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OUTLET BAFFLES — EFFECT ON LIQUID RESIDUALS FROM ZERO-GRAVITY DRAINING OF HEMISPHERICALLY ENDED CYLINDERS

by Eugene P. Symons

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

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SUMMARY

An experimental investigation was conducted to study the relative effectiveness of various outlet baffles in reducing liquid residuals resulting from the draining of hemispherically ended cylindrical tanks in a weightless environment. Three different baffles were employed in the study. The relative effectiveness of each baffle was determined by comparing the results obtained, in the form of liquid residuals, with those results obtained for an unbaffled tank. Data indicate that all the baffles tested reduced residuals. Reductions between 10 and 60 percent were obtained depending on baffle geometry and outflow Weber number.

INTRODUCTION

As a part of the overall study of the behavior of liquids in containers in a weightless environment, the Lewis Research Center has been conducting experimental investigations of the problems associated with the draining of liquids from tanks in zero gravity. The objectives of these studies are to define specific problem areas which might exist during such operations as in-orbit propellant transfer and to establish useful criteria to aid in the solution of such problems.

The initial experimental study of draining from flat-bottomed cylindrical tanks (ref. 1) showed that the liquid-vapor interface is severely distorted during liquid outflow and that this distortion generally increases with liquid outflow rate. This severe distortion contributes to large values of liquid residuals. In addition, the study of reference 1 showed that simple outlet baffles were effective in delaying the ingestion of vapor into the tank outlet and thereby reduced liquid residuals. The studies of reference 2 examined the effects of several outlet baffles in flat-bottomed tanks and found that a large flat plate baffle reduced liquid residuals to about 60 percent of those which were observed without outlet baffles. Additional studies of liquid outflow were reported in references 3 to 9.

The use of baffles has not been restricted to improving liquid outflow performance by reducing liquid residuals. Reference 10 reported the results of a study which demonstrates that baffles can be utilized to improve performance during liquid inflow to hemispherically ended cylinders by permitting higher inflow rates than those possible without baffles.

The objective of this study is to obtain a quantitative measure of the effectiveness of simple outlet baffle geometries in hemispherically ended cylindrical tanks in a zero-gravity environment. Results obtained with each of the baffles tested are compared with the results obtained for an unbaffled tank (ref. 6) and with each other in the form of liquid residuals as a function of the outflow Weber number. This experimental study was conducted in the Lewis Research Center 2.2-Second Zero-Gravity Facility.

APPARATUS AND PROCEDURE

The investigation was conducted in the Lewis Research Center 2.2-Second Zero-Gravity Facility. A complete description of the facility, the experiment package, and the test procedure can be found in the appendix.

Experiment Tank and Outlet Baffles

The experiment tank used in the investigation (see fig. 1) was a 2-centimeter-inside-radius hemispherically bottomed cylinder machined from cast acrylic rod and polished to optical clarity. A flat disk 1 centimeter in radius was positioned 1 centimeter below the pressurant gas inlet port in order to prevent the direct impingement of the incoming gas onto the liquid-vapor interface. The drain line located along the longitudinal axis of the tank had an inside radius of 0.2 centimeter. With the exception of the outlet baffles, the tank used was identical to that used in the study of reference 6.

The tank could be fitted with any of the three outlet baffles tested. The baffles are shown in figure 1 and can be described as follows:

(1) A flat-disk baffle which was machined from cast acrylic plastic and was 1.24 centimeters in radius and 0.32 centimeter thick

(2) A spherical-segment baffle which was machined from cast acrylic plastic and had a radius of 1.95 centimeters and a chord radius of 1.15 centimeters

(3) A stacked-disk baffle (identical to the baffle of ref. 10) which was composed of five closely spaced circular stainless steel disks. Four of the disks were fitted

with central holes to permit liquid passage, the uppermost disk being solid. The disks were spaced 0.1 centimeter apart. Central holes varied in equal increments from 0.8 to 0.2 times the outlet area with the largest hole being nearest to the tank outlet.

The total open flow area was approximately equal to the tank outlet cross-sectional area for the spherical-segment baffle, while the stacked-disk baffle had an open flow area equal to approximately four times the outlet area, and the flat-disk baffle, a flow area equal to approximately 10 times the outlet area. All the baffles were supported by three spacers spaced 120° apart. The spacers were 0.1 centimeter in radius and were cut from stainless-steel tubing.

Test Liquids

Two liquids (trichlorotrifluoroethane and anhydrous ethanol) were employed in this study. Properties of each liquid are presented in table I. Both liquids had an essentially 0° static contact angle on the tank and baffle materials in order to duplicate the static contact angle of most spacecraft liquids on typical tankage materials. A small amount of dye was added to the liquids to improve photographic quality. Previous studies have determined that the addition of the dye does not affect the liquid properties as presented in table I.

RESULTS AND DISCUSSION

Interface Shapes at Vapor Ingestion

Photographs of the liquid-vapor interface at the instant of vapor ingestion are presented in figure 2. While it is clear that vapor ingestion is occurring in the case of the unbaffled tank (fig. 2(a)), the optical distortion due to refractive effects prevents a sharp picture of the phenomena in the case of the outlet baffles. For unbaffled draining, the liquid-vapor interface is highly curved with the bulk of the liquid residual being located at the tank side wall. This is primarily due to the fact that the interface prior to draining is nearly hemispherical with the shortest distance to the vapor being located immediately above the tank drain. Selecting baffles which obstruct the direct path of this vapor to the drain makes it possible to drain liquid from an area of increased liquid depth and thereby increase outflow time. Figures 2(b) to (d) show the liquid-vapor interface at vapor ingestion for the flat-disk baffle, the spherical-segment baffle, and the stacked-disk baffle. Note that the interface has been somewhat flattened near the tank centerline and that some of the liquid has been drained from the tank side wall area.

