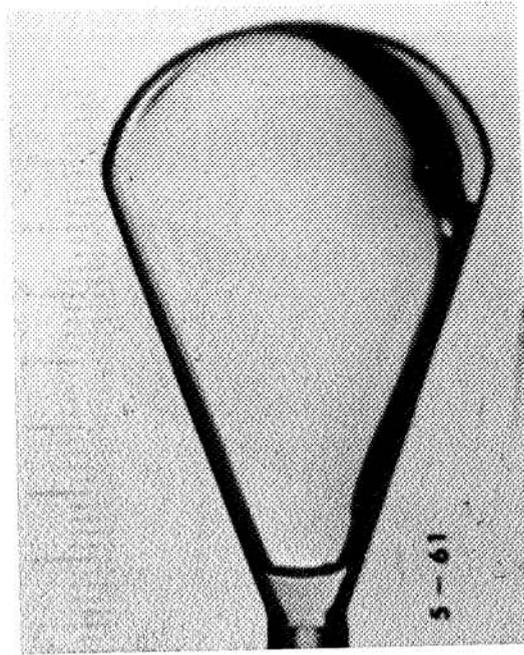
Figure 4. - Effect of cone angle for tank oriented at 0°.

Wet



(a-2) 38.2 percent filling.

(a) 45° tank orientation.



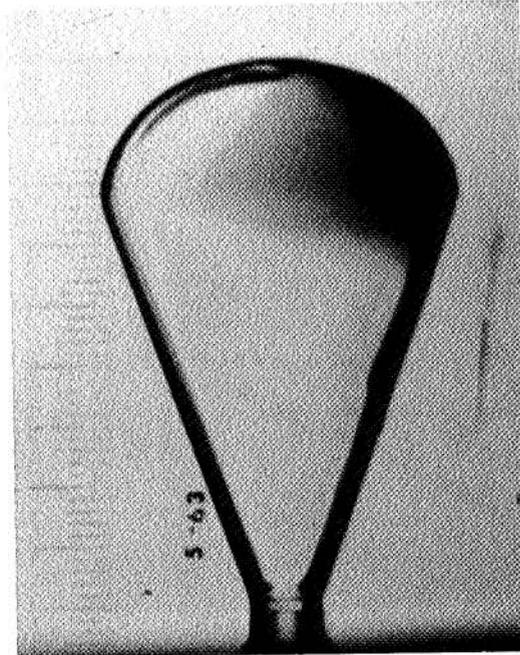
(b-2) 14.9 percent filling.

(b) 90° tank orientation.

Partly wet



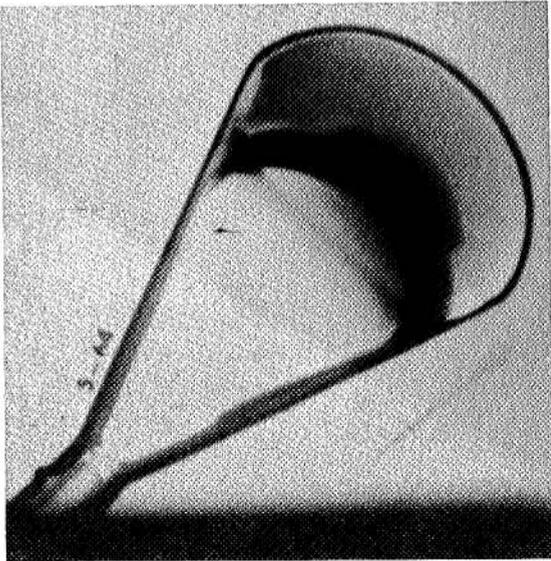
(a-1) 29.6 percent filling.



(b-1) 7.4 percent filling.

