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A PHOTOGRAPHIC STUDY OF LIQUID HYDROGEN UNDER SIMULATED ZERO GRAVITY CONDITIONS

By Irving Brazinsky and Solomon Weiss

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The transient behavior of liquid hydrogen, under conditions of zero gravity, was studied photographically. The hydrogen was subjected to weightlessness by dropping a Dewar containing this liquid from a height of 9 feet. During the weightless period of approximately 3/4 second, the liquid rose along the walls of the Dewar into the original vapor space. The rise occurred at constant velocity for practically the entire duration of this period. Adhesive forces were concluded to be the primary cause of the liquid rise along the wall.

INTRODUCTION

In future rocket applications, propellant tanks partially filled with liquid hydrogen will be subjected to long periods of weightlessness. During these periods the fluid configuration in the tank may be such as to result in the loss of liquid propellant when the tank is vented. In addition, an undesirable low quality liquid-vapor mixture may flow out of the tank outlet to the pump when restarting of the rocket engine is attempted. Studies of liquid-hydrogen configurations at zero gravity are therefore desirable.

This preliminary study was undertaken to obtain some idea of the transient behavior of liquid hydrogen in a zero gravity environment. The liquid hydrogen was subjected to weightlessness by allowing a Dewar containing this liquid to fall freely. With the apparatus employed, only 3/4 second of zero gravity could be obtained. The transient behavior of the liquid during this period gave some indication of the governing forces involved and also of the configuration the liquid hydrogen might assume if it were subjected to longer periods of weightlessness.

APPARATUS

The apparatus employed is essentially the same as that used in experiments with boiling water at zero gravity (ref. 1). For this application the apparatus was modified somewhat so that liquid hydrogen could be used. A schematic representation of the apparatus is shown in figure 1. The main component in the structure is a platform in the form of a cross, which supports a high-speed motion-picture camera, light sources, and a Dewar containing the liquid hydrogen. At the ends of three branches of the platform there are large guide holes through which 1/4-inch vertical cables pass. The cables serve to prevent the accidental tipping of the falling platform. During a normal experimental run, however, little or no contact is made between the platform and the cables. A balancing yoke is attached at the top of the platform and can be adjusted so that the solenoid grapple, which holds the platform from above, will be located above the center of gravity of the freely falling equipment. The apparatus was wired so that the camera started 1/10 second before the solenoid grapple was opened and the platform dropped. The platform was decelerated at the end of the fall by a sandbox 4 feet high.

The vacuum jacketed glass Dewar, which contained the liquid hydrogen, is approximately 12 inches high and has an inner diameter of 5.56 inches and an outside diameter of 7 inches. The inside of the Dewar was cleaned with acetone prior to the run. Details of this Dewar assembly are shown in figure 2. The Dewar was vented to the atmosphere during the free fall through a bellows-type stainless steel tube 12 feet long. The flexibility of the hose permitted the entire assembly to fall freely.

The modified apparatus also consisted of a liquid-hydrogen supply line (fill line) and a dip tube which was inserted into the Dewar through the vent line (as shown in fig. 2). Helium, for purging the Dewar of air, was supplied to the Dewar through the fill line and dip tube. The dip tube was used to obtain more effective purging of the Dewar. Manifolds 1 and 2, which are mounted on the Dewar, were used to bleed helium along the outside of the outer Dewar wall to prevent condensation of moisture on the glass surface through which pictures were taken. The manifold supply lines were also flexible tubes.

A high-speed motion-picture camera, mounted on the same platform as the Dewar, took pictures at about 3500 frames a second. The light source consisted of two 750-watt lamps which were also mounted on this same platform. Thus, the camera, Dewar, and light sources fell freely together. A stationary measuring scale mounted in back of the Dewar was used when studying the motion-picture films to detect the inception of free fall.

It should be noted that the experimental assembly was not at exactly zero gravity during the free fall because of air drag on the platform assembly and on the flexible vent line. However, the gravity level was low enough that the surface tension forces prevailed over the force of gravity in determining the fluid behavior.

PROCEDURE

The procedure employed during the drop test is as follows. Valve 1 (fig. 2) was opened and helium was bled into the Dewar through the fill line. To provide more effective purging of the Dewar, helium was also bled in through the dip tube. After 10 minutes, the dip tube was removed and the hole in the vent line through which the dip tube had been inserted was plugged. Helium was then supplied to manifolds 1 and 2 for the remainder of the run.

The helium supply to the Dewar was shut off and the Dewar was partially filled with liquid hydrogen. Valve 1 was shut and the fill line was disconnected from the Dewar at coupling 2 (fig. 2). The platform was then hoisted to the top of the tower. The lights were turned on, the camera was started, and the platform dropped. Two test drops were made with a single initial filling of the Dewar. In the second test, the initial liquid level was somewhat lower than in the first because of boiloff of the liquid hydrogen. In tests I and II, the levels were 7 inches and $5\frac{1}{4}$ inches, respectively, above the bottom of the Dewar (fig. 3). Pictures were taken on black and white film for the two drops.

RESULTS

The photographic results of tests I and II are shown in figures 4 and 5. A guide cable and the flexible hose are seen in the center of the frame. The bottom of the frame is slightly below manifold 2. The rise of the liquid hydrogen along the walls of the Dewar into the original gas space during the zero gravity period is clearly indicated. It is evident that an equilibrium configuration was not reached during the time of the fall.

During the zero gravity period the vapor bubbles had no motion relative to the liquid. Thus the bubbles rose with the same velocity as the liquid creeping up the wall. In addition, the size of the bubbles did not change during this weightless period.

The liquid rise as a function of time was obtained directly from the motion-picture films of the run. The camera made a timing mark on the film every 1/120 second, and the rise of the liquid above its starting height was measured on each frame on which these timing marks appeared. The height measurements were taken on the liquid adjacent to the Dewar wall on the left side of the photograph. The major portion of the rising liquid edge rose uniformly, and the data obtained at the left wall were felt to be representative of this uniform rise. The height of the liquid at any given time above its starting height was read with the aid of a motion analyzer. The liquid rise data are limited in accuracy to ±10 percent of the value of each height measurement.