Increasing the diameter of the baffle and, hence, increasing the distance between the baffle and the tank outlet could conceivably result in the draining of additional liquid from the tank side wall. However, as the distance from the tank outlet to the baffle increases, the quantity of liquid trapped beneath the baffle also increases. Once the vapor passes the position of the baffle, the tank draining is essentially unbaffled, and it is reasonable to expect that the majority of the liquid beneath the outlet baffle will be a part of the residual. It is possible that an optimum position and size for the baffle might exist; however, an investigation to determine such a location and size, if one exists, is not included as a part of this study.

Effect of Various Baffles on Liquid Residuals

In order to provide a quantitative comparison of the relative effectiveness of each of the baffles employed in this study, the magnitude of the liquid residual remaining in the tank at the moment of vapor ingestion was calculated from known values of initial liquid volume, outflow rate, and time to vapor ingestion.

Residuals are plotted in nondimensional form as a function of the outflow Weber number. The volume contained in the hemispherical tank bottom is used to normalize liquid volume, that is, normalized volume = $2/3\ \pi R^3$, where R is the tank radius. The outflow Weber number is defined as $Q_0^2/\beta R^3$, where Q_0 is the outflow rate, β is the specific surface tension of the liquid, and R is the tank radius. The manner of normalizing liquid volume and the definition of outflow Weber number are consistent with those employed in reference 6 to correlate liquid residual data.

Flat-disk baffle. - Figure 3 presents the results obtained for a tank having a flat-disk baffle and initially filled with ethanol to a height (measured in normal gravity) of 2 tank radii. This height corresponds to a normalized initial liquid volume of 2.5. Residuals ranged from 0.42 at an outflow Weber number of 10 to a value of 1.1 at an outflow number of 60 and above.

The normalized residuals for the unbaffled tank (initial fill = 2R) studied in reference 6 are indicated by the dashed line. In the unbaffled tank, residuals ranged from about 1.1 at an outflow Weber number of 10 to a maximum of 1.45 at outflow Weber numbers of 40 and above. In comparison, residuals were reduced by about 60 percent by the flat-disk baffle at low outflow Weber numbers and by about 20 percent at outflow Weber numbers of 60 and above.

Since the initial normalized liquid volume is known, the percentage of available liquid drained from the tank can be determined. Thus, for the stated conditions, between 55 and 85 percent of the available liquid was drained from the baffled tank prior to vapor ingestion into the tank outlet.

Spherical-segment baffle. - The tank having a spherical-segment baffle and filled with ethanol to a height of 2 tank radii was tested and compared with the unbaffled tank in the same manner as the flat-disk baffle. Results are presented in figure 4. Residuals ranged from about 0.55 at an outflow Weber number of 10 to a value of about 1.25 at outflow Weber numbers of 50 and above. Again, the corresponding values of residuals for the unbaffled tank at the same outflow Weber numbers were 1.1 and 1.45. Thus, the residuals were reduced by about 50 percent by the spherical segment at low outflow numbers and by about 15 percent at outflow numbers of 50 and above.

Again, the results can be expressed in a percentage of available liquid drained from the tank prior to vapor ingestion. For the stated conditions, between 50 and 80 percent of the available liquid was drained from the tank.

Stacked-disk baffle. - The results obtained for a tank having the stacked-disk baffle and initially filled with ethanol to a height of 2 tank radii are presented in figure 5. Residuals ranged from about 0.75 for an outflow Weber number of 10 to a value of about 1.3 for outflow Weber numbers of 60 and above. Comparison with the results for the unbaffled tank show that the stacked-disk baffle reduced residuals by about 30 percent at low Weber numbers and about 10 percent at outflow Weber numbers of 60 and above. The stacked-disk baffle resulted in draining of between 50 and 70 percent of the available liquid prior to vapor ingestion.

Effect of Initial Filling on Liquid Residuals

A series of tests was made by using the flat-disk baffle in order to determine if a change in initial liquid filling had any gross effect on residual fraction. Figure 6 shows the results obtained for tanks initially filled to 2R and 3R liquid heights. The variation in initial filling had no measurable effect on the magnitude of residual fraction at any constant outflow Weber number. This is in contrast to the results presented in reference 6, in which a slight increase in residual fraction occurred with an increase in initial filling. As pointed out in reference 6, this increase is primarily attributed to the amount of liquid contained in the thinning liquid layer which clings to the tank side wall during draining. Since the baffles employed in this study were selected with the expressed purpose of draining liquid from the tank side wall area, it is conceivable that any effects due to a variation in initial fill were minimized. It should be pointed out, however, that these results are not entirely conclusive since only two discrete filling levels were investigated. It is expected that some spread might occur if the initial filling had been varied over a large range because of the residual added by the thin sheet of liquid which clings to the tank side wall. Since it is expected that this wall sheet would be very thin and contribute very little to the residuals, the normalized residual might be considered nearly constant at any outflow Weber number, and hence, the percentage of available liquid drained from the tank would increase with initial filling. For example, an initial filling of 3R and an outflow Weber number of 60 or above results in about 70 percent of the available liquid being drained. This is in contrast to about 55 percent for tanks filled initially to 2 tank radii.

Comparison of Baffle Effectiveness

In figure 7, the relative effectiveness of each baffle tested is shown by plotting residuals obtained with each as a function of the outflow Weber number. In addition, the dashed line shown presents the results obtained in reference 6 for the unbaffled tank (initial fill = 2R). The flat-disk baffle was the most effective in that it resulted in the lowest value of residual at any outflow Weber number. The spherical-segment baffle was slightly better than the stacked-disk baffle at outflow Weber numbers of 40 and below, but their performance was quite similar at high outflow Weber numbers. All baffles tested demonstrated an improvement over unbaffled draining, and none caused significant pressure losses. Nearly the same outflow rate (to within about 5 percent) was achieved with each of the outlet baffles as was achieved with the unbaffled tank at a given accumulator pressure.

