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LOW-G FLUID BEHAVIOR TECHNOLOGY SUMMARIES

December 1974

By
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16. Abstract

This report presents a summarization and categorization of the pertinent literature associated with low-g fluid behavior technology. Initially a literature search was conducted to obtain pertinent documents for review. Reports determined to be of primary significance were summarized in detail. Each summary, where applicable, consists of; (1) report identification, (2) objective(s) of the work, (3) description of pertinent work performed, (4) major results, and (5) comments of the reviewer (GD/C). Pertinent figures are presented on a single facing page separate from the text. Specific areas covered are; interface configuration, interface stability, natural frequency and damping, liquid reorientation, bubbles and droplets, fluid inflow, fluid outflow, convection, boiling and condensation heat transfer, venting effects, and fluid properties. Reports which were reviewed and not summarized, along with reasons for not summarizing, are also listed. Cryogenic thermal control and fluid management systems technology are presented in companion reports (NASA CR-134747 and NASA CR-134748) under this same contract.

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FOREWORD

This report was prepared by the Convair Aerospace Division of General Dynamics Corporation in partial fulfillment of Contract NAS3-17814. The contract was administered by the Lewis Research Center of the National Aeronautics Space Administration, Cleveland, Ohio. The NASA Project Manager was Mr. John C. Aydelott.

A summarization and categorization is presented of the pertinent literature associated with low-gravity fluid behavior technology. Cryogenic thermal control and fluid management systems technology summaries are presented in companion reports under this same contract.

In addition to the project manager, Mr. John A. Stark, a listing of the Convair personnel which contributed to the preparation of this report, along with their primary areas of responsibility, is presented below.

R. D. Bradshaw	-	Interface Configuration, Interface Stability, Natural Frequency and Damping, Bubbles and Droplets and Fluid Inflow.
M. H. Blatt	-	Liquid Reorientation and Fluid Outflow
J. A. Stark	-	Convection, Boiling and Condensation Heat Transfer, Venting Effects and Fluid Properties

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1.0 INTRODUCTION

This report presents a summarization and categorization of the pertinent literature associated with low-g fluid behavior technology.

The initial task was to conduct a literature search to obtain pertinent documents for review. The following sources formed the primary basis for this search.

a. Convair Library and Cryogenic Group files.

b. "Bibliography of References - Space Storage of Cryogenic Propellants," (Report B-777) prepared by the Cryogenic Data Center, NBS, covering the period 10 June 1974 back through 1959.

c. NASA-computer tape search for the period 30 September 1974 back through 1969. Key words used in this search are presented in Appendix C.

d. "The Literature of Low-G Propellant Behavior," by Bowman (NAS9-8939, September 1969) and "The Literature of Low-G Propellant Behavior," by Hastings, et al (NAS9-5174, September 1966). These two documents together cover the period August 1969 back through 1959.

e. Defense Documentation Center (DDC) search of the unclassified literature for the period 3 June 1974 back through 1969.

f. Secondary sources from reports reviewed.

Reports which were determined to be of primary significance are summarized in Sections 2 through 13. Each summary, where applicable, consists of; (1) report title, author(s), organization doing the work, identifying numbers and date, (2) objective(s) of the work, (3) description of pertinent work performed, (4) major results, and (5) comments. The thoughts expressed by the objective, pertinent work performed, and major results sections are those of the author. The thoughts of the reviewer (GD/C) are presented in the comments section. Pertinent figures are presented on a single facing page separate from the text. Units used in the summaries are those from the basic report; i.e., dual units were only used if they were in the report being summarized. Where a reference is cited within the summary, the author(s) and date were used in place of reference number. Uncommon abbreviations, acronyms and nomenclature are defined in the individual summaries, while general definitions and nomenclature are presented in Appendix D.

The summaries are organized by category and date with the most current appearing first. Also, a listing of all summarized reports alphabetically by author is presented in Appendix A.

The categories into which the summaries are divided are listed below, along with a brief description of the work covered in each.

a. Interface Configuration - covering analyses and experimental data for interface geometries and relaxation times and effects of rotational fields.

b. Interface Stability- covering liquid surface response and stability for changes in longitudinal and lateral acceleration, vehicle vibration, and rotational fields, including effects of surface tension interaction and gas flow effects on liquid surfaces.

c. Natural Frequency and Damping - covering lateral and longitudinal sloshing, slosh waves and tank elasticity effects, and slosh suppression by baffles and viscous damping.

d. Liquid Reorientation - covering fluid motion and collection caused by impulsive and sustained settling accelerations.

e. Bubbles and Droplets - covering bubble growth and coalescence, low-g shape, and motion of bubbles and droplets not at a surface.

f. Fluid Inflow - covering tank and baffle geometry and fill-level effects on inlet flow patterns, wall impingement and chilldown.

g. Fluid Outflow - covering draining with and without pullthrough suppression devices and with and without flow throttling.

h. Convection Heat Transfer - covering free and forced convection in single phase fluids including supercritical fluids.

i. Boiling Heat Transfer - covering transition, nucleate, peak, minimum and film boiling, including transient and steady state conditions and bubble dynamics and other characteristics associated with boiling at a solid surface. Both pool and forced flow boiling are considered.

j. Condensation Heat Transfer - covering dropwise and film condensation at liquid and solid surfaces.

k. Venting Effects - covering bulk and surface vapor generation affecting liquid level rise and vent liquid loss and fluid freezing and vehicle dynamics caused by tank venting or leakage.

l. Fluid Properties - covering fluid properties which may be influenced by a reduction in gravity.

It is noted that, though the basic literature analysis was designed to completely cover the above areas, a complete set of literature worthy of summarization was not always found.

Reports which were reviewed and not summarized, along with reasons for not summarizing, are listed in Appendix B. The following ground rules were used in selecting specific reports for summarization.

a. The report must have dealt with some aspect of low-g or the effects of variation in gravity level which could be useful in predicting fluid behavior at low-g.

b. Both non-cryogenic and cryogenic applications were considered.

c. The report must have provided data required for current design and/or added something important to the knowledge required to provide a complete picture of the current state-of-the-art.

d. Emphasis was on the most recent work; however, reports were not summarized if they were just a rehash of other work. If they were primarily connected with other work they must have provided useful consolidations, additions or evaluations.

e. Fluid tankage itself and associated structural details were not included.

f. Monthlies, Quarterlies and classified reports were not summarized.

g. Reports which are not generally available were not included, such as symposium papers where only those in attendance may have copies, and internal company documents such as Independent Research and Development (IRAD) Reports.

2.0 INTERFACE CONFIGURATION

Covering analyses and experimental data for interface geometries and relaxation times and effects of rotational fields.

ZERO-GRAVITY LIQUID-VAPOR INTERFACE
CONFIGURATION IN CONICAL TANKS,
Spuckler, C. M., Abdalla, K. L., NASA-LeRC
TM X-2400, September 1971

OBJECTIVE. - To determine reduced-gravity interface configurations for conical tank shapes with different cone angles, fill levels and initial axial orientations to gravity.

PERTINENT WORK PERFORMED. - The test containers used in this study are described in Figure 1. Tests were conducted using anhydrous ethanol with drops in the 5.1 sec tower. Initial configurations for cone axis were 0, 45, 90, 135 and 180°. By varying the fill level, operating conditions were recognized where the walls are entirely wet and also where the walls are only partially wetted. Movie coverage was the prime method of data collection.

MAJOR RESULTS. -

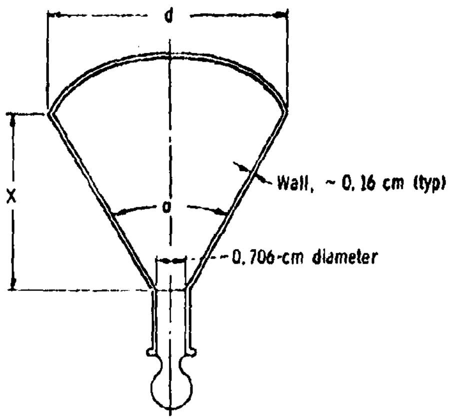
1. In an initial series of tests with 0° orientation (apex down), the fluid configuration and wetted wall conditions were defined as a function of fill level for the range of tank cone angles, see Figure 2. A simple method for a theoretical prediction of wall-wetting which uses a surface of constant curvature is verified in Figure 2. Even when the walls were entirely wet, the bulk of the liquid remained in the apex in this orientation.

2. For the effects of initial orientation, the results for the 39.8° cone angle are typical and are shown in Figure 3. For angles greater than 90° orientation (apex up), the walls were not wetted until larger tank fill levels were used. In the orientation region of 45 to 90°, a decreasing fill-level still resulted in a total enclosed vapor region.

3. The effect of cone angle on the enclosing of the vapor is shown in Figure 4. The curve defined from Figure 3 is shown with other cone angle curves. The results during the 5.1 seconds fluid relaxation indicate a strong sensitivity to initial orientation.

4. At high fill levels the probability for both ends of the tank to be wetted are quite high. This suggests strong involvement with venting and transfer procedures.

COMMENTS. - The results are presented in a highly usable form and leave no immediate questions in this specialized area of investigation.



