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LOW-GRAVITY REORIENTATION IN A SCALE-MODEL CENTAUR LIQUID-HYDROGEN TANK

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16. Abstract

An experiment was conducted to investigate the process of liquid reorientation from one end of a scale-model Centaur liquid-hydrogen tank to the other end by means of low-level accelerations. Prior to reorientation, the liquid was stabilized at the top of the tank at a Bond number of 15. Tanks both with and without ring baffles and with tank radii of 5.5 and 7.0 centimeters were used in the study. Reorientation acceleration values were varied to obtain Bond numbers of 200 and 450. Liquid fill levels of 20 and 70 percent were used. From the data in this study, relations were developed to estimate reorientation event times in unbaffled tanks through the point of final liquid clearing from the top of the tank. The insertion of ring baffles drastically changed the reorientation flow profiles but resulted in only minor differences in the times of tank-top uncovering and liquid collection.

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SUMMARY

An experiment was conducted to investigate the process of liquid reorientation from one end of a scale-model Centaur liquid-hydrogen tank to the other end by means of low-level accelerations. Prior to reorientation, the liquid was stabilized at the top of the tank at a Bond number of 15. Tanks both with and without ring baffles and with tank radii of 5.5 and 7.0 centimeters were used in the study. Reorientation acceleration values were varied to obtain Bond numbers of 200 and 450. Liquid fill levels of 20 and 70 percent were used.

The initial liquid flow was in a layer along the tank wall. In all unbaffled tank tests, the liquid rebounded or geysered back to the tank top after initially being reoriented. Event times from the start of reorientation to when the geyser impacted the top of the tank compared well with predicted event times. The insertion of ring baffles drastically changed the reorientation flow patterns but resulted in only minor differences in the time to clear the top of the tank and to collect the liquid.

INTRODUCTION

The major objectives of liquid-propellant management following periods of engine-off space coast are to position the propellant for an engine restart and, in the case of cryogenics, to position the propellant for venting to maintain tank pressure control. Small auxiliary thrusters can be used to create low-level vehicle accelerations in the direction of main-engine thrust to retain the propellant in its proper orientation. However, the continuous application of these thrusters during extended space missions is impractical and their usage will have to be intermittent. During the off-times, the liquid propellant is expected to be relocated by disturbances and drag forces acting on the vehicle. Various passive retention devices, such as capillary baffles, have been proposed to control the location of the liquid; but it appears that, at least in the present design of large cryogenic propellant tanks, low-gravity auxiliary thrusters must be the primary method of control. The thrust and time required to reorient the liquid propellant back to its desired location must be known to ensure a successful tank venting and/or engine restart sequence and to determine effective thruster parameters.

The initial destabilization and ensuing reorientation or collection flow dynamics have been studied both experimentally and analytically in references 1 to 3 for the limiting cases of initially flat and highly curved interfaces. Experimental scale-model investigations have followed the reorientation process from an initial zero-Bond-number condition through total liquid collection for reorientation Bond numbers to 60 (ref. 3). It was shown that, in most situations, liquid rebounding or geysering occurs following liquid-liquid impingement at the tank bottom and that this geysering results in the circulation of a substantial portion of the liquid rather than a quiescent collection. In these studies, the liquid collection rates depended heavily on the geysering dynamics and there were no quantitative correlations obtained which could be used to extrapolate this behavior to higher reorientation Bond numbers. General analytical and experimental correlations are not possible because of the diversity of space-vehicle characteristics and mission requirements and the complexity of the reorientation process. Predictions of quantitative collection rates for a particular space vehicle and mission depend heavily on experimental observations from scale-model tests which simulate directly such parameters as tank shape, liquid fill level, initial conditions, internal baffling, and Bond number.

This report presents the results of an experimental investigation modeling a specific set of reorientation parameters. The test containers were scale models of a Centaur-space-vehicle, liquid-hydrogen tank both with and without scaled ring slosh baffles. Tests were run at reorientation Bond numbers of 200 and 450, starting from initial conditions with a positive Bond number of 15. Liquid fill levels of 20 and 70 percent were used. These Bond numbers and liquid fill levels were chosen to simulate the Centaur-space-vehicle, liquid-hydrogen-tank Bond numbers and fill levels expected for liquid-hydrogen collection following a zero-gravity coast.

Observations of the reorientation flow are presented and equations are given to estimate reorientation event times through the point of final liquid clearing from the top of the tank. Also presented are the liquid flow patterns occurring in baffled tanks, along with qualitative estimates of the effects of baffles on the final collection time.

APPARATUS AND PROCEDURE

Test Facility and Experimental Vehicle

The experimental investigation was conducted in the Lewis Zero-Gravity Facility (fig. 1). Data were obtained by allowing a vehicle housing the experiment (fig. 2) to free

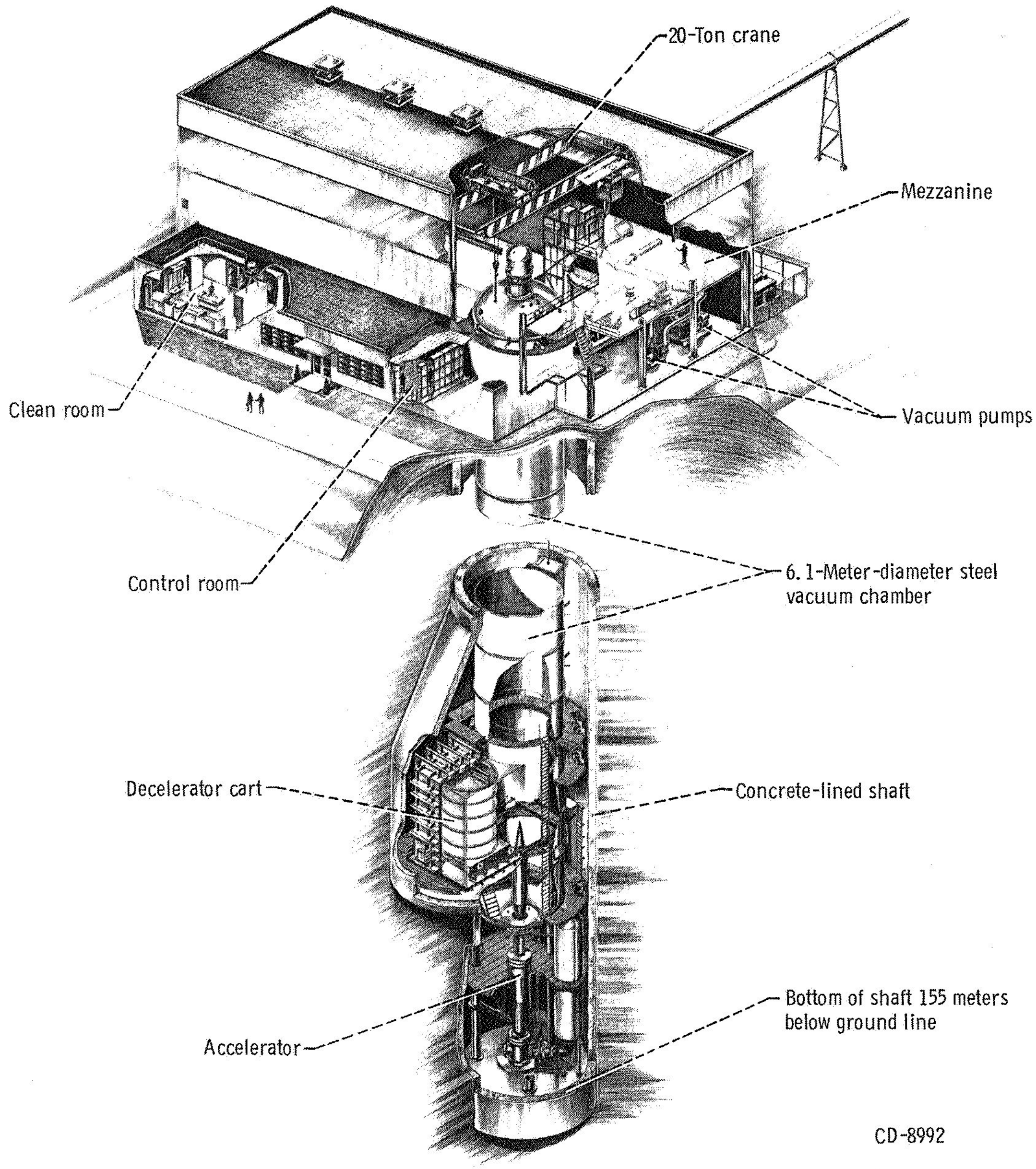


Figure 1. - Zero Gravity Facility.

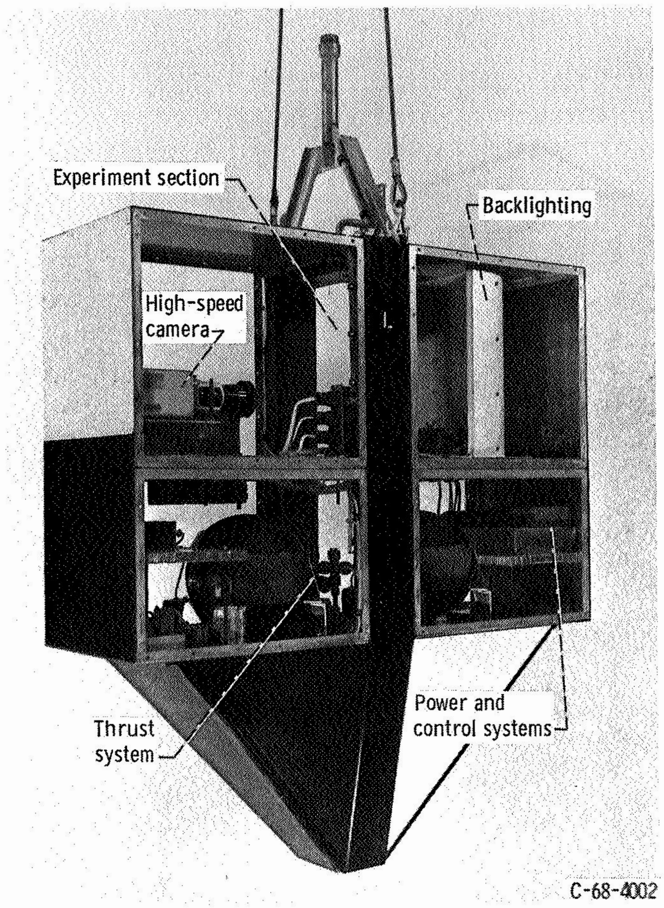


Figure 2. - Experiment vehicle for low-gravity tests.

fall from ground level down a steel vacuum chamber approximately 142 meters deep. This resulted in about 5 seconds of free-fall time. By evacuating the vacuum chamber to a nominal pressure of 13.3 newtons per square meter (1.3×10^{-4} atm), the equivalent gravitational acceleration acting on the experiment due to residual air drag was less than 10^{-5} g. Following the free-fall period, the vehicle and experiment were recovered at the bottom of the chamber in a cart filled with small pellets of expanded polystyrene. Average deceleration of the vehicle during recovery was 32 g's.