CONCLUDING REMARKS

An experimental study was conducted to determine the relative effectiveness of various outlet baffles in reducing the magnitude of liquid residuals resulting from the draining of hemispherically ended cylindrical tanks in a weightless environment. The experiment tank was 2 centimeters in radius and was fitted with a 0.2-centimeter-radius outlet line at the tank bottom. This study was conducted with simple outlet baffle geometries in order to provide a quantitative measure of baffle effectiveness. Results were intended neither for scaling nor for the optimization of any complex draining system. Three different baffles (flat-disk, spherical-segment, and stacked-disk) were evaluated over a range of outflow rates. Two liquids (anhydrous ethanol and trichlorotrifluoroethane) were employed in the study.

All the baffles were effective in reducing liquid residuals compared to the unbaffled tank with the most effective being the flat-disk baffle. This baffle resulted in a decrease in liquid residuals of between 20 and 60 percent with the greatest reduction occurring at the lowest outflow Weber numbers. The next best performance was achieved with the spherical-segment baffle, which reduced residual fractions from 15 to 50 percent. The stacked-disk baffle was least effective and reduced residual fractions from 10 to 30 percent.

Residual fraction was apparently independent of initial filling over the range of test parameters investigated, and as a result, the percentage of available liquid drained from the tank increased with increasing initial filling.

It should be noted that, although baffled draining offers an improvement over unbaffled draining, even the best baffle tested resulted in as much as 45 percent of the initial liquid volume remaining in the tank as residual at the moment of vapor ingestion into the tank outlet. The shape of the tank bottom, coupled with the highly curved liquid-vapor interface, is primarily responsible for the inefficiency obtained with simple outlet baffle geometries.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 13, 1972,
113-31.

APPENDIX - FACILITY, EXPERIMENT PACKAGE, AND TEST PROCEDURE

Test Facility

The experiment data for this study were obtained in the Lewis Research Center 2.2-Second Zero-Gravity Facility. A schematic diagram of this facility is shown in figure 8. The facility consists of a building 6.4 meters (21 ft) square by 30.5 meters (100 ft) tall. Contained within the building is a drop area 27 meters (89 ft) long with a cross section of 1.5 by 2.75 meters (5 by 9 ft).

The service building has, as its major elements, a shop and service area, a calibration room, and a controlled-environment room. Those components of the experiment which require special handling are prepared in the controlled-environment room of the facility. This air-conditioned and filtered room (shown in fig. 9) contains an ultrasonic cleaning system and the laboratory equipment necessary for handling test liquids.

Mode of operation. - A 2.2-second period of weightlessness is obtained by allowing the experiment package to free fall from the top of the drop area. In order to minimize drag on the experiment package, it is enclosed in a drag shield, designed with a high ratio of weight to frontal area and a low drag coefficient. The relative motion of the experiment package with respect to the drag shield during a test is shown in figure 10. Throughout the test the experiment package and drag shield fall freely and independently of each other; that is, no guide wires, electrical lines, etc. are connected to either. Therefore, the only force acting on the freely falling experiment package is the air drag associated with the relative motion of the package within the enclosure of the drag shield. This air drag results in an equivalent gravitational acceleration acting on the experiment which is estimated to be below 10^{-5}g.

Release system. - The experiment package, installed within the drag shield, is suspended at the top of the drop area by a highly stressed music wire which is attached to the release system. This release system consists of a double-acting air cylinder with a hard steel knife attached to the piston. Pressurization of the air cylinder drives the knife edge against the wire, which is backed by an anvil. The resulting notch causes the wire to fail and smoothly release the experiment. No measurable disturbances are imparted to the package by this release procedure.

Recovery system. - After the experiment package and drag shield have traversed the total length of the drop area and have been decelerated in a 2.2-meter- (7-ft-) deep container filled with sand, they are recovered. The deceleration rate (averaging 15 g's) is controlled by selectively varying the tips of the deceleration spikes mounted on the bottom of the drag shield (fig. 10). At the time of the impact of the drag shield in the deceleration container, the experiment package has traversed the vertical distance within the drag shield (compare figs. 10(a) and (c)).

Experiment Package

The experiment package shown in figure 11 is a self-contained unit consisting of an experiment tank, a pumping system, a photographic system, a digital clock, and an electrical system to operate the various components. Indirect illumination of the experiment tank by means of a backlighting scheme provides sufficient light so that the fluid behavior can be recorded with a high-speed 16-millimeter motion-picture camera. An air reservoir, the experiment tank, a solenoid valve, and a liquid collection tank compose the pumping system shown in figure 12. The volume of the air reservoir is much greater than the largest volume of liquid drained from the tank during outflow so that the driving pressure remains essentially constant. Time during weightlessness is observed by reading a digital clock having an accuracy of ±0.01 second. A scale located beside the experiment tank provides an indication of the initial height of liquid contained in the tank prior to outflow as well as the height at the tank centerline during draining. All electrical components are operated through a control box and receive their power from rechargeable nickel-cadmium cells.

Test Procedure

Before the flow components were assembled, the tank and all flow lines were cleaned in an ultrasonic cleaner to assure that the properties of the test liquids would not be affected by contaminants. The parts were then rinsed with distilled water and dried in a warm air dryer. All parts were then assembled and mounted in the experiment package. The tank and the liquid flow lines were filled with liquid, and the system was checked for leaks. Draining was accomplished by means of a pressurization technique, with the flow system shown in figure 12. The air reservoir was filled to a certain pressure, and draining was initiated by opening a solenoid valve located downstream of the tank outlet.