Frustum height, X, cm	Diameter, d, cm	Tank cone angle, α, deg	Volume, cc
8.56	4.75	26.6	91.8
6.63	5.54	39.8	94.2
5.72	6.19	50.6	92.6
3.81	7.53	81.0	84.5

Figure 1. Conical Tanks

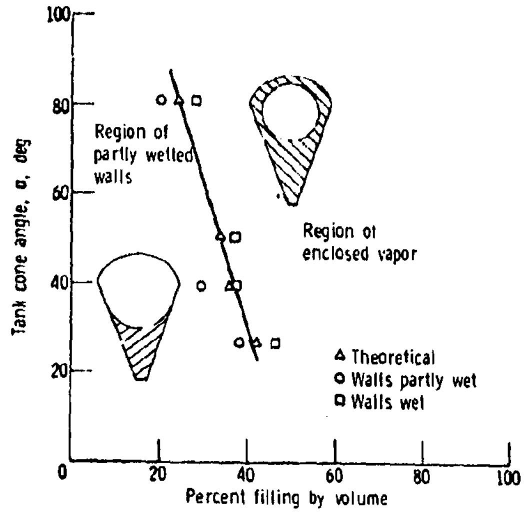


Figure 2. Effect of Cone Angle for Tank Oriented at 0°

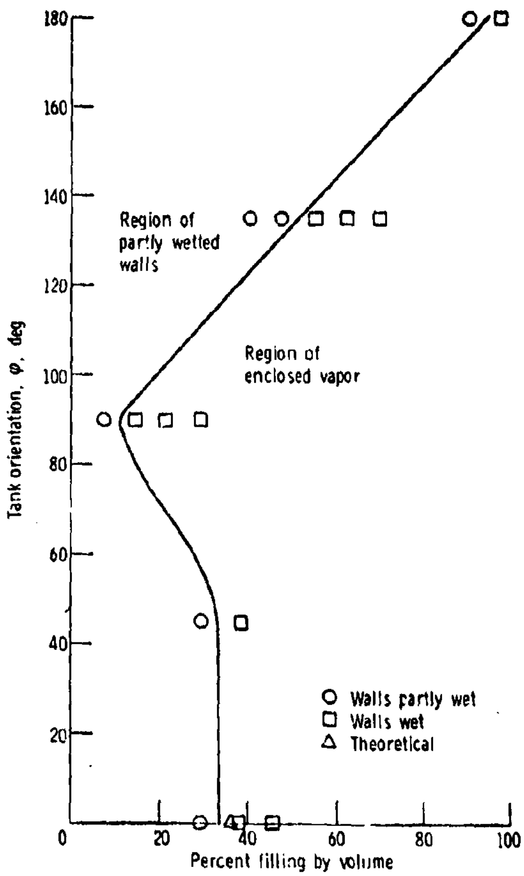


Figure 3. Effect of Orientation for 39.8° Cone Angle Tank

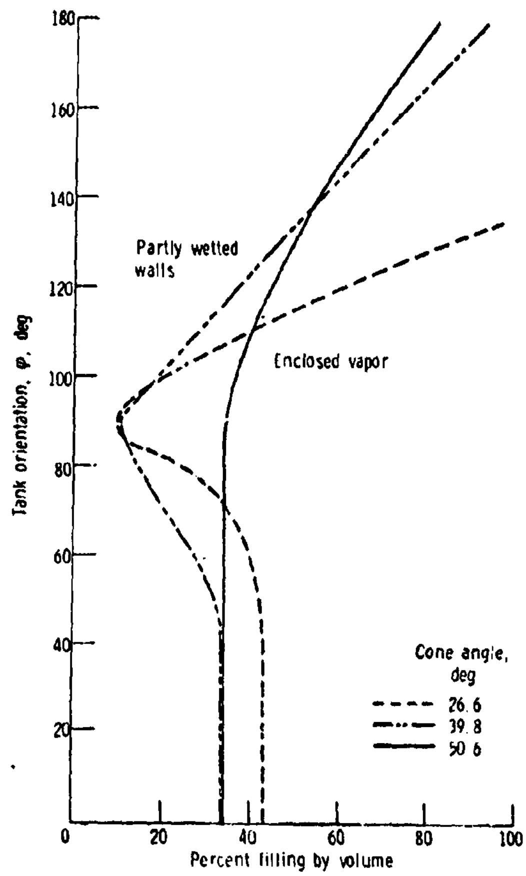


Figure 4. Effect of Orientation

ZERO-GRAVITY EQUILIBRIUM CONFIGURATION
OF LIQUID-VAPOR INTERFACE IN TOROIDAL TANKS
Symons, E.P., NASA-LeRC, TN D-6076, Nov. 1970

OBJECTIVE. - To determine the liquid-vapor interface configuration in toroidal tanks for various tank proportions, fill levels, and tank mounting angles for a zero static contact-angle fluid in reduced gravity.

PERTINENT WORK PERFORMED. - A series of 5.1 sec drop tower tests were conducted to extend earlier work in a shorter drop tower. Four experimental toroidal tanks of cast acrylic plastic with major radii ot 8, 4, 3, and 2 cm and minor radii of 4, 2, 1 and 1 cm were used. Geometry is indicated in Figure 1. The test fluid was anhydrous ethanol. A significant effort was directed toward the effect of mounting angle, an initial configuration variable. Results are presented which describe the expected static equilibrium interface shape.

MAJOR RESULTS. -

1. The interface configuration for tanks initially mounted at 0° mounting angle is characterized by large vapor bubbles over a large range of liquid fill levels in Figure 2. At fill levels below approximately 20%, a toroidal vapor bubble forms near the inner axis. This behavior is observed at higher fill levels in the larger tank, however this is probably an inability to reach a stable configuration during the drop.

2. For canted mounted tanks, a similar behavior was experienced; however, the liquid generally remained in the initially wetted liquid region when non-symmetric configurations occurred. The patterns as affected by mounting angle are presented in Figure 3. This figure indicates final configuration to be insensitive to fill level between 20 to 90% fill for canted tanks. The exceptional fluid configurations indicated at other fill levels are noted.

3. The predominant test results are summarized in Figure 4. Four predictable configurations resulted. For zero mounting angle, the number of vapor bubbles (one to three) were unpredictable as were their location. For canted tanks, only a single bubble was observed and was predicted to occur in the initially wet location.

COMMENTS. - The interface configuration results are most interesting and would be required for application of toroidal tanks. The effect of the initial wet location being dominant may not prevail for longer low-g periods. Gravity and heating effects may override. A very useful extension of earlier work is achieved in this report.

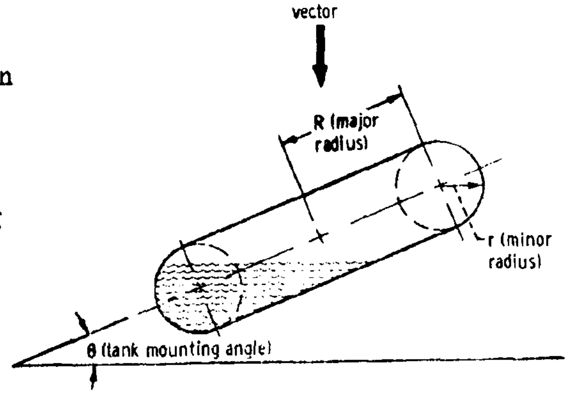


Figure 1. Toroidal Tank Orientation

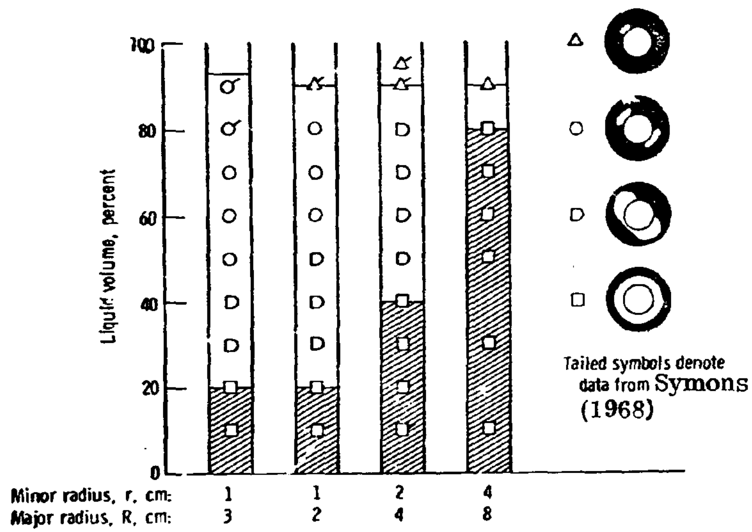


Figure 2. Effect of Percentage of Liquid Volume and Tank Geometry on Liquid-Vapor Interface Configuration During Weightlessness. Tank mounting angle, $\theta = 0°$

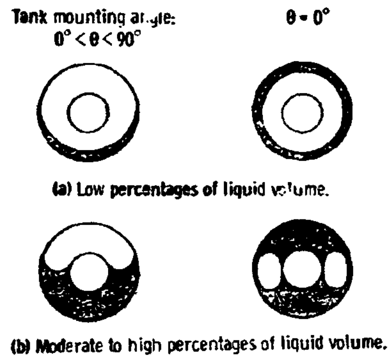


Figure 3. Equilibrium Liquid-Vapor Interface Configurations in a Toroidal Tank. Static Contact Angle of Liquid on Tank Material, Near 0°

