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LIQUID PROPELLANT REORIENTATION IN A LOW-GRAVITY ENVIRONMENT

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SUMMARY

An existing empirical analysis relating to the reorientation of liquids in cylindrical tanks due to propulsive settling in a low-gravity environment was extended to include the effects of geyser formation in the Weber number range from 4 to 10. Predicted liquid reorientation times and liquid leading edge conditions compared favorably with experimental results obtained from previously unpublished data. Estimates of the minimum velocity increment required to be imposed on the propellant tank to achieve liquid reorientation were made. The resulting Bond numbers, based on tank radius, were found to be in the range from 3 to 5, depending upon the initial liquid fill level, with higher Bond numbers required for higher initial fill levels. The resulting Weber numbers, based on tank radius and the velocity of the liquid leading edge, were calculated to be in the range from 6.5 to 8.5 for cylindrical tanks having a fineness ratio of 2.0, with Weber numbers of somewhat greater values for longer cylindrical tanks. It therefore appeared to be advantageous to allow small geysers to form and then dissipate into the surface of the collected liquid in order to achieve the minimum velocity increment.

The Bond numbers which defined the separation between regions in which geyser formation did and did not occur due to propulsive settling in a spherical tank configuration ranged from 2 to 9 depending upon the liquid fill level.

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INTRODUCTION

For space vehicles using liquid propellants, the problem of positioning the propellant over the outlet of the tank in a low-gravity environment, prior to the start of outflow, continues to be an area of concern. There appear to be at least three liquid propellant management techniques that might be utilized depending on the specific mission of the space vehicle. One technique that might be utilized for the tanks of a propellant resupply vehicle, where liquid outflow over a long period of time under zero-gravity or very low-gravity conditions is required, would be the use of either a complete screen liner or multiple screen channels (e.g., ref. 1). A second technique that might be utilized for a propulsion stage (or module) would be the use of a start basket located over the tank outlet, such as proposed in reference 2 for the Centaur vehicle. Although the use of a start basket looks promising for situations where a large number of engine restarts in space is required, there are still some areas of uncertainty when a start basket is proposed for use with a cryogenic liquid. These are primarily due to the possibility of heat leaks into the basket drying out the wicking screens which maintain liquid within the basket between periods of outflow.

One alternate technique to the use of a start basket for cryogenic propellants may be to reorient (or position) the liquid over the tank outlet by means of propulsive settling. This would also free the tank vent of liquid so that venting of vapor could occur. Propulsive settling most often involves the use of small auxiliary thrusters to reorient the propellant by providing a low-gravity acceleration in the direction of the main engine thrust. In order for the propulsive settling technique to be competitive on a weight basis with the start basket technique, the propellant usage and other weight penalties must be minimized. This can be accomplished by providing only the required acceleration to the space vehicle for an optimum period of time (i.e., by providing a minimum velocity increment) so that the propellant is reoriented over the tank outlet without initiating any vapor entrainment, excessive geysering, or other unwanted fluid motion.

Efforts to experimentally determine the liquid reorientation characteristics within propellant tanks were reported in references 3 and 4 for cylindrical tank configurations and in reference 5 for spherical tank configurations. Liquid reorientation was generally achieved by imposing a constant, low-level acceleration on the tank, starting from a weightless condition. The primary purpose of this report is to extend the empirical analysis by including additional data obtained from the original motion picture data films for cylindrical tanks presented in reference 4, so that (1) the total liquid reorientation time could be estimated for a given low-level tank acceleration, and (2) the required vehicle acceleration and propellant reorientation time could be optimized to obtain the minimum auxiliary thruster propellant usage (i.e., the minimum velocity increment imparted to the space vehicle) by allowing some geyser formation to occur. No equivalent analysis exists for a spherical tank configuration. However, a secondary purpose of this report is to present data from the motion picture films for the test results for spherical tanks reported in reference 5 to indicate the Bond numbers where geysering of the liquid begins to occur.

The work presented herein was intended to be a preliminary effort in examining (1) the liquid reorientation characteristics for both cylindrical and spherical tank configurations, and (2) the potential advantages to be gained by using either a constant low-level tank acceleration or an intermittent higher-level tank acceleration. In this preliminary effort, no experimental data generated from recent drop tests was obtained.

SYMBOLS

a acceleration, cm/sec^2

Bo Bond number, $a_T R_T^2/\beta$

FL ratio of liquid volume to tank volume, v_l/v_T

FR fineness ratio, tank length/tank diameter

l length, cm

R radius, cm

t time, sec

V velocity, cm/sec

V_L' instantaneous liquid leading edge velocity at convergence of tank bottom, cm/sec

V_L'' instantaneous liquid leading edge velocity at intersection between cylindrical and spherical portions of tank, cm/sec

v volume, cm^3

We Weber number, $(V_L')^2 R_T/\beta$

β specific surface tension, σ/ζ, cm^3/sec^2

ζ liquid density, g/cm^3

σ liquid surface tension, dynes/cm

Δ increment

Subscripts:

c cylinder

i initial distance liquid leading edge must travel along cylindrical section of tank during reorientation

j distance liquid film must travel along cylindrical section of tank wall after reorientation to reach flat liquid/vapor interface

L leading edge

l liquid

0 ullage

T tank

t total

1-5 reorientation phase

APPARATUS AND PROCEDURE

The experimental apparatus was described in detail in references 4 and 5. The experimental tests were conducted in a 2.2 second zero-gravity drop tower facility. The initial acceleration on the experiment package as a result of air drag was kept below 10^{-5} g by allowing the package to fall freely inside a protective drag shield. This allowed the formation of a highly-curved liquid-vapor interface representing the initial zero-gravity conditions as noted in figure 1. A low-level acceleration was then imposed on the experiment package by means of a cold-gas thruster to reorient the liquid to the opposite end of the tank. The magnitude of the reorientation acceleration ranged from approximately 0.005 to 0.1 g. All data were recorded photographically, and time measurements were obtained by viewing a precision sweep clock with a calibrated accuracy of approximately ±0.01 second.

The liquids and test tanks employed in the experimental investigation were, in general, representative of the properties and tank geometries of typical liquid-propellant systems. The physical properties of the liquids used are noted in table I. All liquids were analytic reagent grade and exhibited static contact angles very near 0° on the tank surfaces. The basic test tank configurations were:

(1) cylindrical tanks with convex hemispherical ends. The tank radii ranged from 1.65 to 3.22 centimeters (0.65 to 1.27 in.), and the fineness ratios (total length to diameter ratios) ranged from 2.14 to 4.

(2) spherical tanks. The tank radii ranged from 2.43 to 3.06 centimeters (0.96 to 1.20 in.).

DISCUSSION OF RESULTS

Cylindrical Tank Configuration

A summary of the test conditions for the cylindrical tank configuration (convex bottomed tanks, ref. 4) is shown in table II. The liquid fill levels (FL) for these tests ranged from 0.29 to 0.83. The Bond numbers resulting from the applied tank acceleration levels ranged from 3.0 to 6.7.

In each of the experimental tests, the low-level tank acceleration was applied to provide the propulsive reorientation of the liquid to the opposite end of the tank where the outlet was assumed to be located (fig. 2(a)). The acceleration was applied at approximately the time that the liquid-vapor interface at the tank longitudinal centerline made its first pass through the normal 0-g equilibrium location. The applied acceleration initiated the flow of a film of liquid along the wall of the tank. The characteristic velocity (V_L) and acceleration (a_L) of the leading edge of the liquid film as well as the velocity of the vapor ullage bubble (V_0) as noted in figure 2(b) have been characterized previously (ref. 4).

The basic sequence of events occurring during the reorientation process are shown in figure 3. The leading edge of the liquid film moved toward the bottom of the tank at a rate defined by the acceleration (a_L) while the vapor ullage bubble moved toward the top of the tank at a relatively constant velocity (V_0). Once the leading edge of the liquid film impinged on the bottom of the tank with velocity V_L', the liquid began to collect in the bottom of the tank. If the velocity of the leading edge (V_L') was sufficiently large (as defined by the Weber number criteria ($We > 4$), ref. 4)), a geyser started to form almost as soon as the liquid began to collect. Assuming that the Weber number ($We = (V_L')^2 R_T/\beta$) was not too large ($We < 10$, for example), the axial progression of the geyser slowed and then regressed so that the geyser would dissipate into the surface of the collected liquid. While the liquid collected at the bottom of the tank, the ullage bubble reached the top of the tank, and the liquid film started to clear from the tank wall. The total time required to reorient the liquid was then considered to be the sum of either $t_1 + t_2 + t_3$ or $t_4 + t_5$, whichever value was larger. The technique used for calculating the time for each phase of the reorientation process is given in appendix A. In general, the time for each phase was written in terms of the final leading edge velocity (V_L'), the tank geometry and the fill level (FL). The leading edge velocity was determined by the value of the Weber number that was considered. The Weber number also defined the severity of the geysering that was to be considered. The applied tank acceleration required to produce the specified reorientation characteristics was then calculated. The listing of a relatively simple computer program to provide the various calculations required is given in appendix B.

A comparison of the measured and calculated leading edge parameters as well as the times required for each phase in the reorientation process to occur is shown in table III. The agreement between measured and calculated values is generally good. Discrepancies of any significance were probably due to the failure to achieve a quiescent 0-g liquid-vapor interface prior to the initiation of thrusting. Difficulties in locating the leading edge and in reading the scale placed alongside the tank due to the motion picture camera being improperly focused also contributed to the uncertainty of some of the measured values. In many cases where the measured values are not shown, the available drop time was not sufficient to complete the liquid reorientation process. Equation (A11) in appendix A, which was used to predict the time required for a small or moderate sized geyser to form and dissipate into the liquid surface, was based on the measured results from tests 1, 5, and 7. In all other tests where a geyser was formed, the available drop time did not allow observation of the complete formation and dissipation of the geyser. Also, the available drop time did not allow for a definitive observation of the time required for the liquid film to clear from the tank wall once the ullage bubble had reached the top of the tank. Therefore, equation (A19) in appendix A represented only a crude approximation, at best, of this phase. More analysis supported by experimental testing would be necessary to provide a better estimate of the time required.

The characteristics of the formation and dissipation of a small geyser are shown in figures 4 and 5 for tests 1 and 5, respectively. The geyser formation started almost immediately after the leading edge had reached the bottom of the tank and before much liquid had accumulated as can be noted in figures 4(a) and 5(a). The geysers formed rapidly and then dissipated into the surface of the collected liquid after a relatively short period of time. There was no indication of turbulent liquid motion or small bubble formation during this period of time. In both cases, the Weber number calculated for these tests was somewhat greater than 4. The curves faired through the data were used to determine the geyser tip velocities relative to the tank as shown in figures 4(b) and 5(b). In both cases, the geyser tip velocities were initially very high in the upward (positive) direction, and then exhibited an S-shaped curve as the geyser tip reached its maximum height and then settled into the surface of the collected liquid. The velocities of the surface of the collected liquid immediately after the geyser had dissipated were approximately twice the calculated vapor ullage bubble velocities (V_0 = 1.60 and 2.64 centimeters per second (0.63 and 1.04 in./sec) for tests 1 and 5, respectively). This may have indicated, perhaps, that the liquid reorientation flow process had not reached a steady state condition prior to the end of the drop.