The experiment vehicle used in obtaining the data was a completely self-contained unit capable of imparting both positive and negative low-level accelerations on the experiment by the use of a cold-gas thrust system. The positive acceleration system was actuated shortly before the vehicle was dropped and remained operating for a specified period of drop time to allow the liquid-vapor interface to approach its low-gravity equilibrium shape. The positive low-gravity environments ranged from 2.4×10^{-3} to 3.8×10^{-3} g to simulate a drag Bond number of 15 for all tests. Upon application of the negative or reorientation acceleration the positive gravity level system was turned off. The reorientation accelerations ranged from 3.2×10^{-2} to 7.1×10^{-2} g and after application remained effective through test termination. The low-gravity acceleration values were obtained from ground calibration curves of the experiment vehicle's thrust system to within ±6 percent. Telemetry data during the test drop were used to corroborate these calibrated thrust values. A more complete description of the facility and test procedures is contained in reference 4.

Test Containers and Liquids

The test containers (fig. 3) were right-circular cylinders machined from II UVA acrylic plastic with spheroidal tops and inverted spheroidal bottoms to scale a Centaur-space-vehicle, liquid-hydrogen tank. The model tanks used had radii R of 5.5 and 7.0

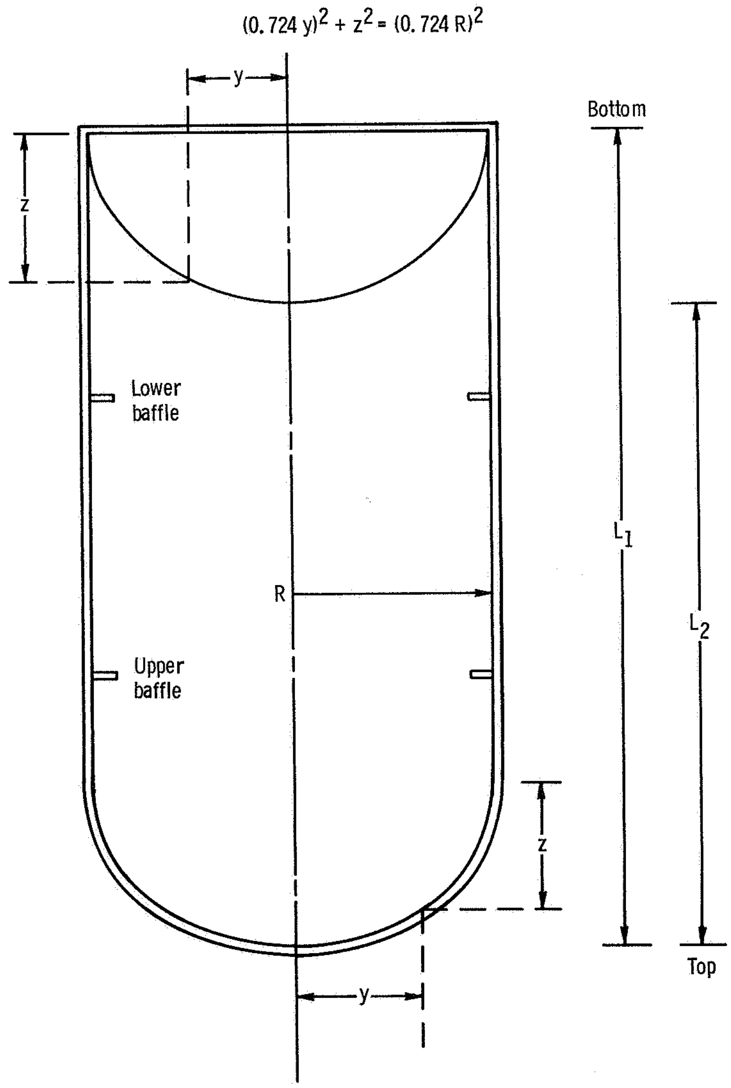


Figure 3. - Geometry of liquid container.

centimeters and lengths L_1 of 21.8 and 27.8 centimeters, respectively. In some tests, internal baffles were fixed to the tank walls to simulate the effects of slosh baffles in a full-size propellant tank. Two ring baffles were used with a width 0.15 R and thickness 0.05 R located at distances of 1.3 R and 2.7 R from the tank bottom.

Freon-TF and FC-78 were used as test liquids. Surface tensions, densities, and viscosities for these liquids are presented in table I. These liquids had static contact angles of very near 0° on the test container surfaces. Although a small quantity of dye was added to each liquid to improve photographic quality, this dye had no measurable effect on the properties of the liquids pertinent to this study.

TABLE I. - SUMMARY OF LIQUID

PROPERTIES AT 20° C

Liquid	Surface tension, σ, dynes/cm	Density, ρ, g/cm^3	Viscosity, η, cP
FC-78[a]	13.2	1.72	0.82
Freon-TF[b]	18.6	1.58	.70

[a]A fluorocarbon solvent obtained from Minnesota Mining and Manufacturing Co.

[b]Trichlorotrifluoroethane obtained from E.I. Dupont de Nemours and Co.

The experimental containers were prepared in a clean-room so that contamination of the liquid and the container surfaces, which could alter the surface tension and contact angle, was carefully avoided. The test containers were cleaned ultrasonically in a detergent-water solution, rinsed with a distilled-water - methanol solution, and dried in a warm-air dryer. Immediately prior to a test, the tanks were rinsed with the test liquid, filled to the required volume at normal atmospheric conditions, and hermetically sealed in the clean-room. The scale-model tanks were then positioned in the test vehicle with their centerline axis parallel to the applied acceleration of the vehicle.

Data Analysis

Data were collected from the experiments by both a high-speed photography system and telemetry; these systems were contained on the experiment vehicle. Telemetry data from thrust nozzle inlet pressures and low-gravity accelerometer outputs were used to verify both positive and negative acceleration values imposed on the vehicle. These data were also used to determine the time when the negative thrust was actually initiated in each test. The liquid reorientation data obtained in this investigation were taken from color data film by use of a motion-picture film analyzer which magnified the image by a factor of 25. From a scale positioned along the tank centerline plane and a digital clock with a calibrated accuracy of 0.01 second, a time history of the liquid surface motion was obtained for each test. Although refraction caused some optical distortion of liquid-vapor profiles, most displacement data were unaffected and no corrections were attempted with these data.

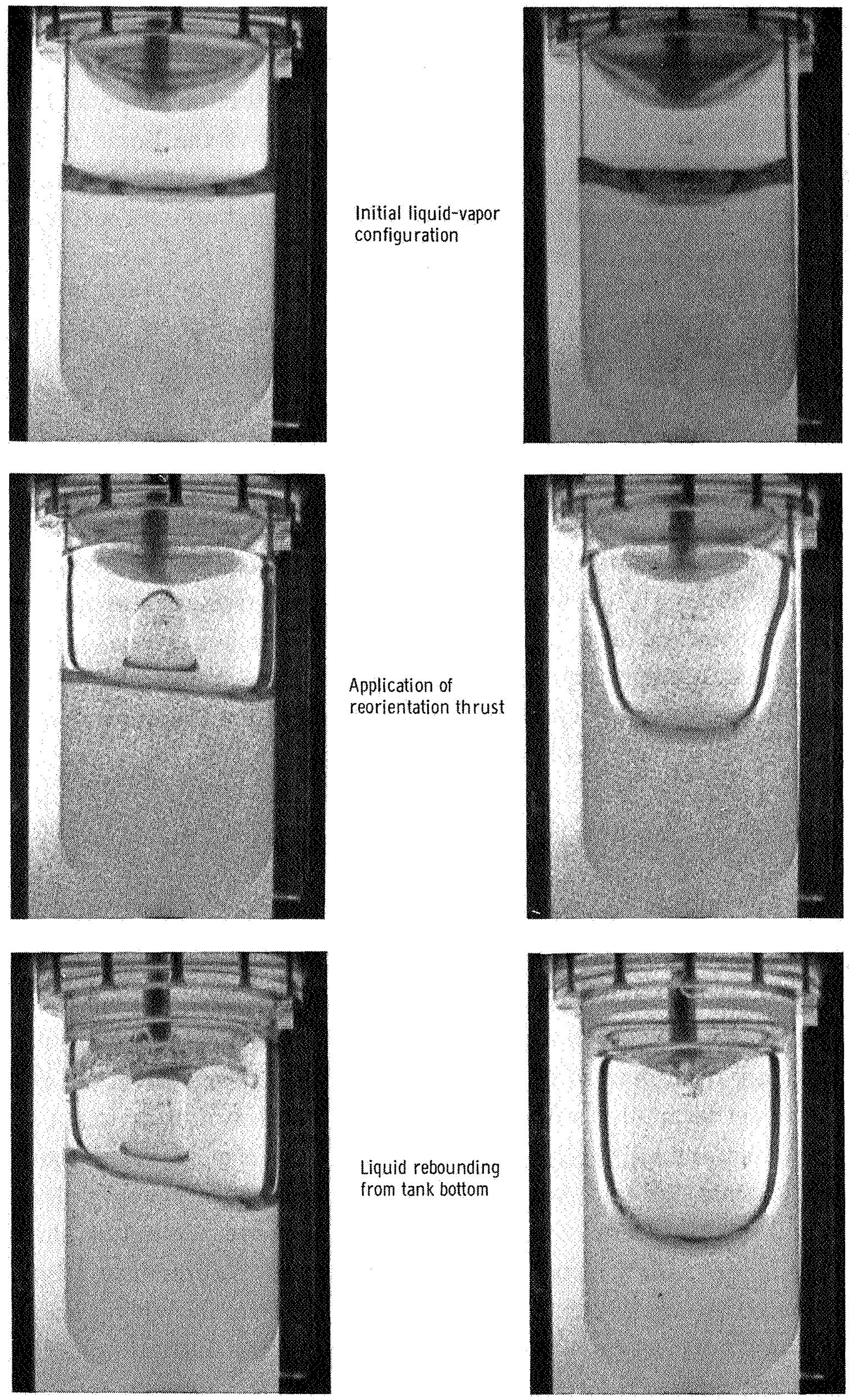
RESULTS AND DISCUSSION

Liquid Reorientation in Unbaffled Tanks

Effects of initial conditions. - The tank size and liquid combinations which were tested in this study were dictated by the desired reorientation Bond number Bo conditions of 200 and 450 ($Bo = aR^2/\beta$) and by the range of negative accelerations which were available. (All symbols are defined in the appendix.) These restrictions on tank size and test liquid prohibited attaining a quiescent liquid-vapor interface condition prior to initiation of the reorientation process. During the transition from its predrop normal-gravity configuration to its quiescent low-gravity configuration, the interface exhibits a number of high-amplitude oscillations. The time history of these oscillations is directly proportional to the quantity $\left(R^3/\beta\right)^{1/2}$ (ref. 4). A number of tests were performed to study the effects of initiating the reorientation thrust at various times during these oscillations.