The observed liquid rise was plotted as a function of time for tests I and II, and these curves are shown in figures 6 and 7. The liquid rose at constant velocity for practically the entire duration of the weightless period and this constant velocity for tests I and II was 5.2 and 6.2 inches per second, respectively. The reason for the difference in these velocities is not apparent. It is also noted that the fluid in test II took a somewhat longer time to attain constant velocity than did the fluid in test I. This observed effect may be due to the uncertainty of the liquid rise measurements at the start of test II. The quality of the film was such that it was difficult to determine the exact location of the edge climbing up the wall at the start of the run.

The photographs of figures 4 and 5 show that the "edge" of the liquid hydrogen climbing up the wall was not completely horizontal. In fact, the leading edge curves downward in the right corner. This is true in both tests I and II. In view of the fact that no lateral motion of the bubbles was observed in the films, the uneven rise cannot be attributed to side loads on the falling platform. Perhaps an explanation for this effect was that the right side of the Dewar wall was not as clean as the left and thus the liquid climbed more easily up the left wall.

DISCUSSION OF RESULTS

For a wetting fluid like hydrogen, the apparent mechanism for the fluid rise is the adhesive force between the liquid and the wall of the container. In the absence of gravity, the forces of adhesion are expected to cause the liquid to rise up along the wall and into the original gas space. However, it is possible that another mechanism, residual fluid motion, might have been the primary cause of the fluid rise along the wall. Heat leak into the liquid hydrogen from the Dewar walls tends to cause convection currents and boiling in the liquid under normal gravity conditions. Such convection currents are indicated schematically in figure 8. Thus, when the Dewar fell freely, the vertical inertia of the convection current could have caused the liquid to rise along the wall into the original gas space. Additional residual currents along the wall might have been set up by the action of the bubble rise in the vicinity of the wall. However, this effect was not considered significant, since the bubble rise was essentially uniform throughout the liquid volume.

In order to evaluate the possible effect of residual convection currents, a rough estimate was made of the magnitude of the maximum velocity of the convection current near the surface while the liquid was still in a normal gravity field. For simplicity, the calculation was made with the assumption that the Dewar wall acted as an infinite vertical wall. For this condition and the estimated wall heat flux, as developed in the appendix, the maximum vertical velocity u_{max} near the liquid surface was calculated to be 1.58 inches per second for test I. The convection current maximum velocity for test II was somewhat smaller because of the lower initial liquid level. The residual velocity of the rising column would be expected to decay during the zero gravity period because of internal damping effects.

Inasmuch as this calculated velocity is still sizeably less than the observed rise velocity, it appears that any contribution to the rise from residual convection currents was comparatively small. It is, therefore, reasonable to conclude that adhesive forces were the primary cause of the liquid rise.

Unfortunately, the duration of the test was insufficient to define the equilibrium configuration for the liquid. However, some observations can be made on the basis of currently available theory. The theoretical study of reference 2 suggests that, for the Dewar and liquid volumes of the experiment, an equilibrium configuration would be a vapor bubble having hemispherical ends joined by a cylindrical section with the walls completely wetted, as illustrated in figure 9(a). Calculations in reference 3 indicate that, for a rectangular tank with large ratio of side dimensions, a zero-g equilibrium configuration would approach a semicylindrical surface for zero contact angle. It can be deduced from these results that, for a cylindrical tank, the corresponding equilibrium surface would be hemispherical with only partial wetting, as illustrated in figure 9(b). For this latter equilibrium configuration to be achieved, the maximum liquid level rise would have been 8.85 and 7.10 inches for tests I and II, respectively. In both tests, however, the liquid hydrogen had already risen to heights greater than these values (greater than 9 in.) and was still rising at a constant rate. Although this indicates that the fluid might be tending toward the fully wetted configuration, a definite conclusion cannot be stated because of the uncertain influence of the wall heat transfer and residual motions on the approach to, and possible oscillations about, the final configuration.

It is also noted that, if the liquid continued to rise at the constant rates observed for tests I and II, the leading edges would meet at the center of the top in approximately the same time, namely 1.50 and 1.54 seconds, respectively. In this respect, the analysis of reference 3 suggests that the time required for equilibrium to be reached would be of the order of magnitude of $\sqrt{L^3\rho/\sigma}$, where L is a characteristic length of the liquid and ρ and σ are liquid density and surface tension, respectively. If the radius of the Dewar is taken as the characteristic length, the estimated equilibrium time is calculated to be of the order of $2\frac{1}{4}$ seconds.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 15, 1961

APPENDIX - CALCULATION OF MAXIMUM CONVECTION

CURRENT VELOCITY

The following equation for maximum convection current velocity along an infinite vertical wall is given in reference 4:

$$u_{max} = 0.66\ \nu\left(0.952 + \frac{\nu}{\alpha}\right)^{-1/2}\left(\frac{g\beta\theta}{\nu^2}\right)^{1/2}\frac{1}{2}$$

where

u_{max} maximum velocity of rising convection current at given height (shown in fig. 8(c)), ft/sec

ν kinematic viscosity, 2.2×10^{-6} sq ft/sec

α thermal diffusivity, 1.95×10^{-6} sq ft/sec

g acceleration due to gravity, 32.17 ft/sec^2

β coefficient of expansion, 0.01 $\frac{1}{^{\circ}F}$

x distance above bottom of Dewar at which u_{max} is desired, ft (taken as 7/12 ft, the initial liquid level in test I)

θ temperature difference between wall of glass Dewar and saturated liquid, $^{\circ}$F

The use of this equation is not strictly valid for calculating the convection current velocity in a finite cylindrical tank with a hemispherical bottom. The thickness of the convection current, however, is very small compared with the height of the Dewar wall, and although the Dewar is cylindrical, the situation is approximately the same as that for an infinitely long vertical plate.