Since it appeared that the empirical model presented in appendix A provided a reasonably good estimate of the time required to reorient the liquid, it was then of interest to optimize the acceleration levels to be applied to the tank so that the liquid would be reoriented with a minimum velocity increment ($\Delta V = a_T t$). The results of a series of calculations for a 3.22 centimeter (1.27 in.) radius tank are shown in figure 6 for a range of liquid specific surface tension from 11.8 to 40.9 cubic centimeters per second squared (0.72 to 2.50 in^3/sec^2). The results indicated that it was desirable to apply an acceleration level to the tank so as to allow a small geyser to form (i.e., the minimum velocity increment occurred for a Weber number slightly greater than 4). The geyser would then have been dissipated into the surface of the collected liquid prior to the time that the liquid film cleared from the tank wall. As the liquid fill level was increased, the applied acceleration and Weber number could be increased because of the increased time required for the ullage bubble to reach the top of the tank. The minimum velocity increment for a given fill level occurred at the same Bond number regardless of the value of the liquid specific surface tension.

It should be noted that, at the minimum velocity increment, the total reorientation time was generally defined by $t_t = t_4 + t_5$ as is shown in table IV for the same conditions noted in figure 6(a), for example. The calculated time (t_5) for the liquid film to clear from the tank wall was a substantial portion of the total reorientation time. Since this calculation was also the weakest link in the empirical model presented in appendix A, a better definition of this phase of the reorientation process is a necessity for future work. The total reorientation time tended to be relatively insensitive to the liquid fill level. The resulting values of Weber number for the minimum velocity-increment reorientation varied between 6.5 and 8.5.

The minimum velocity increment is plotted as a function of the liquid fill level (FL) in figure 7 for the three values of liquid specific surface tension considered previously in figure 6. The minimum velocity increment required to reorient the liquid increased with specific surface tension and also with fill level up to a fill level of 0.60. For fill levels of 0.60 and greater for a tank with a fineness ratio of 2.0, the liquid would most likely wet the entire tank wall in a 0-g environment. In this case, the values of t_1 and t_2 for the reorientation process would be zero (as noted in the sample output of the computer program, appendix B), and the minimum velocity increment remained at a relatively constant value for each value of specific surface tension. In the calculations, however, it was assumed that a pseudo leading edge was still present so that a leading edge velocity (V_L') and acceleration (a_L) could still be defined by means of equations (A5) and (A6) in appendix A where $V_L'' = 0$. This assumption, too, needs to be analyzed further and then supported by experimental testing.

The velocity increment as a function of Bond number is shown in figure 8 for a smaller tank radius ($R_T = 2.0$ centimeters (0.79 in)) than that considered in figures 6 and 7. The resulting minimum velocity increment is shown in figure 9 where it is compared with that of the 3.22 centimeter (1.27 in) radius tank. It can be seen that increasing the tank radius results in a decrease in the minimum velocity increment required to reorient the liquid.

The velocity increment for increasingly longer cylindrical tanks having a radius of 3.22 centimeters (1.27 in) and a fineness ratios of 3.0 and 4.0 is shown in figures 10(a) and (b), respectively. Comparing figure 6(a) along with figures 10(a) and (b), it can be seen that the minimum velocity increment occurred at higher values of the Weber number as the fineness ratio increased (i.e., the severity of the geysering could be increased because of the longer times required for the ullage bubble to reach the top of the tank as the tank length was increased. Hence, there was a longer time available for geyser growth and dissipation into the surface of the collected liquid) The minimum velocity increment is plotted as a function of fill level for fineness ratios of 2.0, 3.0, and 4.0 in figure 11. As the fineness ratio was increased, the minimum velocity increment required to reorient the liquid also increased for any given liquid fill level.

The required Bond number at which the minimum velocity increment occurred is shown as a function of the fill level in figure 12 for all of the data previously calculated and presented in figures 6, 8, and 10. For a fineness ratio of 2.0, a single curve was obtained for all values of the liquid specific surface tension and tank radius considered. For the increasingly longer tanks considered (FR = 3.0 and 4.0), the data fell in the shaded areas adjacent to the curve for FR = 2.0. The data were displaced slightly from the curve in a random manner. This may have been just a problem with the iteration technique for calculating the required tank acceleration at a given Weber number for all values of fill level plus a slight geometry effect for fill levels greater than 0.60. In general, Bond numbers in the range from 3 to 5, depending on the fill level, were required for minimum velocity-increment reorientation of the liquid.

A calculation of the velocity increment required to reorient liquid hydrogen in a 200 centimeter (6.56 ft) radius tank having a fineness ratio of 2.0 was conducted to gain an insight of the propulsive reorientation requirements for a more representative size propellant tank. The selection of this size was arbitrary and was not representative of any particular space vehicle. The results of the calculation are shown in figure 13. The reorientation times and the acceleration levels required to provide the minimum velocity increment over a range of fill levels are noted in table V. The minimum velocity-increment reorientation would require acceleration levels of 0.0015 to 0.0022 centimeters per second squared (4.9×10^{-5} to 7.2×10^{-5} ft/sec^2) for a period from 35.9 to 39.2 minutes. The values of the minimum velocity increment required ranged from 3.28 to 5.23 centimeters per second (0.108 to 0.172 ft/sec). It should be noted that these required acceleration levels are extremely small, ranging from 1.5×10^{-6} to 2.2×10^{-6} g. Depending upon the orbital altitude of the spacecraft, these accelerations may be about the same order of magnitude as the normal atmospheric drag. Therefore, depending upon the attitude of the spacecraft during the reorientation process, it may be necessary to increase the thruster size simply to overcome some component of the atmospheric drag in addition to the thrust required to reorient the propellant.

Spherical Tank Configuration

The test conditions for the drop tower tests conducted with a spherical tank configuration and reported in reference 5 are noted in tables VI and VII for initially curved and initially flat liquid-vapor interface configurations, respectively. The tests for the initially curved interface were conducted by allowing a short period of time under 0-g conditions for the interface to achieve a curvature approximating the normal 0-g equilibrium configuration with a centrally located ullage bubble before applying a low level acceleration to the tank to reorient the liquid. The tests for the initially flat interface were conducted by firing the thruster prior to the time that the experiment package was released for the drop. The thruster then provided a low level acceleration continuously during the drop to reorient the liquid Under both types of test conditions, geysers were observed to form during some of the tests as noted in tables VI and VII. A small geyser was arbitrarily defined to be limited in growth to a maximum height of approximately one-third of the tank radius or less. A moderate to severe geyser was arbitrarily defined to have a maximum height greater than one-third of the tank radius, with the distinction between moderate and severe being somewhat subjective.

An empirical model to describe the liquid reorientation process for a spherical tank undergoing a constant low-level acceleration in a manner similar to that for a cylindrical tank as presented in appendix A does not exist. However, it was possible to define the range of Bond numbers where a geyser would or would not occur from the data presented in tables VI and VII. Extrapolation of this data, which is plotted in figure 14, indicated that the maximum Bond number for which no geyser formation would be expected to occur ranged from approximately 2 to 9 over the range of fill levels $0 < FL < 1.0$. Increasing the Bond numbers to approximately 4 to 11 over the same range of fill levels appeared to define the boundary between small and moderate to severe geyser formations, although the data was admittedly limited to just a few data points.

CONCLUDING REMARKS

The information presented herein represents only an initial look at the characteristics of liquid reorientation in a low gravity environment by means of propulsive settling. Problem areas that were already pointed out as needing further investigation included:

1. Determination of the parameters affecting the growth and dissipation of geysers in both cylindrical and spherical tanks.

2. Determination of the time required to clear the liquid film from the tank wall after the bulk liquid has been reoriented in both cylindrical and spherical tanks.

3. Determination of the ullage bubble rise velocity in cylindrical tanks for cases where the tank is nearly full and the ullage bubble diameter is much smaller than the tank diameter.

4. Determination of the parameters governing the basic liquid reorientation process in spherical tanks so that the minimum velocity increments required may be calculated.

In addition, it would also be of interest to develop an analytical model that would allow characterization of the liquid reorientation process during intermittent propulsive settling (intermittent thrusting). This technique may offer some advantages over the use of continuous thrusting.

And finally, it is necessary to develop experimental techniques and test facilities to verify analyses using reasonably sized test tanks and allowing times sufficiently long to observe the complete reorientation process.

SUMMARY OF RESULTS

An existing empirical analysis relating to the reorientation of liquids due to propulsive settling in cylindrical tanks was extended to include the effects of geyser formation in the Weber number range from 4 to 10. An estimate of the reorientation times and optimum velocity increments required to reorient the liquids in the bottom of cylindrical tank configurations was made. In addition, the Bond number criteria to denote the conditions under which geyser formation would occur in spherical tanks was determined. All experimental data were obtained from a reexamination of the data films originally obtained for the experimental investigations reported by Salzman, Labus, and Masica in references 4 and 5. The following conclusions were reached:

1. The empirical analysis predicted liquid leading edge conditions and reorientation times which compared favorably with those determined experimentally for cylindrical tank configurations where data were available. The time for small geysers to form and dissipate into the collected liquid surface was characterized. The time required to remove the residual liquid film remaining on the tank wall once the ullage bubble reached the forward end of the tank was characterized in a rough-order-of-magnitude sense. Unfortunately, very little experimental data was available concerning this phase of the liquid reorientation process, even though a considerable portion of the total required reorientation time was attributed to it.

2. Calculations of the minimum velocity increment required to be imposed on a cylindrical propellant tank for reorientation of the liquid to occur indicated that Bond numbers in the range from 3 to 5, depending upon the liquid fill level, were required. Bond numbers appeared to be independent of the fineness ratio of the tank. The resulting Weber numbers for the liquid leading edge at the minimum velocity increment conditions (based on tank radius and instantaneous liquid leading edge velocity at the tank bottom) were calculated to be in the range from 6.5 to 8.5 for cylindrical tanks having a fineness ratio of 2.0. It, therefore, appeared to be advantageous to allow a small geyser to form as long as it regressed and dissipated into the surface of the collected liquid prior to the time that the residual liquid film cleared from the tank wall. Somewhat higher values of the Weber number (i.e., somewhat more severe geysering) were calculated for longer (FR > 2) cylindrical tanks.

3. The Bond numbers for a spherical tank configuration which defined the separation between regions in which geyser formations would and would not occur due to propulsive settling were extrapolated from available data and appeared to be in the range from 2 to 9 depending upon the liquid fill level.