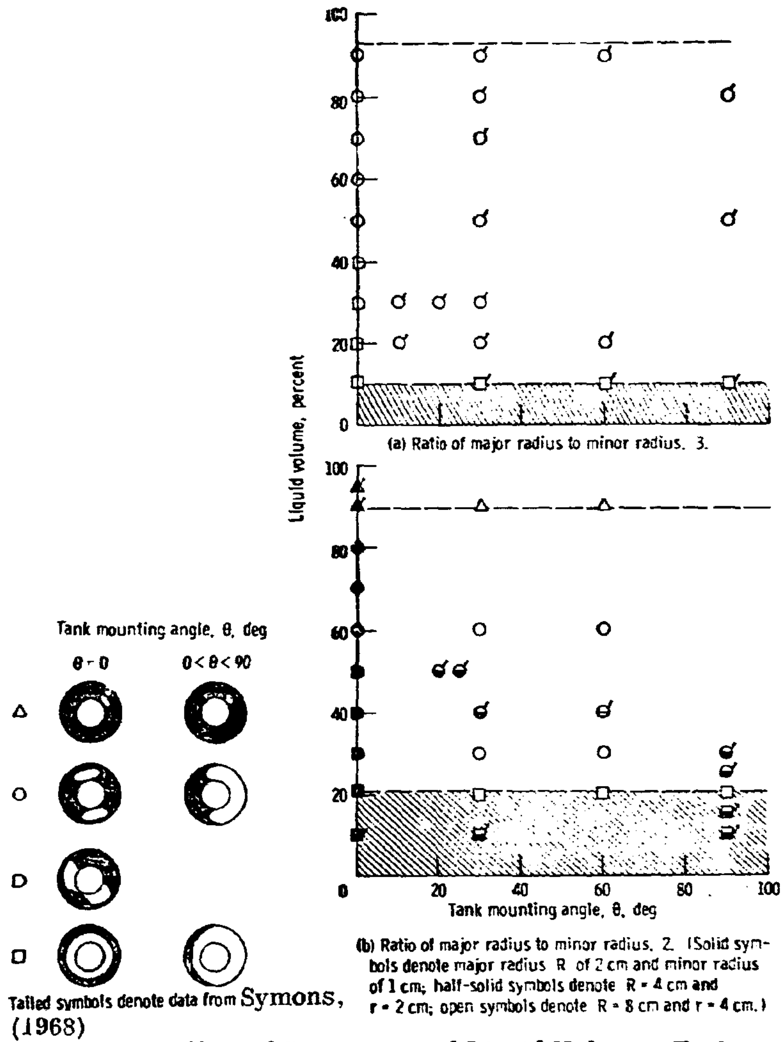


Figure 4. Effect of Percentage of Liquid Volume, Tank Mounting Angle, and Tank Geometry on Liquid-Vapor Interface During Weightlessness

LIQUID-VAPOR INTERFACE CONFIGURATION IN
ANNULAR CYLINDERS
Labus, T.L., NASA-LeRC, NASA TM X-1973, March 1970

OBJECTIVE. - To determine the static equilibrium configuration of liquids contained in annular cylinders in zero and reduced gravity.

PERTINENT WORK PERFORMED. - A series of tests were conducted in the LeRC 5 sec drop tower to define interface profiles for zero contact angle liquids at Bond numbers of 0 and 3. The profile and geometry nomenclature are shown in Figure 1; R was 2.05 cm and r/R varied from 0.02 to 0.50. Primarily data collection was by analysis of movie coverage. This work is an experimental verification of theoretical work reported by Seebold-AIAA 66-425-in 1966.

MAJOR RESULTS. -

1. The theoretical predictions for the various parameters which define the interface are shown in Figure 1 for various annulus ratios. These are typical of curves from Seebold for contact angles 0, 5, 10 and 15°. The parametric study covers the range of Bond number 0 to 30.
2. The experimental results are compared with theory at only the lowest Bond numbers of 3 and 0. Agreement is reasonable as indicated in Figure 2 for the height at the outer wall and for the maximum depression. A significant deviation from predicted results occurred for the height at the inner wall. This deviation was not explainable. A deviation occurred in the shape of the curve for height c in that it peaked at r/R of 0.2 versus predicted 0.5. The author suggested this might have been anticipated from curves on stability (Seebold, 1966) and natural frequency (Labus, 1969).

COMMENTS. - The work of Seebold should be cited for the analytical development. The small annular ratios would be representative of instrumentation liquid level sensors and the deviation is significant enough, increasing with Bond number, that further attention should be devoted to this area. Both analytical and experimental work in the Bond number range 3 to 30 is needed for low-g transfer measurements.

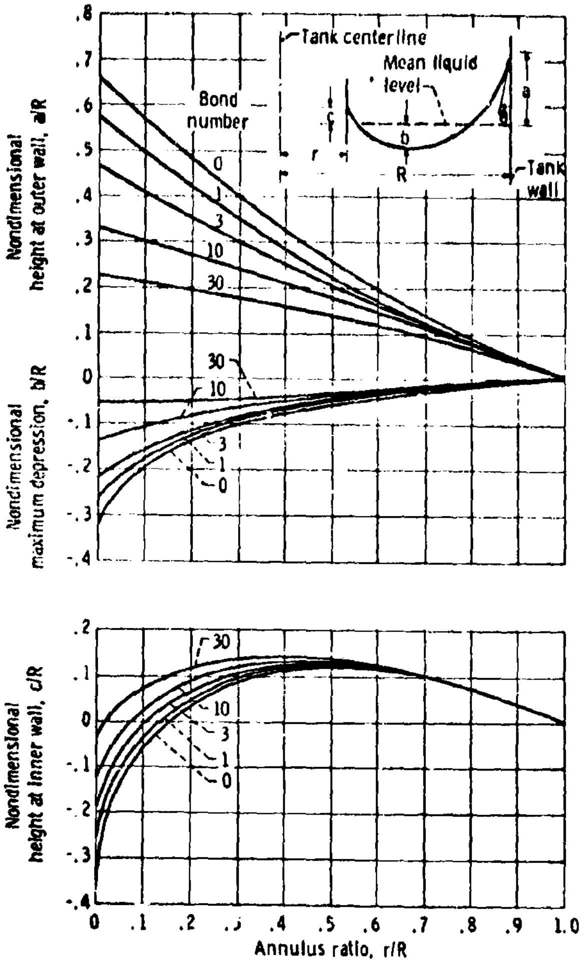


Figure 1. Theoretical annular interface shape parameters; contact angle, θ = 0°. (Seebold, 1966)

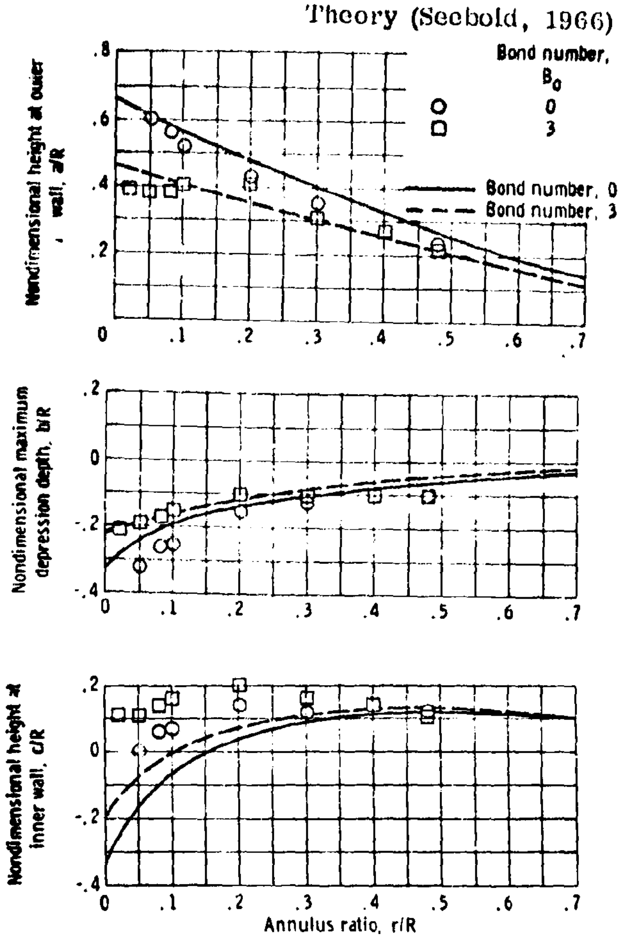


Figure 2. Annular interface shape parameters

LOW-GRAVITY LIQUID-VAPOR INTERFACE CONFIGURATIONS IN SPHERICAL CONTAINERS
Salzman, J. A., NASA-LeRC, TN D-5648, February 1970

OBJECTIVE. - To determine the equilibrium liquid-vapor interface configuration in oblate spheroids in low-gravity environments.

PERTINENT WORK PERFORMED. - A series of drop tower tests to define liquid interface shape were performed in the LeRC 142 m tower with 5 sec free-fall time. A thrust system on the package provided g-levels from 10^{-5} to 3.1×10^{-2}g. The test containers had eccentricities of 0, .5, .68 and .80 with semimajor axes of 2, 3 and 4 cm. Test fluids were ethanol, 2-propanol and FC-43. By selection of size, fluid, and thrust a range of Bond numbers from 0 to 30 were attained. In some tests large oscillatory motion continued for the entire five seconds, however, judicious choice of test conditions resulted in mostly static cases within 5 sec. Interface shapes in photographic studies were corrected for distortion before comparison with computer predictions.

MAJOR RESULTS. -

1. Experimental results agreed with calculated predictions within experimental error. Predictions were made using the method of Concus at LMSC (Nasa LeRC CR-72500, 1969) which agrees with work by Hastings of MSFC (NASA TMX 53790, 1968).

2. For zero Bond numbers, the tank top and bottom both were dry and the liquid took on an annular appearance. The limiting conditions for this phenomena are presented in Table 1. This behavior was predicted by Concus. Figure 1 depicts the strong effect of Bond number at low fill levels. The annular configuration is shown in Figure 1 for a Bond number of 1 with 25 percent fill.

3. At very low Bond numbers, the interface curvature approaches a constant, that of a sphere. As the centerline becomes more planar at higher Bond numbers, the edge curls more to satisfy the contact angle.

4. When fill levels are low, the influence of initial propellant position on low gravity static equilibrium position may be significant. Preliminary tests indicated this at zero Bond numbers.

5. For a range of fill levels, the interface shapes and experimental predictions are compared in Figures 2 and 3. The agreement is sufficient for most applications.

COMMENTS. - This experimental validation in a deeper drop tower with larger containers was performed in order to confirm the earlier theoretical work. The potential for oscillations on departure from high-gravity levels was notable.

Table 1. Experimental Transition Regions for Annular Interface

Tank eccentricity	Bond number	Fill level, percent	Tank bottom -
0.50	0	≤25	Uncovered
	≥1	[a]≥12.5	Covered
0.68	0	≤37.5	Uncovered
	≥1	[a]≥12.5	Covered
0.80	0	≤62.5	Uncovered
	1	≤37.5	Uncovered
	2	≤12.5	Uncovered
	≥5	[a]≥12.5	Covered

[a]Lowest volume tested.