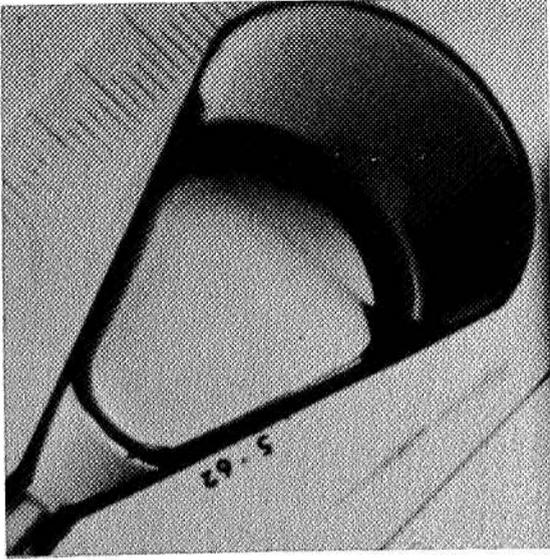
Figure 5. - Interface configurations for various tank orientations and 39.8° cone angle tank.

Partly wet



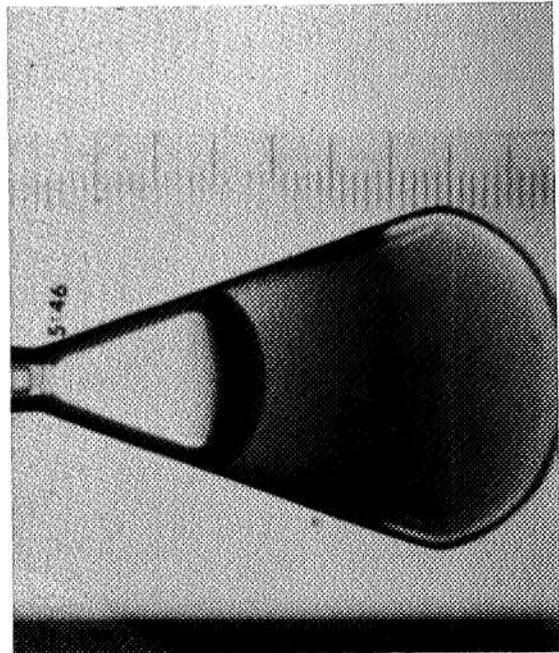
(c-1) 47.8 percent filling.

Wet

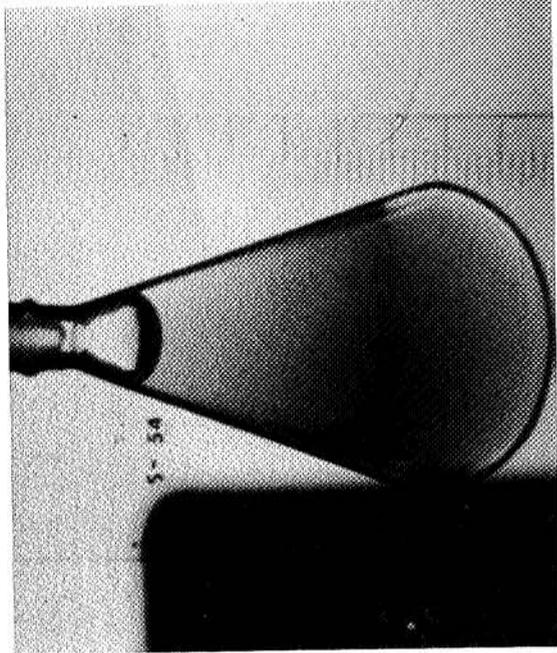


(c-2) 55.3 percent filling.

(c) 135° tank orientation.



(d-1) 90.2 percent filling.



(d-2) 97.6 percent filling.

(d) 180° tank orientation.
Figure 5. - Concluded.

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clo.

