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# EXPERIMENTAL INVESTIGATION OF INTERFACIAL BEHAVIOR FOLLOWING TERMINATION OF OUTFLOW IN WEIGHTLESSNESS

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## SUMMARY

An experimental study was conducted to investigate the behavior of the liquid-vapor interface following termination of outflow from a cylindrical tank in weightlessness. It was found that an axial geyser may occur that can transfer a small amount of liquid to the inlet end of the tank. The occurrence of such a geyser was dependent on Weber number, interface displacement, kinematic viscosity, and the vapor-ingestion phenomenon.

## INTRODUCTION

As part of a continuing study of the behavior of liquids stored in space-vehicle tanks under weightless conditions (zero gravity), the Lewis Research Center is currently investigating the effect of various disturbances, connected with the outflow or draining process, on the liquid-vapor interface. These investigations are conducted in the 100-foot drop tower, which provides a 2.25-second period of weightlessness.

An initial effort in this area (ref. 1) was a photographic study of the outflow process from a cylindrical container. The study included the effects of inlet and outlet baffling. Further study (ref. 2) showed that, for some typical cylindrical-tank configurations, distortion of the interface occurred during outflow, which resulted in liquid being left on the tank walls. The degree of interface distortion was related to Weber number and initial filling.

A thorough understanding of the behavior of the liquid-vapor interface in a storage tank when exposed to a weightless environment is required to ensure the efficient transfer of liquid from such a tank. Therefore, this study was undertaken to investigate another facet of that behavior: the effect of terminating liquid outflow in weightlessness, which could initiate disturbances that would disrupt the liquid-vapor interface. These disturbances could be shock waves caused by a rapidly closing valve (similar to the "water hammer" phenomenon); they could result from using a valve of such design that when it was closed, it would physically force liquid back into the tank; or they could be strictly interfacial in nature, perhaps caused by the necessity of dissipating the kinetic energy of the moving fluid when flow is stopped. Whatever the cause, such disturbances could conceivably initiate mass transfer of the liquid to the opposite end of the vessel. This disturbance would most likely be in the form of an axial geyser, or spike of liquid, which could carry some or all of the liquid with it. Such an occurrence could uncover the tank outlet, precluding any further outflow, and cover the tank vent, at least until reorientation could be effected.

It is somewhat self-evident that a geyser can be caused by a valve physically forcing liquid back into the vessel. This phenomenon can, in fact, be observed even under normal gravity conditions. Since the characteristics of such a geyser depend primarily on the valve design, it was decided not to explore this case in the present study. Thus, the outlet valve was designed to eliminate this type of geyser.

The results of this study show that a geyser can, in fact, occur after termination of liquid outflow in weightlessness, but only under the proper conditions. Mass transfer of liquid away from the outlet was minimal, even when geysering did occur.

## SYMBOLS

| | |
|---|---|
| $D$ | tank diameter, cm |
| $d$ | outlet diameter, cm |
| $H$ | zero-gravity-interface height above outlet, cm |
| $H_F$ | zero-gravity-interface height above outlet at termination of pumping, cm |
| $R$ | tank radius, cm |
| $V_m$ | mean liquid velocity in tank, cm/sec |
| We | Weber number, $\rho V_m^2 R/\sigma$ |
| $\Delta H$ | interface displacement, cm |
| $\Delta H/R$ | relative interface displacement |
| $\mu$ | absolute viscosity, g/(cm)(sec) |
| $\nu$ | kinematic viscosity, $\mu/\rho$, $cm^2/sec$ |
| $\rho$ | mass density, $g/cm^3$ |

$\sigma$ surface tension, dynes/cm

$\sigma/\rho$ specific surface tension, $cm^3/sec^2$

# APPARATUS AND PROCEDURE

## Test Facility

The experimental investigation was conducted at Lewis in a zero-gravity research facility, the 100-foot drop tower, schematically represented in figure 1. The test package was allowed to free fall over an 85-foot distance, thereby providing 2.25 seconds of test time under virtually weightless conditions. The acceleration level on the experiment was maintained below $10^{-5}$ g through use of a heavy air-drag shield that completely enclosed the test package during a drop. Although air drag produced a decelerating effect on the drag shield, this deceleration was not transmitted to the experiment inside because it was allowed to free fall relative to the shield. A drop was terminated when the wooden spikes attached to the underside of the drag shield impinged in a sand bed at the bottom of the tower. This procedure controlled deceleration of the test package and allowed it to be recovered intact.

## Experiment Package

The experiment package is shown in figure 2. It consisted of an aluminum framework, the experiment tank containing the test liquid, a 16-millimeter high-speed camera for photographing the behavior of the liquid, and the necessary auxiliary equipment. Auxiliary equipment included a specially designed outlet valve for the tank, separate pressure supply systems to operate the valve and provide pumping pressure to the experiment tanks, rechargeable nickel-cadmium batteries, a digital clock, and the necessary electrical controls. The digital clock was accurate to 0.01 second and was observable in the camera's field of view through a mirror system. The electrical controls included two time-delay relays by which both the total outflow time and the time between start of weightlessness and inception of outflow (interface formation time) could be varied.

Outflow was produced by pressurizing the experiment tank and opening the outlet valve, which was operated by a solenoid-controlled air piston. This valve was designed to terminate outflow without physically forcing liquid back into the tank. It operated on the sliding-vane principle, controlling flow by a thin, rotating, sliding plate in which a square-edged orifice was cut. The orifice rotated past an O-ring that was concentric with the outlet. In this manner, the valve could be sealed in either the open or closed position. A schematic diagram of the valve is presented in figure 3.