The initial destabilization and ensuing flow of the reorientation process are heavily dependent on both the shape and dynamic conditions of the liquid-vapor interface at thrust initiation. The two tests shown in figure 4 were conducted with the same reorientation parameters, and only the times of thrust initiation were different. If the reorientation acceleration or thrust is applied when the interface is nearly flat or has a convex curvature near the tank centerline, the reorientation flow is in a sheet along the tank walls and in a dome or spike along the tank centerline. This dome then grows in size until it impacts on the tank bottom. As the flow progresses, the dome centerline shifts toward the tank walls. This mode of flow is typical of that observed in reference 1 for high-Bond-number reorientation from an initially flat interface condition. When the interface is not flat and exhibits only concave curvature at the time of thrust initiation, all the reorientation flow is along the tank walls.

During the remainder of this study, the reorientation thrust was applied at a time during the first cycle of interface oscillation when its configuration approximated most



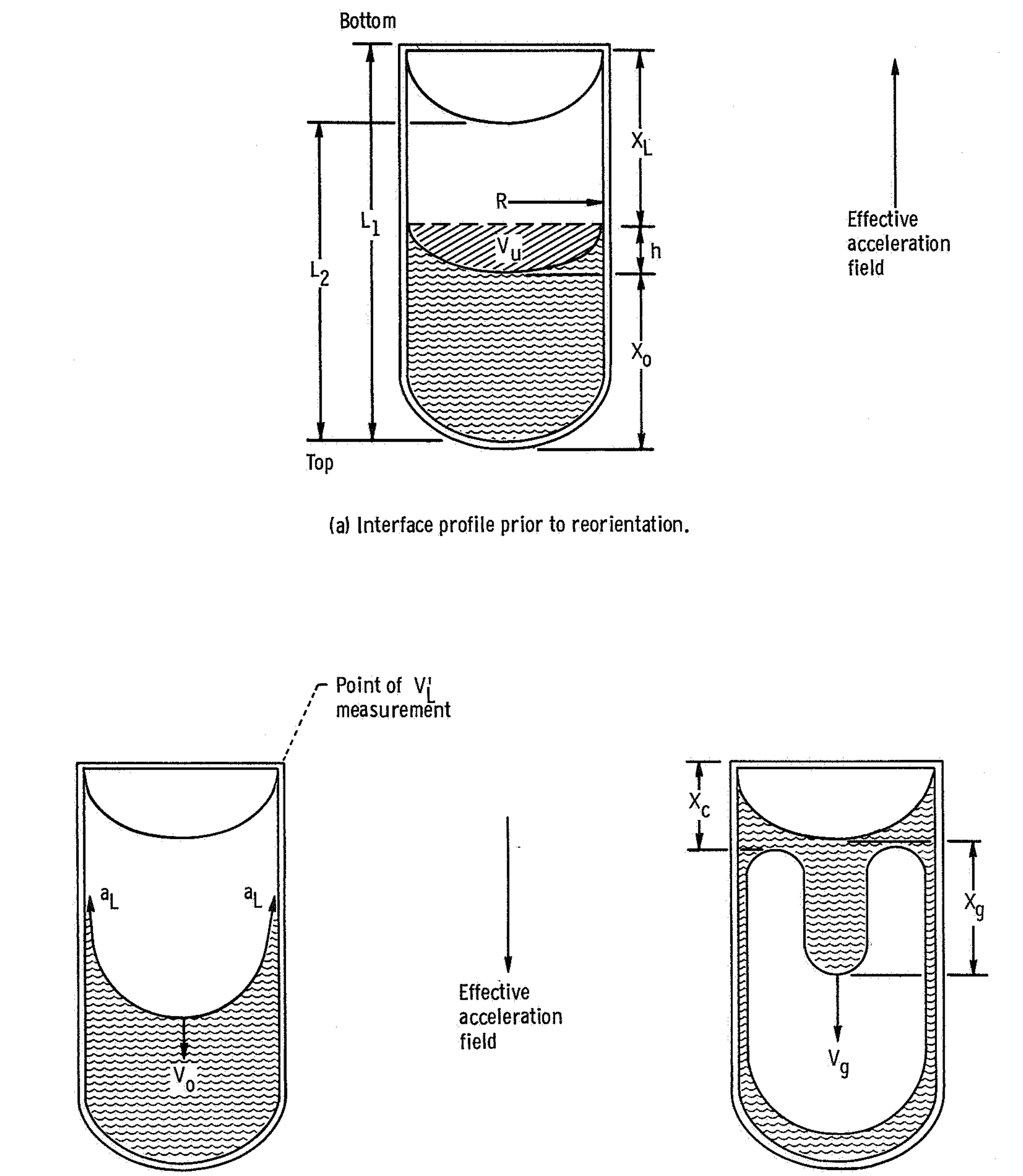
(a) Thrust initiation at 3.80 seconds.

(b) Thrust initiation at 2.60 seconds.

Figure 4. - Effect of initial conditions on liquid reorientation profiles. Tank radius, 7.0 centimeters; system acceleration, 0.032 g's; 70-percent fill; FC-78.

nearly its quiescent low-gravity shape (i. e., for Bo = 15) and had only a concave curvature. By plotting the time history of the interface displacement after drop initiation, this time was determined to be equal to $0.38\left(R^3/\beta\right)^{1/2}$. When employing this time for thrust initiation, the reorientation flow was always along the tank walls in all the tests.

Basic reorientation dynamics and parameters. - The various liquid profile and displacement parameters which were characteristic of each test are illustrated in figure 5.



(a) Interface profile prior to reorientation.

(b) Interface profile during reorientation.

(c) Collection profile during reorientation.

Figure 5. - Basic liquid reorientation profiles.

The liquid position prior to application of the reorientation thrust is as shown in figure 5(a). Both the interface height h and the portion of the ullage V_u that the interface surface encompasses can be obtained from relations given in reference 5. For a positive Bond number of 15, the interface height is calculated to be 0.42 R and the encompassed ullage volume is calculated to be $0.28\ \pi R^3$. The distance X_L from the edge of the liquid-vapor interface to the tank bottom and the distance X_o from the interface centerline to the tank top can then be calculated by using these interface dimensions and a knowledge of the liquid volume. These dimensions were measured for each test and were observed to be consistent with the calculated values.

The liquid flow dynamics after application of the reorientation thrust and before liquid impingement at the tank bottom were similar to those described in references 3 and 6. A typical displacement history of the liquid leading-edge flow down the tank walls is shown in figure 6. As observed in references 3 and 6 for Bond numbers greater

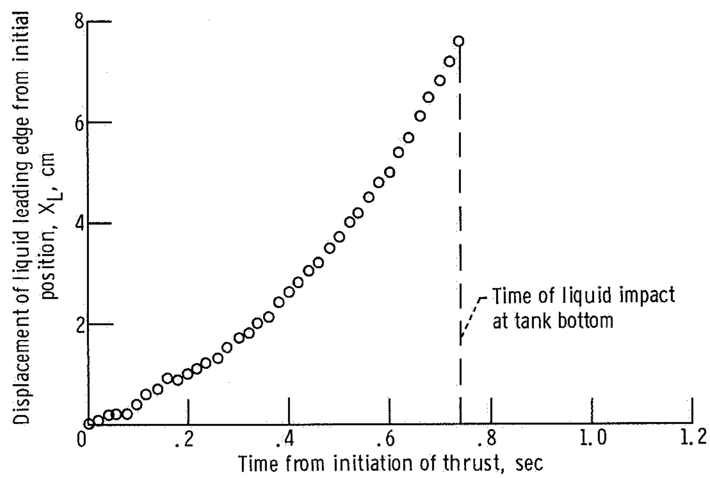


Figure 6. - Displacement characteristics of liquid leading-edge during test 5.

than 12, the acceleration rate a_L of the leading edge (fig. 5(b)) was approximately equal to 0.90 a, resulting in an instantaneous leading-edge velocity V_L' upon impingement at the tank bottom of magnitude

$$V_L' = (1.8\ aX_L)^{1/2} \tag{1}$$

The displacement of the liquid-vapor interface was also measured (fig. 7) and its velocity V_o (fig. 5(b)) was described by the relation (ref. 6)

$$V_o = 0.48(aR)^{1/2} \tag{2}$$

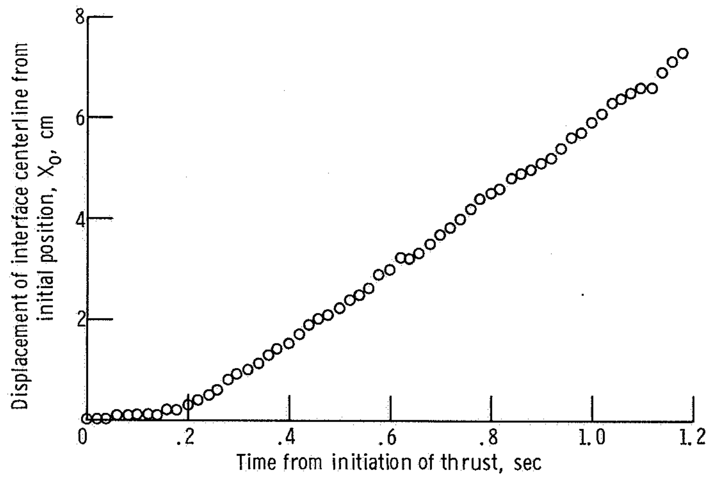


Figure 7. - Displacement characteristics of liquid-vapor interface during test 5.

It is noted in reference 7 that as the ullage approaches the tank top, the liquid-vapor interface velocity may slow down for values of X_o less than 0.25 R. In this study, however, no attempt was made to measure the behavior at very low values of X_o because of optical refraction problems and because other aspects of the reorientation process (e.g., geysering) were, generally, affecting the liquid-vapor interface. In all tests, after the wall flow met at the tank bottom, the liquid rebounded or geysered back toward the tank top (fig. 5(c)). The column of rebounding liquid (i.e., the geyser) had an average radius of 0.3 R and its tip progressed along the tank centerline at a nearly constant rate (fig. 8). The average geyser tip velocity V_g was found to be 2.2 V_L'. These geyser

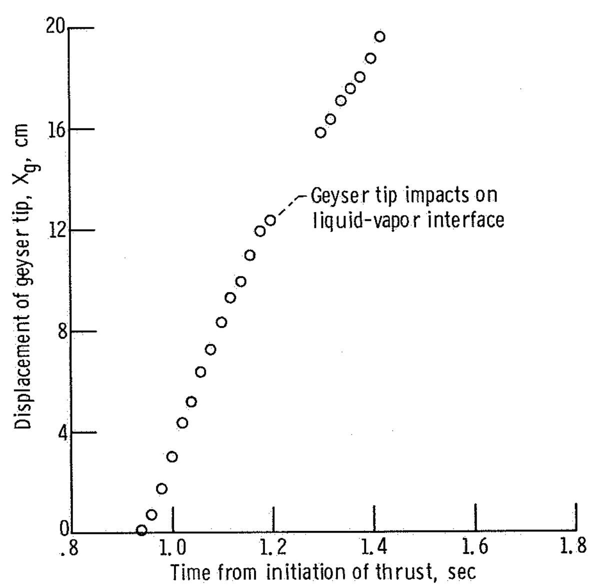


Figure 8. - Displacement characteristics of geyser tip during test 5.