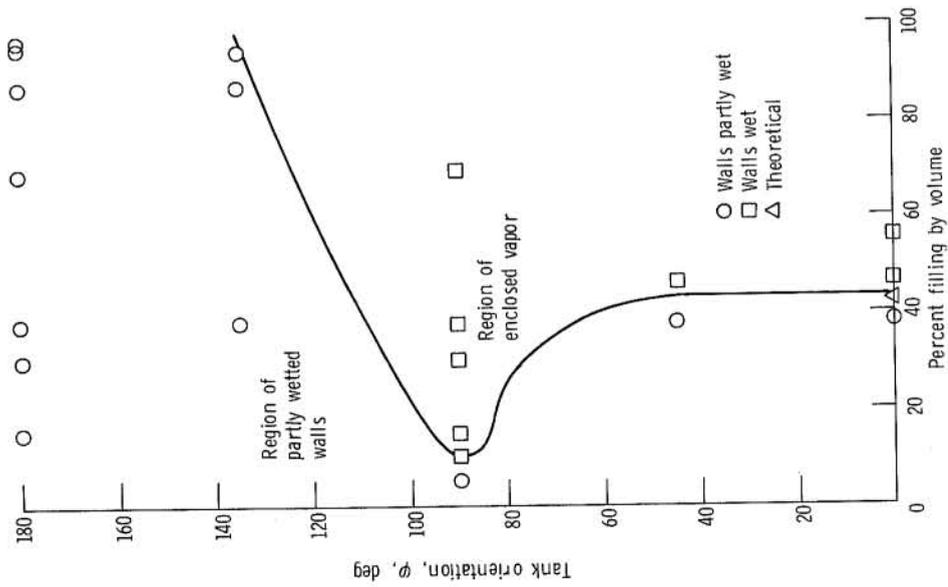


Figure 6. - Effect of orientation for 26.6 cone angle tank.

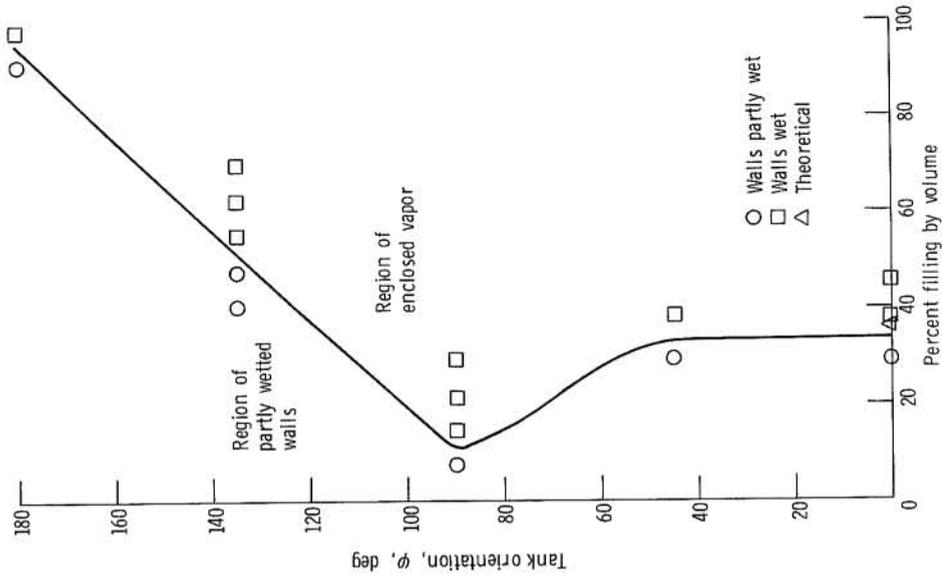


Figure 7. - Effect of orientation for 39.8° cone angle tank.