The temperature difference was found as follows. The heat flux into the glass Dewar, while still in a normal gravity field, was determined by measuring the rate of boiloff of the liquid hydrogen in the Dewar. A 10-inch scale was placed alongside the Dewar, and, as the liquid hydrogen evaporated, the height of the liquid-vapor interface was measured at specified time intervals. After the liquid level was more than one-third of the way down from the top of the Dewar, the heat flux assumed a constant value of about 90 Btu per hour per square foot for the remainder of the run. The constant value indicated that the heat flux was uniform across the wetted Dewar area. The liquid-hydrogen boiling curve given in reference 5 was extrapolated slightly, and it was found that a heat flux of 90 Btu per hour per square foot implied a temperature difference of 0.35° F between the Dewar wall and the saturated liquid.

Based on this temperature difference, the maximum convection current velocity was calculated to be 1.58 inches per second.

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2. Li, Ta: Liquid Behavior in a Zero-G Field. Paper 61-20, Inst. Aerospace Sci., Inc., 1961.

3. Benedikt, E. T.: General Behavior of a Liquid in a Zero or Near Zero Gravity Environment. Rep. ASG-TM-60-9Z6, Norair Div., Northrop Corp., May 1960.

4. Eckert, E. R. G., and Drake, Robert M., Jr.: Introduction to the Transfer of Heat and Mass. McGraw-Hill Book Co., Inc., 1950, p. 161.

5. Class, Charles R., DeHaan, James R., Piccone, Marshall, and Cost, Robert B.: Pool Boiling to a Cryogenic Fluid. Tech. Rep. 58-528, WADC, Oct. 1958, p. 6b.

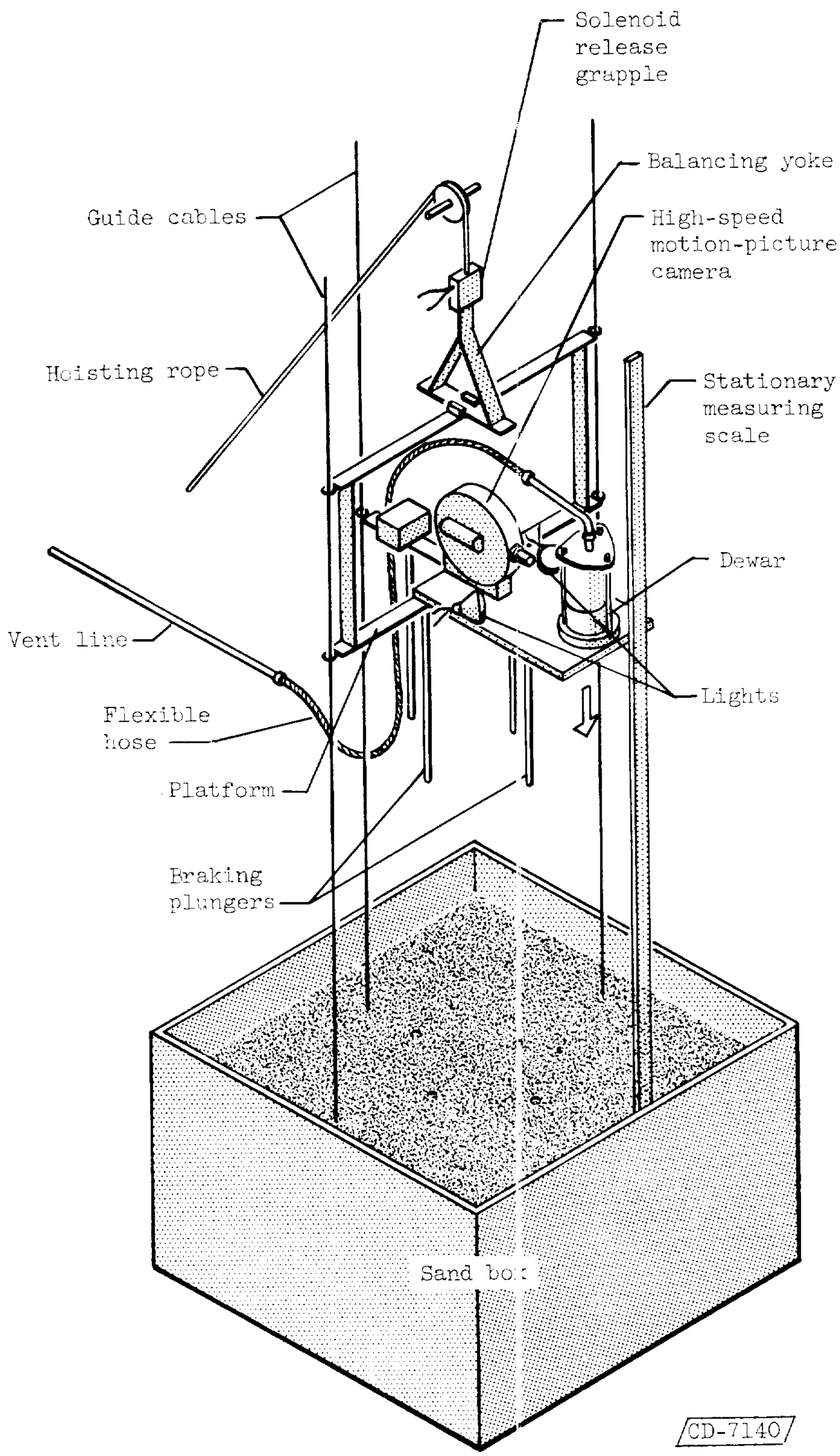


Figure 1. - Apparatus for zero gravity tests.