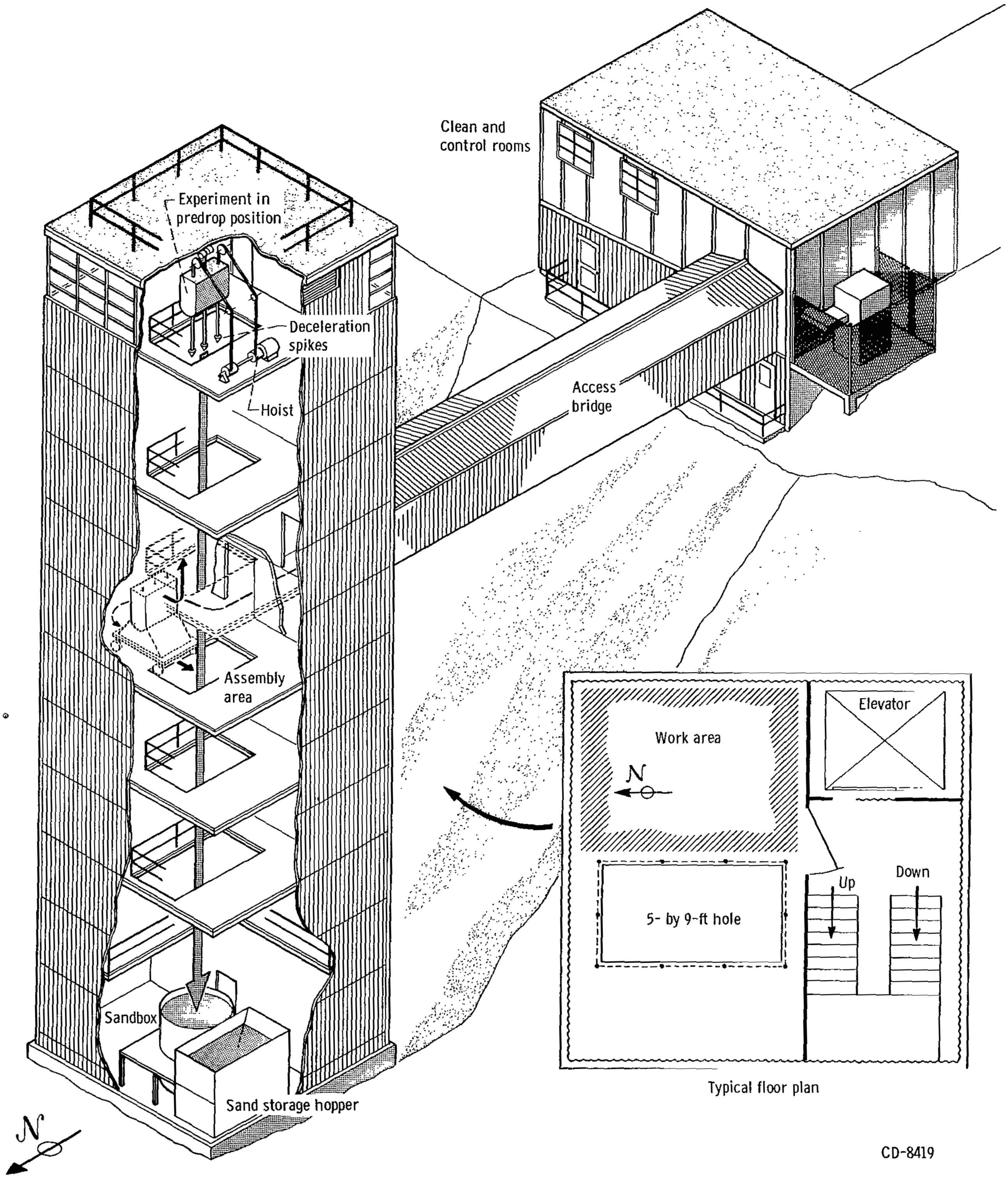
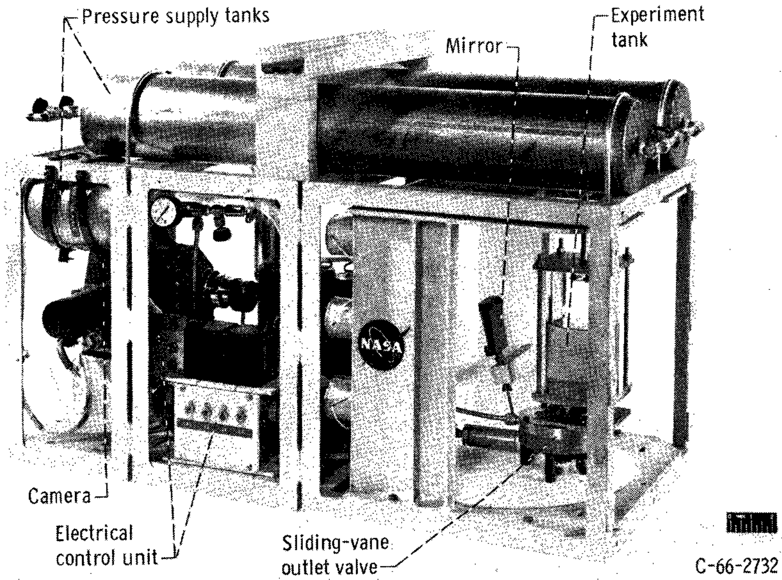
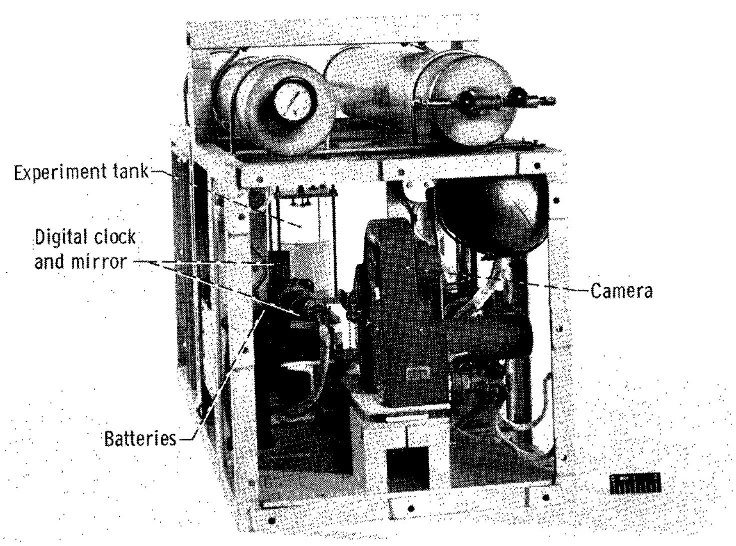



Figure 1. - Schematic drawing of 100-foot drop tower at Lewis Research Center.




(a) Side view.




(b) View from camera end. C-66-2733

Figure 2. - Experiment package.

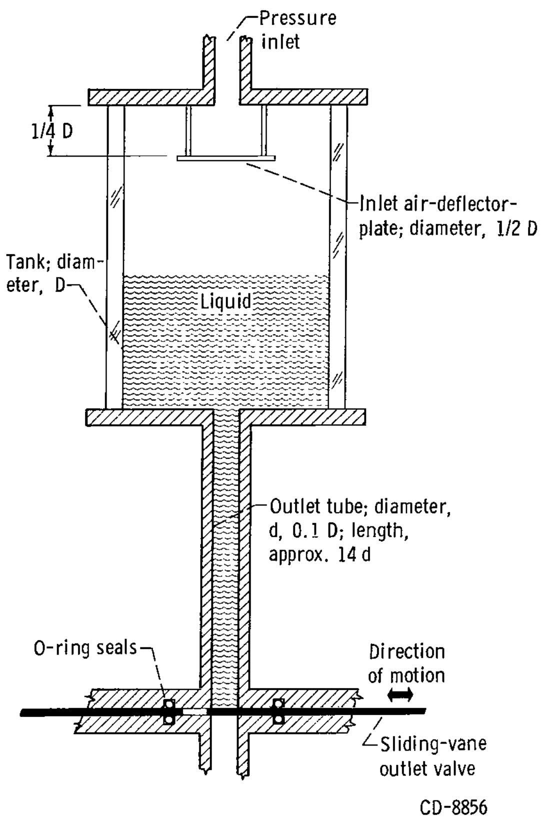



Figure 3. - Schematic drawing of typical test tank.