dynamics are in agreement with reference 3 for systems with Weber numbers ($We_R = (V'_L)^2 R/\beta$) greater than 30, where effects due to surface tension are considered negligible compared with the inertia of the geyser flow. Also, as in reference 3, in all the tests some liquid did accumulate at the tank bottom and could be considered reoriented or collected. In particular, the tank volume below the top of the spheroidal dome always filled quite rapidly. Attempts were made in each test to measure the collected liquid height as it progressed above this point (fig. 9). In most cases, at some point in the

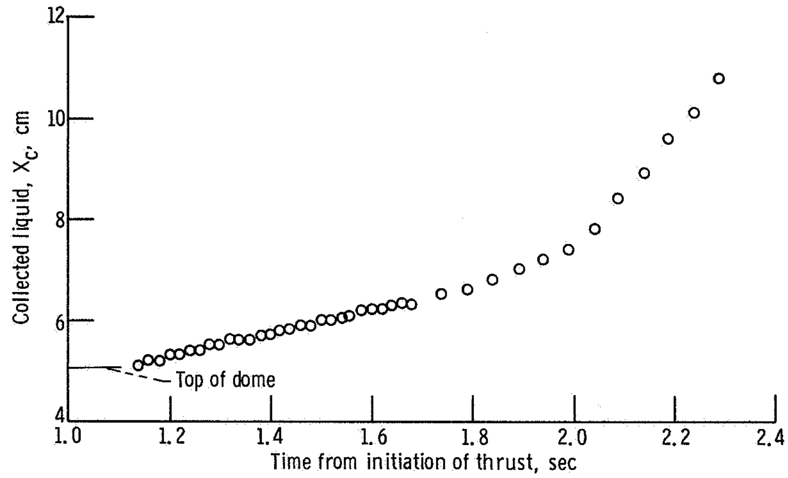
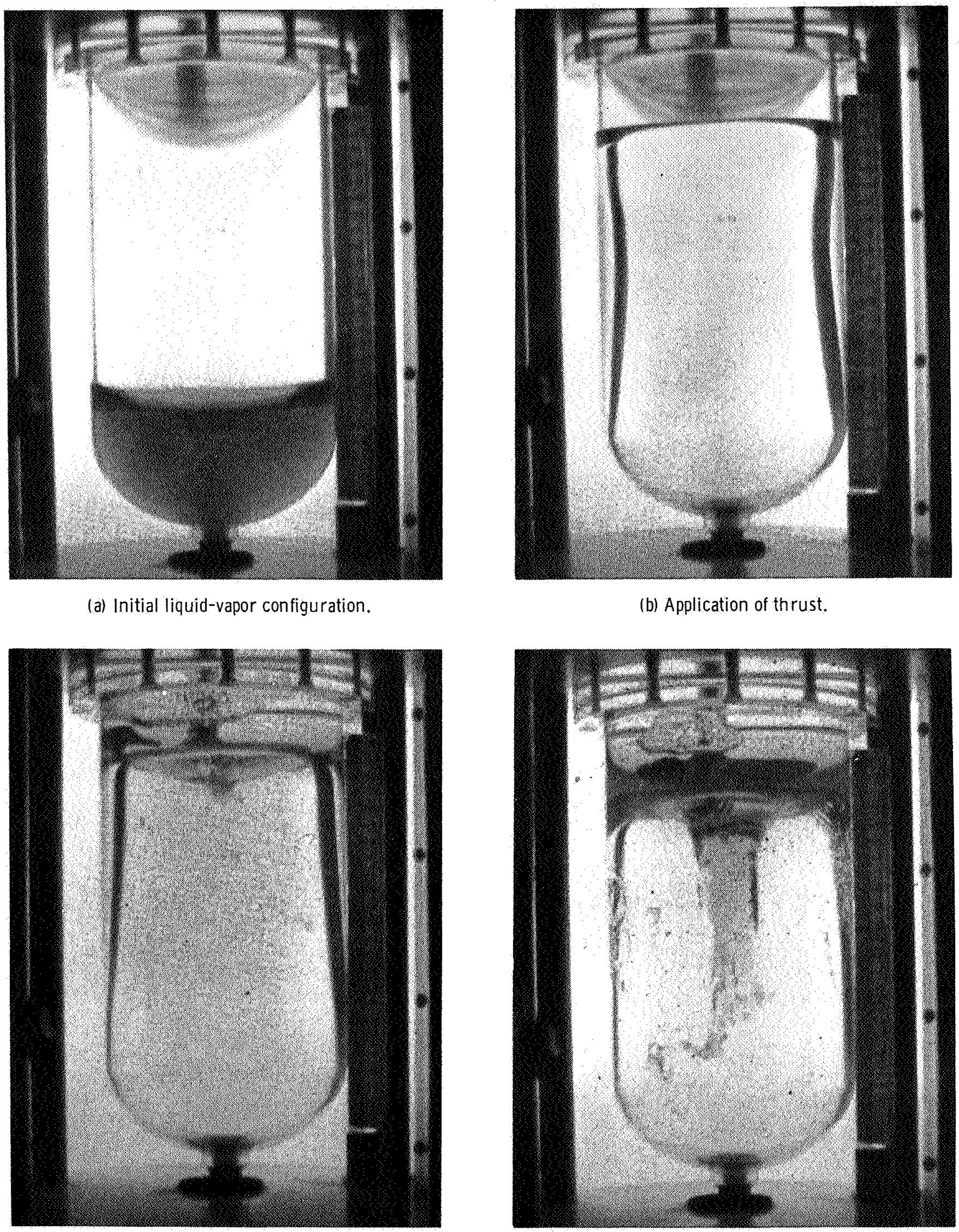


Figure 9. - Liquid collection during test 5.

reorientation process the collected liquid surface became quite turbulent and bubbles were formed in the bulk of the liquid, necessitating the measurement of some mean collected liquid height based on the judgment of the observer. As in reference 3, the rate of liquid collection was heavily dependent on other dynamics of the reorientation process, such as geyser flow and liquid depletion at the tank top. Because of this and the uncertainties involved in making a quantitative measurement, the establishment of correlations involving a collection rate was not attempted in this study.

Effects of liquid fill level. - The two liquid fill levels considered in this study resulted in quite different liquid behavior patterns during the reorientation process. The basic liquid flow dynamics during reorientation of a 20-percent liquid fill are illustrated in figure 10. The initial configuration of the liquid-vapor system is shown in figure 10(a). After application of the reorientation thrust, liquid flow down the tank walls depletes the liquid reservoir at the tank top and before the liquid leading-edge reaches the tank bottom, the liquid layer thickness near the tank top begins to thin (fig. 10(b)). By the time the leading-edge converges at the tank bottom, initiating geysering, the tank top is uncovered and all the liquid is at the tank bottom or along the tank side walls (fig. 10(c)). At this particular point in the reorientation process, the top of the tank is momentarily clear of liquid and venting of vapor would be possible without loss of liquid.



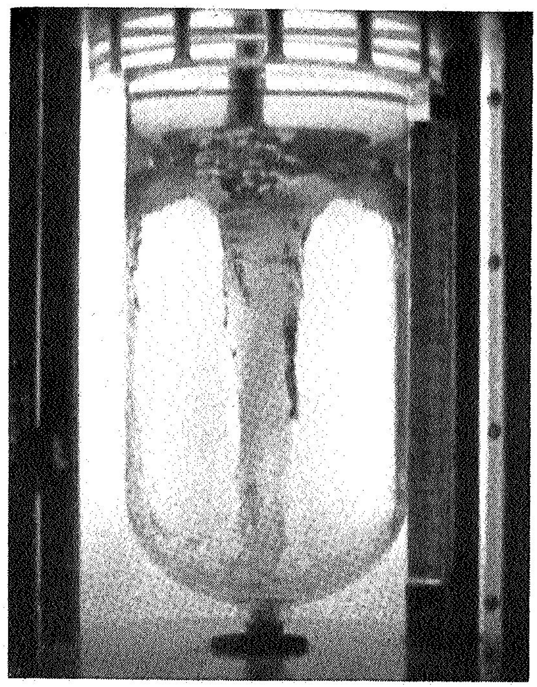
(a) Initial liquid-vapor configuration.

(b) Application of thrust.

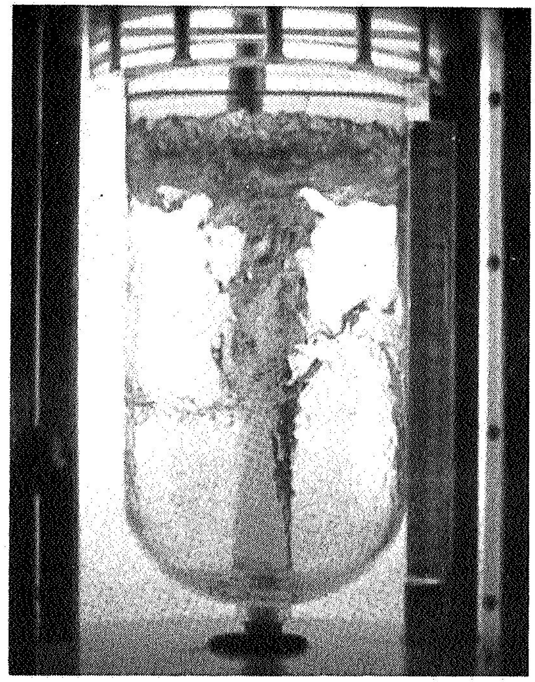
(c) Initiation of geyser.

(d) Geyser progression.

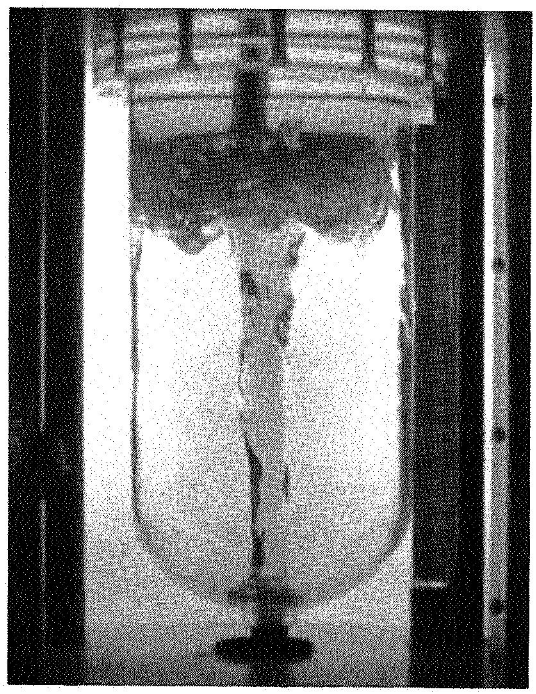
Figure 10. - Reorientation process in unbaffled tank with 20-percent liquid fill. Test 2.