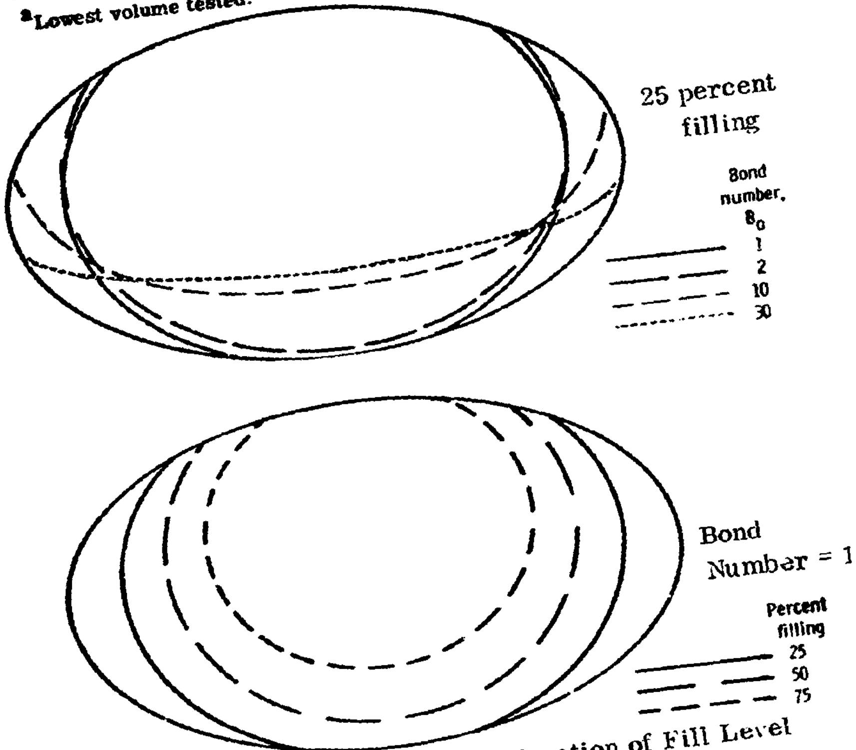


Figure 1. Interface Curvature as Function of Fill Level or Bond Number. Eccentricity, 0.80.

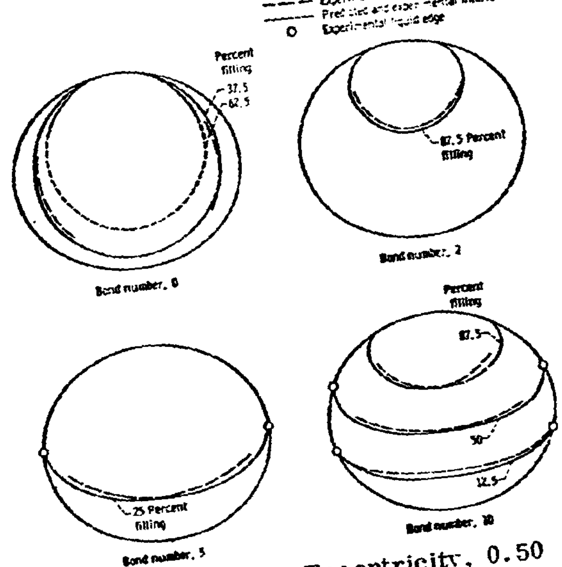


Figure 2. Eccentricity, 0.50

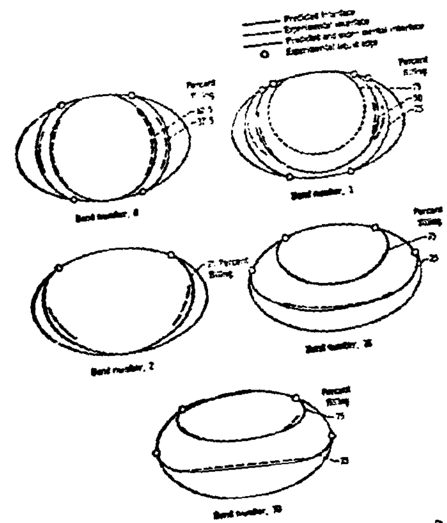


Figure 3. Eccentricity, 0.80

EXPERIMENTAL STUDY OF THE RESPONSE OF A STATIC LIQUID-VAPOR INTERFACE AFTER A SUDDEN REDUCTION IN ACCELERATION

Hastings, L.J., NASA-MSFC TMX-53841, June 1969

OBJECTIVE. - To experimentally define the time-dependent interface behavior of a fluid in a container after a sudden reduction in acceleration and to generalize the results to a general form for design application.

PERTINENT WORK PERFORMED. - The dynamic change of the interface on entering low-g was experimentally determined in the MSFC 4.3 sec drop tower. Tests were limited to a 6-inch diameter model S-IVB fuel and oxidizer tank using petroleum ether as the test fluid. Twenty-five tests in the cylindrical container were conducted over a range of Bond numbers 24 to 94; four tests were performed in an elliptical tank at Bond number of 80 at different fill levels. Oscillations at lower Bond numbers prevented reaching an equilibrium state, however, quasi-equilibrium data were collected on the oscillation period and the damping time. The results were correlated using a dimensionless time parameter consisting of the Bond number, diameter, and kinematic surface tension.

MAJOR RESULTS. -

1. The time-dependent interface motion was compared with its predicted final static configuration for each test. Typical results appear in Figure 1 indicating the rapid approach to equilibrium near the wall and the extended oscillations at the centerline.

2. Results for cylindrical containers indicate the number of oscillation cycles and the damping time increase from 2 to 10 and 4 to 30 sec as Bond number is decreased from 80 to 20. Above Bond numbers of 100, oscillations beyond one cycle are not typical.

3. A correlation for a dimensionless time, $\bar{t}_p$, for the first oscillation period was developed. The verification with data for a cylindrical section is presented in Figure 2. The correlation with the easily defined Bond number makes the correlation useful.

4. Total damping time, $\bar{t}_t$, was also correlated and is presented in Figure 3. Note the dimensionless times are only functions of kinematic surface tension and container diameter. In spherical containers, fill level is a configuration variable. Results are presented for zero contact angle fluids; contact angle is a dependent variable.

5. In general, the lengths of the transients are a function of the interface low-gravity curvature; the higher the curvature for the final equilibrium static configuration, the higher the magnitude and duration of the oscillations.

COMMENTS. - The relaxation times are important to instrumentation design and heat transfer analysis. Extension below current limits of Bond numbers of 20 will be required. Drop tower work is hampered by inadequate time for total relaxation of the surface energies.