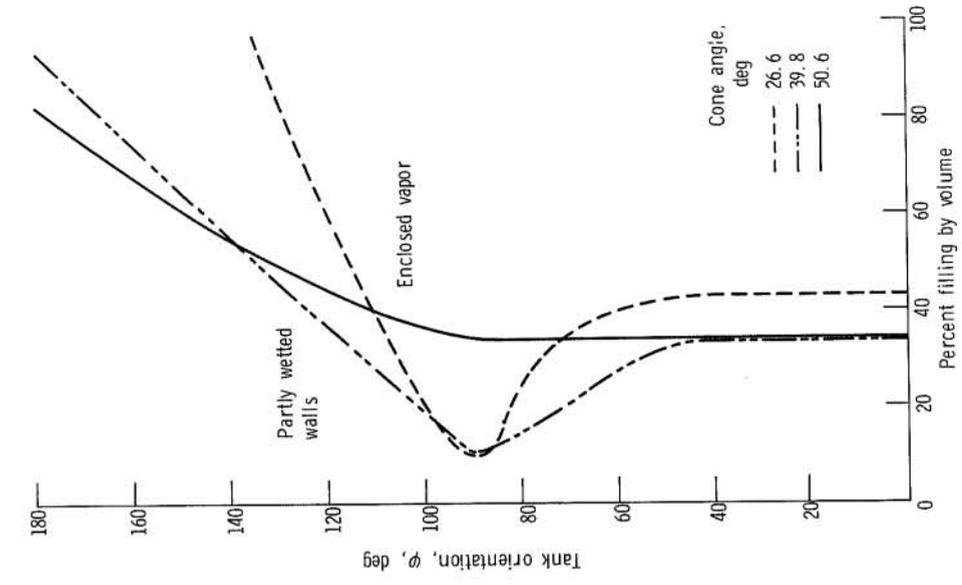


Figure 9. - Effect of orientation.

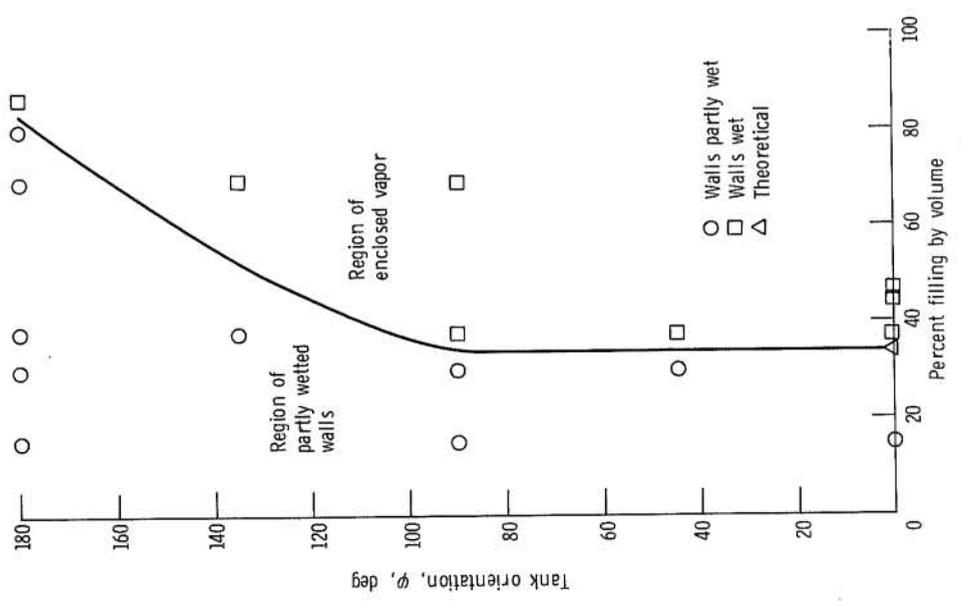


Figure 8. - Effect of orientation for 50.6° cone angle tank.