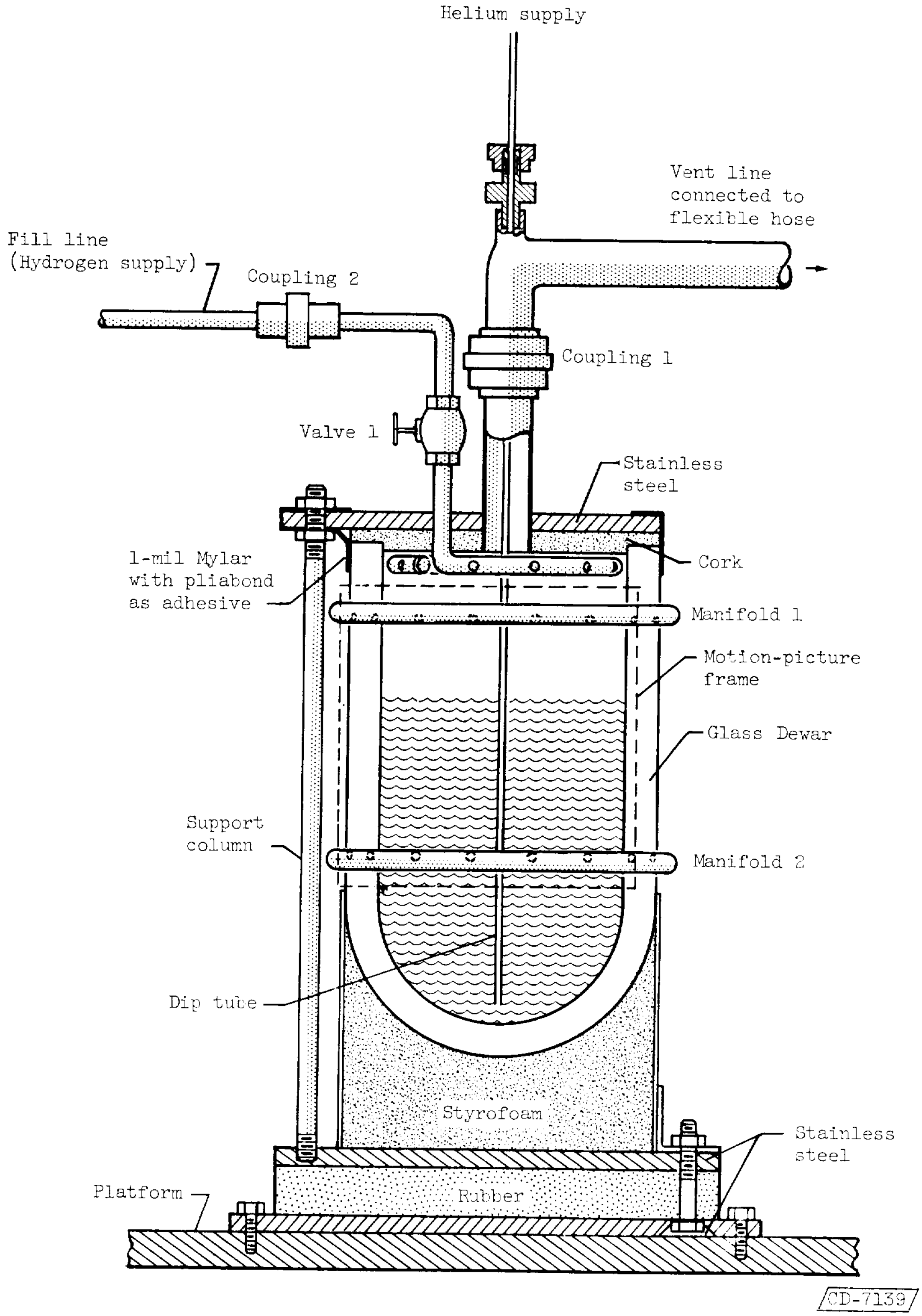


Figure 2. - Dewar assembly.

