NASA TECHNICAL MEMORANDUM

NASA TM X-52095

NASA TM X-52095

N66-22264 (ACCESSION NUMBER)	(THRU)
15 (PAGES)	1 (CODE)
TMX-52095 (NASA CR OR TMX OR AD NUMBER)	12 (CATEGORY)

FACILITY FORM 602

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 1.00

Microfiche (MF) .50

ff 653 July 65

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TECHNICAL PREPRINT prepared for Symposium on Fluid Mechanics and Heat Transfer Under Low Gravitational Conditions sponsored by the United States Air Force and Lockheed Missiles and Space Company
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1965

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E-2947

INTRODUCTION

The demand for optimum solutions to the problems associated with space-vehicle propellant systems has generated considerable interest in the field of liquid-vapor interface dynamics. However, while the attention given to the subject of propellant behavior during the powered phase of the flight has reached voluminous proportions, only recently has serious discussion considered the gross motion of the propellant under conditions of low gravity-induced environments. The control and stability of the flight of the vehicle are indeed dependent on a knowledge of the former aspects of propellant behavior, but the further requirements of reliable restart capabilities and adequate venting characteristics following durations of weightlessness encountered in coasting flight have made the later aspect of low gravity-induced hydrodynamics equal in significance.

The NASA Lewis Research Center is currently conducting experimental investigations of the behavior of the liquid-vapor interface under the influence of low acceleration environments. The purpose of this paper is to present the results of several phases of these investigations. In particular, the stability characteristics of the interface, the quantitative description of the motion of the interface, and the mechanism of reorientation or collection in response to adverse constant translational accelerations will be discussed.

SYMBOLS

a	system acceleration, cm/sec^2
a_L	interface leading edge acceleration, cm/sec^2
Bo	Bond number
R	cylinder radius, cm
V_L	instantaneous velocity of leading edge, cm/sec
V_O	rate of vapor penetration, cm/sec
ρ	liquid density, gm/cm^3
σ	surface tension, dynes/cm

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To provide the proper environment for the creation of the low-gravity fields with the liquid-vapor interface approaching its quiescent zero-gravity configuration, the investigations were conducted in a 2.3-second drop-tower facility. The low accelerations were imposed on the experiment by means of a fast-response gaseous thrust system calibrated on the ground by a combined load-cell, air-bearing stand. The center of mass of the experiment package was located along the thrust axis, and the experiments were carefully aligned so that the adverse low acceleration was parallel to the longitudinal axis of the container and was directed normally from the vapor to the liquid phase. Air drag on the experiment package is kept below 10^{-5} g by allowing the package to fall inside a protective drag shield, designed with a high weight-to-frontal-area ratio and low drag coefficient and modified by the use of interchangeable spacers to accomodate the added relative displacement of the accelerated package. A schematic of the drag shield and experiment package assembly and the sequence of the test drop are shown in figure 1.

The magnitudes of the low accelerations in these programs ranged from approximately 0.1 to 0.01 g and could be determined by the ground calibration technique to within 4 percent. (This value could be substantiated during the test by observing the net accelerated time in the known available distance in the drag shield.) Limits to the attainable acceleration levels were imposed by practical drag-shield spacer additions and reasonable acceleration time in which to observe data. Further limitations on the maximum radial dimension of the experiment geometry, due not to absolute size but rather to zero-gravity formation periods (an effect to be discussed on p. 7), restricted attainable Bond numbers to less than 100.

The liquids employed in the investigation were analytic reagent grade and were restricted to zero-degree contact angles on the containment surfaces. To insure perfect wetting, elaborate cleaning procedures were adopted, and contamination of the liquids and solid surfaces was carefully avoided. A more thorough discussion of operating procedure is given in reference 1.

CRITICAL BOND NUMBER AND STABILITY OF INTERFACE

The formulation of the dimensionless Bond number grouping, consisting essentially of the ratio of acceleration to capillary forces, has led to the successful correlation of the magnitude of acceleration required to disrupt the established liquid-vapor interface configuration (refs. 1 to 3). The retentive property of the capillary forces provides a region of stability in which the liquid-vapor interface, though deformed, remains static under the influence of adverse gravitational or acceleration-induced forces. The subject has attracted the academic interest of many investigators, but even in view of its apparent popularity, detailed studies of the phenomenon have been lacking. With perhaps two exceptions (refs. 4 and 5), only recently have the additional variables of edge effects, contact angles and hysteresis, geometries other than cylindrical, and conclusive experimental verification of the fundamental concepts been considered.