## Experiment Tanks

The test tanks were cylinders that had inner diameters of 2, 4, and 8 centimeters. Some tanks were machined from cast acrylic plastic, and others were fabricated from borosilicate glass tubing. These materials were used interchangeably. The ends were stainless-steel plates with O-ring seals. An inlet air-deflector plate, which was equal in diameter to the tank radius, was located one-half radius from the top of the tank on the tank centerline (fig. 3). The outlet was centered at the opposite end of the tank, and was a square-edged orifice with a diameter equal to one-tenth the diameter of the tank. The outlet tube leading to the valve was a straight channel that was 14 outlet-diameters long. Figure 3 is a schematic drawing of a typical tank and outlet configuration. Some tests were made in 8-centimeter-diameter tanks that were 4 radii long, to approximate dimension ratios of typical spacecraft tanks. Other tests were made in 2- and 4-centimeter-diameter tanks that were 8 radii long to allow higher initial fillings and thus longer outflow times.

## Test Liquids

The liquids used in this investigation and their pertinent physical properties are listed in table I. All the liquids had $0^{\circ}$ contact angles with the tank walls. To improve the photographic quality of the data film, a small quantity of dye was added to each of the liquids. The dye had no measureable effect on the physical properties of the liquids given in the table.

## Operating Procedure

Prior to a series of test runs, the experiment tank, valve, and tank-filling equipment were thoroughly cleaned ultrasonically in an aqueous detergent solution. Cleaning was followed by a distilled-water rinse, an ethanol rinse, and complete drying in warm,

TABLE I. - LIQUID PROPERTIES

| Liquid[a] | Surface tension, $\sigma$, dynes/cm | Mass density, $\rho$, g/cm$^3$ | Specific surface tension, $\sigma/\rho$, cm$^3$/sec$^2$ | Absolute viscosity, $\mu$, g/(cm)(sec) | Kinematic viscosity, $\nu = \mu/\rho$, cm$^2$/sec |
|---|---|---|---|---|---|
| Ethanol | 22.3 | 0.789 | 28.3 | $1.200\times10^{-2}$ | $1.52\times10^{-2}$ |
| Trichlorotrifluoroethane | 18.6 | 1.58 | 11.8 | .70 | .443 |
| Methanol | 22.6 | .793 | 28.5 | .597 | .756 |
| 90 Percent water, 10 percent ethanol[b] | 49.6 | .985 | 50.4 | 1.42 | 1.44 |
| Acetone | 23.7 | .792 | 29.9 | .32 | .404 |
| Butanol-1 | 24.6 | .809 | 30.4 | 2.95 | 3.58 |
| 60 Percent ethanol, 40 percent glycerol[b] | 26.9 | .988 | 27.2 | 15.4 | 15.6 |

[a]At 20° C.
[b]Percent composition by volume.

filtered air. The parts were then assembled and installed in the experiment package. This preparatory procedure was followed to prevent contamination of the test liquid and ensure wetting of the tank walls by the liquid.

For each test run, the tank was filled with liquid to the desired height. The tank and the pressure-supply system were filled with filtered air to the required pumping pressure, sealed, and checked for leaks. The timing relays to control the outflow sequence were set. The camera was then loaded with film, and the experimental package was balanced about its vertical axis by adding weights. After a final check of all systems, the package was ready for the data run.

For each data point, two tests were conducted: a ground test at 1 g, and a drop test at zero gravity. For the two tests, all other parameters remained identical. The ground test was used to determine the mean liquid velocity in the tank during outflow by measuring the slope of a displacement-time curve for the flat interface. The mean liquid velocity in the tank for the corresponding drop test was then obtained by comparing the interface height in the tank after the drop test with the final interface height from the ground test. If the interface heights were identical, the velocities were considered to be equal because the outflow times were essentially the same in each case. For those cases where slight differences in the interface heights occurred, the zero-gravity velocity was calculated from the ratio of the interface displacements.

## RESULTS AND DISCUSSION

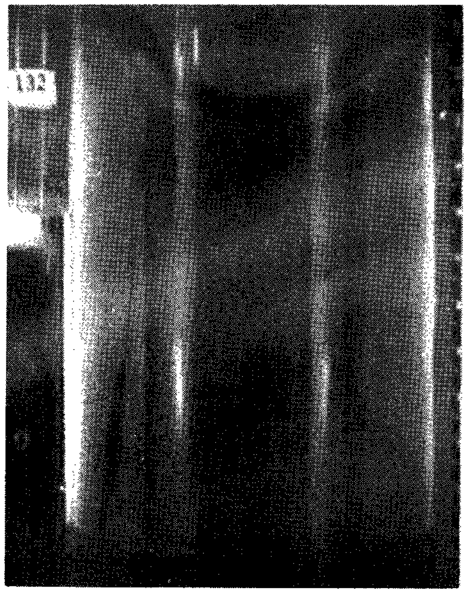
The results of this study show that an interface disturbance in the form of an axial geyser of liquid can occur, under the proper circumstances, on termination of outflow from a cylindrical tank in weightlessness. Two distinct categories of geysers were observed. One, which is defined as the normal case, occurred when outflow was terminated and the zero-gravity interface was at some distance from the outlet, that is, when the interface was in its normal outflow configuration - a slightly distended hemisphere (ref. 2). The other type of geyser occurred when the interface had approached near enough to the outlet that outflow was terminated during the interface distortion preceding vapor ingestion (entrance of vapor into the tank outlet).

### Interfacial Geysering Resulting From Normal Outflow Termination

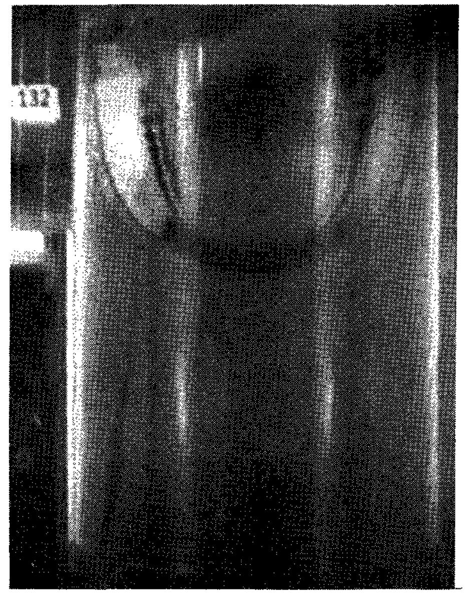
Observed interface behavior. - For the normal outflow-termination case, a geyser may or may not occur, depending on the conditions in the tank just before flow is ended. The geyser condition and how it differs from the case in which no geyser occurs are illustrated in figures 4 to 6. These figures are photographic sequences taken from high-speed films. The liquid is a mixture of 90 percent water and 10 percent ethanol; the tank is 8 centimeters in diameter and 4 radii (16 cm) long. The tank was filled initially to a depth of 3 radii (12 cm) in each case.