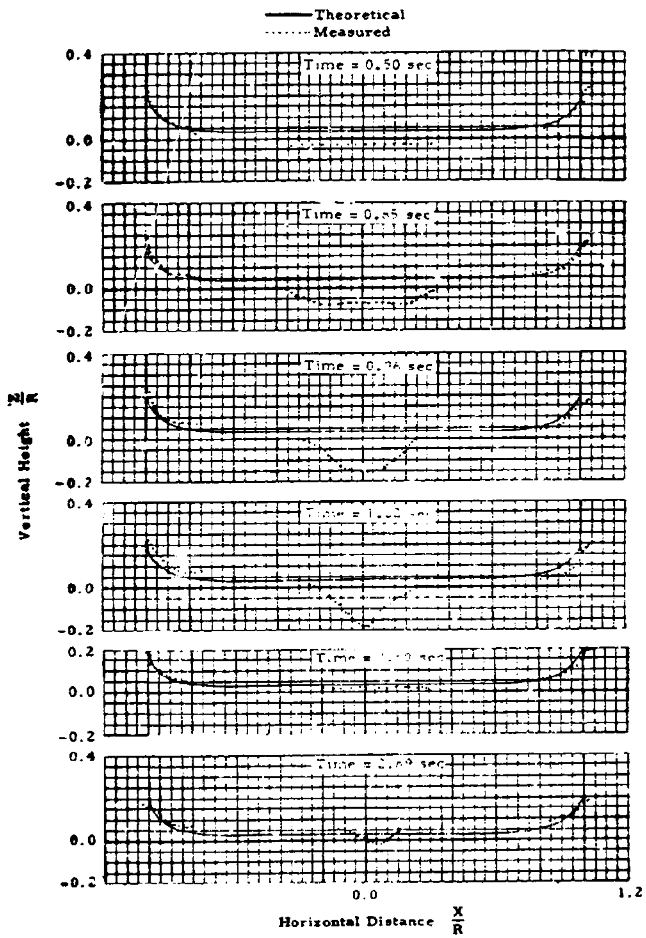


FIGURE 1. EXPERIMENTAL INTERFACE SHAPES IN A CYLINDER AT BOND NUMBER = 80

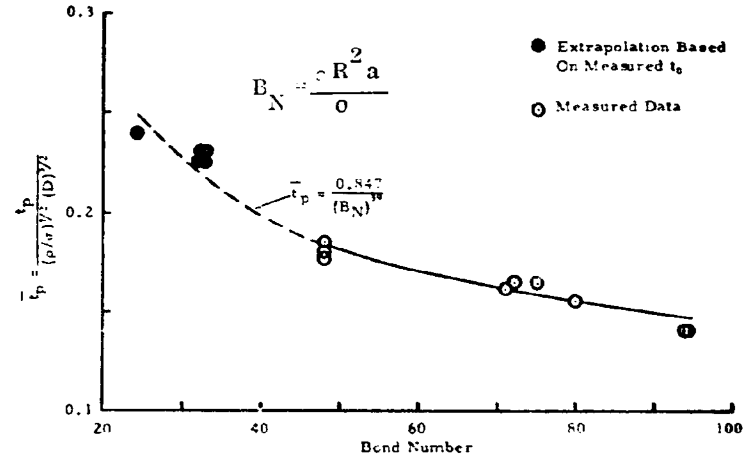


FIGURE 2. NON-DIMENSIONALIZED INTERFACE OSCILLATION PERIOD IN A CYLINDER VERSUS BOND NUMBER

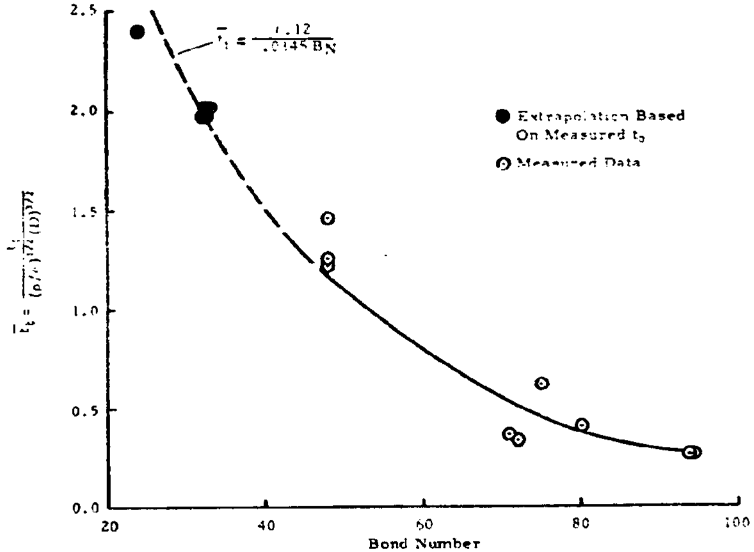


FIGURE 3. NON-DIMENSIONALIZED TIME REQUIRED FOR INTERFACE TO ATTAIN QUASI-EQUILIBRIUM IN A CYLINDER VERSUS BOND NUMBER

SMALL AMPLITUDE LATERAL SLOSHING IN SPHEROIDAL CONTAINERS UNDER LOW GRAVITATIONAL CONDITIONS
Concus, P., et al, NASA-LeRC, CR-72500, LMSCA944673, NAS3-9704, February 1969

OBJECTIVE. - To define the static equilibrium interface configuration in spheroidal tanks in reduced-and zero-gravity.

PERTINENT WORK PERFORMED. - The differential equation for the meridian of the equilibrium free-surface was solved with the boundary condition of a contact angle of 5° in spheroidal tanks of eccentricity 0, 0.5, 0.68 and 0.8 for liquid fills ranging from 1/8 to 7/8. The Bond numbers considered were 0, 1, 2, 5, 10, 30 and 100 where the acceleration is axial and the linear dimension a is the semi-major axis. Numerical methods required a finite contact angle however 5° is an adequate representation of a low-g propellant case.

MAJOR RESULTS. -

1. Interface configurations for selected Bond numbers and eccentricities are shown in Figures 1 to 4. These are representative data for the above variables.
2. At higher Bond numbers, the liquid ranges from a flat puddle to a deep liquid mass enclosing a flattened bubble at the top of the tank. As the Bond number decreases, the liquid moves outward forming an annular region at the equator. At lower fill levels, the bottom of the tank is uncovered.

COMMENTS. - This equilibrium interface condition study was the initial fluid definition for a sloshing study which is also summarized, moreover it is the only documented data for spheroids. The wide range of variables makes the graphical presentation of data most useful.

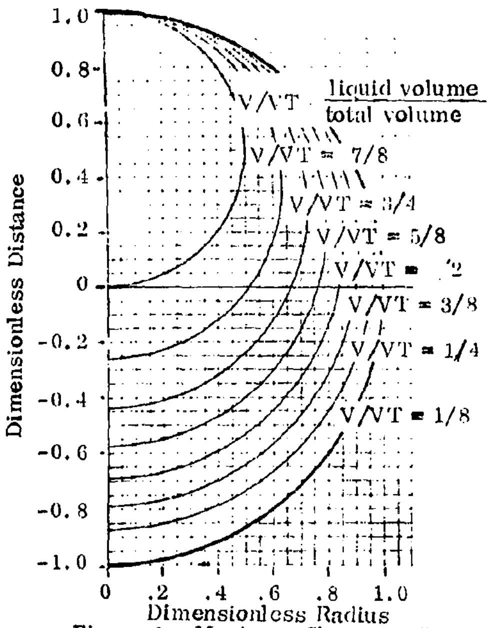


Figure 1. Meniscus Shapes at Bo = 0 With Tank Eccentricity 0

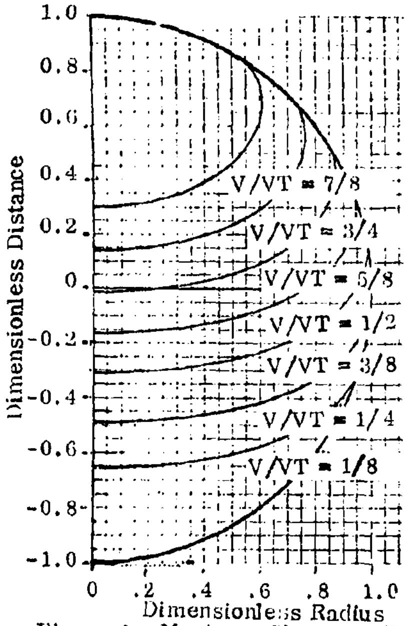


Figure 3. Meniscus Shapes at Bo = 10 with Tank Eccentricity 0

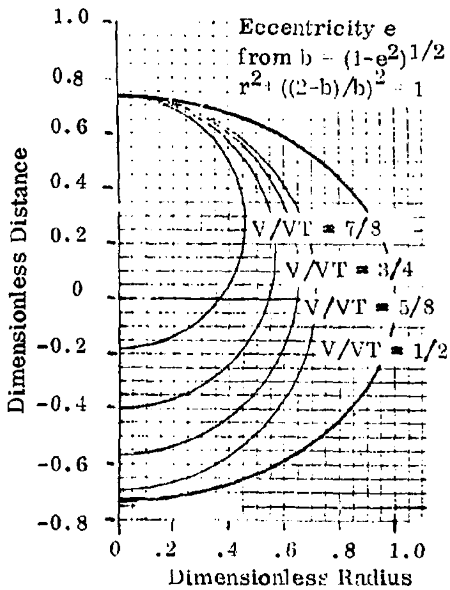


Figure 2. Meniscus Shapes at Bo = 0 for Tanks of Eccentricity 0.68

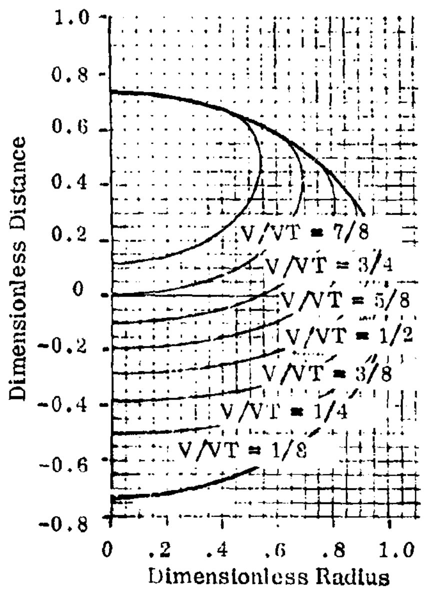


Figure 4. Meniscus Shapes at Bo = 10 for Tanks of Eccentricity 0.68

LOW GRAVITY LIQUID-VAPOR INTERFACE SHAPES IN AXISYMMETRIC CONTAINERS AND A COMPUTER SOLUTION
Hastings, L. J., Rutherford III, R., NASA-MSFC, TM X-53790, October 1968

OBJECTIVE. - To provide a general analytical/computer solution to define static equilibrium low-gravity interface shapes for liquids, in axisymmetric containers in axial acceleration fields less than normal gravity.

PERTINENT WORK PERFORMED. - The interface differential equation was derived from the familiar principle of minimum surface and potential energy using the calculus of variations. The use of polar coordinates was a unique approach which eliminated the convergence difficulties encountered at low contact angles by previous workers. The Bond number in this derivation is based on a characteristic container dimension which is an improvement over some derivations based on the interface radius of curvature. The basic equation was programmed — a relatively small simple computer code — for solution by a Runge-Kutta numerical technique which poses no significant limitations on the Bond number or the contact angle. The solutions are applicable to cylinders, spheres and ellipsoids with variables of Bond number, contact angle, container dimensions, and vapor volume fraction. The mathematical model was verified with experimental data for water, carbon tetrachloride, and methylalcohol in 0.375 to 0.75-inch containers. Due to distortion in these small containers, predictions are probably more accurate than measurements.

MAJOR RESULTS. -

1. Eleven graphical working charts provide dimensionless data for interface shapes for a range of Bond numbers from 0 to 200 and for contact angles of zero, 5, 20, 45, and 90 degrees. Centerline and wall height deviations are presented as a function of Bond numbers from 0.1 to 1000 for zero contact angle, Figure 1. The dimensionless plot for a cylinder is shown in Figure 2, and for a sphere in Figure 3.
2. The strong effect of contact angle on the interface shape in cylinders at zero Bond number is indicated in Figure 4.
3. The effect of contact angle on surface shapes decreases with increasing Bond number and becomes negligible as the zero-degree contact angle liquid surface becomes flat.
4. The influence of Bond number on interface shape is most significant for Bond numbers from 2 to 20, as indicated in Figure 1, and is negligible at Bond numbers above 200.
5. The influence of vapor fraction and/or contact angle are much more significant in ellipsoids/spheres than in cylinders.

COMMENTS. - This is the most useful design report for defining interface shapes known. The small container size raises some question on the measurement accuracy for validation.