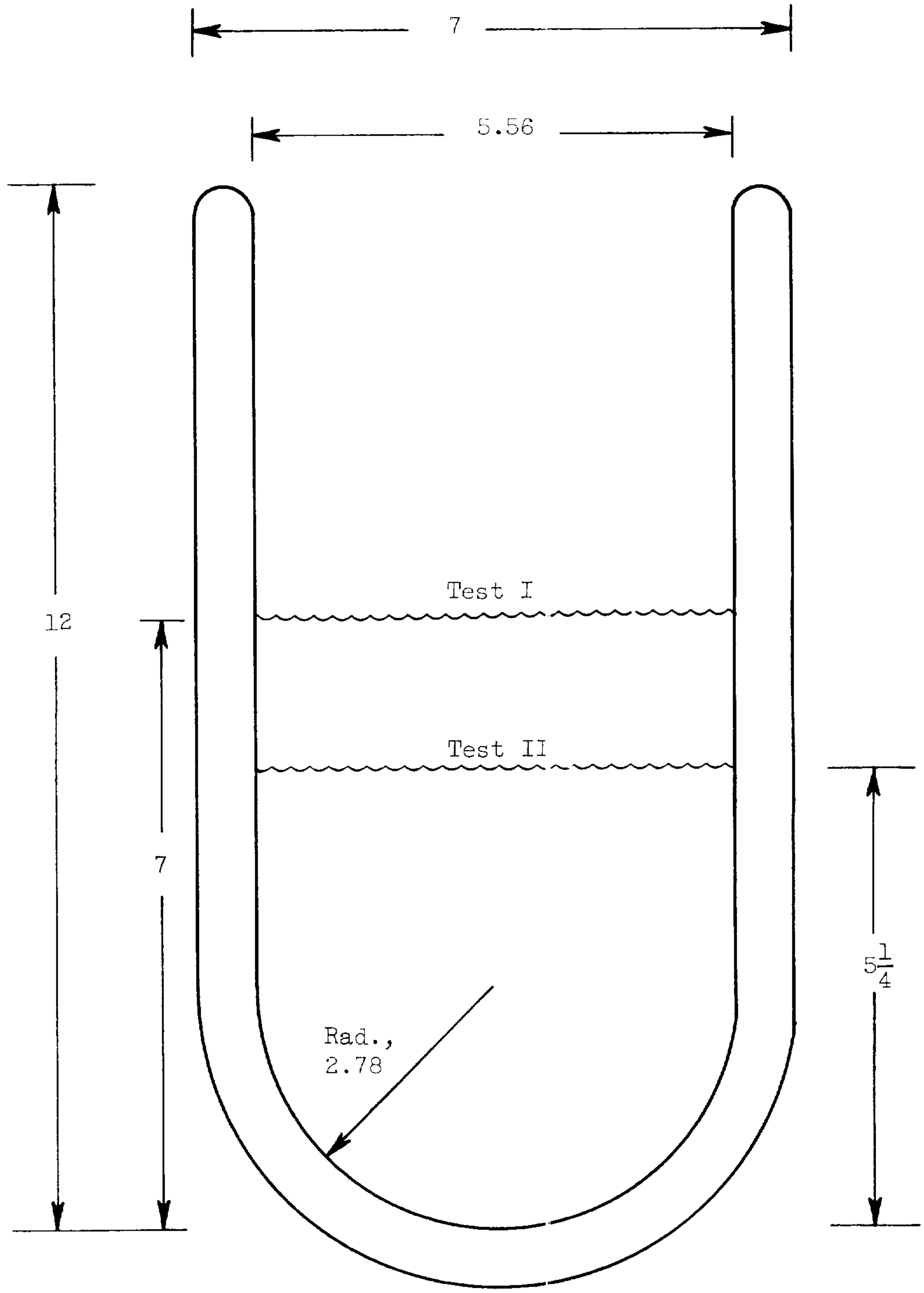


Figure 3. - Initial liquid-hydrogen levels for tests I and II. (Dimensions are in inches.)

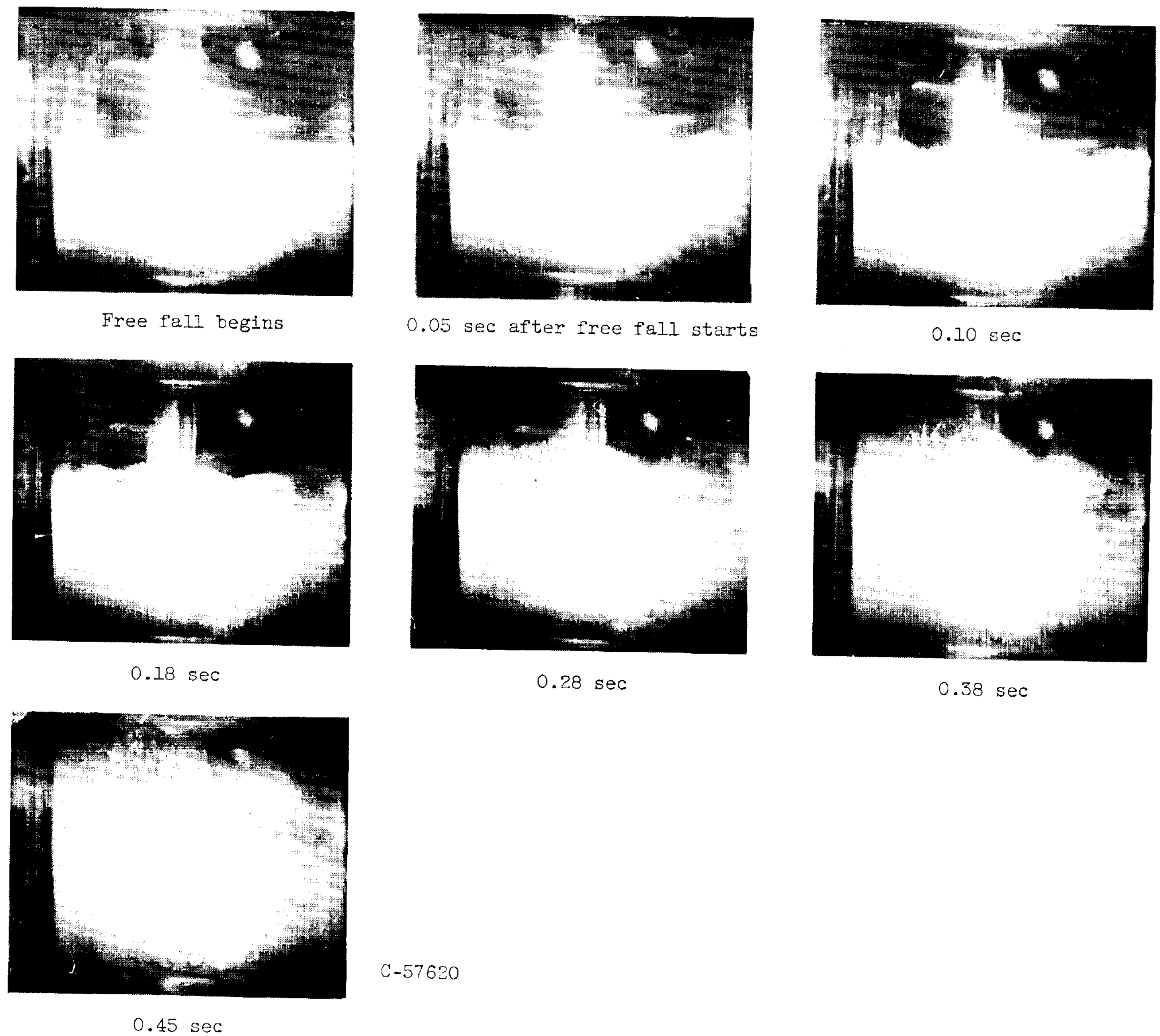
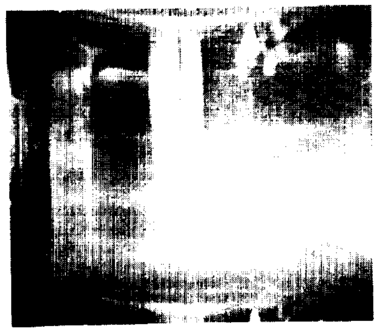
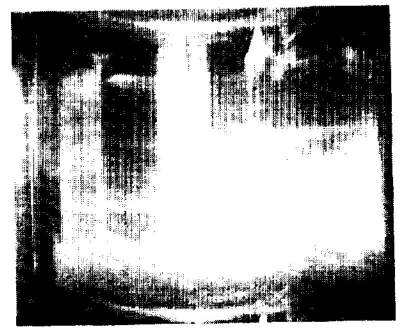