APPENDIX A

ESTIMATE OF LIQUID REORIENTATION TIME FOR A CYLINDRICAL TANK CONFIGURATION

The fineness ratio for a cylindrical propellant tank having hemispherical ends (fig. 1(a)) was defined as the ratio of the total length to the diameter, or:

$$FR = \frac{2R_T + l_c}{2R_T} \tag{A1}$$

The volume of the tank is then:

$$v_T = \frac{4}{3}\pi R_T^3 + l_c \pi R_T^2$$

$$= \left(FR - \frac{1}{3}\right) 2\pi R_T^3 \tag{A2}$$

For a partially filled propellant tank, the length (l_i) of the cylindrical section of the wall that the leading edge of the liquid must travel (fig. 2(b)) must then be determined. Assuming that the liquid fill level (FL) of the propellant tank is given, the length (l_i) can be determined from:

$$l_i = \left[\frac{(1 - FL)v_T - \frac{4}{3}\pi R_T^3}{\pi R_T^2}\right]$$

$$= \left[(1 - FL)\left(FR - \frac{1}{3}\right) - \frac{2}{3}\right] 2R_T \tag{A3}$$

It is desired to reorient the liquid from one end of the tank to the other by applying a constant low-level acceleration to the propellant tank in the direction noted in figure 1(b). In order to minimize the resulting velocity increment imposed on the tank, it is necessary to expend only the amount of energy required to reorient the propellant without creating vapor entrainment, excessive geysering, or other unwanted fluid motions. The presence of any of these conditions indicates that excess energy has already been imparted to the liquid, and that even more energy will have to be expended by the settling thrusters to finally settle the liquid to a relatively quiescent condition.

Previous work conducted and reported in reference 4 indicated that a Weber number criteria may be utilized to describe conditions of liquid motion within the propellant tank where excessive geysering of the liquid can be avoided. The Weber number was defined as:

$$We = \frac{(V_L')^2 R_T}{\beta} \tag{A4}$$

where V_L' is the velocity of the liquid impinging on the bottom of the tank of the longitudinal centerline. Once the value of the Weber number has been given which limits the disturbances imposed on the liquid, the velocity (V_L') then assumes a specific value

$$V_L' = \left(\frac{We\beta}{R_T}\right)^{1/2} \tag{A5}$$

The velocity of the leading edge of the liquid at the cylinder/sphere intersection of the tank was further defined in reference 4 as:

$$V_L'' = \left[(V_L')^2 - 2a_L R_T\right]^{1/2} \tag{A6}$$

Assuming that the leading edge acceleration is constant, the velocity (V''_L) can also be written as:

$$V''_L = (2a_L l_i)^{1/2} \tag{A7}$$

Substituting equation (A7) into equation (A6) results in an expression for the leading edge acceleration that is dependent only on the initially specified velocity V'_L and the tank/liquid geometry:

$$a_L = \frac{(V'_L)^2}{2(l_i + R_T)} \tag{A8}$$

The time required for the liquid leading edge to flow over the distance (l_i) to the cylinder/sphere tank intersection can then be determined from:

$$t_1 = \frac{V''_L}{a_L} = \frac{2}{V'_L} (l_i)^{1/2}(l_i + R_T)^{1/2} \tag{A9}$$

The additional time for the liquid to flow from the cylinder/sphere tank intersection to the bottom of the tank can be given by:

$$t_2 = \frac{V'_L - V''_L}{a_L}$$

$$= \frac{2(l_i + R_T)}{V'_L} \left[1 - \left(\frac{l_i}{l_i + R_T}\right)^{1/2}\right] \tag{A10}$$

For the cases where the liquid fill level in the tank was sufficiently large such that the calculated value of l_i (eq. (A3)) was negative, it was assumed that the liquid wetted the entire tank surface and values for t_1 and t_2 would then be zero.

For the cases where the Weber number was greater than 4, but less than 20, drop tower films indicated that a geyser would form and then disappear into the liquid collecting at the bottom of the tank (ref. 4). The geyser formation started almost immediately after the leading edge of the liquid reached the bottom of the tank. The time required for the geyser to form and then disappear was assumed to be a function of both the Bond number and Weber number. From the limited data available, it appeared that the following empirical equation would predict the required time:

$$t_3 = 0.0516 B_o We \left(\frac{R_T^3}{\beta}\right)^{1/2} \tag{A11}$$

The time required for the ullage bubble to reach the top of the tank was described by:

$$t_4 = \frac{l_c - l_i}{V_0} \qquad \text{for } l_i > 0 \tag{A12}$$

Noting that:

$$V_0 = \left(\frac{1}{3.8} a_L R_T\right)^{1/2} \tag{A13}$$

from reference 4, equation (A12) can be rewritten:

$$t_4 = 2.76 \frac{l_c - l_i}{V_L'\left(\frac{R_T}{l_i + R_T}\right)^{1/2}} \tag{A14}$$

For the cases where the tank was relatively full, and the calculated value of $l_i < 0$, the distance that the ullage bubble had to travel was calculated from:

$$l_0 = 2(R_T \times FR - R_0) \tag{A15}$$

where:

$$R_0 = \left(\frac{3}{4\pi} v_0\right)^{1/3} = \left[\frac{3}{4\pi} v_T (1 - FL)\right]^{1/3} \tag{A16}$$

The time for the ullage bubble to move to the top of the tank was then determined from:

$$t_4 = \frac{l_0}{V_0} \tag{A17}$$

For the computational process, it was assumed that V_L' could be still described by equation (A5) and that a_L could be calculated from equation (A8) where $l_i = 0$. The time for the ullage bubble to move to the top of the tank was then calculated from:

$$t_4 = \frac{2\left[(R_T \times FR) - R_0\right]}{\left[\frac{1}{3.8}\ \frac{(V_L')^2}{2R_T} R_T\right]^{1/2}} = 5.51\ \frac{(R_T \times FR) - R_0}{V_L'} \tag{A18}$$

Values of t_4 calculated in this manner probably become more and more subject to question for $R_0 << R_T$. However, this technique was used for lack of a more reliable method of calculating the ullage bubble velocity in a low gravity environment.

The time required for the liquid film on the tank wall to disperse once the ullage bubble had reached the top of the tank was calculated from:

$$t_5 = 2\left(\frac{1_j + R_T}{V_L'}\right) \tag{A19}$$

where

$$1_j = \left[(FR - 1) - FL\left(FR - \frac{1}{3}\right) + \frac{1}{3}\right]2R_T$$

It was assumed that the liquid/vapor interface was essentially flat due to the applied acceleration during the reorientation process. This may or may not be true depending upon the level of the applied acceleration being considered. It should be noted, however, that equation (A19), at best, represents only an estimate of the time required to disperse most of the liquid film. Equation (A19) has not been confirmed by any drop tower data due to the limited low-gravity environment time available (ref. 4). Any refinement of the time required to disperse the liquid film will necessarily have to be the subject of further investigation.

The total time required to reorient and settle the liquid in the bottom of the propellant was taken as the greater time calculated from either:

$$t_t = t_1 + t_2 + t_3 \tag{A20}$$

or

$$t_t = t_4 + t_5 \tag{A21}$$

The tank acceleration required to reorient the liquid in the bottom was determined by an iterative process from the following equation (ref. 4):

$$V_0 = 0.48(a_T R_T)^{1/2}\left[1 - \left(\frac{0.84\beta}{a_T R_T^2}\right)^{a_T R_T^2/4.7\beta}\right] \qquad \text{(A22)}$$

The velocity increment required to reorient the liquid was then determined from:

$$\Delta V_T = a_T t_t$$

The velocity increment is indicative of the propulsion system performance required; the lower the ΔV_T, the smaller is the amount of propellant required by the propulsion system assuming all other things are equal.

APPENDIX A

LISTING OF COMPUTER PROGRAM TO ESTIMATE LIQUID REORIENTATION TIME DUE TO PROPULSIVE SETTLING IN A LOW GRAVITY ENVIRONMENT

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C
C     PROPULSIVE SETTLING IN A LOW GRAVITY ENVIRONMENT
C     COMPUTER PROGRAM TO ESTIMATE LIQUID REORIENTATION TIME FOR A
C     CONSTANT LOW-LEVEL THRUST
C
C     M = NUMBER OF WEBER NUMBER AND ASSUMED ACCELERATION LEVELS
C     CONSIDERED
C
      READ(5,2)M
    2 FORMAT(I6)
C
C     N = NUMBER OF LIQUID FILL LEVELS TO BE CONSIDERED FOR EACH WEBER
C     NUMBER
C
      J=1
      DIMENSION FL(10)
      READ (5,12)N
   12 FORMAT(I6)
      READ(5,14)(FL(I),I=1,N)
   14 FORMAT(F6.2)
      REAL LC,LI,LJ
      READ(5,15)RT,FR,B
   15 FORMAT(3F6.2)
C
C     DETERMINE TANK VOLUME FROM RADIUS AND FINENESS RATIO (EQ A2)
C
      VT=(FR-(1.0/3.0))*6.28319*(RT**3.0)
      LC=2.0*RT*(FR-1.0)
    5 CONTINUE
      READ(5,8)WE,AT
    8 FORMAT(2F6.2)
C
C     WE = SPECIFIED WEBER NUMBER FOR REORIENTATION
C     AT = ASSUMED (OR INITIAL) VALUE FOR TANK ACCELERATION
      S=0.001
      I=1
   16 CONTINUE
      VL=VT*FL(I)
C
C     DETERMINE THE LOCATION OF THE INTERSECTION OF THE INITIAL 0-G
C     LIQUID/VAPOR INTERFACE WITH THE TANK WALL (EQ A3)
C
      LI=((1.0-FL(I))*(FR-(1.0/3.0))-(2.0*(1.0/3.0)))*2.0*RT
      IF(LI.LE.S)GO TO 50
C
C     PREVIOUS STATEMENT DETERMINES IF FILL LEVEL IS SO LARGE THAT A
C     SPHERICAL ULLAGE BUBBLE WILL EXIST AT END OF TANK
C
C     DETERMINATION OF TIME FOR LEADING EDGE TO MOVE DISTANCE LI TO
C     INTERSECTION BETWEEN CYLINDRICAL SIDEWALL AND HEMISPHERICAL END OF
C     TANK (EQS A5 TO A9)
C
```

```
      VLP=SQRT((WE*B)/RT)
      AL=(VLP**2.0)/(2.0*(LI+RT))
      VLPP=SQRT(2.0*AL*LI)
      T1=(2.0/VLP)*SQRT(LI)*SQRT(LI+RT)
C
C     DETERMINATION OF TIME FOR LEADING EDGE TO MOVE FROM CYLINDER/SPHERE
C     INTERSECTION TO APEX OF HEMISPHERICAL END (EQ A10)
C
      T2=(2.0*(LI+RT)/VLP)*(1.0-SQRT(LI/(LI+RT)))
C
C     CALCULATE VELOCITY OF RISE OF ULLAGE BUBBLE (EQ A13)
C
      V0=SQRT(AL*RT/3.8)
C
C     DETERMINATION OF APPLIED TANK ACCELERATION AND BOND NUMBER (EQ A22)
C
   18 K=1
   20 CONTINUE
      EXP=(AT*(RT**2.0))/(4.7*B)
      V01=0.48*(SQRT(AT*RT))*(1.0-((0.84*B)/(AT*(RT**2.0))))**EXP)
      VOD=V0-V01
      DIFFV=0.0025*V0
      IF(ABS(VOD).LT.DIFFV)GO TO 40
      IF(VOD)30,32,34
   30 AT=AT-(0.0002*AT)
      K=K+1
      GO TO 20
   32 GO TO 40
   34 AT=AT+(0.0002*AT)
      K=K+1
      GO TO 20
   40 CONTINUE
      BO=AT*(RT**2.0)/B
C
C     DETERMINATION OF TIME REQUIRED FOR GEYSER TO FORM AND REGRESS INTO
C     SURFACE OF COLLECTED LIQUID (EQ A11)
C
      IF(WE.LE.4.0)GO TO 41
      T3=0.0516*BO*WE*SQRT((RT**3.0)/B)
      GO TO 42
   41 CONTINUE
      T3=0.0
   42 CONTINUE
      IF(LI.LE.S)GO TO 45
C
C     DETERMINATION OF TIME REQUIRED FOR ULLAGE BUBBLE TO RISE TO TOP OF
C     TANK (LIQUID COLLECTING IN BOTTOM OF TANK) (EQ A14)
C
      T4=2.76*(LC-LI)/(VLP*(SQRT(RT/(LI+RT))))
   45 CONTINUE
C
C     ESTIMATE OF TIME REQUIRED FOR LIQUID FILM ON TANK WALL TO DISPERSE
C     (EQ A19)
C
      LJ=2.0*RT*((FR-1.0)-(FL(I)*(FR-(1.0/3.0))))+(1.0/3.0))
C
C     LJ WAS CALCULATED ASSUMING THAT THE LIQUID/VAPOR INTERFACE WAS
C     FLAT AFTER REORIENTATION
C
      T5=2.0*((LJ+RT)/VLP)
C
C     DETERMINE MAXIMUM TIME DESCRIBING REORIENTATION PROCESS (EQS A20
C     AND A21)
C
      TT1=T1+T2+T3
      TT2=T4+T5
      IF(TT1.GT.TT2)GO TO 43
```