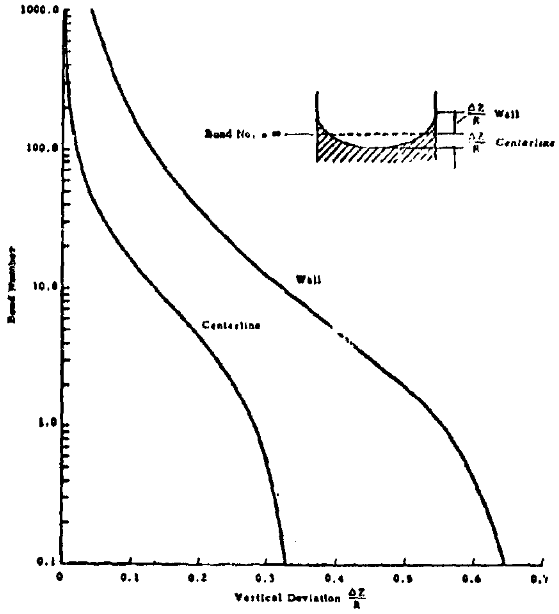


FIGURE 1. ZERO CONTACT ANGLE INTERFACE DEVIATION FROM THE INFINITE BOND NUMBER LEVEL IN A CYLINDER

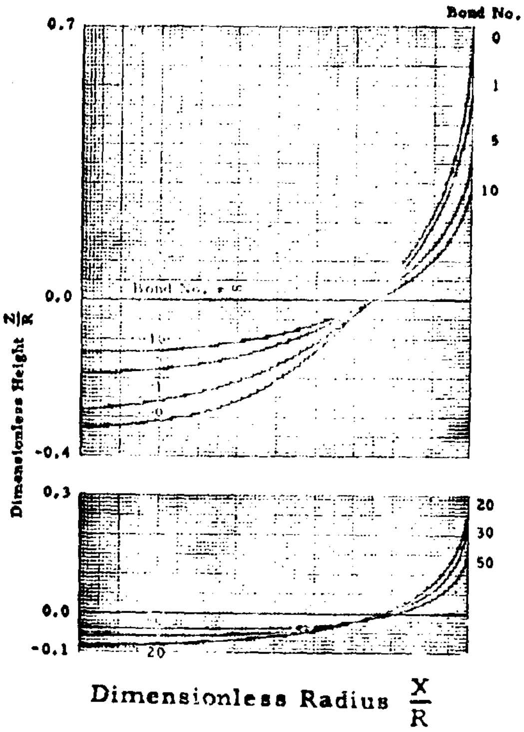


FIGURE 2. LOW GRAVITY ZERO CONTACT ANGLE INTERFACE SHAPES IN CYLINDRICAL CONTAINERS

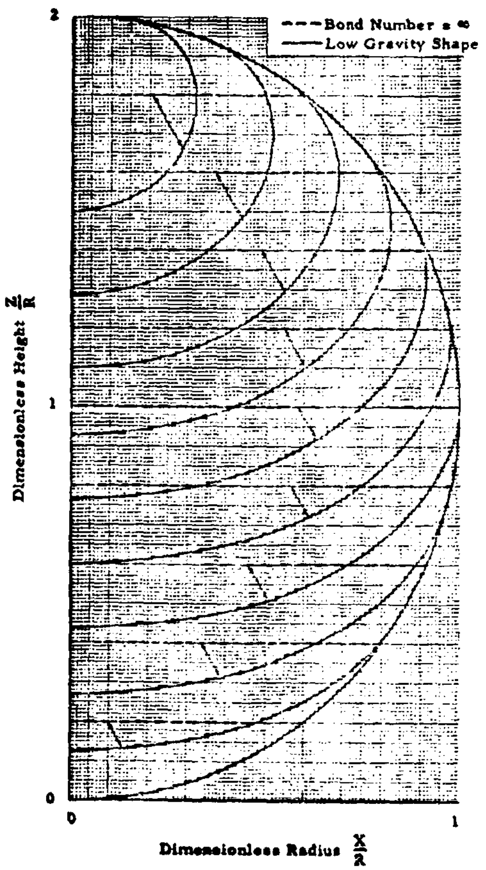


FIGURE 3. ZERO CONTACT ANGLE INTERFACE SHAPES IN SPHERICAL CONTAINERS FOR BOND NUMBER = 5

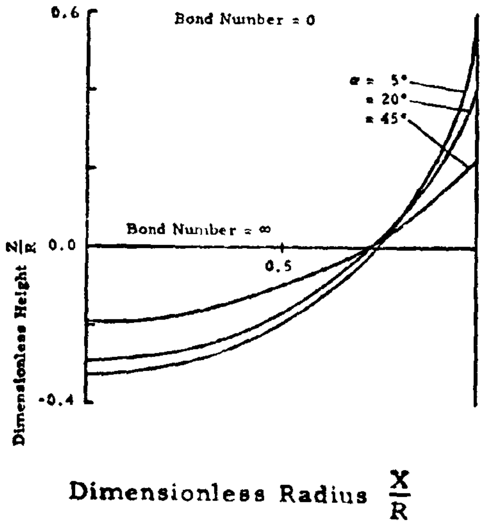


FIGURE 4. EFFECT OF CONTACT ANGLE ON SURFACE SHAPES IN A CYLINDER

STATIC MENISCI IN A VERTICAL RIGHT CIRCULAR CYLINDER, Concus, P., Lawrence Radiation Laboratory
J. Fluid Mechanics, Vol. 34, part 3, pp. 481-495, 1968

OBJECTIVE. - To solve the differential equations defining the static equilibrium meniscus for a complete range of Bond numbers and contact angles in a right circular cylinder.

PERTINENT WORK PERFORMED. - The differential equation was solved describing the equilibrium meniscus in a right circular cylinder. Solutions were obtained for the complete range of Bond number from the negative critical Bond number defined by stability of the inverted meniscus through large Bond numbers for contact angles 0 to 180°. Asymptotic solutions were used for high and low Bond numbers and numerical values were calculated for the intermediate range. Non-dimensional variables calculated over this range are f(r), the height of the interface above the centerline height versus r, the non-dimensional radius where both values are normalized by the cylinder radius; also defined are normalized surface areas and meniscus volume and a mean radius of curvature.

MAJOR RESULTS. -

1. The meniscus heights at the cylinder wall for the range of Bond number and contact angle are presented in Figure 1. Note that contact angles $> 90°$ are equivalent to $180 - \theta$. The height h is measured from the centerline value of h equal to zero.
2. Surface area for the interface is given in Figure 2. The volumes are presented above (or below) a value of h equal to zero for the meniscus in Figure 3.
3. Interface profile shapes are presented in Figure 4 for the complete range of Bond numbers. These shapes have been normalized and are displaced vertically so that they have a mean h equal zero and each represent the same liquid volume.

COMMENTS. - This is a highly mathematical paper, however the graphical data presented are the most complete as to range and accuracy. No experimental verification is included, however Salzman - TN D-5648 (1970) - experimentally verified the mathematical predictive methods used here in his comparisons with drop tower studies. An earlier study by Satterlee and Chin (1965) contained similar data but not in the extent represented here.

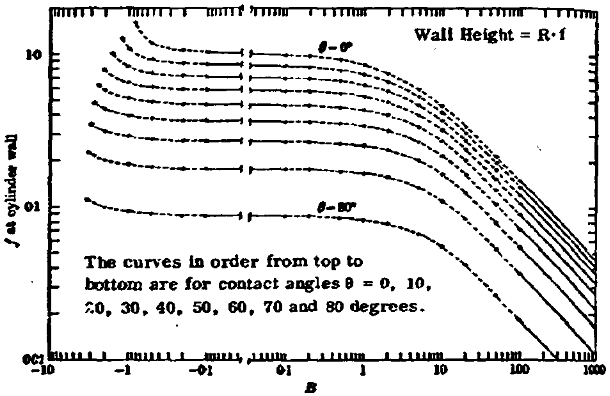


Figure 1. f (1/2 π - θ), Meniscus Height at the Cylinder Wall vs B, Bond No.

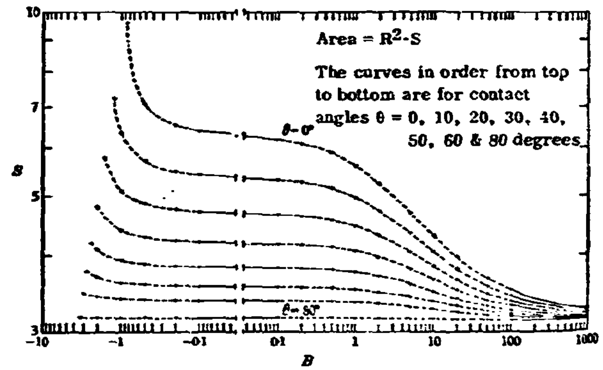


Figure 2. S, Meniscus Area, vs. B, Bond No.

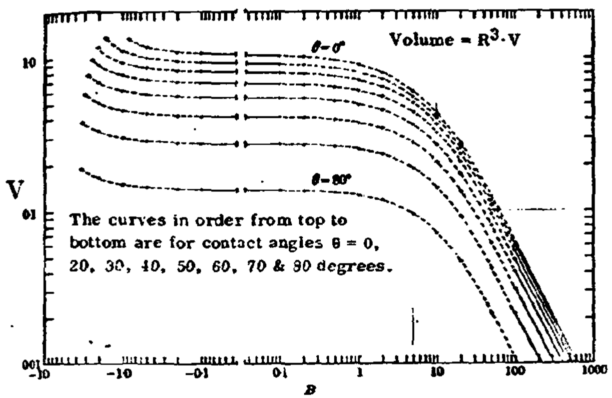


Figure 3. V, Volume Between the Meniscus and the Plane z = 0, vs B, Bond No.

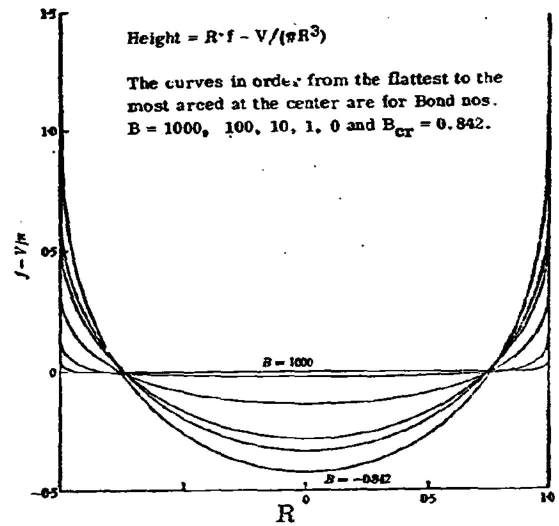


Figure 4. Menisci for Contact Angle θ = 0 deg.