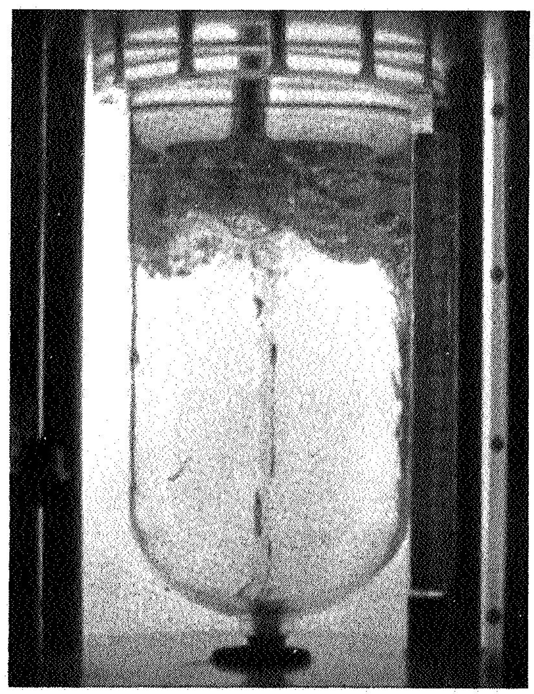
(e) Geyser impact at tank top.



(f) Liquid recirculation.



(g) Geyser reduction.



(h) Geyser profile at end of test.

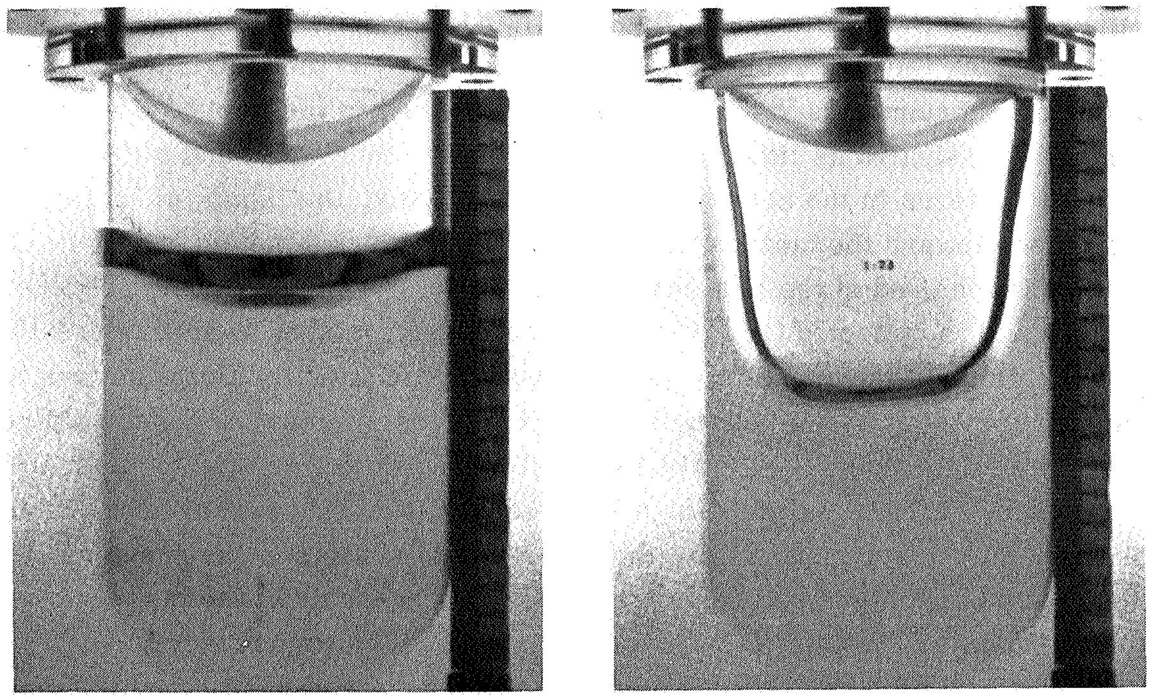
Figure 10. - Concluded.

However, as the reorientation process continues, a significant portion of the collected liquid flows back toward the tank top in the form of a geyser (fig. 10(d)). This geyser impacts at the top of the tank (fig. 10(e)) and a recirculation pattern is established (fig. 10(f)). During this recirculation the liquid collected at the tank bottom becomes quite turbulent and numerous vapor bubbles are entrained in the liquid. The magnitude of geysering is dissipated as liquid is depleted from the side walls and turbulence disrupts the flow patterns in the collected liquid. Eventually, the liquid in the geyser begins to recede toward the tank bottom (fig. 10(g)). Although the geyser tip remains at the tank top until the end of the test shown in figure 10, its radius is being reduced and most of the liquid is collected (fig. 10(h)). Although it cannot be seen in figure 10(h), at the end of this test, the geyser tip had started to move radially along the tank top and was beginning to recede to the tank bottom. In those tests where the geyser did recede, the geyser tip remained attached to the tank wall while moving toward the tank bottom.

The behavior of the liquid flow for a 70-percent fill level is shown in figure 11. Through the point of geyser initiation, the flow is quite similar to the previous 20-percent fill case with the exception that the liquid reservoir at the tank top is still of a substantial volume. Because the tip velocity of the developing geyser is greater than the ullage velocity along the tank centerline, the geyser impacts on the liquid-vapor interface (fig. 11(d)) with sufficient momentum to penetrate through the liquid reservoir and eventually reach the tank top (fig. 11(e)). After impacting the liquid-vapor interface, the geyser progresses toward the tank top at approximately 60 percent of its original velocity.

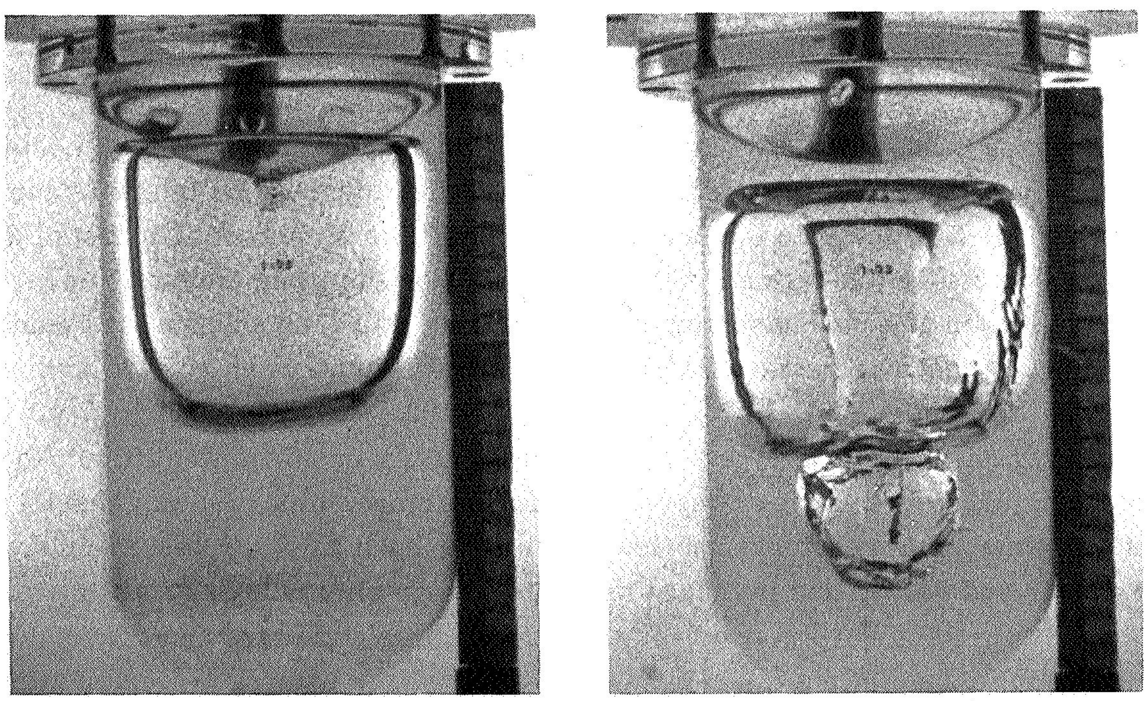
Upon geyser penetration, the liquid reservoir at the tank top is forced into an annular volume along the tank walls. This disruption of the liquid-vapor interface increases the liquid volume flow towards the tank bottom. In all the 70-percent fill tests the geyser flow was deformed and influenced by this liquid flow down the tank wall (e.g., fig. 11(f)). This had an effect of hastening the geyser recession and subsequent liquid collection. For the test represented in figure 11, "total" liquid reorientation was obtained prior to test termination (fig. 11(g)).

Reorientation time estimates. - As previously noted, it was quite difficult to measure a meaningful liquid collection rate. And, furthermore, this rate was heavily dependent on a number of reorientation flow processes, such as liquid reservoir depletion, geyser growth and decay, and interface breakup. As an alternative to a collection rate correlation for predicting total reorientation times, time estimates and correlations were obtained for the distinct liquid flow events which occur during a reorientation process through the time when the tank top is clear of liquid. These event-time estimates are summarized in table II, where time zero is defined at the initiation of reorientation thrust.



(a) Initial liquid-vapor configuration.

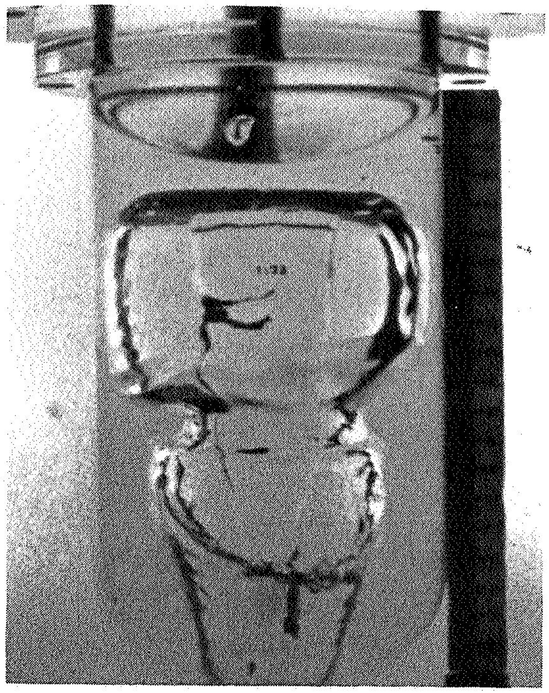
(b) Application of thrust.



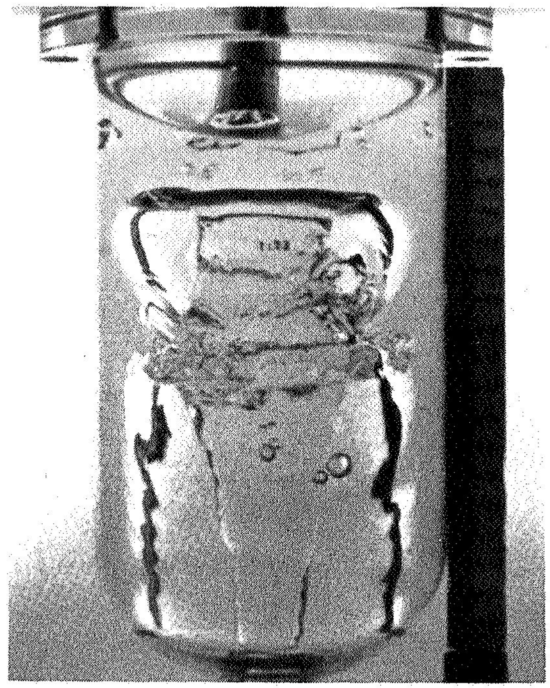
(c) Initiation of geyser.