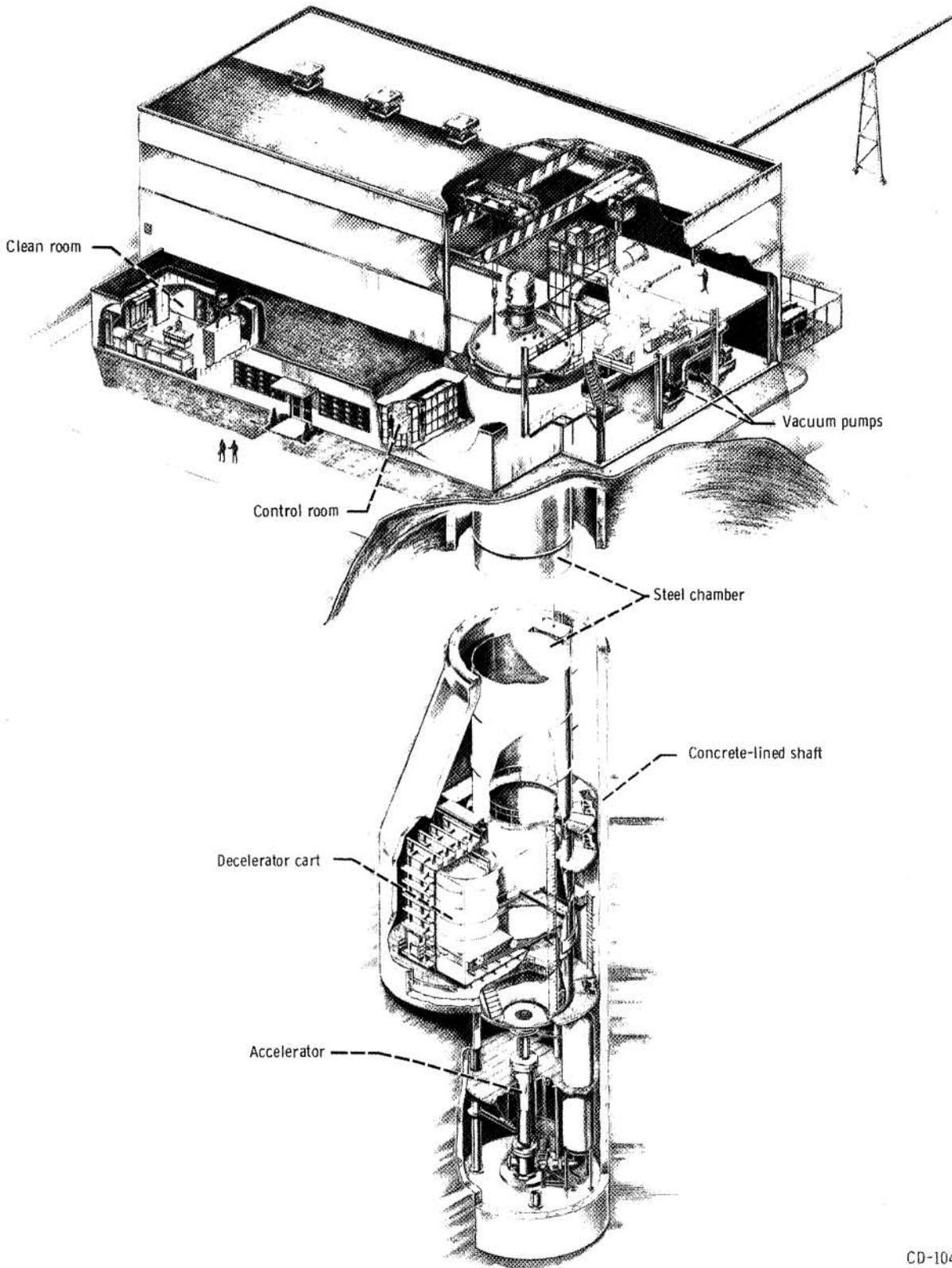
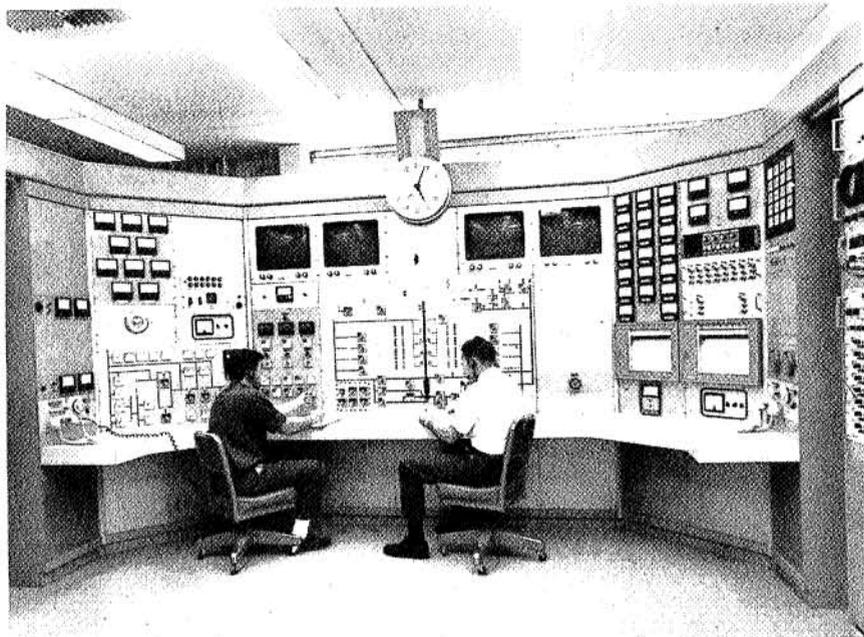