THE EQUILIBRIUM FREE SURFACE OF A CONTAINED LIQUID UNDER LOW GRAVITY AND CENTRIFUGAL FORCES
Blackshear, W.T., Eide, D.G., NASA-Langley, TN D-2471, October 1964.

OBJECTIVE. - To investigate and describe the equilibrium free surface of a liquid in a tank subject to both translational acceleration and rotational acceleration about an axis perpendicular to the axis of liquid symmetry.

PERTINENT WORK PERFORMED. - A general differential equation describing the interface was developed for initial fields of translational acceleration, angular velocity and surface tension. A closed form solution was found for acceleration fields dominating and surface tension negligible; the surface is described by an elliptic paraboloid. For equal order fields, rectangular tank two dimensional solution curves are obtained for various contact angles and vapor volumes using numerical integration techniques. The fluid and inertial fields are shown in Figure 1. The two dimensional solutions are described by a centrifugal number (a ratio of centrifugal to surface tension force which is defined $\rho\omega^2 R^3/2\sigma$), the Bond number, and the surface tension field. Solutions were limited to contact angles greater than 30° for non-zero Bond number.

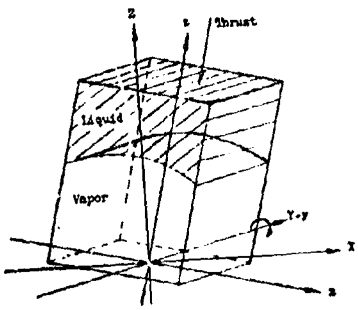
MAJOR RESULTS. -

1. Solutions for the liquid intercept along the z-axis (Figure 2) are presented for tank fill levels and a range of centrifugal numbers. The solutions are limited to contact angles 45, 60 and 90 degrees.

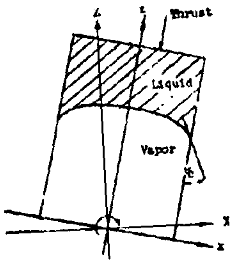
2. The strong dependence on contact angle - which was limited in this investigation by the numerical technique - is shown in Figure 3. It completely dominates the interface shape for low Bond number of 3 and centrifugal number of 2.

3. For a constant Bond number of 3 and contact angle of 90°, typical effects of the centrifugal number are shown in Figure 4.

COMMENTS. - This summary points up the serious limitations encountered in numerical solutions for interface shape in this complex inertial field. The limitation of contact angle > 30° limits the applicability for propellants, however, the approach is of interest. Seebold in LG-4 (1966) addresses this problem for zero-gravity cases ($N_{Bo} = 0$); the report is summarized under Interface Stability. If rotational control methods are used in transfer, additional interface definition work is required.

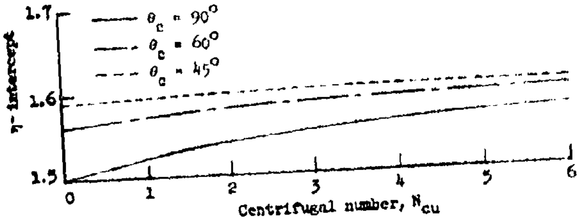


(a) Three-dimensional view.

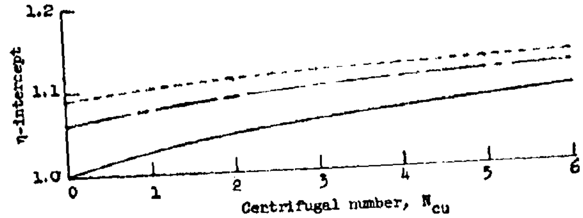


(b) Two-dimensional view.

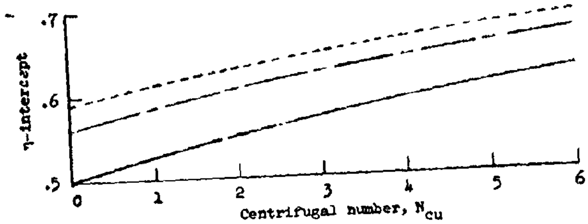
Figure 1.- Liquid fuel tank under the influence of a constant thrust in the negative z-direction and a constant rate of rotation about the Y-y axis.



(a) Vapor area ratio of 3.



(b) Vapor area ratio of 2.



(c) Vapor area ratio of 1.

Figure 2. Variation of the η-intercept with centrifugal number for Bond number equal to 3.

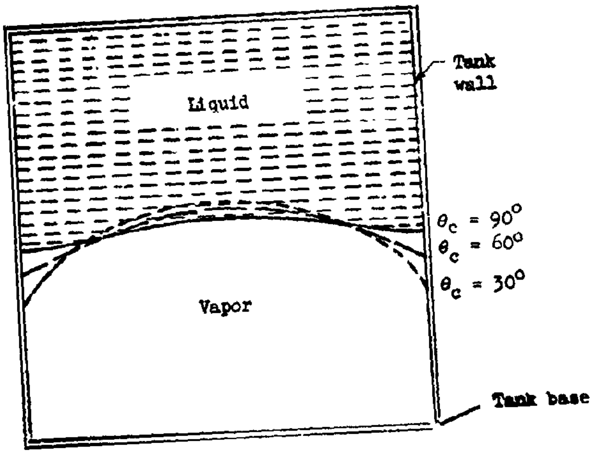


Figure 3. Variations in free surface due to changes in contact angle. Bond number, 3; centrifugal number, 2; vapor area ratio, 2; total tank area, 4.

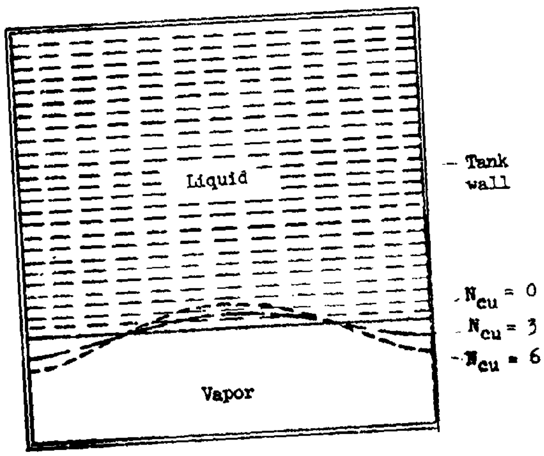


Figure 4. Variations in free surface due to changes in centrifugal number. Bond number, 3; contact angle, 90°; vapor area ratio, 1; total tank area, 4.

TIME FOR A TOTALLY WETTING LIQUID TO DEFORM FROM A GRAVITY-DOMINATED TO A NULLED-GRAVITY EQUILIBRIUM STATE
Paynter, H. L., MMC, AIAA Journal, Vol. 2, No. 9, September 1964

OBJECTIVE. - Analytically determine the time required for a liquid to deform from a gravity dominated condition to that of a nulled gravity equilibrium state.

PERTINENT WORK PERFORMED. - The analysis assumed; (1) Complete transformation of surface energy to kinetic energy. (2) Heat, viscosity and gravity forces are negligible. (3) The liquid/vapor interface has constant curvature. (4) Only the displaced liquid volume is accelerated during deformation. (5) The initial condition was a flat interface with a thin film of liquid around the tank wall.

Free surface energy was converted into kinetic energy by incrementing the fluid motion, computing the surface energy, and solving for deformation time with a digital computer, (Figure 1).

MAJOR RESULTS. -

1. Results computed for liquid hydrogen in a sphere of 1 foot radius from digital computer integration are shown in Figure 2. R is the tank radius, β is the ratio of surface tension to density, τ is the deformation time and τ_p is the dimensionless deformation time.

2. Results of Figure 2 were compared to drop tower data, indicating modification was required in terms of a coefficient H so that;

$$\tau = \frac{H \tau_p R^{3/2}}{\beta^{1/2}} \quad \text{where } H = \frac{1}{0.86 \cdot (R_c/R)}, \quad R > 1.16\, R_c$$

   where R_c is one cm (constant).

3. Results using this modified method for spherical tanks were compared to drop tower data in Figure 3. Data and semi-empirical analysis were in good agreement. The method was declared applicable to other tank geometries.

4. Data must be extended to include low filling levels of fluid. The analysis should be extended to incorporate viscous energy.

COMMENTS. - It appears that the coefficient, H was determined from the data of Figure 3. In order to validate the correlation, independent data is needed.