During normal-gravity calibration tests, the liquid-vapor interface as a function of draining time was recorded with the high-speed camera. From this interface velocity (which remained constant during draining), the outflow rate as a function of accumulator pressure was obtained. The assumption was made that, for a given pressure setting, the outflow rate in weightlessness was the same as it was in normal gravity; that is, effects due to static head were negligible. This assumption is warranted on the basis of previous results (see refs. 1 and 3).

During a test in weightlessness, sufficient time was allowed for the liquid-vapor interface to form a zero-gravity configuration prior to initiation of the draining process. Since the time required for the interface to reach a static equilibrium configuration was so long that it would have precluded draining, outflow was initiated at the time that the interface reached its lowest oscillation point in its first pass through equilibrium. The interface velocity at this time was zero.

Electrical timers on the experiment package were set to control the initiation and the duration of outflow during the drop. Liquid was placed in the experiment tank to the desired level, the air reservoir was pressurized, the camera was loaded, and the experiment was balanced about the horizontal axes and positioned within the prebalanced drag shield. The wire support was then attached to the experiment package through an access hole in the drag shield (see fig. 10). Properly sized spike tips were installed on the drag shield. Then the drag shield, with the experiment package inside, was hoisted to the predrop position at the top of the facility (fig. 8). The wire support was attached to the release system, and the entire assembly was suspended from the wire. After final electrical checks and switching to internal power, the system was released. After completion of the test, the experiment package and the drag shield were returned to the preparation area.

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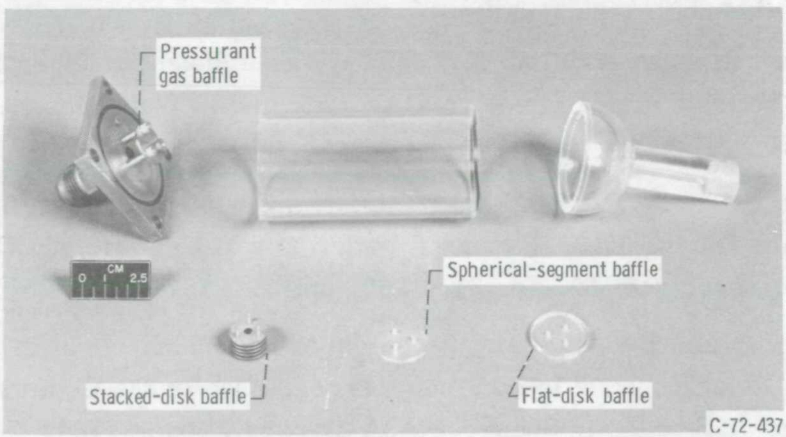
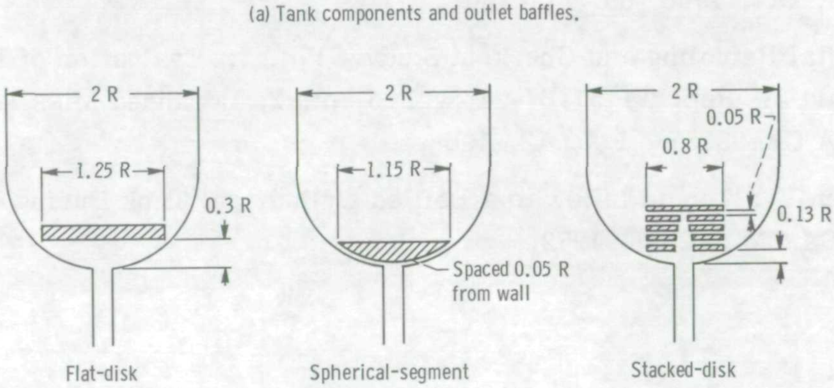
TABLE I. - PROPERTIES OF TEST LIQUIDS

[Static contact angle with cast acrylic plastic in air, 0^o.]

Liquid	Surface tension at 20^o C, σ, N/cm (10^5 dynes/cm)	Density at 20^o C, ρ, g/cm^3	Viscosity at 20^o C, μ, g/(cm)(sec)	Specific surface tension, β, cm^3/sec^2
Anhydrous ethanol	22.3×10^{-5}	0.79	1.2×10^{-2}	28.3
Trichloro-trifluoro-	18.6×10^{-5}	1.58	$.7\times10^{-2}$	11.8