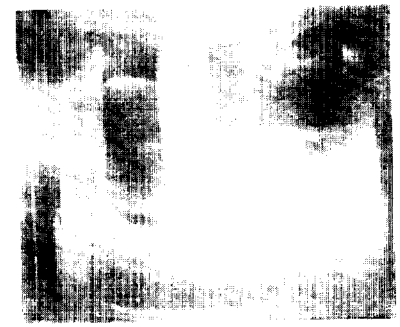
Figure 4. - Liquid hydrogen at zero gravity. Test I.



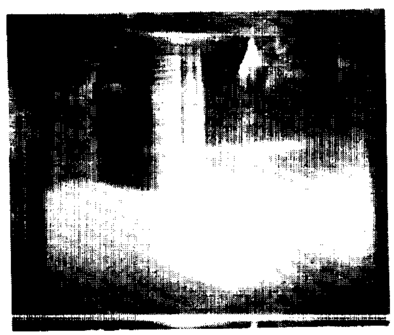
Free fall begins



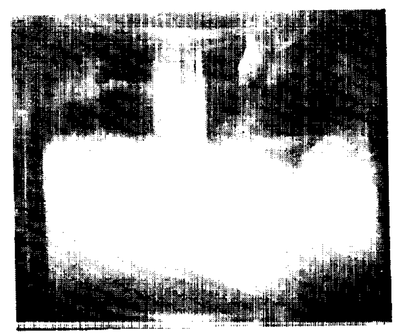
0.07 sec after free fall starts



0.15 sec



0.28 sec



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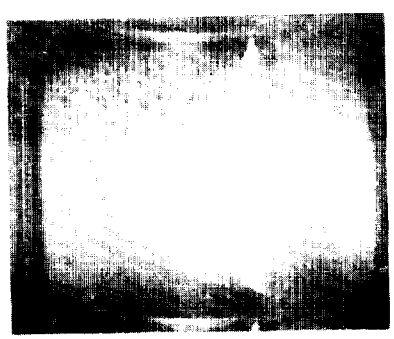
0.55 sec



0.65 sec

C-57621

Figure 5. - Liquid hydrogen at zero gravity. Test II.