```
C
C     DETERMINATION OF REQUIRED DELTA V ON TANK (EQ A23)
C
      DELV=AT*TT2
      TTOL=TT2
      GO TO 44
   43 CONTINUE
      DELV=AT*TT1
      TTOL=TT1
   44 CONTINUE
      FLI=100.0*FL(I)
      IF(I.GT.1)GO TO 80
      GO TO 60
   50 CONTINUE
C
C     CALCULATIONS FOR VAPOR BUBBLE DIAMETER LESS THAN TANK DIAMETER
C
      T1=0.0
      T2=0.0
C
C     ASSUME THAT THE VELOCITY AT THE APEX OF THE HEMISPHERE CAN STILL
C     BE DEFINED BY THE WEBER NUMBER CRITERIA
C
      VLP=SQRT((WE*B)/RT)
C
C     FURTHER ASSUME THAT VLPP = 0 SO THAT (EQ A6)
      VLPP=0.0
      AL=(VLP**2.0)/(2.0*RT)
C
C     FLUID COLLECTION TIME TO SETTLE IN BOTTOM OF TANK
C
      VO=SQRT(AL*RT/3.8)
C
C     CALCULATE ULLAGE BUBBLE RADIUS (EQ A16)
C
      RO=0.62035*((VT*(1.0-FL(I)))**0.333333)
C
C     CALCULATE TIME FOR ULLAGE BUBBLE TO MOVE TO OTHER END OF TANK
C     (EQ A18)
C
      T4=5.51*((RT*FR)-RO)/VLP
      GO TO 18
   60 WRITE(6,62)RT
   62 FORMAT(1H1,13HTANK RADIUS =,F6.2,1X,2HCM)
      WRITE(6,63)FR
   63 FORMAT(1H0,21HTANK FINENESS RATIO =,F6.2)
      WRITE(6,64)VT
   64 FORMAT(1H0,13HTANK VOLUME =,F6.2,1X,3HCM3)
      WRITE(6,65)B
   65 FORMAT(1H0,35HSPECIFIC SURFACE TENSION OF FLUID =,F6.2,1X,8HCM3/SE
     *C2)
      WRITE (6,66)WE
   66 FORMAT(1H0,45HWEBER NUMBER CRITERIA TO SUPPRESS GEYSERING =,F6.2)
      WRITE(6,74)
   74 FORMAT(1H0,47HTTOL = TOTAL TEST TIME REQUIRED TO SETTLE FLUID)
      WRITE(6,76)
   76 FORMAT(1H0,10X,6HVOLUME,19X,7HLEADING,3X,5HFLUID)
      WRITE(6,77)
   77 FORMAT(1X,7HPERCENT,3X,6HLIQUID,4X,12HLEADING EDGE,3X,4HEDGE,6X,5H
     *COLL.,8X,26HTIME TO ACHIEVE EACH EVENT,7X,6HSYSTEM)
      WRITE(6,78)
   78 FORMAT(1X,6HLIQUID,4X, 7HIN TANK,3X,12HVEL., CM/SEC,3X,6HACCEL.,4X
     *,4HVEL.,6X,2HT1,4X,2HT2,4X,2HT3,4X,2HT4,4X,2HT5,3X,4HTTOL,3X,6HACC
     *EL.,4X,4HBOND,3X,2HLI,3X,7HDELTA V,4X,2HLJ)
      WRITE(6,79)
   79 FORMAT(1X,7HIN TANK,6X,3HCM3,5X,4HVLPP,4X,3HVLP,3X,7HCM/SEC2,3X,6H
     *CM/SEC,3X,3HSEC,3X,3HSEC,3X,3HSEC,3X,3HSEC,3X,3HSEC,3X,3HSEC,4X,7H
     *CM/SEC2,3X,3HNO.,4X,2HCM,5X,6HCM/SEC,4X,2HCM)
```

```
   80 CONTINUE
      WRITE(6,86)FLI,VL,VLPP,VLP,AL,VO,T1,T2,T3,T4,T5,TTOL,AT,BO,LI,DELV
     *,LJ
   86 FORMAT(1HO,F6.1,F11.2,F8.2,F7.2,F9.2,F10.2,F7.2,5F6.2,F10.2,F7.2,F
     *7.2,F10.2,F6.2)
      IF(I.EQ.N)GO TO 90
      I=I+1
      GO TO 16
   90 CONTINUE
      IF(J.EQ.M)GO TO 96
      J=J+1
      GO TO 5
   96 CONTINUE
      STOP
      END