The water-ethanol mixture was used only for these illustrative tests because the high specific surface tension ($\sigma/\rho = 50.4\ cm^3/sec^2$) allowed a relatively short cycle from interface formation through outflow, geyser formation, geyser termination, and interface recovery (fig. 4). For this mixture, the entire cycle could be completely observed in the 2.25 seconds available; this was not possible in the 8-centimeter tank with any of the other liquids used because of their considerably lower values of specific surface tension. (A discussion of the effect of liquid properties on interface formation time is presented in ref. 3.) Difficulty in obtaining consistent wetting ($0^o$ contact angle) of the tank walls by the water-ethanol mixture precluded its use for other than illustrative purposes.

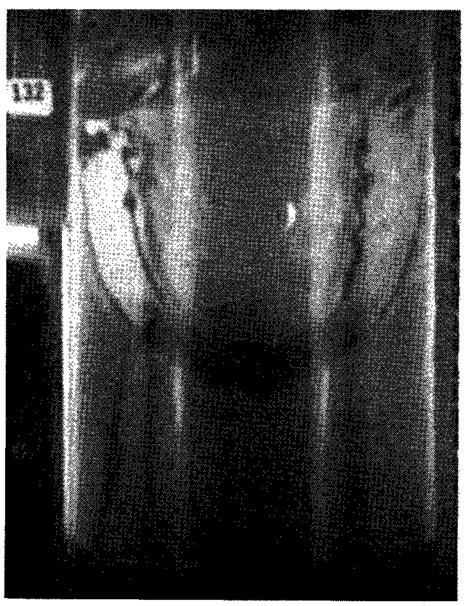
Typical geyser development after termination of outflow is shown in figure 4. The interface configuration at initiation of outflow (fig. 4(a)) was reached at about 0.45 second after the start of weightlessness. In figure 4(b) the interface shape during outflow is shown. The configuration of the interface at the time of outflow termination is shown in figure 4(c). Figures 4(d) to (f) show the geyser formation and imminent impingement on the tank inlet baffle which is out of view. Figures 4(g) and (h) show the geyser "pinching off" and collecting on the baffle, while the greater mass of liquid remains in the original orientation as the hemispherical interface re-forms. Only a small percentage of the liquid is displaced to the inlet end of the tank.




(a) Weightless configuration at initiation of outflow. Time, 0 second.




(b) Time, 0.12 second.




(c) Termination of outflow. Time, 0.25 second.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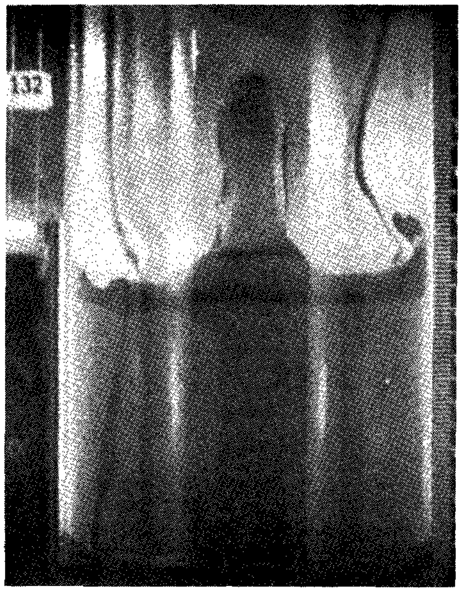
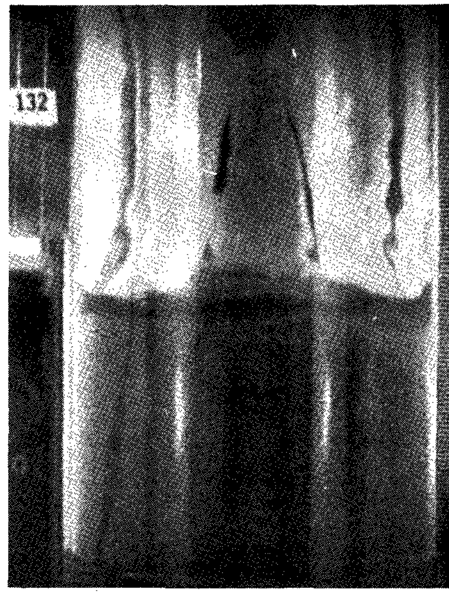
(d) Time, 0.35 second.

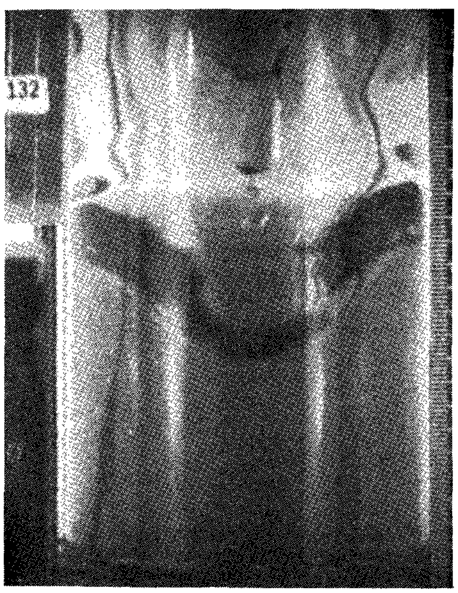
Figure 4. - Typical geyser following termination of outflow from cylindrical tank in weightlessness. Liquid, 90 percent water, 10 percent ethanol.



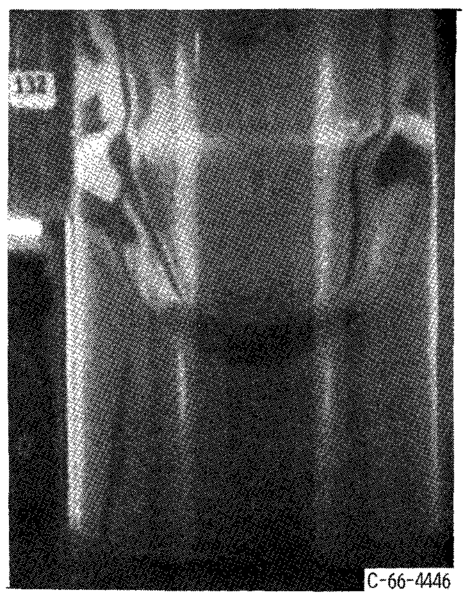

(e) Time, 0.54 second.