The critical Bond number delineating the stable and unstable regions of the interface in cylinders was shown to be independent of the applied acceleration field and was verified to be 0.84 for solid-liquid-vapor systems possessing zero-degree contact angles exhibiting no hysteresis (ref. 1):

$$Bo_{crit} = 0.84 = \frac{\rho a R^2}{\sigma} \qquad (1)$$

where the density of the vapor phase has been neglected.

Experimental evidence supporting the validity of these conclusions is shown in figure 2 where correlation of data obtained both in normal gravity and low acceleration-induced environments has been made with the graph of equation (1). The procedure used in obtaining the data resulted in a range of cylinder radii in which stability (no motion of the interface) or instability was observed for each combination of liquid and acceleration field. As such, the critical radius was bracketed, with the net deviation being as small as the physical observation of the disruption or stability of the interface would permit.

The fact that the critical Bond number of 0.84 is independent of the acceleration field (Of course, the other parameters must then change to keep the relation constant.) is not really astonishing in view of the nature of the surface-tension stabilizing parameter. Such statements, however, are only made, for rather obvious reasons, after verification. The fact is significant from two viewpoints. First, the scaling of equation (1) to actual vehicle tank dimensions can now be made with certitude. Second, the Bond number itself gains stature as the proper descriptive indication of environmental condition. It is in this last regard that the phrase "low-acceleration" environment must be used with reservation.

ADVERSE BOND NUMBERS GREATER THAN CRITICAL: MOTION OF THE INTERFACE

It can be seen from equation (1) that the acceleration required to disrupt the interface in realistic space-vehicle tanks is quite small; however, space vehicles will be subjected to a number of disturbances of magnitude most likely to exceed the critical level of allowed acceleration. Various schemes, both active and passive, have been proposed to locate the interface in the presence of these perturbations. The proposed use of small auxiliary thrustors designed to maintain the proper orientation of the propellant by inducing a low body force environment is one popular example of active locating methods. The efficiency of the auxiliary thrust method is dependent on the ratio of induced Bond number to the Bond number resulting from the extraneous disturbances; an optimum solution would demand that the auxiliary thrustors should never lose control of the interface. But for missions requiring long-term coast durations, the continual use of these thrustors may cause excessive weight penalties, thus their operation may have to be reduced to intermittent durations. Reliable restart can be insured by a combination of collection-thrust and pump-inlet baffling; efficient venting characteristics, however, appear to be solely dependent on the performance of these ullage control thrustors to reposition or collect the propellant following interface disruption. The dynamic behavior of the interface during this collection mode is of immediate interest.

The mode of liquid flow following the disruption of the interface in a low acceleration field has been noted in the critical Bond number studies and was observed to be similar to the gravitational motion of large (>1 diameter) bubbles in closed vertical tubes. An extensive program conducted under normal-gravity conditions extended the existing correlation of bubble rise velocity through a carefully documented region of Bond numbers ranging from 3.49 to 1870. The rate of penetration of the vapor phase into the liquid phase for low viscous fluids was found to be described by the empirically derived equation

$$Vo = 0.48(aR)^{1/2}\left[1 - \left(\frac{0.84}{Bo}\right)^{Bo/4.7}\right] \tag{2}$$

For Bond numbers greater than 12, equation (2) reduces to

$$Vo = (0.48)(aR)^{1/2} \tag{3}$$

or the form predicted by the inviscid potential theory of G. I. Taylor (ref. 6). The NASA experimental data for large Bond numbers at 1 g and intermediate Bond numbers at low gravity are presented in figure 3 with the curve of equation (2). Other published data is also shown, and the agreement with the empirical equation is seen to be excellent, including Bond numbers approaching one.

The extension of the investigation to low gravity-induced environments verified the validity of the above results in terms of a correct scaling relation. The low-acceleration data in figure 3 are satisfactorily correlated by equation (2). A photograph showing the profile of the interface under an imposed acceleration of 36.3 cm/sec^2 is shown in figure 4(a) and is typical of the observed symmetry of the vapor penetration when adequate zero-gravity formation time and proper thrust alignment were provided. The observed symmetry of the profile, especially the progression of the leading edge, was extremely sensitive to small misalignments in acceleration direction.