END OF COMPILATION          NO  DIAGNOSTICS.
```

TANK RADIUS = 3.22 CM

TANK FINENESS RATIO = 2.00

TANK VOLUME =349.62 CM3

SPECIFIC SURFACE TENSION OF FLUID = 28.30 CM3/SEC2

WEBER NUMBER CRITERIA TO SUPPRESS GEYSERING = 3.00

TTOL = TOTAL TEST TIME REQUIRED TO SETTLE FLUID

PERCENT LIQUID IN TANK	VOLUME LIQUID IN TANK CM3	LEADING EDGE VEL., CM/SEC VLPP	LEADING EDGE VEL., CM/SEC VLP	LEADING EDGE ACCEL. CM/SEC2	FLUID COLL. VEL. CM/SEC	TIME TO ACHIEVE EACH EVENT T1 SEC	T2 SEC	T3 SEC	T4 SEC	T5 SEC	TTOL SEC	SYSTEM ACCEL. CM/SEC2	BOND NO.	LI CM	DELTA V CM/SEC	LJ CM
10.0	34.96	4.06	5.13	1.54	1.14	2.64	.70	.00	.94	4.18	5.12	7.35	2.69	5.37	37.67	7.51
20.0	69.92	3.88	5.13	1.75	1.22	2.21	.71	.00	1.76	3.76	5.53	7.63	2.80	4.29	42.17	6.44
30.0	104.89	3.63	5.13	2.05	1.32	1.77	.73	.00	2.45	3.34	5.79	7.98	[illegible]	3.22	46.24	5.37
40.0	139.85	3.25	5.13	2.46	1.44	1.32	.77	.00	2.98	2.93	5.91	8.44	3.09	2.15	49.82	4.29
50.0	174.81	2.57	5.13	3.07	1.61	.88	.84	.00	3.33	2.51	5.84	9.06	3.32	1.07	52.88	3.22
60.0	209.77	.00	5.13	4.09	1.86	.00	.00	.00	3.46	2.09	5.55	10.00	3.66	.00	55.43	2.15
70.0	244.73	.00	5.13	4.09	1.86	.00	.00	.00	3.77	1.67	5.44	10.00	3.66	-1.07	54.41	1.07
80.0	279.70	.00	5.13	4.09	1.86	.00	.00	.00	4.17	1.25	5.42	10.00	3.66	-2.15	54.20	-.00
90.0	314.66	.00	5.13	4.09	1.86	.00	.00	.00	4.73	.84	5.57	10.00	3.66	-3.22	55.67	-1.07

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TANK RADIUS = 3.22 CM

TANK FINENESS RATIO = 2.00

TANK VOLUME =349.62 CM3

SPECIFIC SURFACE TENSION OF FLUID = 28.30 CM3/SEC2

WEBER NUMBER CRITERIA TO SUPPRESS GEYSERING = 4.00

TTOL = TOTAL TEST TIME REQUIRED TO SETTLE FLUID

PERCENT LIQUID IN TANK	VOLUME LIQUID IN TANK CM3	LEADING EDGE VEL., CM/SEC VLPP	VLP	LEADING EDGE ACCEL. CM/SEC2	FLUID COLL. VEL. CM/SEC	TIME TO ACHIEVE EACH EVENT T1 SEC	T2 SEC	T3 SEC	T4 SEC	T5 SEC	TTOL SEC	SYSTEM ACCEL. CM/SEC2	BOND NO.	LI CM	DELTA V CM/SEC	LJ CM
10.0	34.96	4.69	5.93	2.05	1.32	2.29	.61	.00	.82	3.62	4.44	8.00	2.93	5.37	35.51	7.51
20.0	69.92	4.48	5.93	2.34	1.41	1.92	.62	.00	1.53	3.26	4.78	8.31	3.04	4.29	39.74	6.44
30.0	104.89	4.19	5.93	2.73	1.52	1.54	.64	.00	2.12	2.90	5.02	8.72	3.19	3.22	43.73	5.37
40.0	139.85	3.75	5.93	3.28	1.67	1.14	.67	.00	2.58	2.53	5.11	9.25	3.39	2.15	47.32	4.29
50.0	174.81	2.96	5.93	4.09	1.86	.72	.72	.00	2.88	2.17	5.06	9.99	3.66	1.07	50.54	3.22
60.0	209.77	.00	5.93	5.46	2.15	.00	.00	.00	2.99	1.81	4.80	11.14	4.08	.00	53.49	2.15
70.0	244.73	.00	5.93	5.46	2.15	.00	.00	.00	3.27	1.45	4.71	11.14	4.08	-1.07	52.51	1.07
80.0	279.70	.00	5.93	5.46	2.15	.00	.00	.00	3.61	1.09	4.70	11.14	4.08	-2.15	52.30	-.00
90.0	314.66	.00	5.93	5.46	2.15	.00	.00	.00	4.10	.72	4.82	11.14	4.08	-3.22	53.73	-1.07

TANK RADIUS = 3.22 CM

TANK FINENESS RATIO = 2.00

TANK VOLUME =349.62 CM3

SPECIFIC SURFACE TENSION OF FLUID = 28.30 CM3/SEC2

WEBER NUMBER CRITERIA TO SUPPRESS GEYSERING = 5.00

TTOL = TOTAL TEST TIME REQUIRED TO SETTLE FLUID

PERCENT LIQUID IN TANK	VOLUME LIQUID IN TANK CM3	LEADING EDGE VEL., CM/SEC VLPP	VLP	LEADING EDGE ACCEL. CM/SEC2	FLUID COLL. VEL. CM/SEC	TIME TO ACHIEVE EACH EVENT T1 SEC	T2 SEC	T3 SEC	T4 SEC	T5 SEC	TTOL SEC	SYSTEM ACCEL. CM/SEC2	BOND NO.	LI CM	DELTA V CM/SEC	LJ CM
10.0	34.96	5.24	6.63	2.56	1.47	2.05	.54	.88	.73	3.24	3.97	8.57	3.14	5.37	34.00	7.51
20.0	69.92	5.01	6.63	2.92	1.57	1.71	.55	.92	1.37	2.91	4.28	8.91	3.27	4.29	38.15	6.44
30.0	104.89	4.69	6.63	3.41	1.70	1.37	.57	.96	1.90	2.59	4.49	9.38	3.44	3.22	42.09	5.37
40.0	139.85	4.19	6.63	4.09	1.86	1.02	.60	1.03	2.31	2.27	4.57	9.99	3.66	2.15	45.72	4.29
50.0	174.81	3.31	6.63	5.12	2.08	.65	.65	1.11	2.58	1.94	4.52	10.86	3.98	1.07	49.12	3.22
60.0	209.77	.00	6.63	6.82	2.40	.00	.00	1.25	2.68	1.62	4.30	12.22	4.48	.00	52.49	2.15
70.0	244.73	.00	6.63	6.82	2.40	.00	.00	1.25	2.92	1.30	4.22	12.22	4.48	-1.07	51.52	1.07
80.0	279.70	.00	6.63	6.82	2.40	.00	.00	1.25	3.23	.97	4.20	12.22	4.48	-2.15	51.32	-.00
90.0	314.66	.00	6.63	6.82	2.40	.00	.00	1.25	3.67	.65	4.31	12.22	4.48	-3.22	52.72	-1.07

ORIGINAL PAGE IS OF POOR QUALITY

TANK RADIUS = 3.22 CM

TANK FINENESS RATIO = 2.00

TANK VOLUME =349.62 CM3

SPECIFIC SURFACE TENSION OF FLUID = 28.30 CM3/SEC2

WEBER NUMBER CRITERIA TO SUPPRESS GEYSERING = 6.00