(f) Time, 0.81 second.

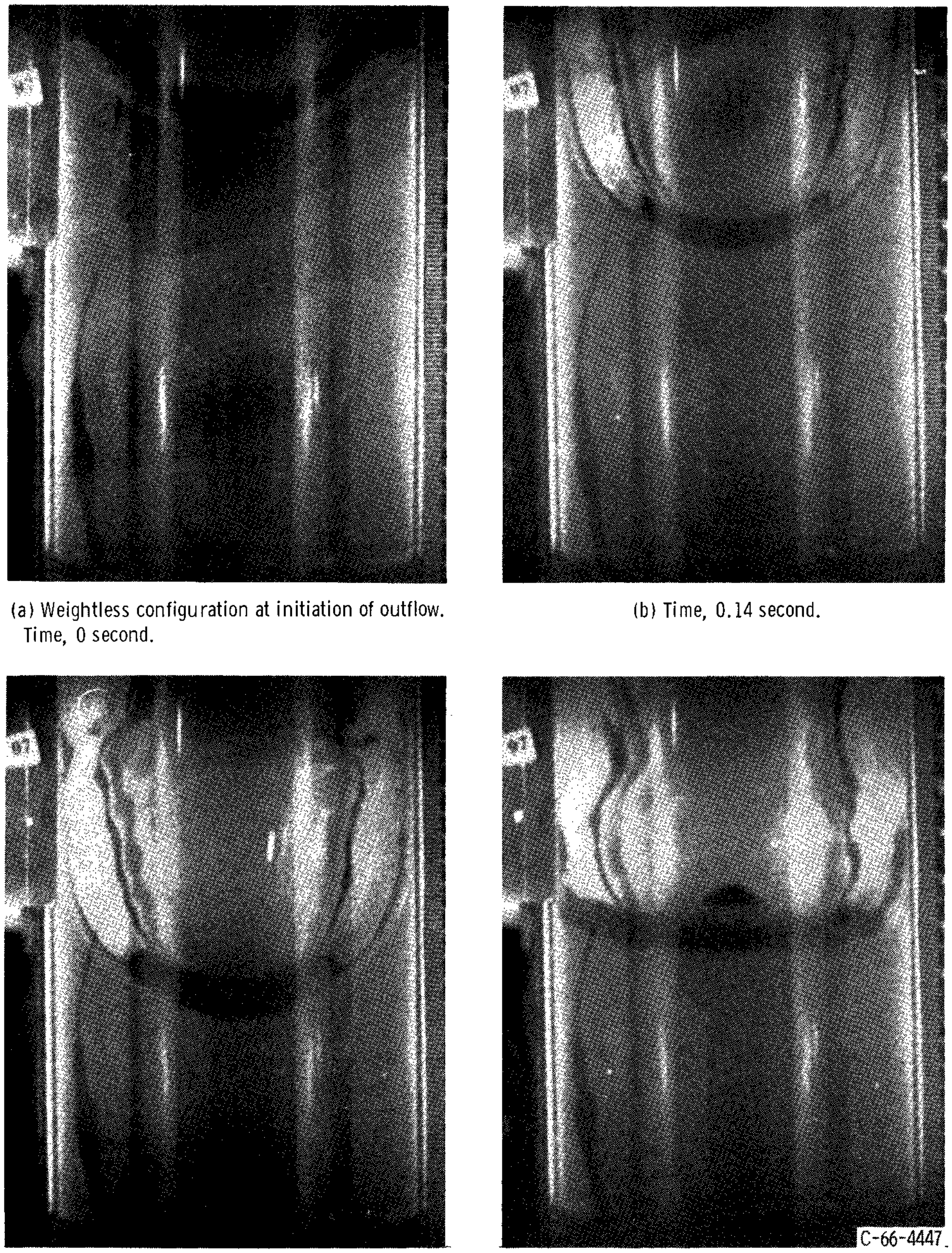



(g) Time, 1.40 seconds.




(h) Time, 1.55 seconds.

Figure 4. - Concluded.




(a) Weightless configuration at initiation of outflow. Time, 0 second.

(b) Time, 0.14 second.

(c) Termination of outflow. Time, 0.28 second.

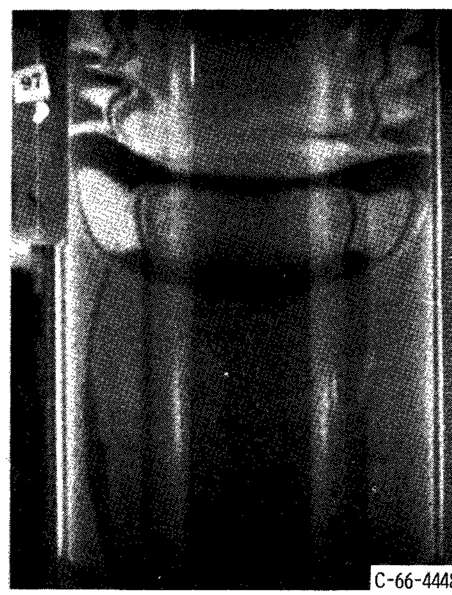
(d) Time, 0.41 second.

Figure 5. - Typical no-geyser case following termination of outflow from cylindrical tank in weightlessness. Liquid, 90 percent water, 10 percent ethanol.


(e) Time, 0.75 second.

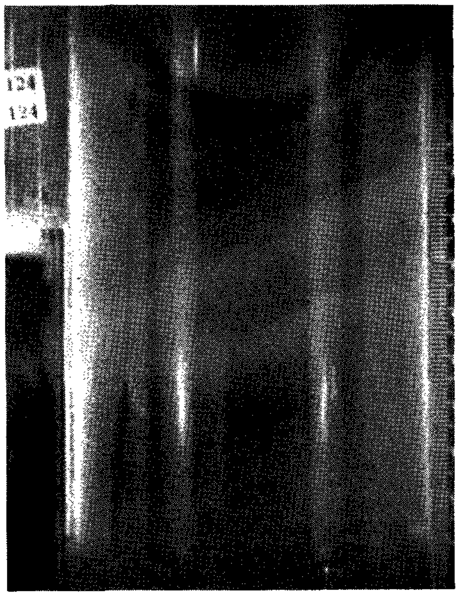

(f) Time, 1.05 seconds.


(g) Time, 1.15 seconds.

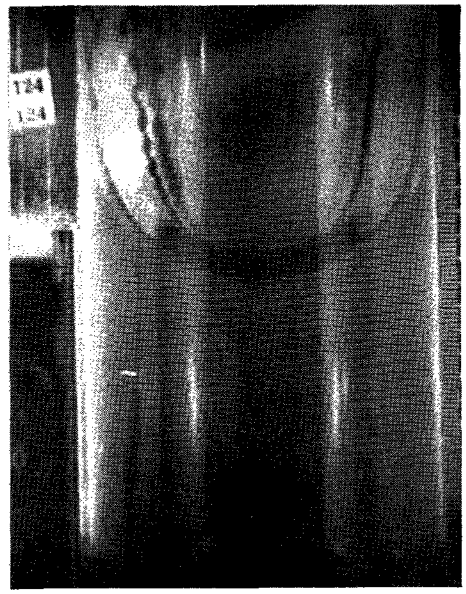



(h) Time, 1.30 seconds.