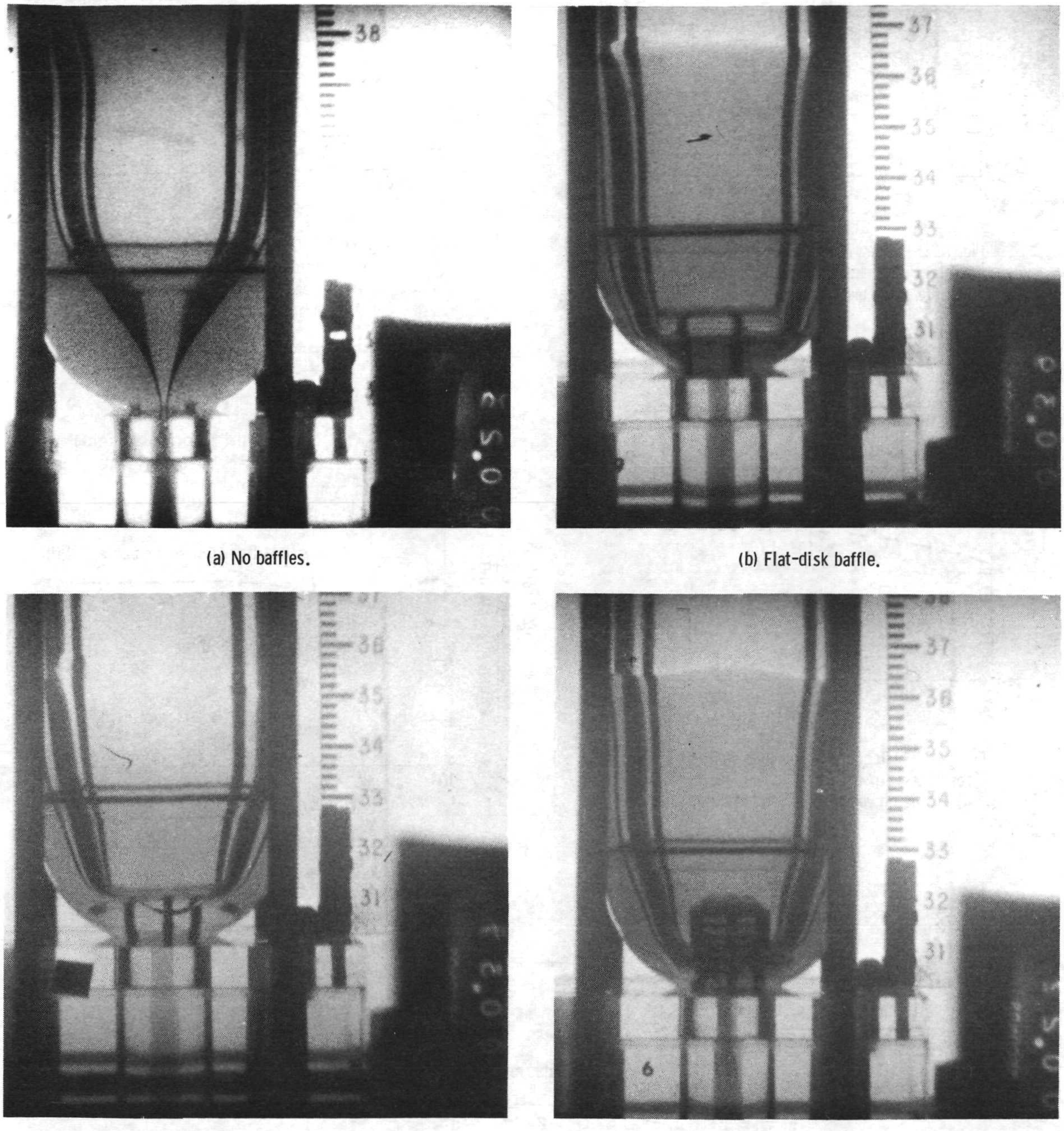


(a) Tank components and outlet baffles.



(b) Sketches showing relative locations and sizes of baffles.

Figure 1. - Experiment tank and outlet baffles.



(a) No baffles.

(b) Flat-disk baffle.

(c) Spherical-segment baffle.

(d) Stacked-disk baffle.

Figure 2. - Vapor ingestion in weightlessness with and without outlet baffling. Initial fill, 2 tank radii; Weber number, approximately 60.

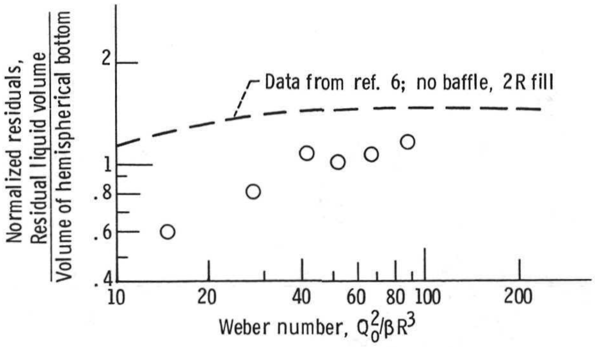


Figure 3. - Effect of flat-disk-baffle on liquid residuals. Initial fill, 2 tank radii; normalized initial liquid volume, 2.5; test liquid, ethanol.

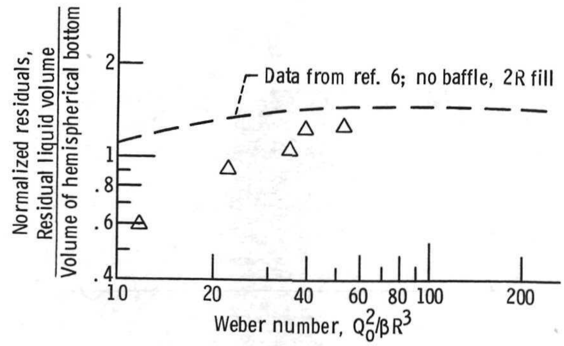


Figure 4. - Effect of spherical-segment baffle on liquid residuals. Initial fill, 2 tank radii; normalized initial liquid volume, 2.5; test liquid, ethanol.

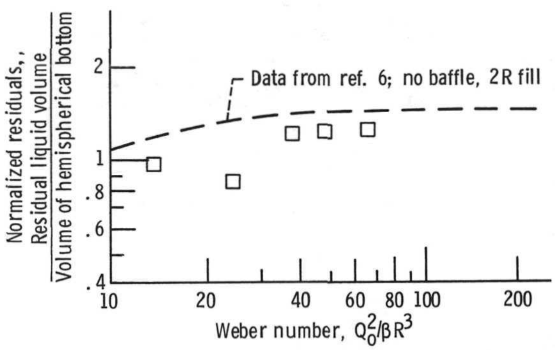


Figure 5. - Effect of stacked-disk baffle on liquid residuals. Initial fill, 2 tank radii; normalized initial liquid volume, 2.5; test liquid, ethanol.