TTOL = TOTAL TEST TIME REQUIRED TO SETTLE FLUID

PERCENT LIQUID IN TANK	VOLUME LIQUID IN TANK CM3	LEADING EDGE VEL., CM/SEC VLPP	LEADING EDGE VEL., CM/SEC VLP	LEADING EDGE ACCEL. CM/SEC2	FLUID COLL. VEL. CM/SEC	TIME TO ACHIEVE EACH EVENT T1 SEC	T2 SEC	T3 SEC	T4 SEC	T5 SEC	TTOL SEC	SYSTEM ACCEL. CM/SEC2	BOND NO.	LI CM	DELTA V CM/SEC	LJ CM
10.0	34.96	5.74	7.26	3.07	1.61	1.87	.50	1.12	.67	2.96	3.62	9.08	3.33	5.37	32.91	7.51
20.0	69.92	5.49	7.26	3.51	1.72	1.56	.51	1.17	1.25	2.66	3.91	9.47	3.47	4.29	37.00	6.44
30.0	104.89	5.13	7.26	4.09	1.86	1.25	.52	1.23	1.73	2.36	4.10	9.99	3.66	3.22	40.93	5.37
40.0	139.85	4.59	7.26	4.91	2.04	.93	.54	1.32	2.11	2.07	4.18	10.69	3.92	2.15	44.64	4.29
50.0	174.81	3.63	7.26	6.14	2.28	.59	.59	1.44	2.36	1.77	4.13	11.68	4.28	1.07	48.24	3.22
60.0	209.77	.00	7.26	8.19	2.63	.00	.00	1.64	2.44	1.48	3.92	13.27	4.86	.00	52.05	2.15
70.0	244.73	.00	7.26	8.19	2.63	.00	.00	1.64	2.67	1.18	3.85	13.27	4.86	-1.07	51.09	1.07
80.0	279.70	.00	7.26	8.19	2.63	.00	.00	1.64	2.95	.89	3.83	13.27	4.86	-2.15	50.89	-.00
90.0	314.66	.00	7.26	8.19	2.63	.00	.00	1.64	3.35	.59	3.94	13.27	4.86	-3.22	52.28	-1.07

@FIN

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TABLE I. - PROPERTIES OF TEST LIQUIDS

Liquid	Density at 20° C (ρ), g/cm^3	Surface tension at 20° C (σ), dynes/cm	Specific surface tension (β), cm^3/sec^2
Trichlorotrifluoroethane	1.58	18.6	11.8
Carbon tetrachloride	1.59	26.8	16.8
Ethanol, anhydrous	.789	22.3	28.3
Methanol	.793	22.6	28.5
Ethanol, 20 percent[a]	.973	39.8	40.9

[a]Composition by volume with distilled water.

TABLE II. - SUMMARY OF TEST CONDITIONS FOR THE CYLINDRICAL TANK CONFIGURATIONS

Test	Tank radius (R), cm	Fineness ratio (FR)	Test fluid	Specific surface tension (β), cm^3/sec^2	Fill level (FL)	Tank acceleration (a_T), cm/sec^2	Bond number (Bo)
1	1.65	4	Trichlorotrifluoroethane	11.8	0.71	16.7	3.9
2	↓	↓	Trichlorotrifluoroethane	11.8	.83	16.7	3.9
3			Ethanol, anhydrous	28.3	.81	36.3	3.5
4			Ethanol, 20 percent[a]	40.9	.72	45.1	3.0
5	2.0	2.25	Ethanol, anhydrous	28.3	.62	29.4	4.2
6	↓	↓	Ethanol, anhydrous	28.3	.29	29.4	4.2
7			Methanol	28.5	.51	29.4	4.1
8			Methanol	28.5	.33	29.4	4.1
9			Carbon tetrachloride	16.8	.38	16.7	4.0
10			Trichlorotrifluoroethane	11.8	.77	11.8	4.0
11			Trichlorotrifluoroethane	11.8	.45	11.8	4.0
12	3.22	2.14	Ethanol, anhydrous	28.3	.71	10.8	4.0
13	↓	↓	Ethanol, anhydrous	28.3	.45	10.8	4.0
14			Carbon tetrachloride	16.8	.39	10.8	6.7
15			Carbon tetrachloride	16.8	.67	10.8	6.7

[a]Composition by volume with distilled water.

TABLE III. - COMPARISON OF MEASURED TEST RESULTS WITH CALCULATED RESULTS FOR CYLINDRICAL TANK CONFIGURATIONS

Test	Applied Bond number, Bo	Measured leading edge conditions			Calculated test conditions		Calculated leading edge conditions		Calculated Bond number, Bo	Time required for fluid motion, sec										Remarks
										t_1		t_2		t_3		t_4		t_5		
		l_i, cm	V_L, cm sec	a_L, cm sec^2	V_L, cm sec	We	l_i, cm	a_L, cm sec^2		meas.	calc.	meas.	calc.	meas.	calc.	meas.	calc.	meas.	calc.	
1	3.9	1.25	3.09	7.65	5.90	4.87	1.31	5.89	3.55	0.52	0.[illegible]	0.20	0.34	0.53	0.55	----	5.37	-----	1.38	Small geyser
2	3.9	-.2	----	7.65	4.65	3.02	-.14	6.54	3.67	0	0	.42	0	-----	----	----	5.92	-----	1.12	No geyser
3	3.5	.05	1.55	13.7	6.90	2.78	.10	13.6	3.50	.24	.12	.30	.3	-----	----	----	4.03	-----	.82	No geyser
4	3.0	1.15	7.36	13.0	9.85	3.91	1.19	17.1	3.34	.44	.37	.18	[illegible]	-----	----	----	3.20	-----	.80	No geyser
5	4.2	.02	2.30	13.5	7.7	4.19	.25	13.2	3.97	.17	.19	.4[illegible]	.39	.47	.46	----	1.80	-----	.92	Small geyser
6	4.2	2.8	8.85	13.5	11.5	9.35	2.78	13.9	4.06	0.74	0.63	0.21	0.20	>0.72	1.04	0.76	0.82	>0.90	1.06	Large geyser
7	4.1	.5	5.43	13.6	9.16	5.89	1.09	13.[illegible]	4.00	.34	.40	[illegible]	.27	.73	.64	1.23	1.46	-----	.96	Moderate geyser
8	4.1	2.5	9.47	13.6	12.0	10.1	2.47	16.1	4.29	.60	.55	[illegible]	.19	.75	1.18	.70	.87	.85	.96	Large geyser
9	4.0	1.9	7.52	7.7	9.35	10.4	2.09	10.[illegible]	4.51	[illegible]	.62	.33	.25	.55	1.67	1.11	1.23	>.24	1.16	Large geyser
10	4.0	-.9	----	5.4	3.3	1.85	-.90	2[illegible]	3.13	----	0	.45	[illegible]	----	----	----	4.60	-----	1.48	No geyser
11	4.0	1.6	4.54	5.4	6.5	7.16	1.55	95	4.09	-	0.72	0.45	0.37	>0.50	1.25	1.65	1.95	-----	1.50	Large geyser