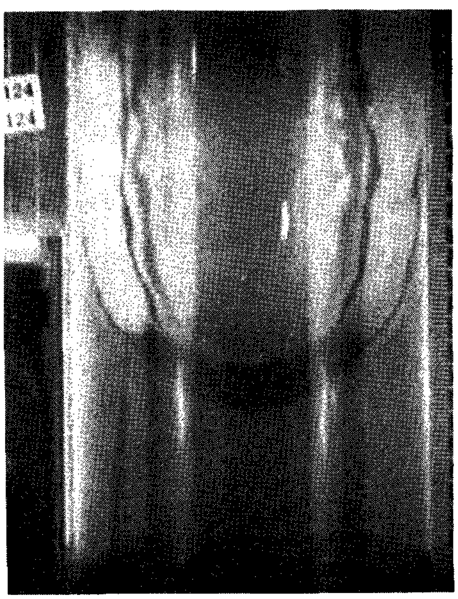
Figure 5. - Concluded.



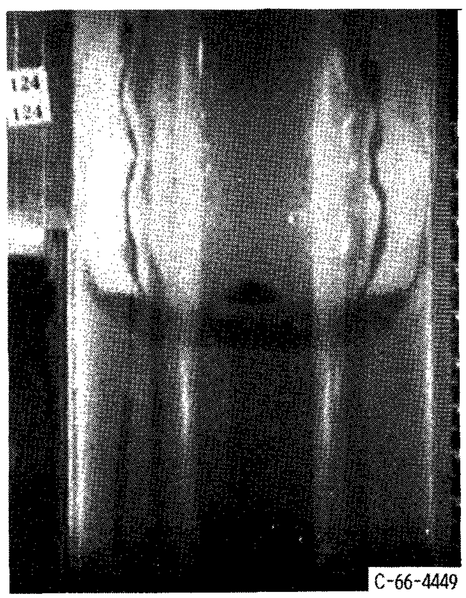

(a) Weightless configuration at initiation of outflow. Time, 0 second.




(b) Time, 0.17 second.




(c) Termination of outflow. Time, 0.33 second.

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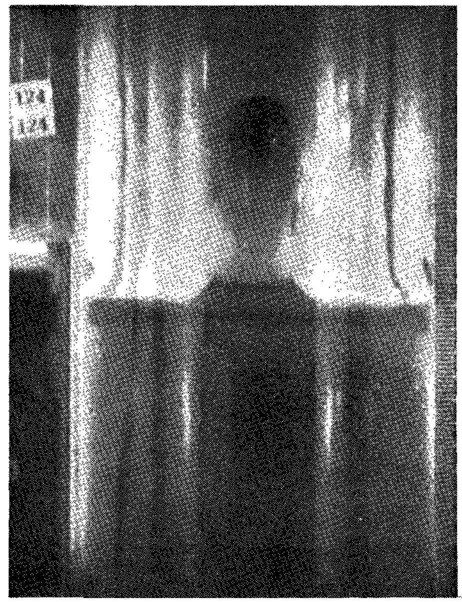
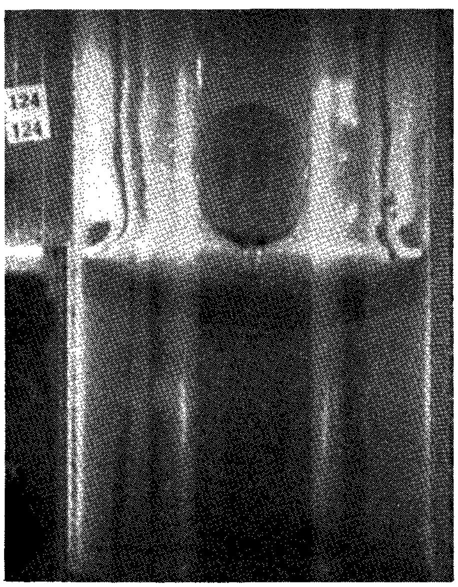
(d) Time, 0.43 second.

Figure 6. - Typical borderline geyser following termination of outflow from cylindrical tank in weightlessness. Liquid, 90 percent water, 10 percent ethanol.

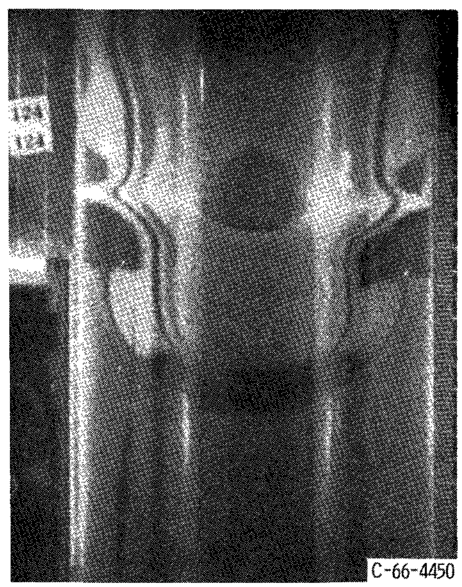

(e) Time, 0.71 second.




(f) Time, 0.96 second.




(g) Time, 1.29 seconds.




(h) Time, 1.58 seconds.

Figure 6. - Concluded.

Figure 5 shows the case where the geyser never develops. Rather, the interface develops an axial hump of liquid that is pulled back into the liquid mass by surface tension. The interface then re-forms.

In figure 6, the borderline condition between the geyser and no-geyser case is shown. Here the hump of liquid pinches off before it can be pulled back into the liquid mass. However, the resulting sphere of liquid has no velocity in either direction and remains in the position shown while the interface re-forms.

For the purposes of this study, the borderline geyser condition was defined as the pinchoff of a small quantity of liquid that had no velocity in either direction. If the pinched-off liquid had a velocity in either direction, it was defined as the geyser or no-geyser case, depending on the direction of the velocity.