It is to be noted that the time allowed for the formation of the zero-gravity interface configuration was generally not sufficient to insure completely quiescent conditions prior to the initiation of the imposed acceleration. This fact is not to be minimized because the formation period represents an initial perturbation to the mode of liquid flow, and a transition region necessarily occurs prior to steady-state regular flow. The mode shape excited by the sudden transition from 1-g to zero gravity resembles, descriptively, a "hump" centered along the major axis of the cylinder. If sufficient time is not allowed for adequate decay of this formation mode, subsequent vapor penetration rates will be severely affected. In fact, if the formation time is "properly chosen", the imposed acceleration will cause the formation mode to grow exponentially in time in the form of the classic Taylor instability. The competition between formation, transition, and regular flow time in the present 2.3-sec drop-tower facility restricted the radii of the cylinders to a maximum of 4.5 cm.

As a result of these investigations, it is now possible to predict the vapor penetration or ullage velocity under an imposed collection acceleration in real vehicle propellant tanks. For tank radii of the order of 150 cm (5 ft), a typically imposed collection acceleration of 10^{-2} g will result in an ullage velocity of slightly greater than 18 cm/sec. However, one should not estimate the total time required to reorient the propellant (e.g., from the vent portion of the tank) solely from the above results because the situation presented is quite ideal. The ullage velocity correlation given by equation (2) has been obtained in unbaffled, flat-bottomed, cylindrical geometries. Internal tank hardware could alter the regular symmetric stage of propellant flow, and the effect of tank extremities may reduce the velocity magnitude. The latter aspect is somewhat doubtful because no observable effect on the ullage velocity due to the flat bottom of right circular cylinders has been noted in the low acceleration studies. The net adverse effect of these two aspects would be a reduction in ullage velocity; therefore, equation (2) represents a reasonable estimate of the ullage velocity under a given collection acceleration even when the geometry is less than ideal. Time estimates, however, for complete collection still cannot be inferred because of the motion of the leading edge of the interface.

The interface leading edge velocity (V_L in fig. 4(a)), unlike the ullage velocity, is not constant. The result is consistent with inviscid theory: if the profiles of the interface and ullage velocity in response to both inertial and gravitational body force accelerations are identical, the continuity equations demand that the bounded leading edge accelerate - a necessary converse of Taylor's argument. An analysis of the leading edge displacement characteristics led to the following equation:

$$a_L = \frac{3.8\ V_0^2}{R} \qquad \text{for} \quad Bo > 1.7 \tag{4}$$

where a_L is the magnitude of the leading edge acceleration and V_0 is the ullage velocity given by equation (2). The empirical correlation of the above equation was based on the actual ullage velocity as observed in each test and is accurate to within 10 percent, the accuracy increasing with increasing Bond numbers. For Bond numbers greater than 12

$$a_L = 0.87\ a \tag{5}$$

which indicates a slight departure from the ideal free-fall condition at the wall. The leading edge displacement is undoubtedly viscosity dependent but for low-viscous fluids of the order of 1 centipoise and available accelerating distances comparable to cylinder fineness ratios of 2, the above relations are valid within the stated accuracy.

PROPELLANT COLLECTION BY LOW ACCELERATION-INDUCED FORCES

The significance of the leading edge displacement is that the instantaneous leading edge velocity may be quite large when the liquid eventually converges at the tank bottom. The resultant momentum could then cause the propellant to rebound or geyser back to the top of the tank, and the attempt at collection would merely result in circulating the propellant. The presence of a prominant geyser in flat-bottomed, convex-bottomed (Apollo), and concave-bottomed (Centaur and Saturn) geometries and the subsequent recirculation were determined quite early in the drop-tower investigations. It is the presence of this geyser that currently makes total-time estimates of collection literally estimates.

The geysering phenomenon in the Bond number region from 10 to 60 was quite ordered and repeatable with surprisingly little turbulence. Although direct measurements of the geyser were impaired both by refraction and capillary waves in the liquid film along the tank wall, some geometric observations were evident. The geyser is basically a continuous liquid column with a width of between 1/4 and 1/2 of the tank diameter. Other than at its initial formation, the geyser maintains its size relative to the tank, exhibiting only slight wave motion due undoubtedly to Rayleigh instability. Representative photographs of the geyser in a Centaur geometry model are shown in figure 4(b). In all instances, the geyser was observed to move at a constant velocity, the magnitude being approximately twice the instantaneous leading edge velocity calculated at tank bottom impingement. Further data is needed, however, to firmly establish this correlation. Once the geyser reached the top of the model geometry, the liquid was recirculated.

Despite the geysering formation and recirculation, liquid does accumulate at the bottom of the tank. Actual ratios of liquid accumulation to geyser volume per unit time were estimated, for example, in the Centaur models to be as high as 1/3. The relation, however, describing the accumulation rate is not apparent and sufficient test time is not presently available to obtain total accumulation.