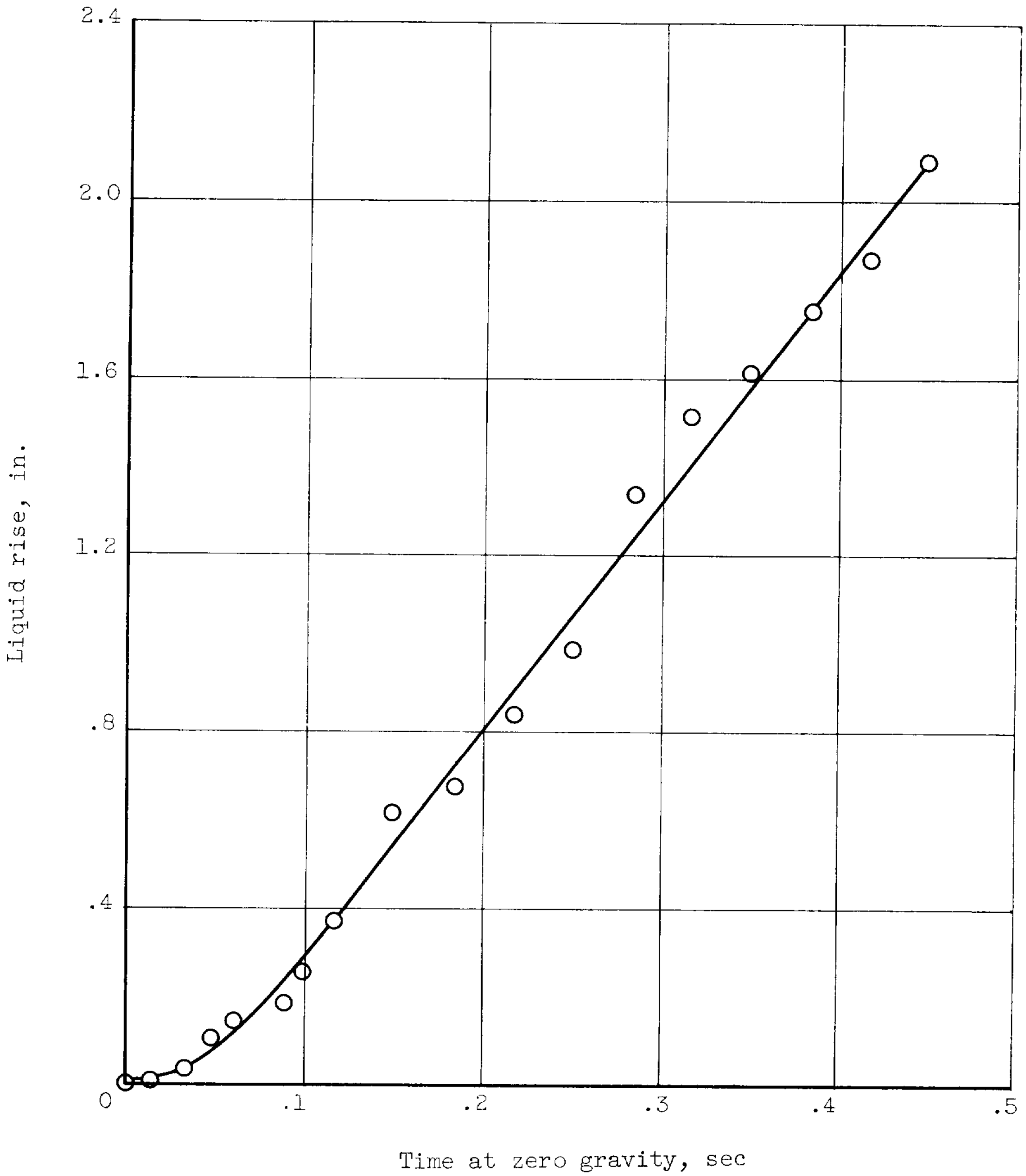


Figure 6. - Rise of liquid hydrogen. Test I.

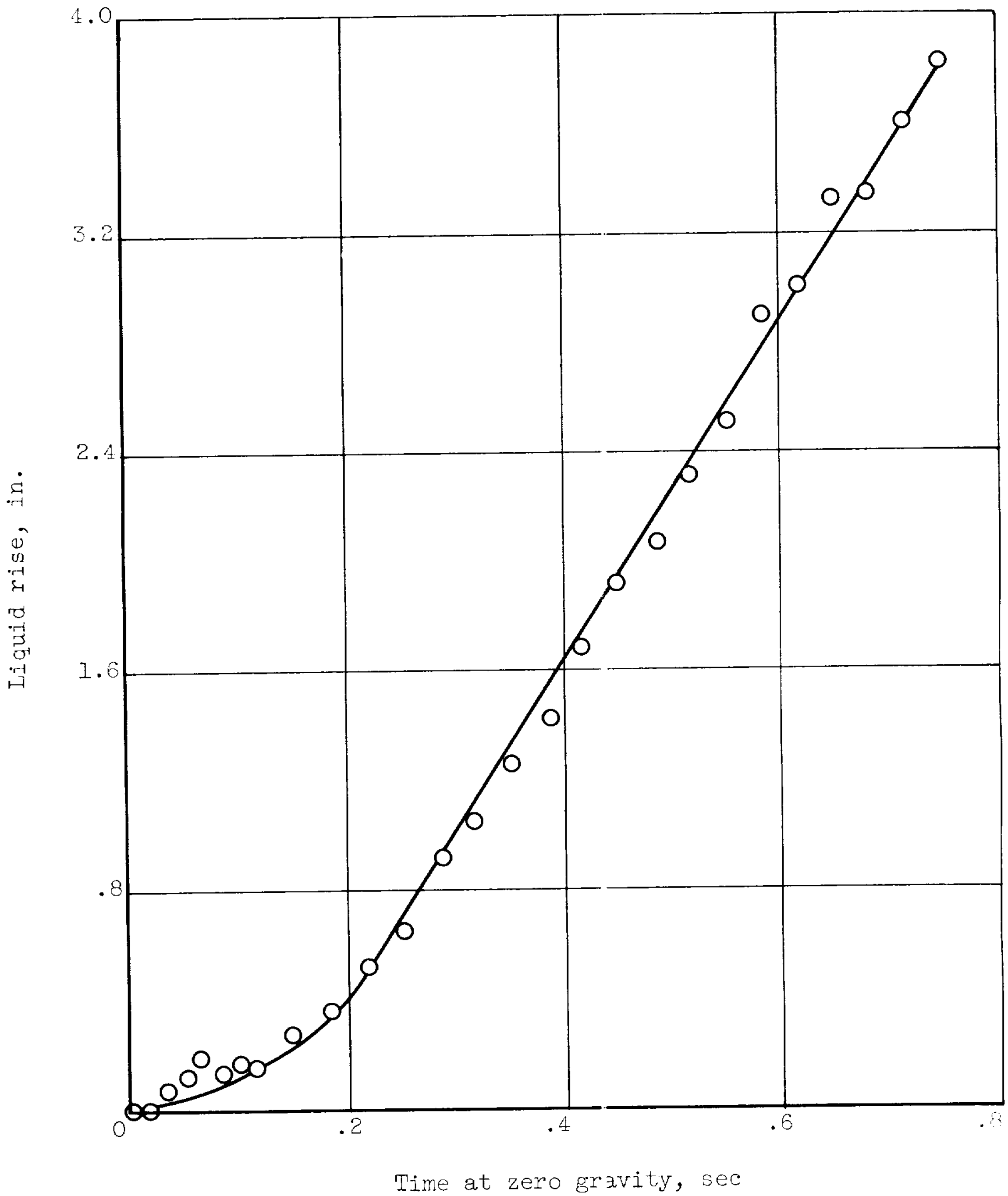


Figure 7. - Rise of liquid hydrogen. Test II.