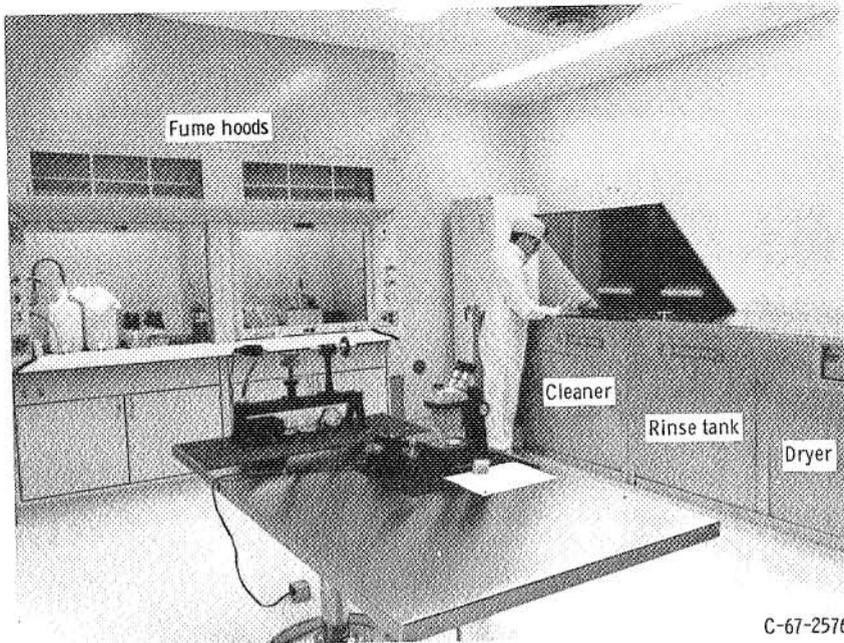
Figure 10. - Schematic diagram of 5- to 10-Second Zero-Gravity Facility.

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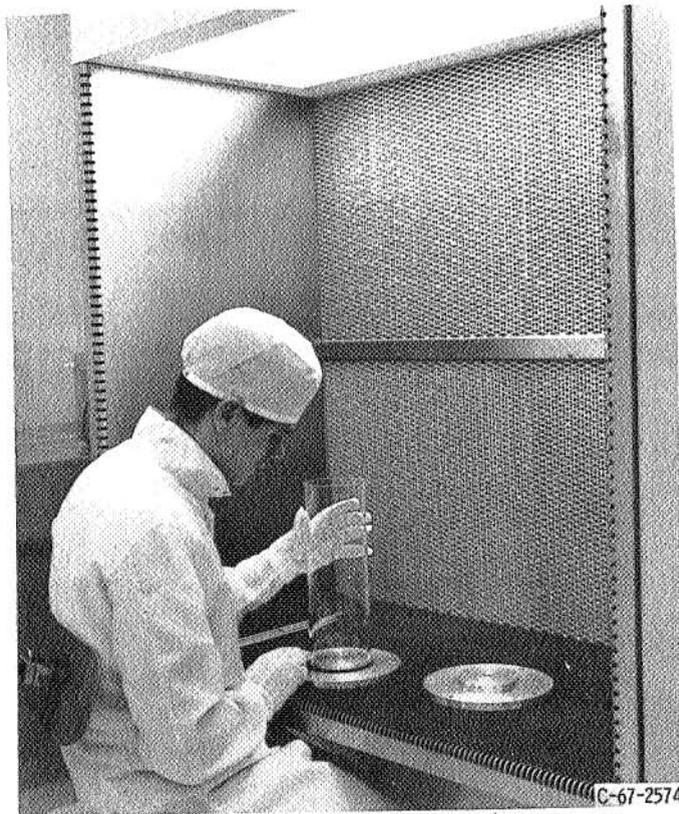
C-67-2568

Figure 11. - Control room.