Obviously, the requirements of efficient venting are not compatible with the severity of the geyser in the basic collection mode. The reliance on viscous damping to end the recirculation mode would make time durations for collection excessively long. Methods for eliminating or at least alleviating the geysering problem consist simply of changing the direction of flow momentum and dissipating the kinetic energy due to the leading edge flow. Although the latter results in considerable turbulence and small bubble formation, this appears to be the only feasible solution. Deliberate collection acceleration misalignment and suitable tank baffles were investigated as means of impeding and redirecting the geyser flow. While the former method may not be too practical, it does merit attention because of its simplicity. For example, a 15° thrust misalignment with the major axis of the geometry causes a large angle in the progression of the leading edge. When the leading edge converges at the tank bottom, the resultant geyser is directed toward the wall, and the ensuing agitation causes a considerable increase in total liquid accumulation over symmetrical collection for identical time intervals. The geyser, however, was noted to re-form parallel to the collection acceleration after liquid had been accumulated; the applicability is only for small residual percentages of propellant. Varieties of baffles in the forms of plates, rings, and shells were also tried to completely eliminate the geysering problem and to obtain total liquid collection. In general it was discovered that the approach was, in part, feasible, and that any baffling scheme which would impede and redirect the geyser flow direction to the tank walls or back to the tank bottom would cause a substantial increase in collected liquid. Once these baffles were covered with accumulated liquid, however, their effectiveness was completely lost, and the geyser reappeared almost immediately. For example, a ring-type baffle, placed around the inverted hemispherical bottom of a Centaur model, diverted the leading edge and caused a reservoir of liquid to accumulate with no apparent geyser. Shortly after the collected liquid had covered the ring, however, geysering appeared with little, if any, reduction in severity.

Another baffling technique, which has proven thus far to be the most successful, relies on distinct liquid levels and on an estimate of the residual propellant to be collected. The method is shown in figure 5. Before collection is attempted, the liquid level is above the angled ring baffle. The collection acceleration causes a typical geysering formation, but once the liquid level drops below the baffle, the leading edge is diverted toward the center of the tank. The geyser flow and the newly directed leading edge flow impinge on each other, which results in considerable turbulence and bubble formation. The turbulence, however, is an effective dissipation factor and the numerous small bubbles settle out quite rapidly. The previously stated relations describing the leading edge and geyser velocities were entirely adequate in determining the point of flow impingement. The photograph in figure 5 of a test run using this baffling technique shows successful complete liquid reorientation despite present experimental time limitations.

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CONCLUSION

In summary, it may be stated that the motion of the liquid-vapor interface in response to low acceleration-induced forces can be predicted; however, accurate time estimates of complete propellant reorientation or collection cannot presently be made because of the geysering phenomena. Baffling techniques designed to obtain collection can be effective, but they result in considerable propellant agitation with possible concurrent vehicle control problems.

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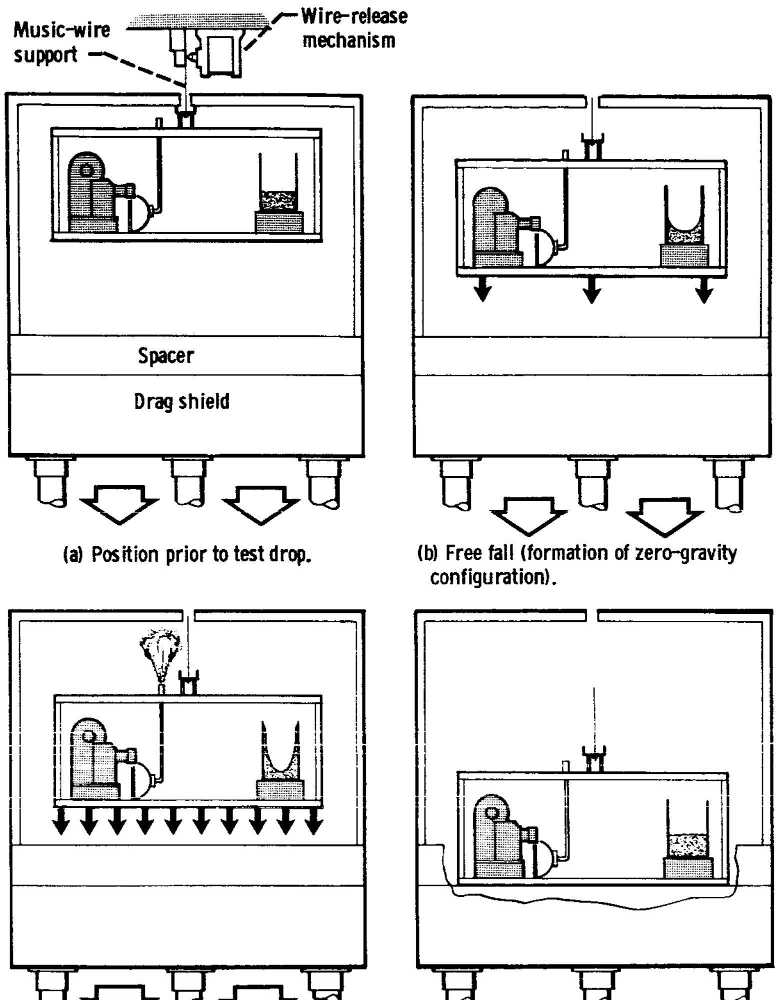