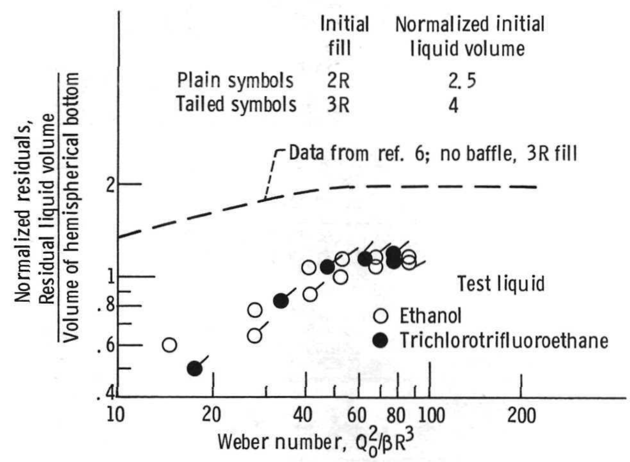


Figure 6. - Effect of initial filling on liquid residuals for flat-disk baffle.

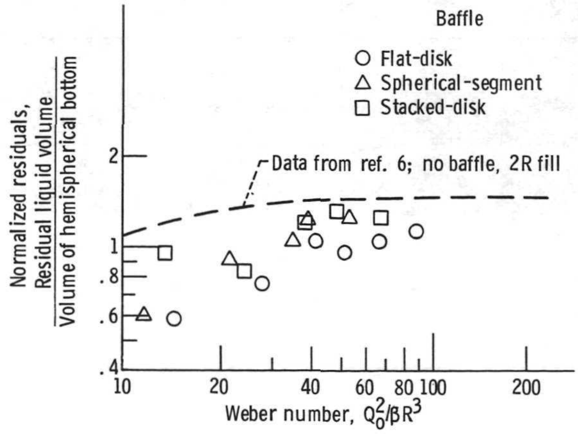