C-67-2576

(a) Ultrasonic cleaning system.



C-67-2574

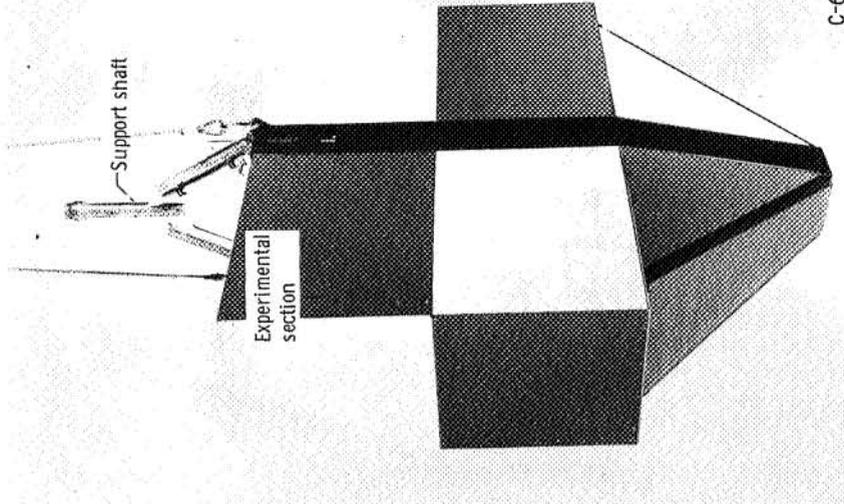
(b) Laminar-flow work station.

Figure 12. - Clean room.



C-66-3684

Figure 13. - Deceleration system.



C-68-4001

Figure 14. - Experimental vehicle.

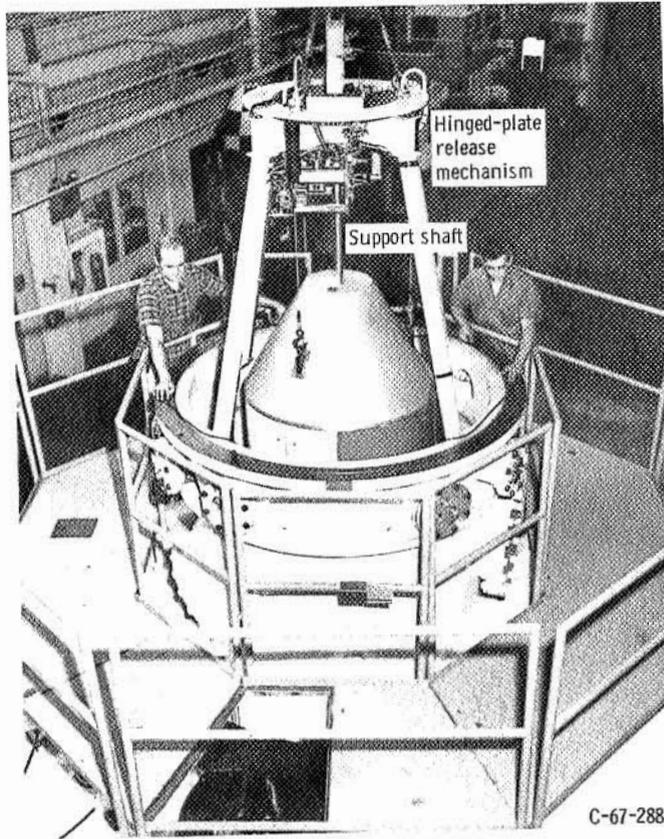


Figure 14. - Experimental vehicle.



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