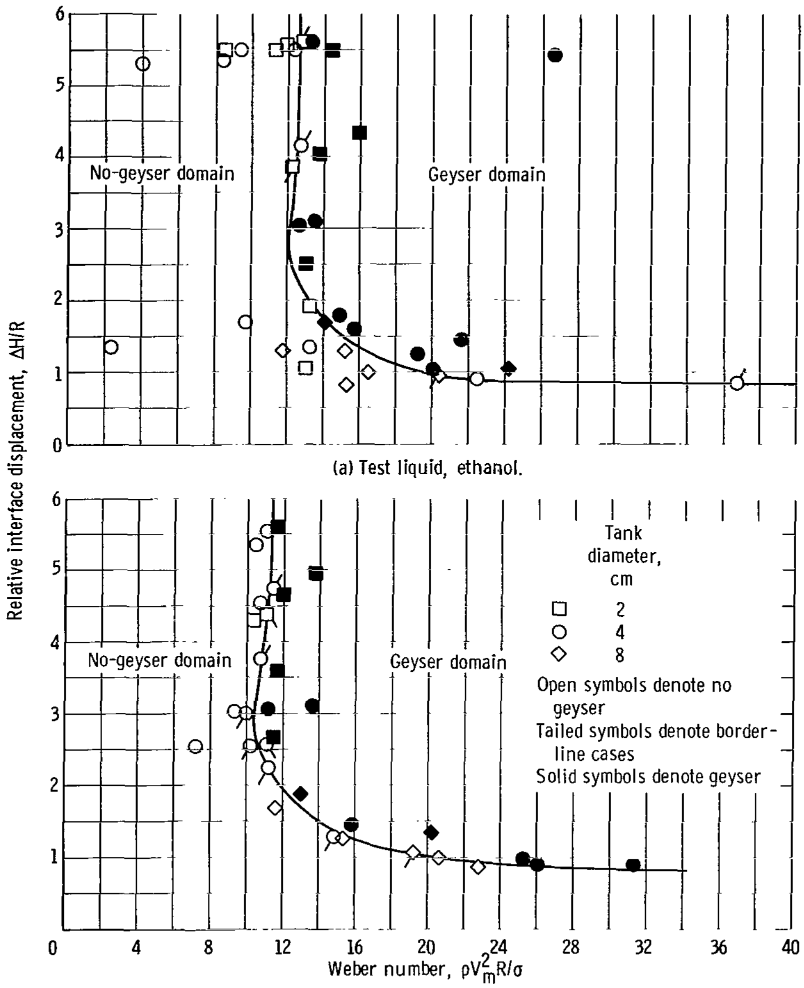
Because the borderline condition was defined so restrictively (pinchoff with no velocity), it occurred infrequently in the data runs. Most data points were considered to be either geyser or no-geyser cases, and thus the geyser and no-geyser domains could be sharply defined.

Effect of Weber number and interface displacement. - The primary findings of the investigation are summarized in figure 7 which shows the geyser and no-geyser domains for two liquids, ethanol and trichlorotrifluoroethane. The data are presented in terms of dimensionless parameters that are applicable to the general problem of outflow during weightlessness, that is, the results are presented as functions of the relative interface displacement $\Delta H/R$ and the Weber number $\rho V_m^2 R/\sigma$. The actual displacement $\Delta H$ of the zero-gravity interface during outflow, for example, is the difference in interface heights between figures 4(a) and (c).

Figure 7 shows that for Weber numbers less than 10 to 12, geysers do not occur in these liquids on termination of outflow. For larger Weber numbers, geysers may or may not occur, depending on the relative interface displacement. In general, the interface displacement must be greater than approximately 1 tank radius for a geyser to occur. For displacements greater than about 2 radii, the geyser phenomenon for these liquids appears to depend only on the value of the Weber number.

Effect of viscosity. - Figure 7 indicates that the Weber number below which geysering does not occur is slightly different for the two liquids. This appears to be an effect of viscosity. This facet of the phenomenon was investigated by performing several tests with other liquids in the 4-centimeter-diameter tank at interface displacements greater than 5 radii. Figure 8 shows the change in the Weber number that defines the geyser domain as a function of kinematic viscosity. Because the effect appears to be only minor, a more comprehensive study of the phenomenon was not attempted.

Effect of tank bottom. - The data presented in figure 7 were taken at various initial fillings in order to study the effect of the proximity of the interface to the tank bottom or outlet for a given interface displacement. No effect was found; the correlating function




(b) Test liquid, trichlorotrifluoroethane.

Figure 7. - Geyser and no-geyser domains as a function of relative interface displacement and Weber number.

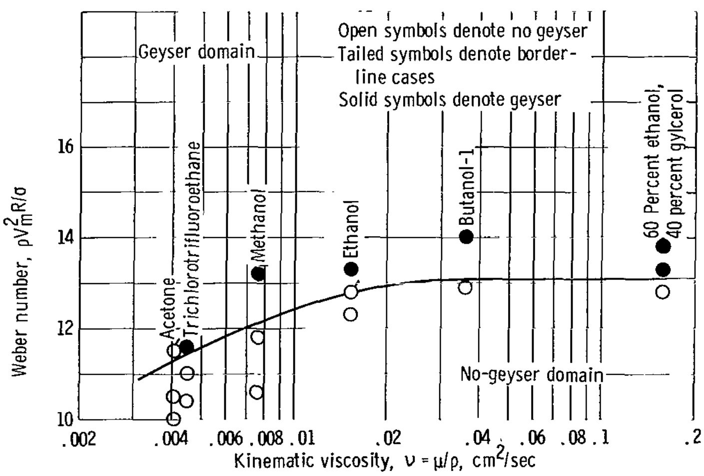



Figure 8. - Geyser and no-geyser domains as function of Weber number and kinematic viscosity for relative interface displacements of less than 5.

was strictly interface displacement. This would seem to lead to the conclusion that geysering is not caused by disturbances emanating from the outlet tube, but is solely an interfacial phenomenon. The geysering phenomenon is apparently related to the amount of fluid kinetic energy present with respect to the surface-tension forces available (Weber number) and to the relative interface displacement.

## Interfacial Geysering Resulting From Outflow Termination During Vapor-Ingestion Phenomenon

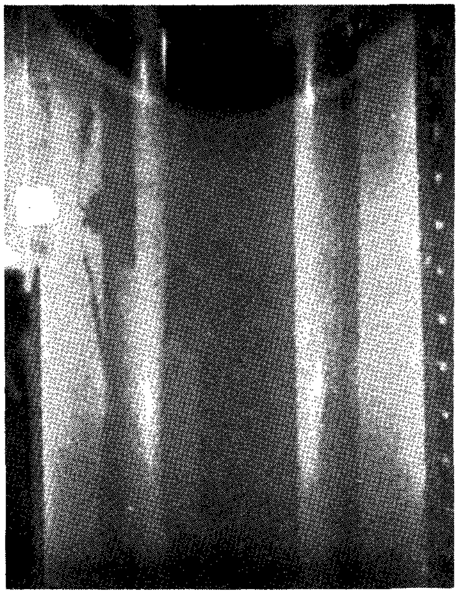
When the liquid-vapor interface approaches the outlet during outflow in weightlessness, vapor ingestion occurs (i.e., the ingestion of vapor into the outlet before the entire volume of liquid has been removed from the tank). This phenomenon begins as an axial distortion of the interface. This distortion increases rapidly until vapor actually enters the tank outlet. Vapor ingestion can be observed in both the 1-g and zero-gravity tests. Photographic examples of the zero-gravity case are given in references 1 and 2.