Figure 7. - Comparison of performance of baffles.

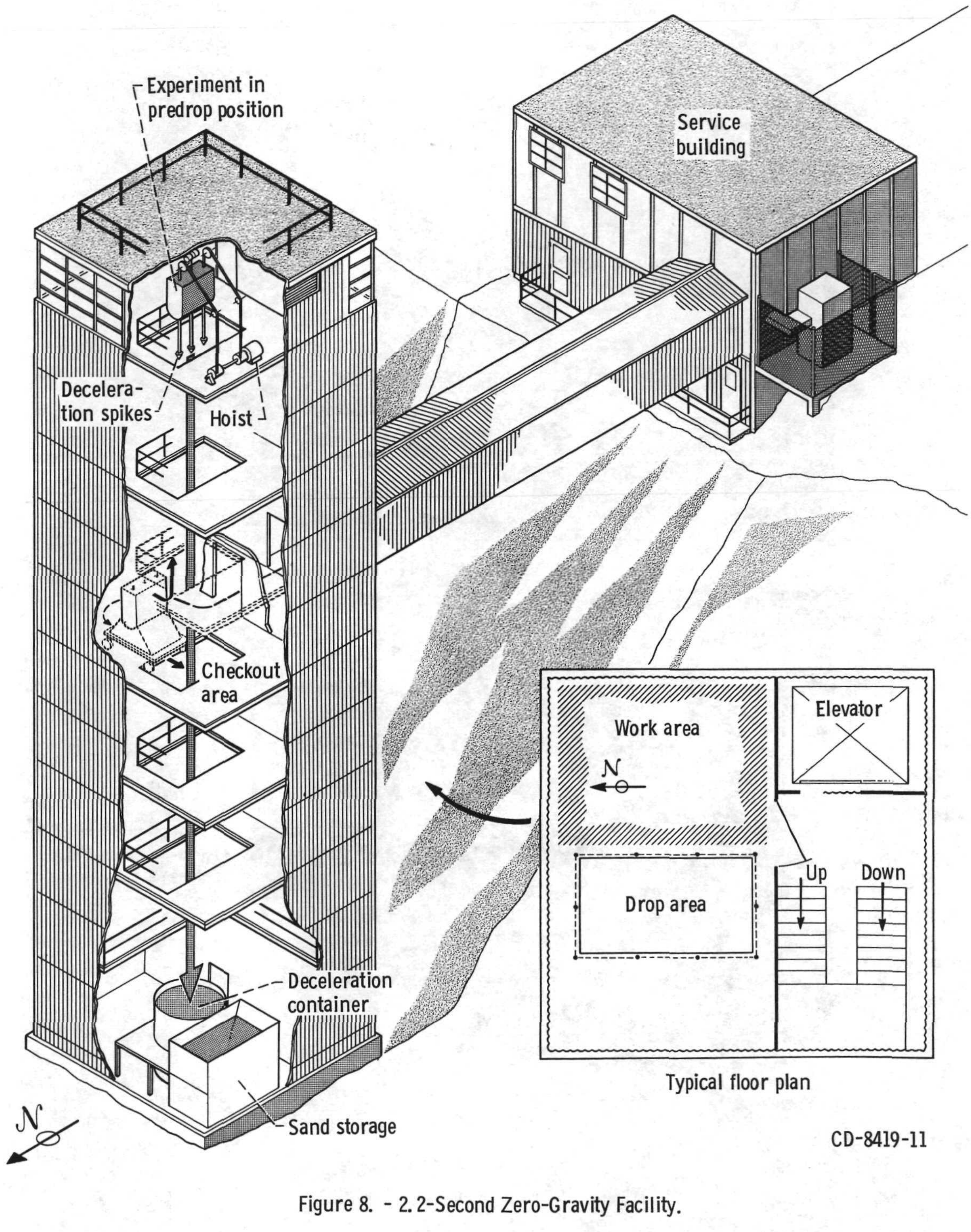
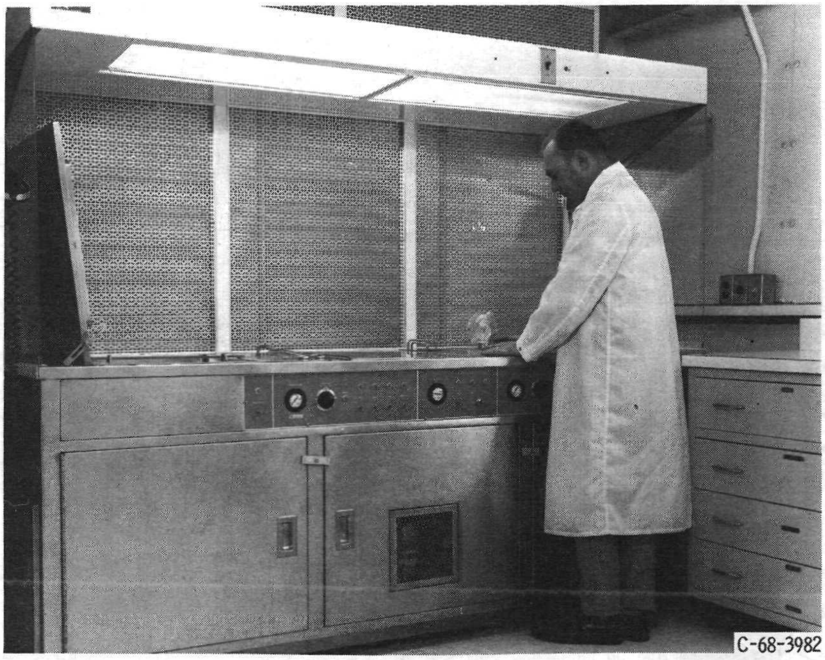
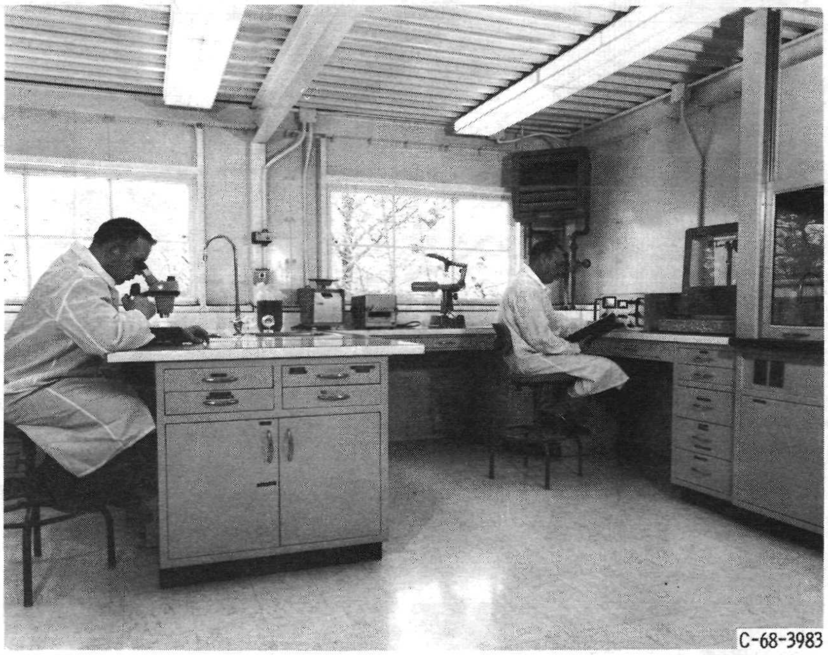