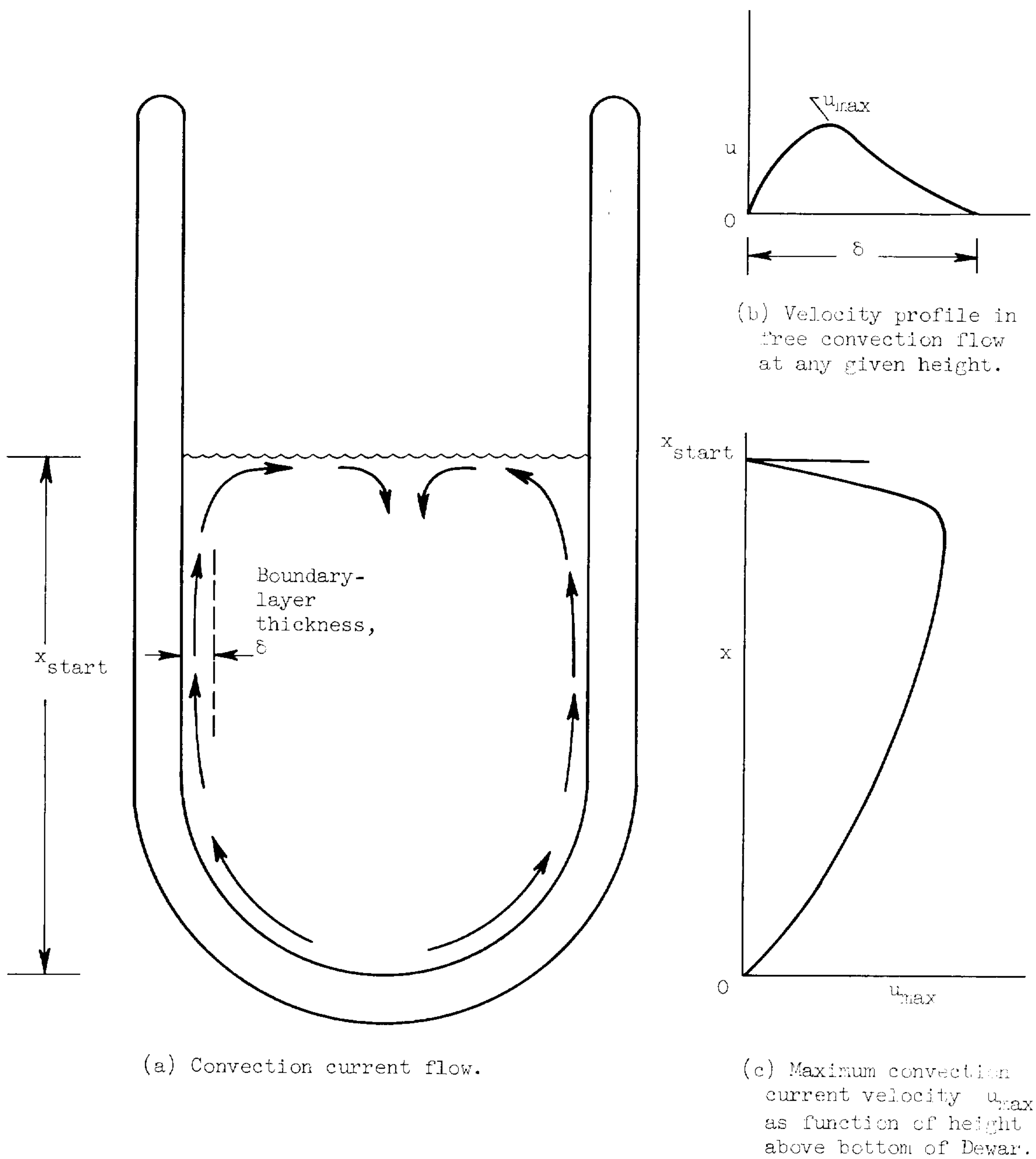
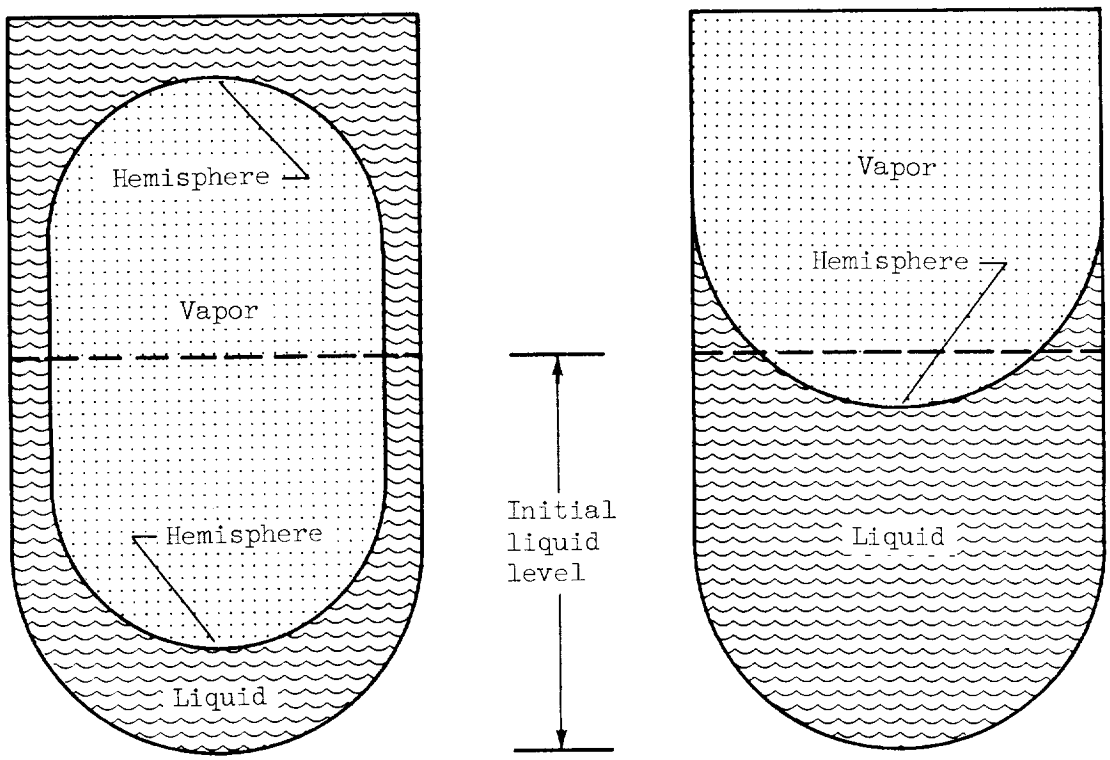


Figure 8. - Convection currents in Dewar due to heat leak.



(a) From reference 2.

(b) Deduced from reference 3.

Figure 9. - Theoretical equilibrium configuration of wetting liquid in zero gravity field according to references 2 and 3.

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