12	4.0	-.7	----	5.1	3.96	1.78	-.92	45	3.09	-	0	.50	0	-----	----	----	5.46	-----	2.24	No geyser
13	4.0	2.3	3.17	5.1	6.55	4.88	2.11	4.03	3.65	.75	1.02	.70	.60	-----	1.00	----	2.83	-----	2.28	Insufficient time
14	6.7	3.2	6.49	8.65	9.89	18.7	2.80	8.10	6.49	.75	.83	.38	.39	>.47	8.82	1.60	1.73	-----	1.66	Large geyser
15	6.7	.5	-----	8.65	6.96	9.29	-.45	7.53	6.15	.05	0	.61	0	>.94	4.16	----	3.00	-----	1.42	Large geyser

TABLE IV. - REORIENTATION TIME AND TANK ACCELERATION REQUIRED FOR LIQUID REORIENTATION WITH MINIMUM VELOCITY INCREMENT

[R_T = 3.22 cm; FR = 2.0; β = 11.8 cm^3/sec^2.]

Fill level, (FL)	Time required for each phase of reorientation, sec					Reorientation time (t_t), sec	Tank acceleration (a_T), cm/sec^2	Bond number (Bo)	Minimum velocity increment (ΔV), cm/sec	Weber number (We)
	t_1	t_2	t_3	t_4	t_5					
0.10	2.78	0.74	1.92	0.99	4.40	[a]5.44	3.88	3.41	21.1	6.5
.20	2.17	.70	2.44	1.72	3.69	[b]5.41	4.27	3.75	23.1	7.5
.30	1.68	.70	2.83	2.32	3.17	[b]5.49	4.64	4.08	25.5	8
.40	1.22	.71	3.33	2.74	2.69	[b]5.43	5.14	4.52	27.9	8.5
.50	.77	.77	3.69	3.06	2.31	[b]5.37	5.70	5.01	30.6	8.5
.60	.00	.00	2.85	3.64	2.20	[b]5.84	5.75	5.06	33.6	6.5
.70	.00	.00	↓	3.97	1.76	[b]5.73	↓	↓	32.9	↓
.80	.00	.00	↓	4.39	1.32	[b]5.71	↓	↓	32.8	↓
.90	.00	.00	↓	4.98	.88	[b]5.86	↓	↓	33.7	↓

[a] $t_t = t_1 + t_2 + t_3$.

[b] $t_t = t_4 + t_5$.

TABLE V. - REORIENTATION TIME AND TANK ACCELERATION REQUIRED FOR LIQUID REORIENTATION WITH MINIMUM VELOCITY INCREMENT

[R_T = 200 cm; FR = 2.0; $\beta = 17.6\ cm^3/sec^2$.]

Fill level, (FL)	Time required for each phase of reorientation, min					Reorientation time (t_t), min	Tank acceleration (a_T), cm/sec^2	Bond number (Bo)	Minimum velocity increment (ΔV), cm/sec	Weber number (We)
	t_1	t_2	t_3	t_4	t_5					
0.10	18.6	4.9	12.9	6.6	29.4	[a]36.4	0.00150	3.42	3.28	6.5
.20	14.5	4.7	16.3	11.5	24.6	[b]36.1	.00165	3.75	3.58	7.5
.30	11.2	4.7	18.9	15.5	21.2	[b]36.7	.00180	4.08	3.95	8
.40	8.1	4.7	22.3	18.3	18.0	[b]36.3	.00199	4.52	4.32	8.5
.50	5.1	5.1	25.7	20.5	15.4	[b]35.9	.00220	5.01	4.74	8.5
.60	0.0	0.0	19.1	24.3	14.7	[b]39.0	.00220	5.05	5.20	6.5
.70	↓	↓	↓	26.5	11.8	[b]38.3	↓	↓	5.11	↓
.80				29.3	8.8	[b]38.1			5.09	
.90				33.3	5.9	[b]39.2			5.23	

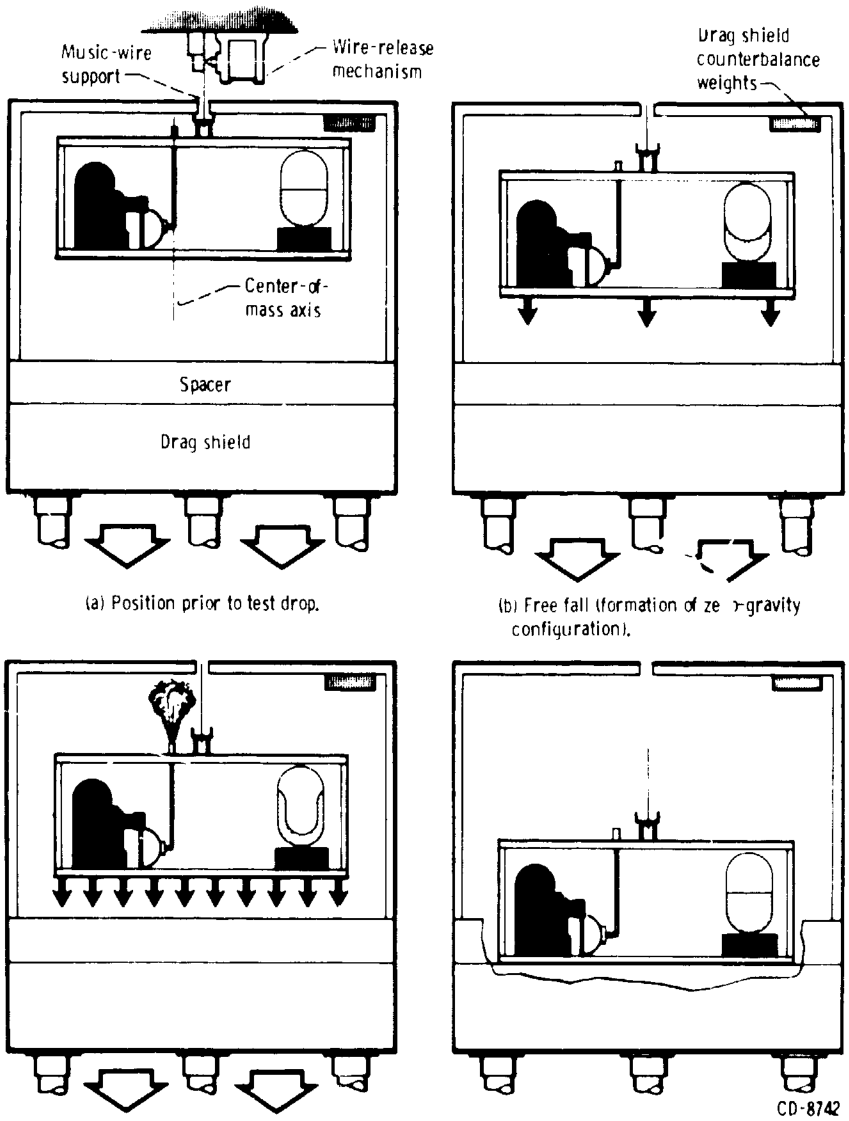
[a] $t_t = t_1 + t_2 + t_3$.
[b] $t_t = t_4 + t_5$.

TABLE VI. - SUMMARY OF TEST CONDITIONS FOR INITIALLY CURVED LIQUID/VAPOR INTERFACE IN SPHERICAL TANK

Run	Tank radius (R_T), cm	Liquid	Fill level (FL)	Specific surface tension (β), cm^3/sec^2	Bond number (Bo)	Geyser formation
1	3.00	Ethanol	0.40	28.3	3.1	None
2					↓	None
3			↓		6.2	Small
4			.50		3.1	None
5	↓				6.2	Small
6	3.06	↓		↓	9.7	Moderate
7		Freon TF	↓	11.8	23.3	Severe
8		Ethanol	.60	28.3	3.2	None
9					↓	None
10			↓		6.5	Small
11			.70		3.2	None
12			↓		6.5	None
13			.80		3.2	None
14	↓		↓		6.5	None
15	2.62		.40		2.38	None
16	2.59		↓		4.65	None
17			.50		2.32	None
18	↓		↓		4.65	None
19	2.43		.40		2.04	None
20			.50		↓	None
21			↓		4.09	None
22			.60		2.04	None
23	↓	↓	↓	↓	↓	None

TABLE VII. - SUMMARY OF TEST CONDITIONS FOR INITIALLY FLAT LIQUID/VAPOR INTERFACE IN SPHERICAL TANK

Run	Tank radius (R_T), cm	Liquid	Fill level (FL)	Specific surface tension (β), cm^3/sec^2	Bond number (Bo)	Geyser formation
1	3.06	Ethanol	0.30	28.3	1.62	None
2					3.24	None
3					4.86	Small
4					6.49	Moderate
5			.40		1.62	None
6					3.24	None
7					4.86	Small
8					6.49	Small
9			.50		1.62	None
10					3.24	None
11					4.86	None
12					8.11	Moderate
13					6.49	Small
14	2.12		.30		1.56	None
15			.40			None
16			.50			None
17			.60			None
18			.70			None
19	3.06	Freon TF	.50	11.8	23.3	Severe



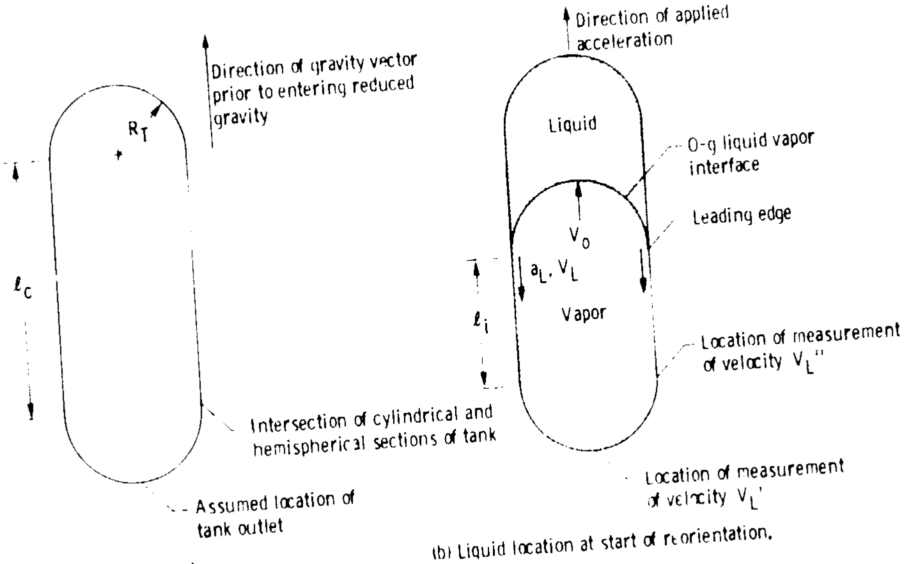
(a) Position prior to test drop.

(b) Free fall (formation of ze r-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.



(a) Tank geometry.

(b) Liquid location at start of reorientation.

Figure 2. - Definition of tank geometry and liquid location.

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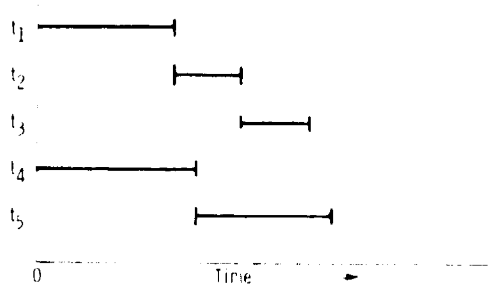


t_1 time for liquid leading edge to reach cylindrical-hemi-spherical intersection.

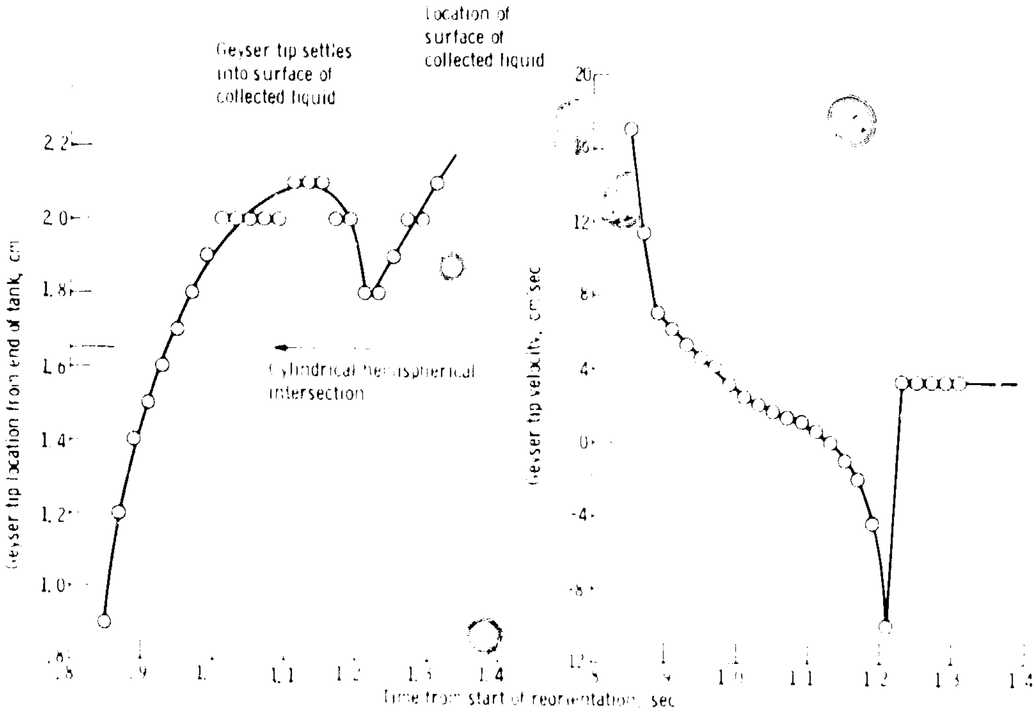