In this report, vapor ingestion refers to the actual entrance of vapor into the outlet, and vapor ingestion phenomenon refers to the entire phenomenon beginning with the first noticed distortion of the interface.

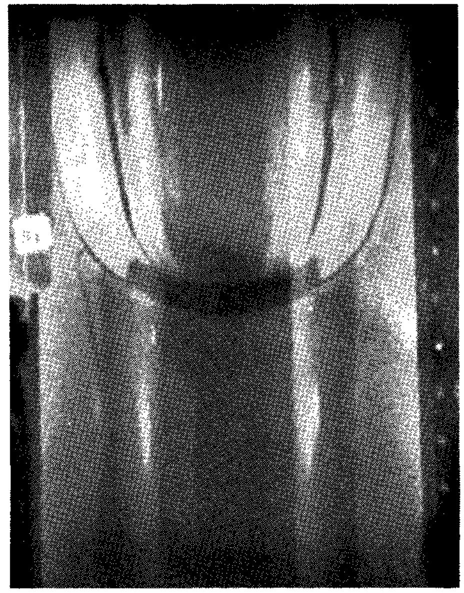
Some data were obtained in which outflow was terminated during the vapor-ingestion phenomenon. These data, which are presented in table II, indicate that a geyser occurred in nearly every case, regardless of the Weber number or interface displacement. The only exception noted was when the interface distortion at termination of outflow was relatively small, in which case the geyser did not fully develop. In general, the vapor-ingestion phenomenon and the ensuing geyser at termination of outflow occurred only when the interface was within approximately 1 tank radius above the outlet.

TABLE II. - INTERFACE BEHAVIOR DURING VAPOR-INGESTION PHENOMENON

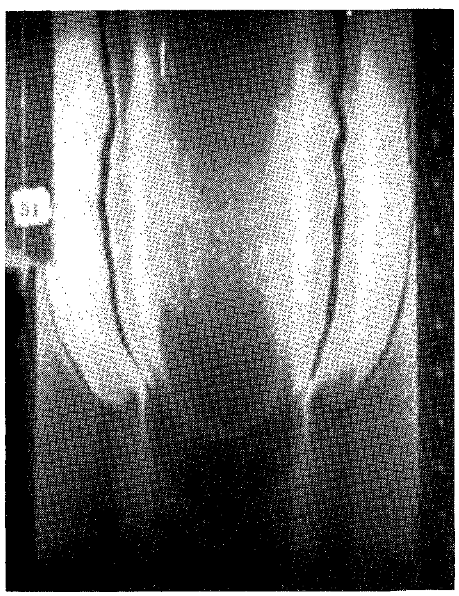
| Liquid | Weber number, We | $H_F/R$ | Interface behavior |
|---|---|---|---|
| Ethanol | 9.75 | 0.60 | Geyser (borderline) |
| | 9.75 | .38 | Geyser |
| | 9.50 | .48 | Geyser |
| | 4.76 | .45 | Geyser |
| | 4.76 | 0 | Geyser |
| Trichlorotri-fluoroethane | 11.8 | 0 | Geyser |



(a) Weightless configuration at initiation of outflow. Time, 0 second.



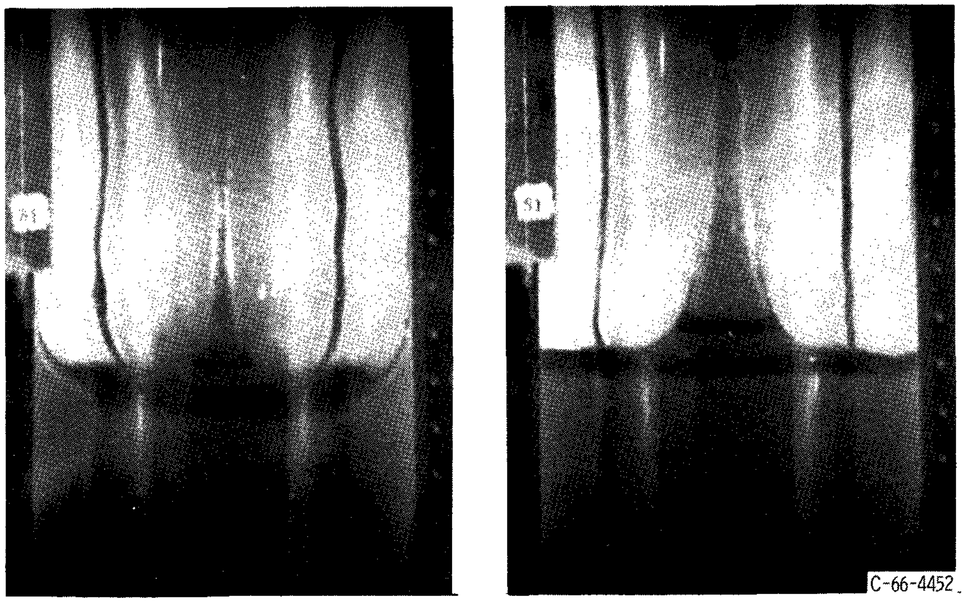
(b) Time, 0.32 second.



(c) Termination of outflow. Time, 0.71 second.


(d) Time, 0.75 second.

Figure 9. - Typical geyser following termination of outflow during the interface distortion associated with the vapor-ingestion phenomenon in weightlessness. Cylindrical, flat-bottom tank; liquid, ethanol; Weber number, 9.7.



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(e) Time, 0.91 second. (f) Time, 1.47 seconds.

Figure 9. - Concluded.

Figure 9 shows a typical geyser produced when outflow is terminated during the vapor-ingestion phenomenon. The liquid is ethanol, and the Weber number is 9.7, which is well into the no-geyser domain. Figure 9(c) shows the distortion of the interface at outflow termination, and figures 9(d) to (f) show the formation of the resulting geyser. As in the normal case, only a small percentage of the liquid is transferred to the opposite end of the tank.

## CONCLUDING REMARKS

Under the proper conditions, a geyser can occur at the liquid-vapor interface on termination of outflow from a cylindrical container in weightlessness. Geyser formation is a function of Weber number and interface displacement and is slightly affected by kinematic viscosity. A geyser nearly always occurred when outflow was terminated while the interface was distorted during the vapor-ingestion phenomenon, regardless of the Weber number or interface displacement.

The geysering phenomenon was not caused by disturbances emanating from the outlet tube but was a function of interfacial conditions only. As such, geyser formation appears to be readily predictable. Also, even in the worst geysering cases, only a small percentage of liquid was transferred to the inlet end of the tank.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 1, 1966,
124-09-03-01-22.

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