(a) Position prior to test drop.

(b) Free fall (formation of zero-gravity configuration).

(c) Application of thrust (low acceleration field).

(d) Position after test drop.

Figure 1. - Schematic drawing showing sequential position of experiment package and drag shield before, during, and after test drop.

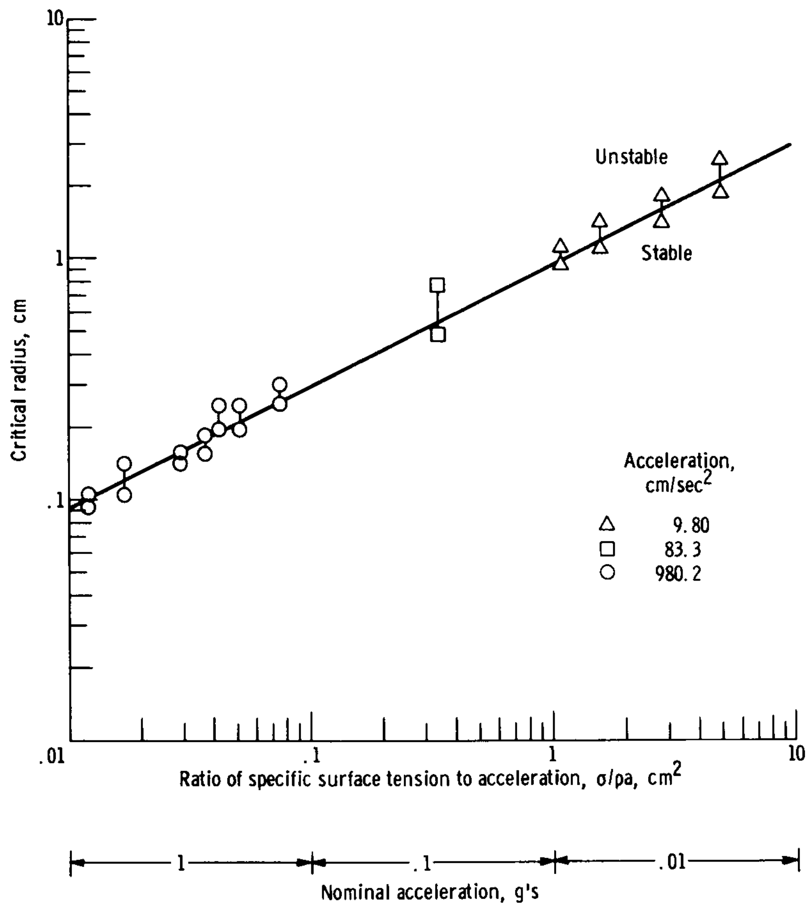

Figure 2. - Interface stability delineated by Bond number criterion.