(d) Geyser penetration through interface.

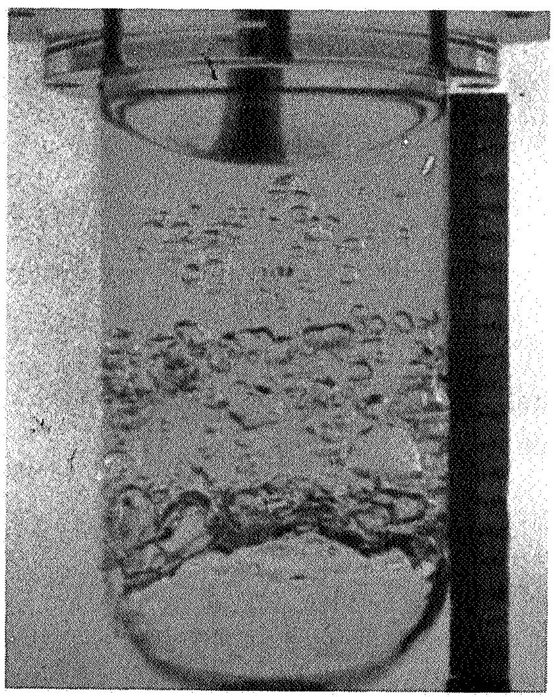
Figure 11. - Reorientation process in unbaffled tank with 70-percent liquid fill. Test 7.



(e) Geyser impact at tank top.



(f) Geyser deformation.



(g) Liquid collection at end of test.

Figure 11. - Concluded.

TABLE II. - SUMMARY OF REORIENTATION EVENT TIMES

[All times are defined from initiation of thrust.]

Reorientation event time	Symbol	Formula
Time of liquid impact at tank bottom	t_1	$\left(\frac{2.2 X_L}{a}\right)^{1/2}$
Time of geyser initiation	t_2	$\left[0.60 - 0.12\left(\frac{R}{X_L}\right)^{1/2}\right]\left(\frac{R^2}{aX_L}\right)^{1/2} + t_1$
Time of geyser impact on liquid-vapor interface	t_3	$\frac{0.48(aR)^{1/2}t_2 + L_2 - X_o}{2.95(aX_L)^{1/2} - 0.48(aR)^{1/2}} + t_2$
Time of geyser impact on tank top:	t_4	
70-Percent fill		$\frac{L_2 - 2.95(t_3 - t_2)(aX_L)^{1/2}}{1.74(aX_L)^{1/2}} + t_3$
20-Percent fill		$\frac{L_2}{2.95(aX_L)^{1/2}} + t_2$
Time when tank top is clear of liquid	t_5	$K\left[\frac{2.95(aX_L)^{1/2} + (8.7\, aX_L - 2aL_2)^{1/2}}{a}\right] + t_2$ K = 0.5 for 20-percent fill K = 1.3 for 70-percent fill

The time t_1 that it takes for the liquid to initially impact at the tank bottom can be determined from the relation

$$t_1 = \left(2.2 \frac{X_L}{a}\right)^{1/2} \tag{3}$$

which is simply obtained from the acceleration characteristics of the leading-edge flow. After impact, the liquid leading-edge converges upon itself at the tank centerline, covering the tank bottom and initiating a geyser flow. The time that it takes for this to occur can be approximated from volume flow considerations. The leading-edge at impact at the tank bottom has a thickness δ which is approximated by the relation (ref. 7)

$$\delta = 0.18\left(\frac{R^3}{X_L}\right)^{1/2} \tag{4}$$

The volume V_δ of a liquid film of thickness δ covering the tank bottom can be geometrically approximated to be

$$V_\delta = \pi(1.6\ \delta R^2 - 1.7\ \delta^2 R) \tag{5}$$

The liquid flow rate down the tank walls, as obtained from the equations of reference 6, is approximately

$$\omega = 0.48\ \pi\left(aR^5\right)^{1/2} \tag{6}$$

From equations (5) and (6), the time required to cover the tank bottom with a liquid layer of thickness δ and, hence, initiate geysering is given by the equation

$$\Delta t_2 = \left[0.60 - 0.12\left(\frac{R}{X_L}\right)^{1/2}\right]\left(\frac{R^2}{aX_L}\right)^{1/2} \tag{7}$$

As previously stated, the geyser progresses at a relatively constant velocity V_g equal to 2.2 V'_L. If the time it takes for the liquid-vapor interface to reach the tank top (i.e., $X_o/0.48(aR)^{1/2}$) is long enough, the geyser tip will first impact on the interface, as in the 70-percent fill tests of this study. The time of impact from geyser initiation is given by the equation

$$\Delta t_3 = \frac{0.48(aR)^{1/2} t_2 + L_2 - X_o}{2.2(1.8\ aX_L)^{1/2} - 0.48(aR)^{1/2}} \tag{8}$$

If, as in the 20-percent fill tests, the ullage reaches the tank top prior to geyser impingement, the geyser simply impacts on the tank top at a time after initiation equal to

$$\left(\Delta t_4\right)_{20\%} = \frac{L_2}{V_g} \tag{9}$$

or

$$\left(t_4\right)_{20\%} = \left[\frac{L_2}{2.95(aX_L)^{1/2}}\right] + t_2 \tag{10}$$

In those cases where the geyser first impinges on and penetrates the ullage interface, its velocity is impeded (i.e., reduced to 0.60 V_g) and it impacts on the tank top at a time, after ullage contact, equal to

$$\left(\Delta t_4\right)_{70\%} = \frac{L_2 - (\Delta t_3)(2.2)(1.8\ aX_L)^{1/2}}{1.3(1.8\ aX_L)^{1/2}} \tag{11}$$

or

$$\left(t_4\right)_{70\%} = \frac{L_2 - (\Delta t_3)(2.95)(aX_L)^{1/2}}{1.74(aX_L)^{1/2}} + t_3 \tag{12}$$

With the exception of the empirically established geyser velocity relations, the times given by equations (3) to (12) have been established in previous NASA Lewis programs (refs. 3 and 6). Even the geyser velocity without ullage impingement was established to be near that obtained in this study (i.e., $V_g = 2.5\ V_L'$ in ref. 3). A time estimate of when the geyser recedes or when the tank top clears of liquid, however, requires a completely empirical correlation from data obtained in this study.

Because the Weber numbers obtained in this study were high (i.e., $We_R > 300$), the effects of surface tension on geyser recession were considered negligible. Therefore, geyser momentum and the effective gravity level were the two controlling parameters. As an indicator of the relative effects of these two parameters, a calculation was made of the time required for a free particle to overshoot and then recede to a distance L_2, considering only that it leaves the tank bottom at velocity V_g in a gravity field a and is not constrained by the tank top. This time is given by

$$T = \frac{V_g + \left(V_g^2 - 2aL_2\right)^{1/2}}{a} \tag{13}$$

A comparison of the data with this indicator revealed that for the 20-percent fill cases

$$\left(\Delta t_5\right)_{20\%} = 0.5\ T$$

and for the 70-percent fill cases

$$\left(\Delta t_5\right)_{70\%} = 1.3\ T$$

The next sequential event in any reorientation process would be the time when all the liquid was collected or completely reoriented. There have been a number of definitions proposed to describe complete reorientation, with the ultimate, of course, being when the total volume of liquid is positioned over the tank bottom in a quiescent, bubble-free condition.

Any estimate of the time required for this type of complete reorientation requires the prediction of a number of associated processes, such as bubble rise times and large-amplitude sloshing. Unfortunately, no data of this type were available in this study because of the limited low-gravity test times. If all that is required for complete reorientation is the recession of the geyser into the bulk of the liquid after the tank top clears, the time for this can be estimated by assuming the liquid in the geyser simply falls into the bulk liquid because of an effective gravity field of magnitude a. This type of "complete" collection was achieved in two of the data tests (note fig. 11(g)). Although no correlations were attempted for these tests, the times were of the order of that predicted by a falling-particle analogy.

A comparison of the event times calculated from these relations with those measured in all the experiments is given in table III; a representative comparison is shown in figure 12. As seen from both table III and figure 12, the accuracy of the calculations is quite good considering the complex dynamic processes involved in reorientation. As expected, the largest absolute error occurs when calculating the times for clearing the top of the container. But even these are less than 20 percent in error. The relations presented in table II contain only primitive parameters of the system, such as tank size, acceleration level, and liquid fill dimensions, so that no scaling is necessary to use them for calculations involving a full-size propellant system.

Bubble formation. - As can be seen from figures 10 and 11, a considerable number of bubbles were contained in the collected liquid during the reorientation process. Reference 7 predicts that the wall flow will entrain vapor into the collected liquid if certain flow criteria are satisfied. The incipient vapor entrainment criteria are based on a combination Reynolds number - Weber number condition ($Re_\delta > 1500$ and $We_\delta > 0.50\ Re_\delta^{2/3}$, where $Re_\delta \equiv V'_L \delta\rho/\eta$ and $We_\delta \equiv (V'_L)^2\delta/\beta$). In the tests performed

TABLE III. - SUMMARY OF REORIENTATION TEST DATA

Test	Tank radius, R, cm	Liquid	Reorientation acceleration, a, cm/sec^2	Liquid fill, percent	Reorientation event times, sec									
					t_1		t_2		t_3		t_4		t_5	
					Calcu-lated	Meas-ured	Calcu-lated	Meas-ured	Calcu-lated	Meas-ured	Calcu-lated	Meas-ured	Calcu-lated	Meas-ured
1	7.0	FC-78	31	20	1.15	1.23	1.31	1.34	----	----	1.63	1.72	3.73	>2.54
2	7.0	Freon-TF	48	↓	.91	.96	1.04	1.03	----	----	1.30	1.27	2.70	[a]3.07
3	5.5	FC-78	50	↓	.80	.84	.91	.94	----	----	1.14	1.23	2.36	2.15
4	7.0	FC-78	69	↓	.76	.85	.87	.94	----	----	1.09	1.29	2.26	2.50
5	7.0	FC-78	31	70	.74	.78	.96	.96	1.35	1.23	1.53	1.55	3.96	>2.51
6	7.0	Freon-TF	48	70	.58	.63	.76	.74	1.08	.93	1.23	1.11	3.05	2.98
7	5.5	FC-78	50	70	.49	.46	.65	.58	.92	.71	1.09	1.04	2.52	2.68

[a]Tank top clear of liquid except for very thin column extending the tank length (shown in fig. 10(h)).