t_2 time for liquid leading edge to continue from cylindrical-hemispherical intersection to bottom of tank.

t_3 time for geyser to form and dissipate into collected liquid

t_4 time for ullage bubble to reach top of tank.

t_5 time for liquid film to clear from tank wall

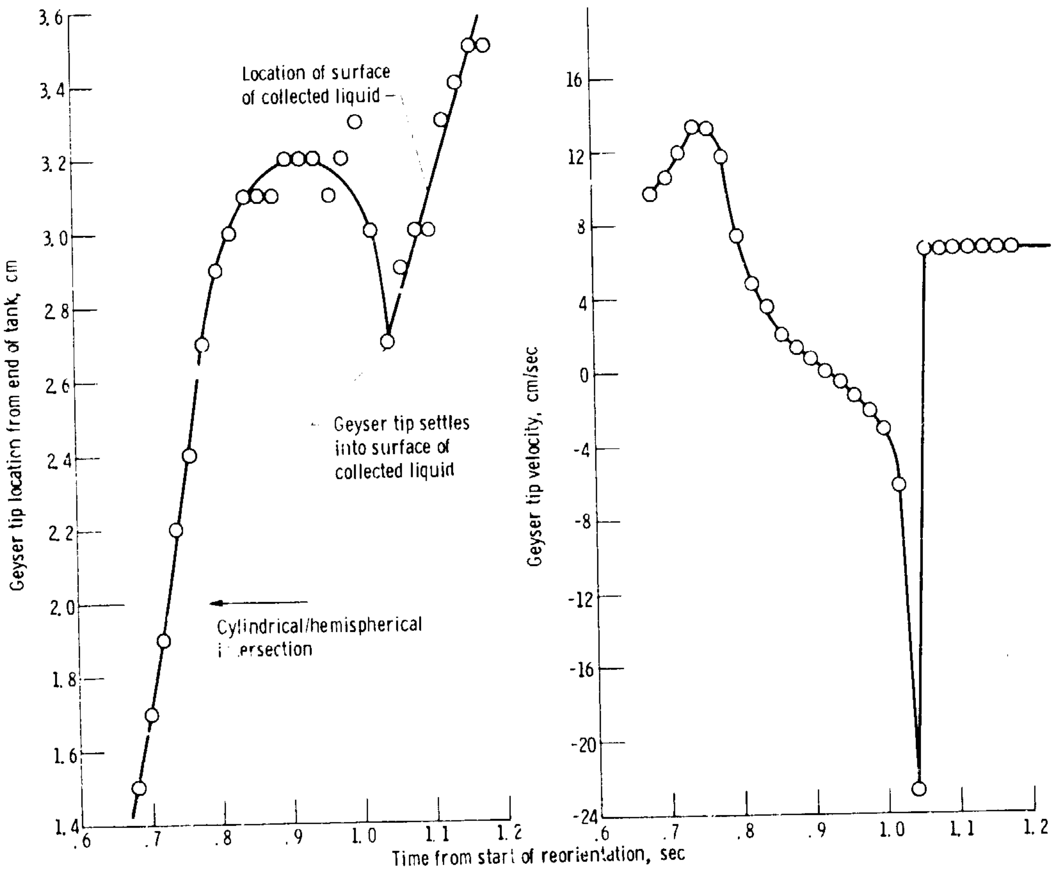
Figure 3. - Sequence of events for determining time required to complete liquid reorientation process.



(a) Geyser tip location.

(b) Geyser tip velocity.

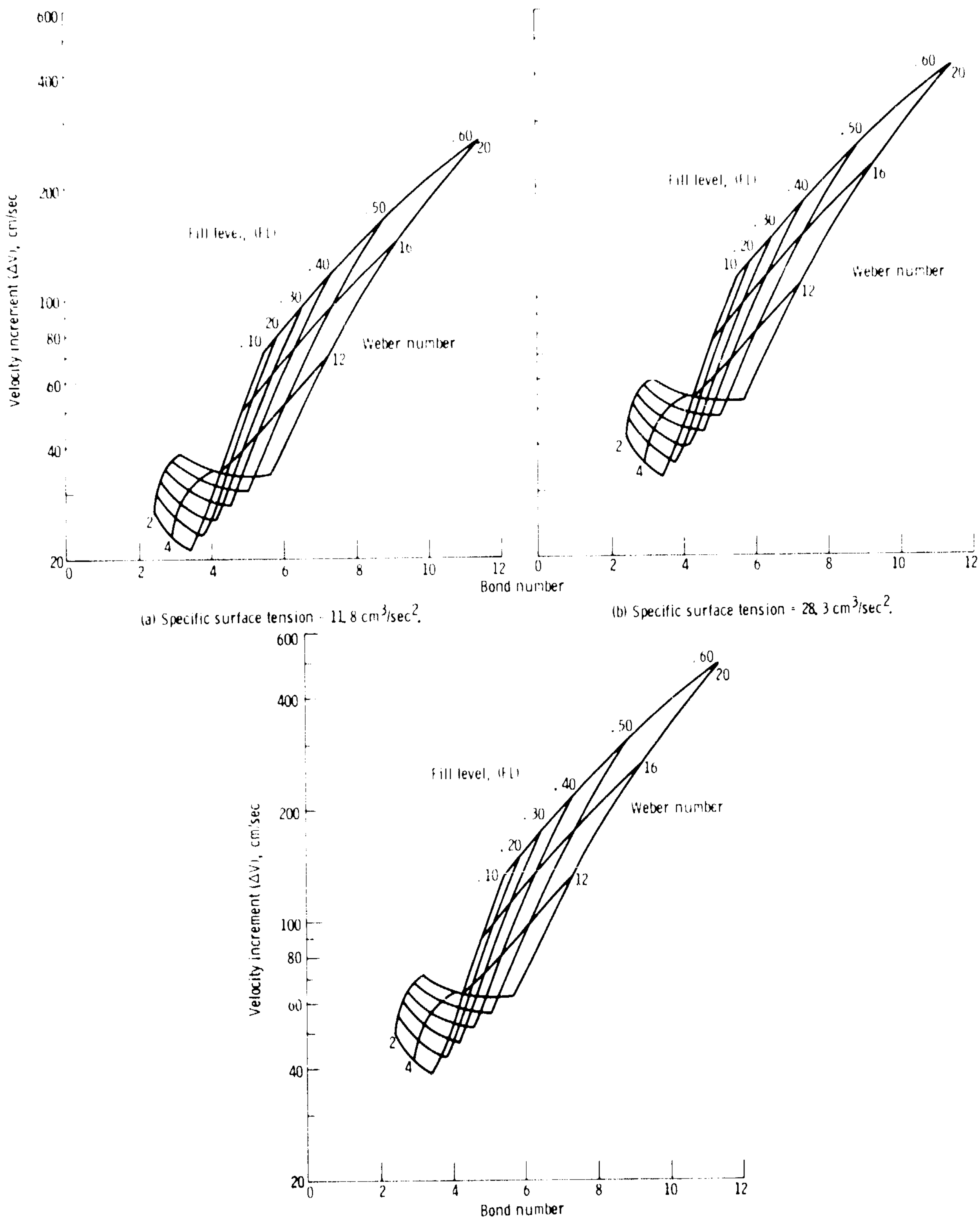
Figure 8. - Geyser characteristics - test 1, [illegible] 11.8 cm^3/sec^2, Bo = 3.9



(a) Geyser tip location.

(b) Geyser tip velocity.

Figure 5. - Geyser characteristics - test 5, R_T = 2.0 cm, β = 28.3 cm^3/sec^2, Bo = 4.2.



(a) Specific surface tension = 11.8 cm^3/sec^2.

(b) Specific surface tension = 28.3 cm^3/sec^2.

(c) Specific surface tension = 40.9 cm^3/sec^2.

Figure 6. - Velocity increment required to reorient liquid as a function of Bond number and fill level; tank radius = 3.22 cm, fineness ratio = 2.0.

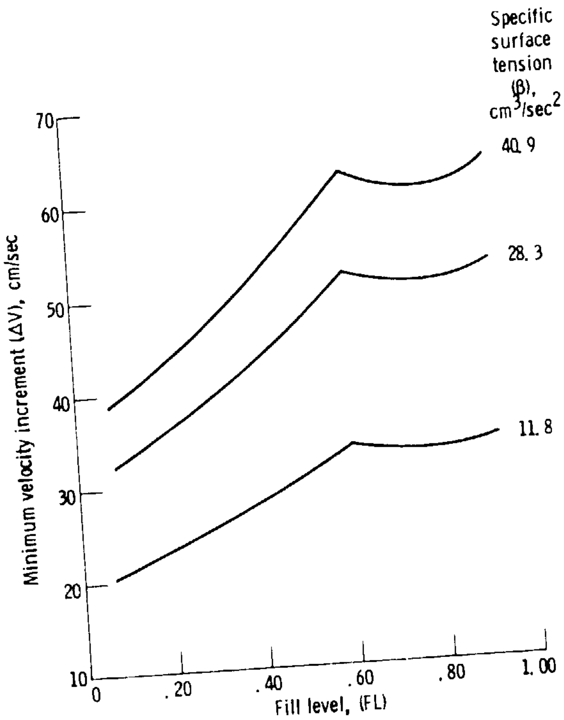


Figure 7. - Minimum velocity increment required to reorient liquids with varying specific surface tension; tank radius = 3.22 cm, fineness ratio = 2.0.

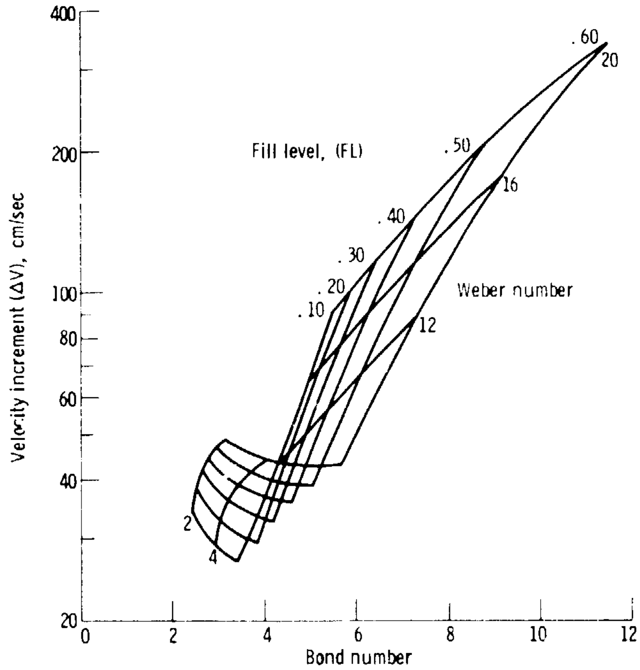


Figure 8. - Velocity increment required to reorient liquid as a function of Bond number and fill level; tank radius = 2.0 cm, fineness ratio = 2.0, specific surface tension = 11.8 cm^3/sec^2.

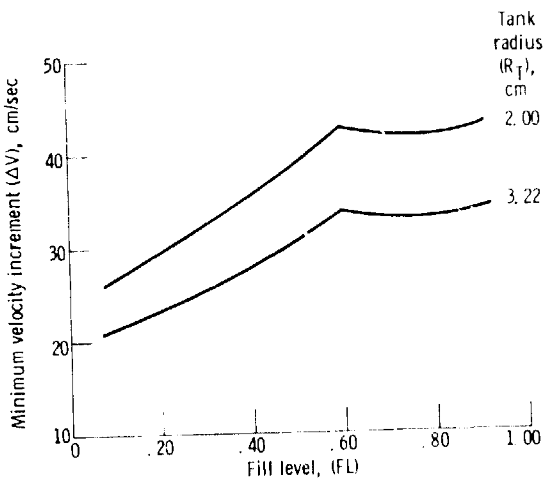
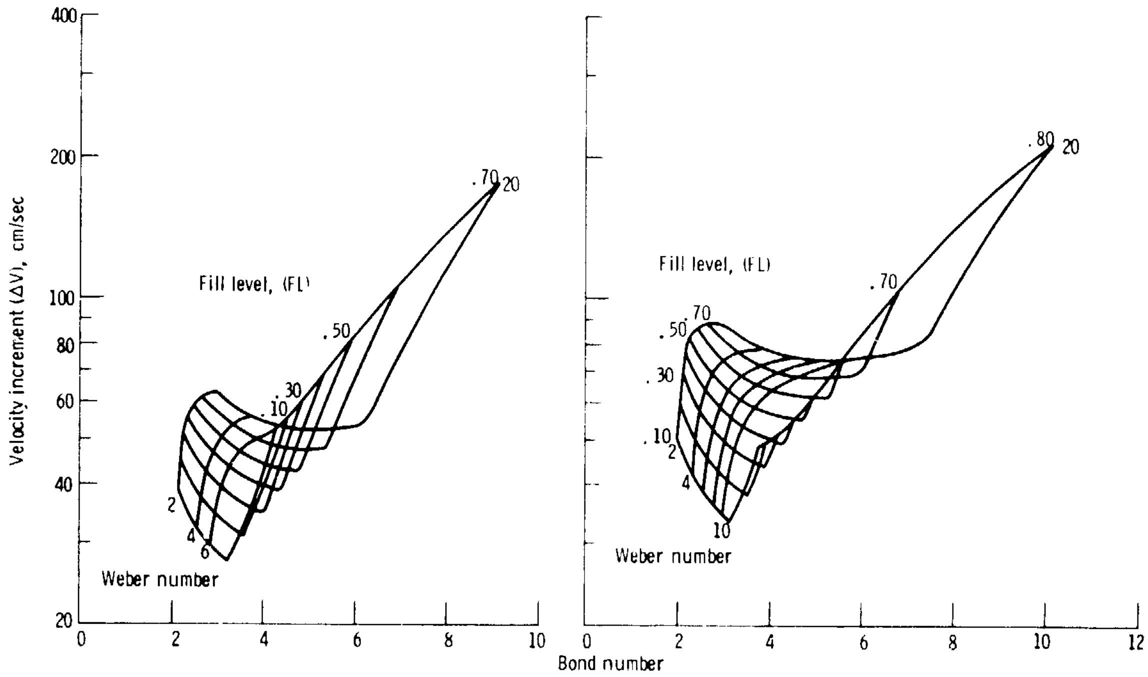


Figure 9. - Minimum velocity increment required to reorient liquid for varying fill level and tank radius; specific surface tension = 11.8 cm^3/sec^2, fineness ratio = 2.0.



(a) Fineness ratio = 3.0.

(b) Fineness ratio = 4.0.

Figure 10. - Velocity increment required to reorient liquid as a function of Bond number and fill level; tank radius = 3.22 cm, specific surface tension = 11.8 cm^3/sec^2.

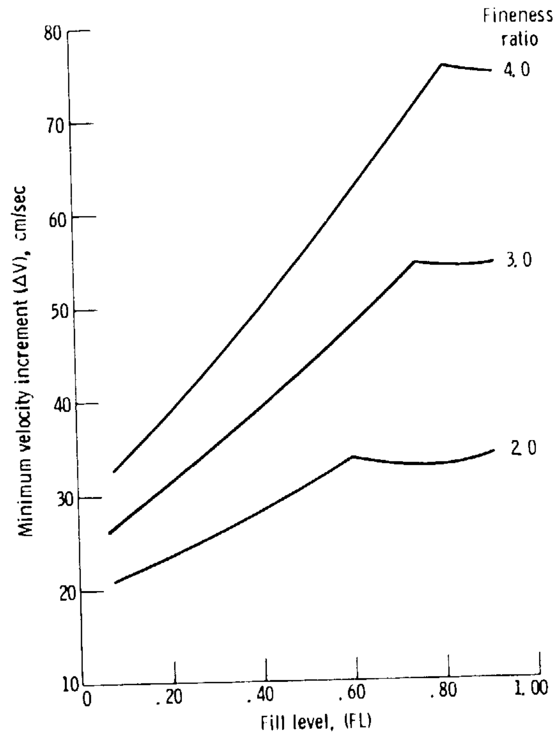


Figure 11. - Minimum velocity increment required to reorient liquid; tank radius = 3.22 cm, specific surface tension = 11.8 cm^3/sec^2.

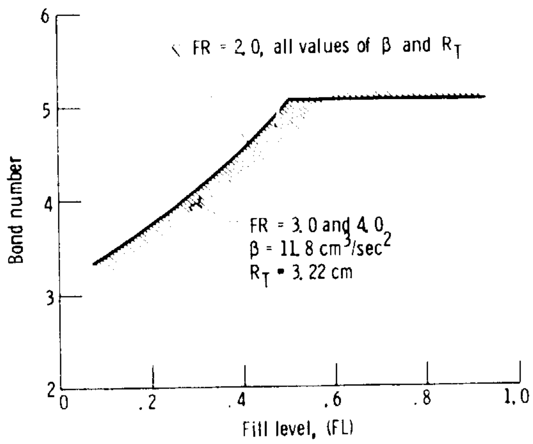


Figure 12. - Bond number required for minimum velocity increment.

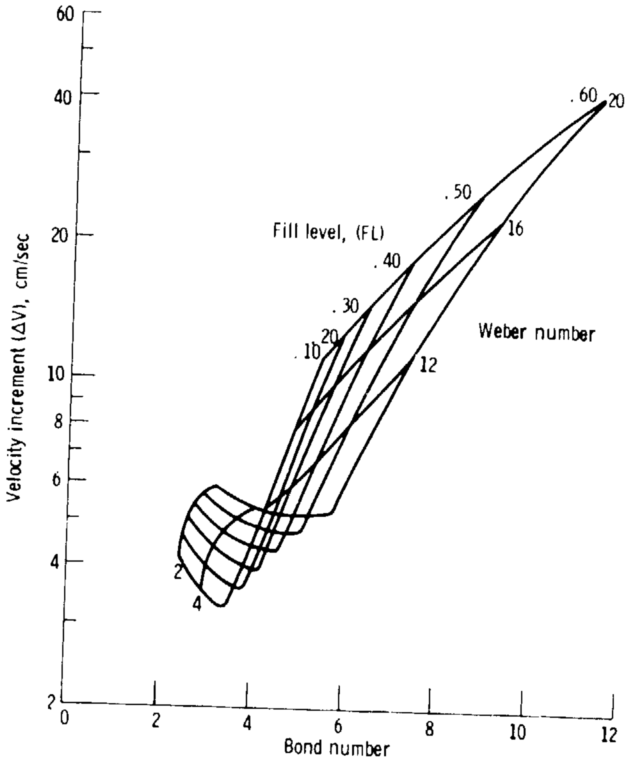


Figure 13. - Velocity increment required to reorient liquid hydrogen in a cylindrical propellant tank having a radius of 200 cm and a fineness ratio of 2.0, specific surface tension = 17.6 cm^3/sec^2.

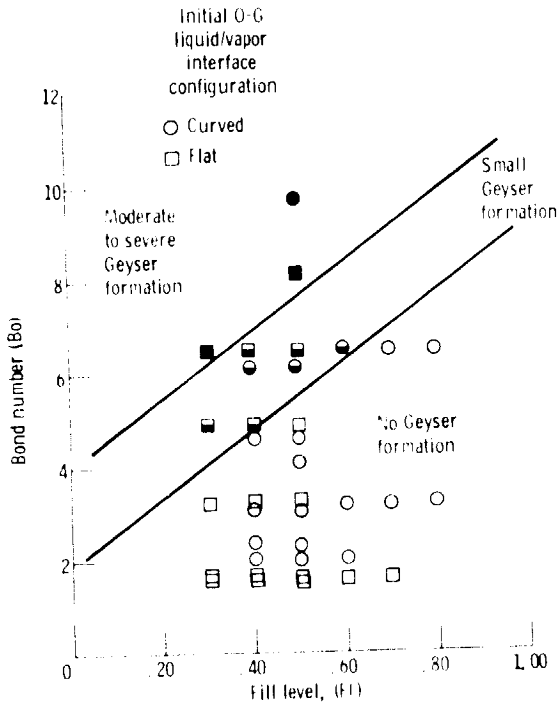


Figure 14. - Bond number criteria for which Geyser formation occurred in spherical tanks.

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15. Supplementary Notes

16. Abstract

An existing empirical analysis relating to the reorientation of liquids in cylindrical tanks due to propulsive settling in a low-gravity environment was extended to include the effects of geyser formation in the Weber number range from 4 to 10. Predicted liquid reorientation times and liquid leading edge conditions compared favorably with experimental results obtained from previously unpublished data. Estimates of the minimum velocity increment required to be imposed on the propellant tank to achieve liquid reorientation were made. The resulting Bond numbers, based on tank radius, were found to be in the range from 3 to 5, depending upon the initial liquid fill level, with higher Bond numbers required for higher initial fill levels. The resulting Weber numbers, based on tank radius and the velocity of the liquid leading edge, were calculated to be in the range from 6.5 to 8.5 for cylindrical tanks having a fineness ratio of 2.0, with Weber numbers of somewhat greater values for longer cylindrical tanks. It therefore appeared to be advantageous to allow small geysers to form and then dissipate into the surface of the collected liquid in order to achieve the minimum velocity increment. The Bond numbers which defined the separation between regions in which geyser formation did and did not occur due to propulsive settling in a spherical tank configuration ranged from 2 to 9 depending upon the liquid fill level.

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