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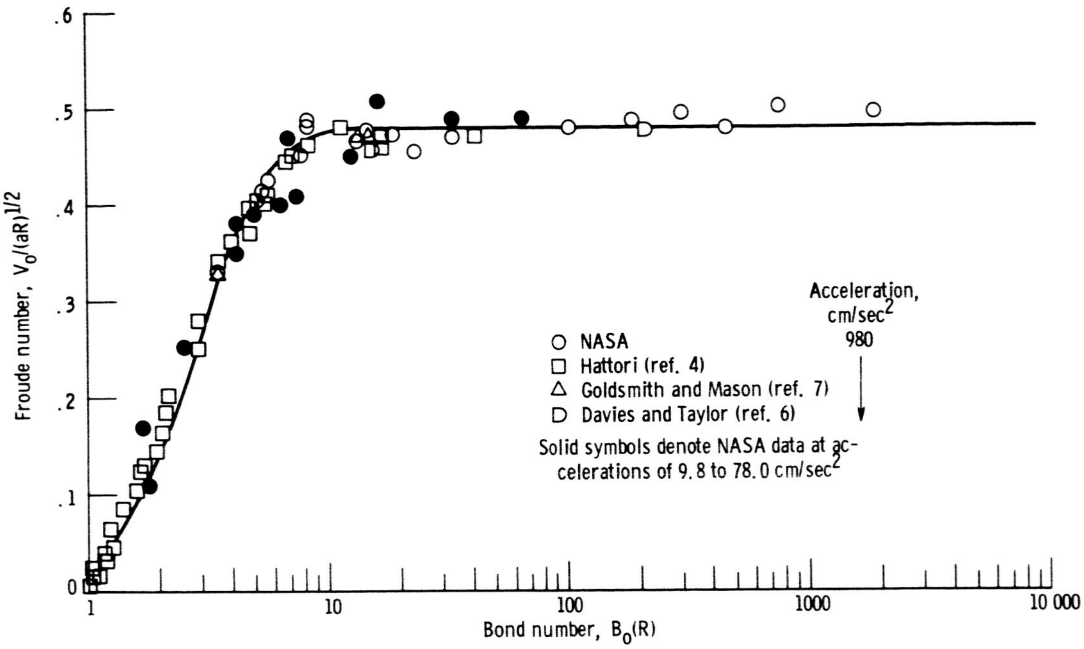
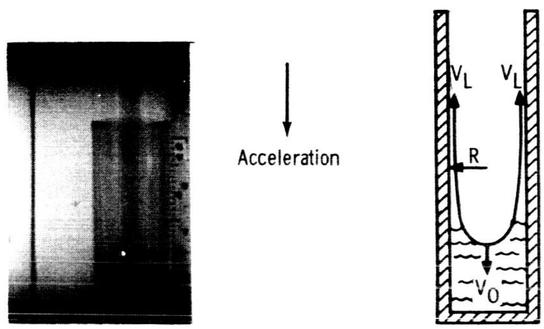
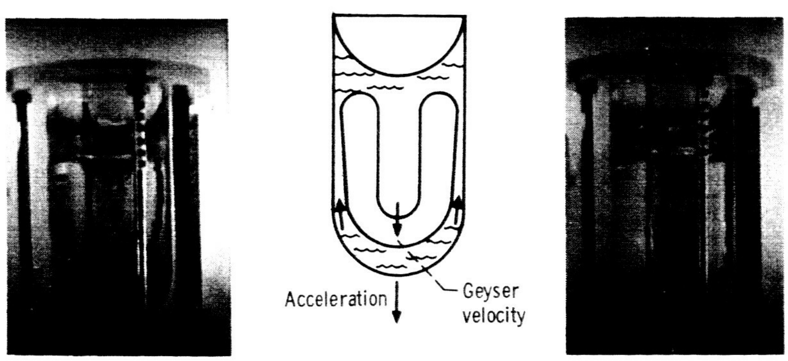


Figure 3. - Experimental correlation of vapor penetration rate with Bond number.



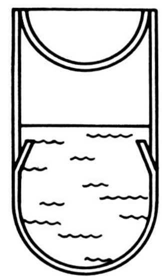
(a) Interface profile under imposed acceleration of 36.3 cm/sec^2.



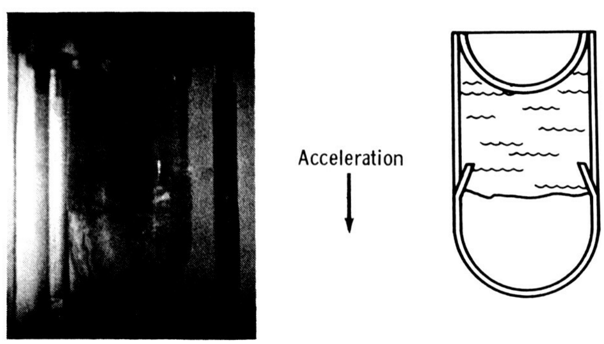
Geyser formation Flow pattern Recirculation

(b) Geyser formation and recirculation in Centaur model geometry.

Figure 4. - Interface profile and geyser formation and recirculation.



Initial liquid location prior to collection



Final configuration during collection mode

Figure 5. - Collection in baffled Centaur tank geometry.