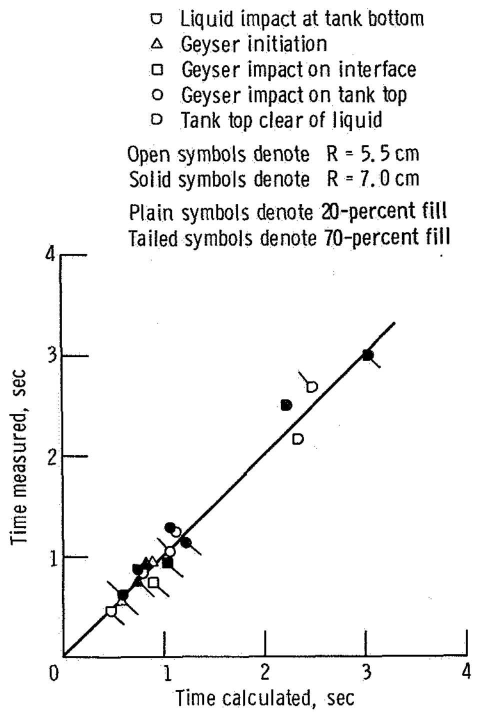


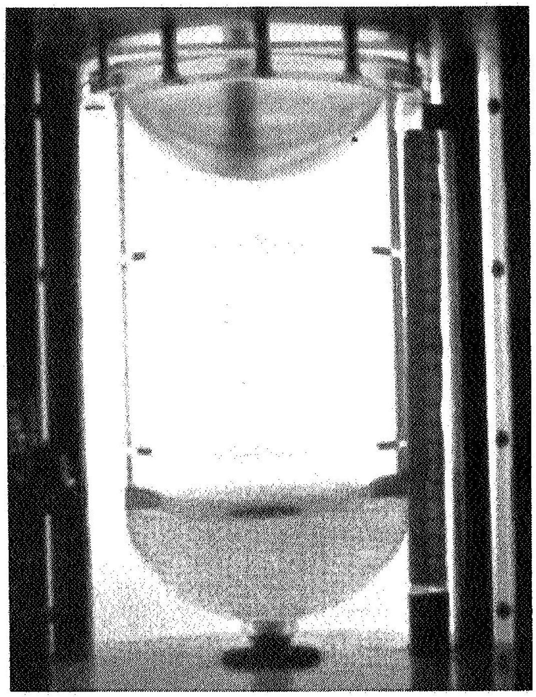
Figure 12. - Comparison of predicted and actual times of reorientation flow events.

in this study, this condition was satisfied in only one test (i. e., Bo = 450) and this was a borderline case. Accordingly, no vapor entrainment due to undisturbed wall flow was observed in this study. When the wall flow was disrupted or broken up as after geyser impact or in recirculation, however, vapor was observed to be entrained by this flow (note fig. 10(f)). Vapor was also observed to be entrained by the geyser recession back into the collected liquid.

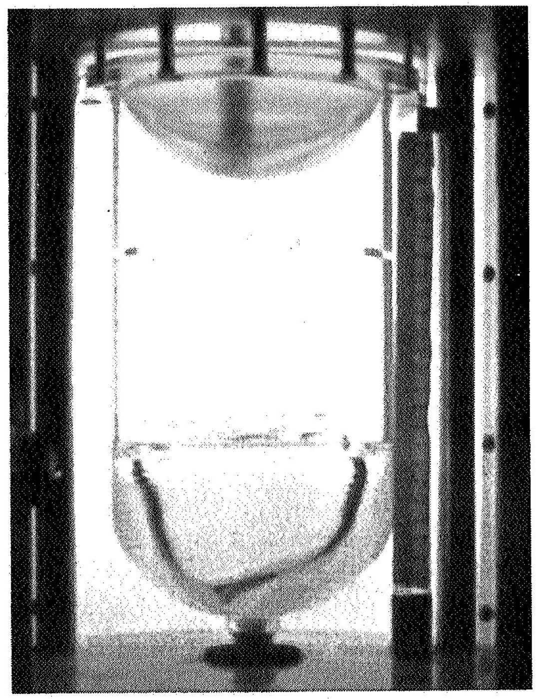
A larger source of bubble formation was vapor entrapment in the bulk liquid caused by various liquid flow patterns. When the liquid leading-edge impacts the tank bottom and begins to flow around the dome, vapor is normally trapped in the corner or wedge where the dome meets the tank side wall. This vapor normally coalesces into one large bubble near the tank bottom (figs. 10(c) and (d)). Similar entrapment occurs when opposing liquid flows impinge upon each other and pockets of vapor are pinched off from the bulk of the ullage (fig. 11(f)). Whether formed by entrainment or entrapment of vapor, a large number of bubbles were always present in the collected liquid at the end of each test.

Liquid Reorientation in Baffled Tanks

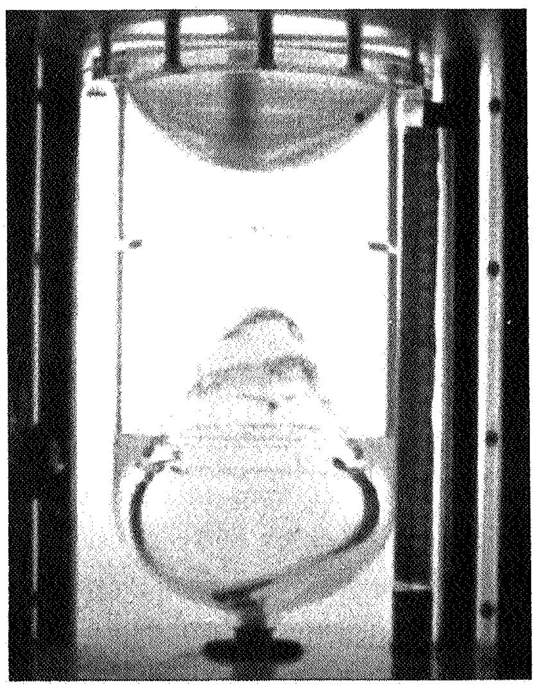
Because most space-vehicle propellant tanks contain a variety of internal hardware,



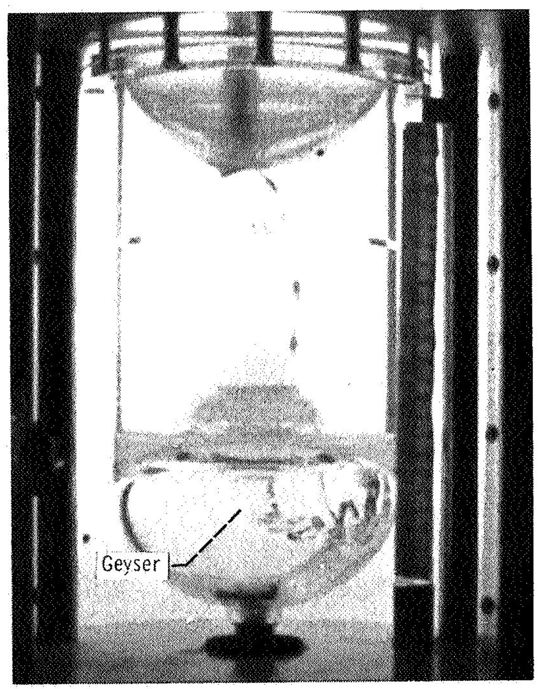
(a) Initial liquid-vapor configuration.



(b) Liquid flow around baffle.

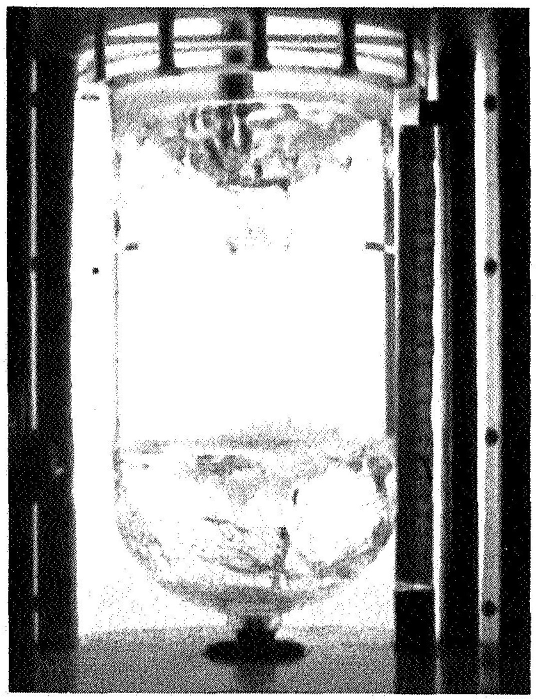


(c) Progression of liquid column toward tank bottom.

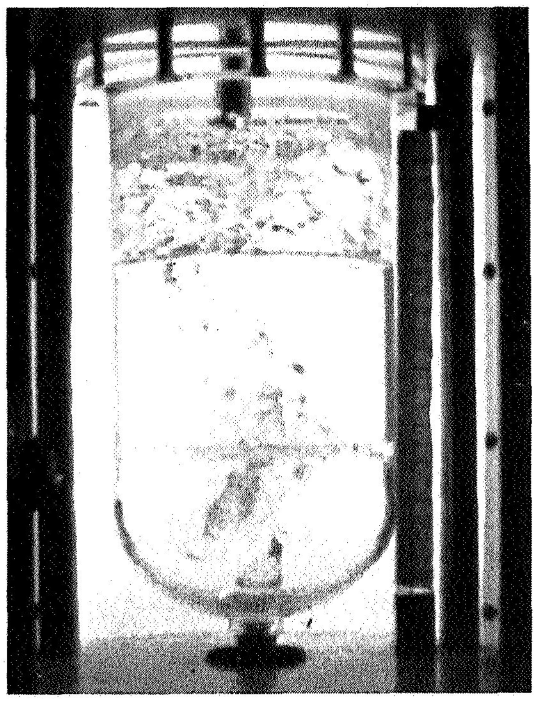


(d) Impact of liquid column at tank bottom and geyser formation.

Figure 13. - Reorientation process in baffled tank with 20-percent liquid fill.



(e) Liquid rebound and recirculation flow.

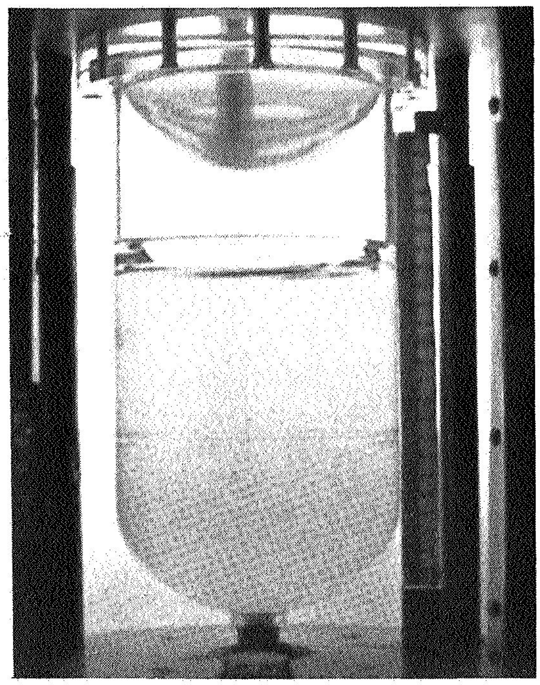


(f) Reorientation profile at end of test.