Figure 8. - 2.2-Second Zero-Gravity Facility.



(a) Ultrasonic cleaning system.



(b) Laboratory equipment.

Figure 9. - Controlled environment room.

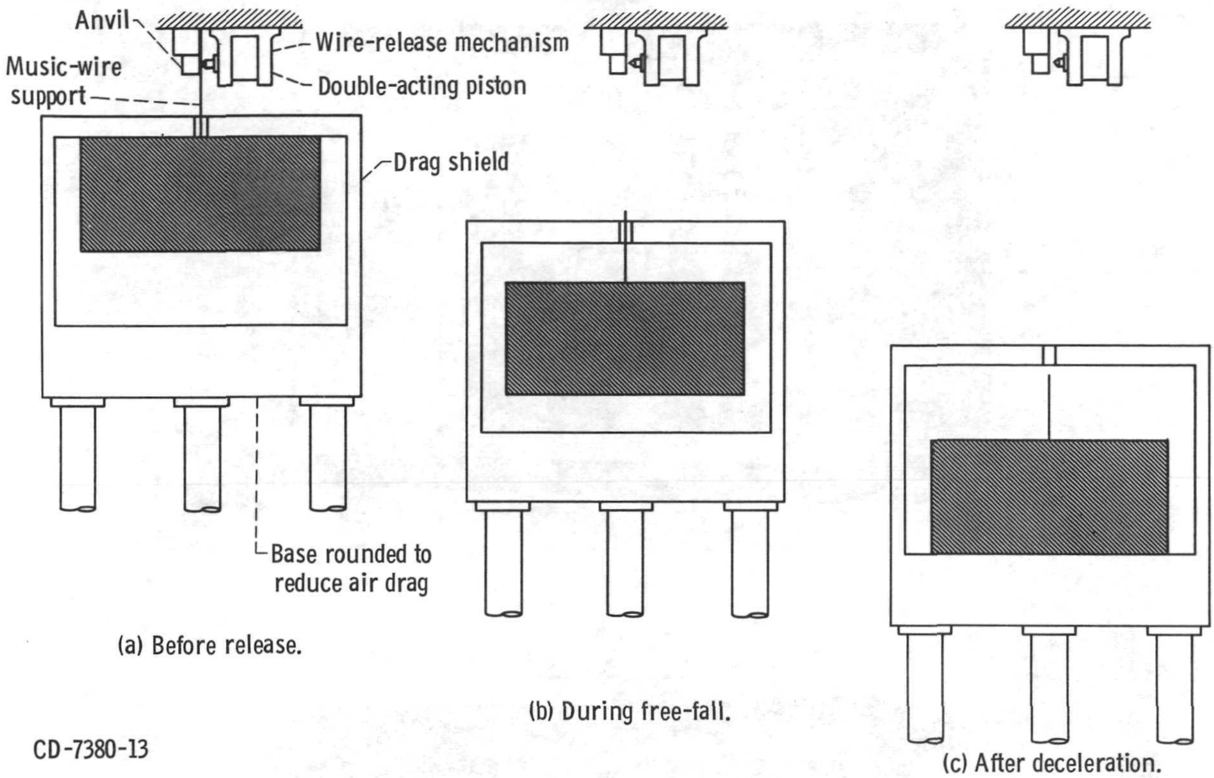
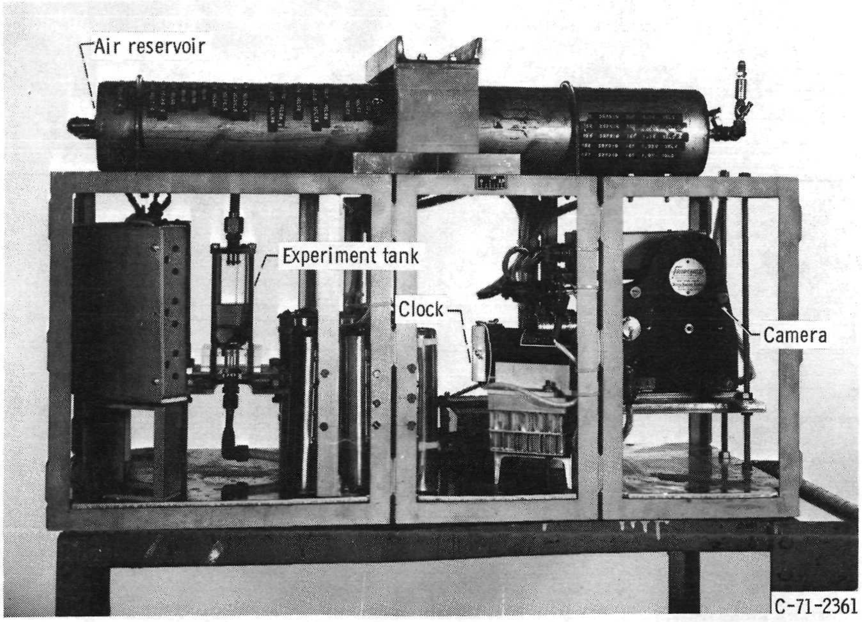
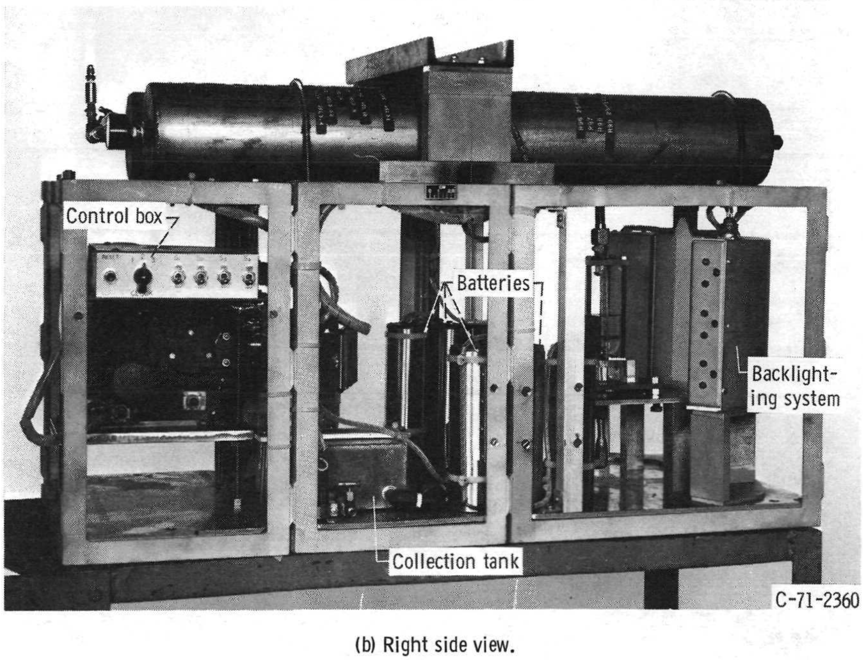


Figure 10. - Position of experiment package and drag shield before, during, and after test drop.



(a) Left side view.



(b) Right side view.

Figure 11. - Experiment package.

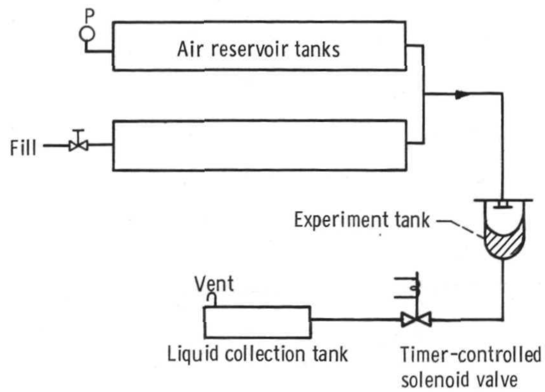


Figure 12. - Schematic drawing of pumping system.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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