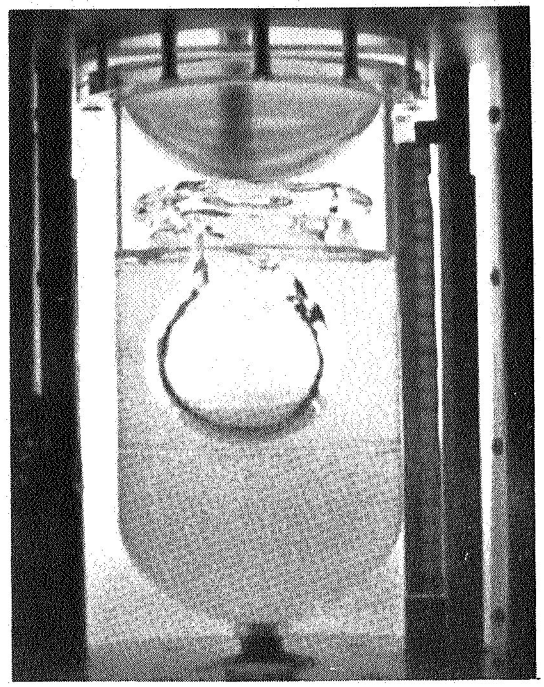
Figure 13. - Concluded.

including slosh baffles and ring stiffeners, a series of tests were performed to determine the effects of one such baffle configuration on the basic reorientation process. The baffle sizes and positions were geometrically scaled to an actual baffle arrangement in the Centaur-space-vehicle, liquid-hydrogen tank. The basic flow patterns obtained during reorientation in these tanks were very similar to those predicted in reference 7 and previously observed in reference 8.

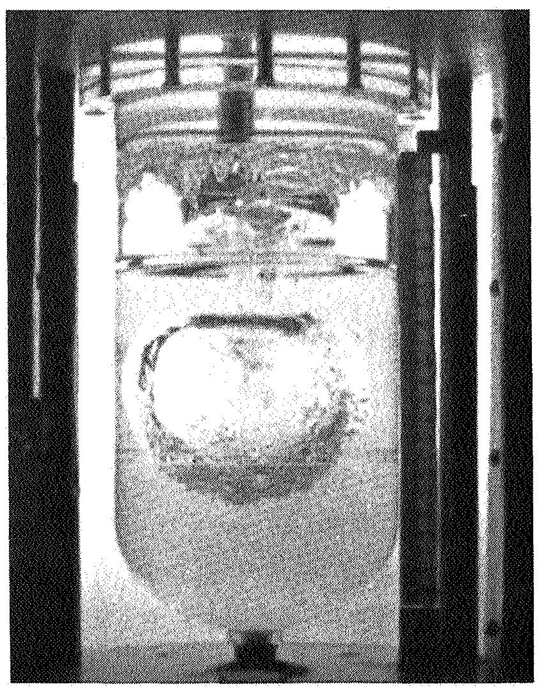
The reorientation flow for a 20-percent liquid fill is illustrated in figure 13. At this initiation of the reorientation thrust, the liquid-vapor interface edge is located a short distance from the upper baffle. As the liquid leading-edge accelerates down the tank wall, its flow is diverted toward the tank centerline after contact with the baffle (fig. 13(b)). Then as it progresses toward the tank bottom, it finally converges and impinges upon itself to form a single liquid column (fig. 13(c)). Upon convergence, a geyser is formed which progresses toward the tank top, resulting in a flow pattern where liquid is proceeding in both directions along the tank centerline (fig. 13(d)). The liquid column eventually impinges on the tank bottom centerline, and liquid flows around the bottom dome and up the tank walls where it impinges on the lower ring baffle. During the same time period, the geyser flow impinges on the tank top, progresses down the tank wall, and impinges on the upper baffle (fig. 13(e)). The resulting liquid behavior is chaotic but, in general, from this point in the process the liquid does collapse slowly toward



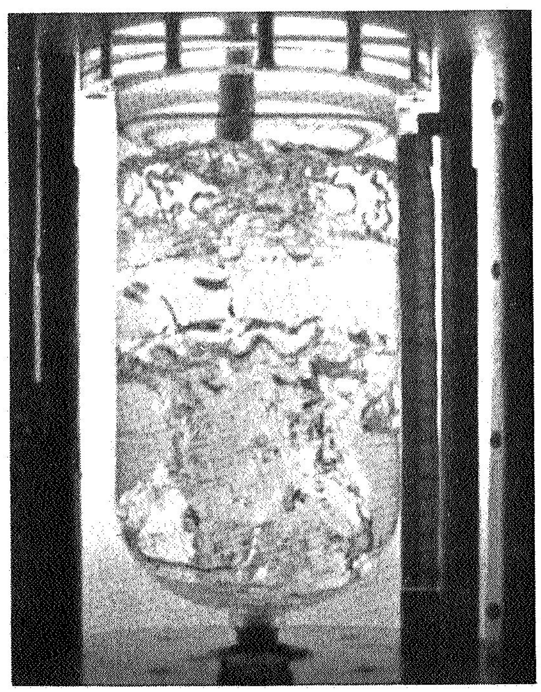
(a) Initial liquid-vapor configuration.



(b) Liquid flow around baffle.

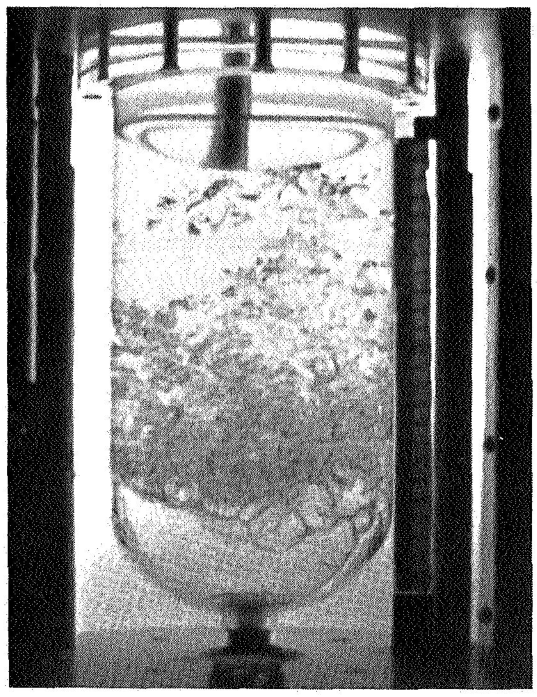


(c) Liquid rebound and geyser formation.



(d) Liquid breakup and turbulent flow pattern.

Figure 14. - Reorientation process in baffled tank with 70-percent liquid fill.



(e) Liquid collection at end of test.

Figure 14. - Concluded.

the tank bottom.

The corresponding reorientation flow for the 70-percent fill case is shown in figure 14. Prior to initiation of the reorientation thrust, the liquid-vapor interface is in contact with the lower baffle (fig. 14(a)). As in the 20-percent fill case, the leading-edge flow around the baffle results in a convergent flow pattern toward the tank centerline. In this case, however, the liquid impacts on the tank bottom before it converges upon itself. Again, liquid flows around the dome and up the walls and a geyser is formed along the tank centerline. A complete breakup of the liquid flow patterns eventually occurs and liquid is dispersed throughout the tank (fig. 14(d)). Although the liquid does collapse toward the tank bottom and is reoriented (fig. 14(e)), its behavior is totally chaotic.

While baffles drastically alter the reorientation process and the resulting behavior is obviously not conducive to detailed analysis, it is possible to estimate some times to tank-top clearing. Two baffled-tank experiments were conducted with test parameters identical to those previously acquired with unbaffled tank tests, where some times for the liquid to clear the tank top were obtained. The times of tank-top clearing were slightly shorter in the baffled tests (i.e., 2.15 and 2.50 sec compared to 2.50 and 2.68 sec, respectively). Also, in other baffled-tank testing where tank-top clearing was not achieved but similar unbaffled-tank data were available, the volumes of bulk liquid collected at test termination were quite comparable. For these reasons, it is assumed that time estimates of tank-top clearing and possibly total liquid collection calculated for unbaffled-tank systems can also be conservatively applied to tanks containing baffles of the type tested. However, the opposing flow patterns in the baffled tanks resulted in considerably more bubble entrapment and entrainment than in comparable unbaffled tanks. Therefore, suitable bubble-rise-time corrections might be necessary for complete reorientation time estimates.

SUMMARY OF RESULTS

An experimental investigation was conducted on the process of liquid reorientation from one end of a scale-model Centaur liquid-hydrogen tank to the other end by means of low-level accelerations. Prior to reorientation, the liquid was stabilized at the top of the tank at a Bond number of 15. The study was conducted on tanks both with and without ring baffles and with radii of 5.5 and 7.0 centimeters. Reorientation acceleration values were varied to obtain Bond numbers of 200 and 450. The study was conducted at liquid levels of 20 and 70 percent. It yielded the following results:

1. When the original liquid-vapor interface was free of large surface perturbations, all the initial liquid flow was in a layer along the tank walls.

2. In all cases, liquid rebounded or geysered back to the tank top after initially being reoriented.

3. The sequential times when the liquid initially reached the tank bottom, when the geyser was initiated, and when the geyser impacted on the tank top were generally as predicted by relations derived from previous studies.

4. Complete reorientation times were heavily dependent on time histories of the geyser dynamics. Estimates of the time required to clear the liquid from the tank top can be predicted from an empirically determined correlation.

5. Although high bubble concentrations were generated during reorientation, no bubble entrainment due to leading-edge flow was observed. The bubbles generally resulted from entrapment, leading-edge flow breakup, and turbulence formed by liquid-liquid impingements.

6. The insertion of ring baffles completely changed the reorientation flow profiles but resulted in only minor differences in the times to clear the liquid from the top of the tank and to collect the liquid. Considerably more bubbles were observed in the baffled tanks.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 2, 1972,
909-72.

APPENDIX - SYMBOLS

a	system acceleration, cm/sec^2
a_L	acceleration of liquid leading-edge, cm/sec^2
Bo	Bond number, $Bo = aR^2/\beta$
h	interface height (fig. 5), cm
L_1	total tank length (fig. 3), cm
L_2	intermediate tank length (fig. 3), cm
R	tank radius, cm
Re_δ	Reynolds number, $Re_\delta = V_L' \delta \rho/\eta$
T	geyser recession time indicator, sec
t_1	time of liquid impact at tank bottom, sec
t_2	time of geyser initiation, sec
t_3	time of geyser impact on interface, sec
t_4	time of geyser impact on tank top, sec
t_5	time when tank top is clear of liquid, sec
V_g	geyser tip velocity (fig. 5), cm/sec
V_o	ullage velocity (fig. 5), cm/sec
V_u	volume of ullage encompassed by liquid-vapor interface (fig. 5), cm^3
V_δ	volume of liquid film of thickness δ, cm^3
V_L'	instantaneous leading-edge velocity at tank bottom, cm/sec
We_R	Weber number, $We_R = (V_L')^2 R/\beta$
We_δ	Weber number, $We_\delta = (V_L')^2 \delta/\beta$
X_c	collected liquid height (fig. 5), cm
X_g	geyser tip displacement (fig. 5), cm
X_L	distance from interface edge to tank bottom (fig. 5), cm
X_o	distance from interface centerline to tank top (fig. 5), cm
β	specific surface tension, σ/ρ, cm^3/sec^2
δ	liquid layer thickness, cm
η	viscosity, cP

ρ liquid density, g/cm^3

σ surface tension, dynes/cm

ω liquid flow rate, cm^3/sec

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