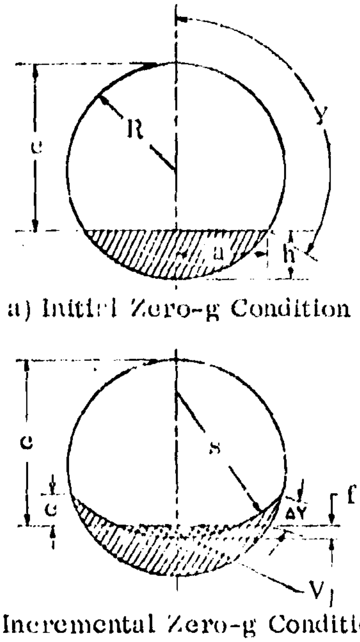


Figure 1. Incremental Zero-G Energy Change

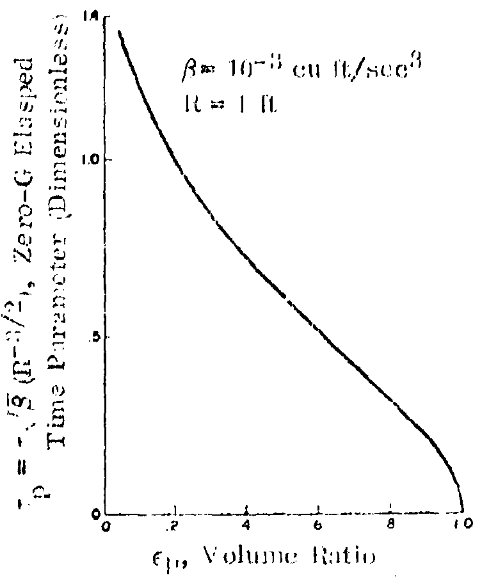


Figure 2. Dimensionless Time Parameter vs Liquid-to-Container Volume Ratios

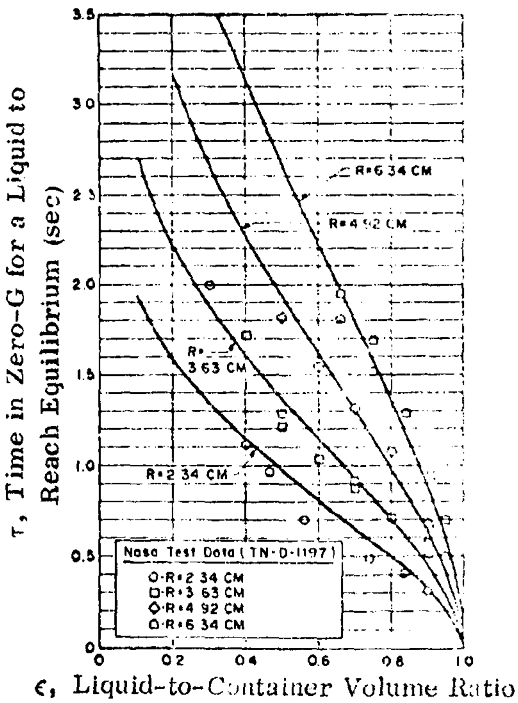


Figure 3. Correlation of Analytical Zero-G Deformation Rates With NASA Drop-Test Data, Ethyl Alcohol

EFFECT OF SURFACE ENERGY ON THE LIQUID-VAPOR INTERFACE CONFIGURATION DURING WEIGHTLESSNESS
Petrash, D. A., et al, NASA-LeRC, TN D-1582, January 1963

OBJECTIVE. - To define the effect of surface energy on the transient motion of a liquid-vapor interface in a capillary-tube and annulus in cylindrical and spherical tanks.

PERTINENT WORK PERFORMED. - Drop tower tests were performed with a 2.3 sec free-fall time. Both capillary-rise experiments in .58 to 5.90 cm dia tubes and liquid positioning experiments in cylindrical and spherical tanks (Figure 1) were performed with ethyl alcohol. The report contains several photographic sequences which indicate the fluid motion with time. An analytical expression for the rate of capillary-rise is derived from a force balance (Figure 2). This resulted in an equation based only on the physical system without empirical constants. This equation is integrated to give velocity and distance.

$$\ddot{Z} = \frac{\frac{2\sigma_{\ell v}\cos\theta}{\rho}\left(\frac{1}{r} - \frac{1}{R-r}\right) - \frac{1}{2}K\dot{Z}^2 - \frac{8\nu(\ell_t + Z)}{r^2}\dot{Z}}{\left(1 - \frac{A_t^2}{A_a^2}\right)Z + \ell_t + \frac{A_t}{A_c}\ell_c + \frac{A_t}{A_a}\ell_a}$$

A_a cross-sectional area of annulus, cm^2
A_c cross-sectional area connecting passage, cm^2
A_t cross-sectional area of tube, cm^2
K entrance-loss coefficient
ℓ_a initial liquid height in annulus, cm
ℓ_c effective length in connecting passage, cm
ℓ_t initial liquid length in tube, cm
R radius of tank, cm
r radius of tube, cm
Z height, cm
θ contact angle
ν viscosity, gm/cm-sec
ρ density, g/m^3
σ surface tension, dynes/cm

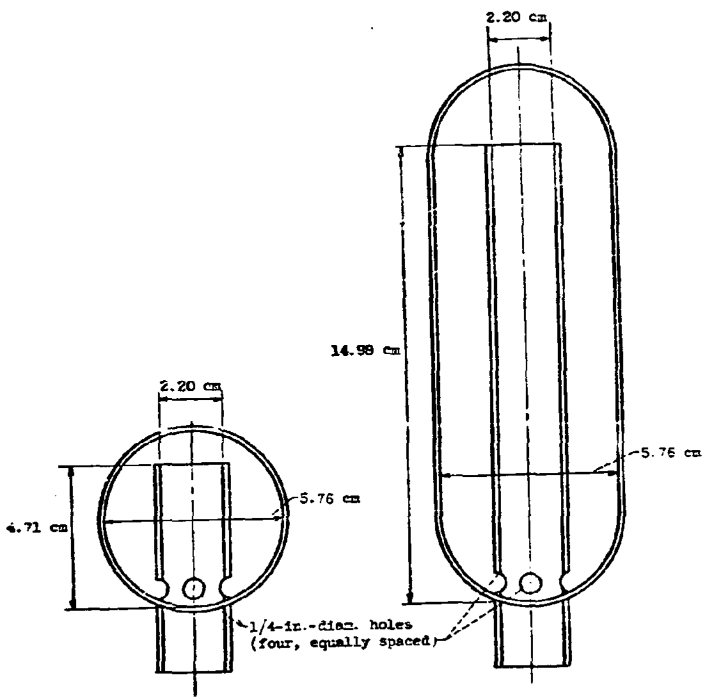
MAJOR RESULTS. -

1. Experimental verification of the liquid-vapor-solid system to adjust to a minimum total surface energy was shown. When the radius of the inner tube is greater than one-half the tank radius, the liquid rises in the annulus via the center tube.

2. The time response of the interface motion is plotted in Figure 3 where the solid line is the integration of the above equation. Data for the annulus is correlated in Figure 4 and required a four-fold increase in K from the capillary correlation of Figure 3. The correlations indicate the equation to be valid for determining velocities and displacements.

3. The configurations in Figure 1 and capillary tubes were tested at several fill levels. It was established that in reduced gravity the liquid can be collected in the bottom of the container. The vapor remains in the top of the tank and a configuration of minimum energy is assumed.

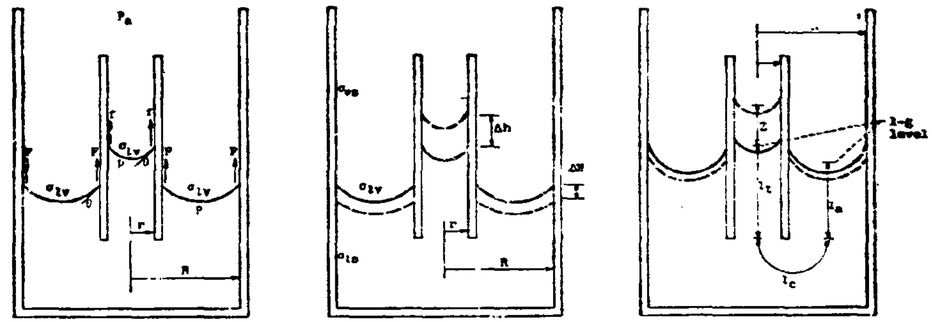
COMMENTS. - A more elaborate treatment of capillary hydrostatics in annuli is given in AIAA Paper 66-425 by Seebold, et al. Petrash's work is useful in its treatment of the dynamics of the motion.



(a) 100-milliliter sphere with standpipe.

(b) 440-milliliter cylinder with standpipe.

Figure 1.- Sketch of spherical and cylindrical tanks with capillary surface-tension baffles.

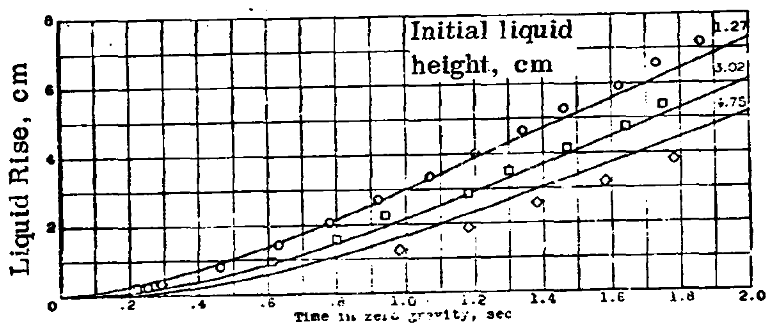


(a) Capillary-force parameters.

(b) Surface-energy parameters.

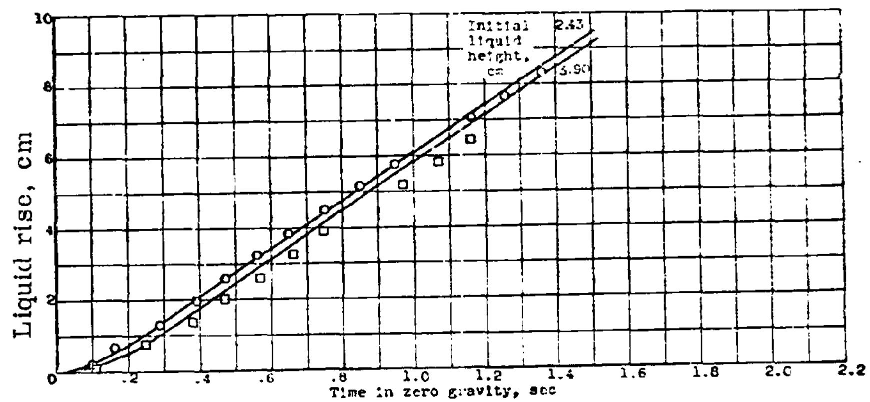
(c) Liquid-motion parameters.

Figure 2. - Sketch of capillary system under consideration showing system parameters



(c) Tube diameter, 2.20 centimeters.

Figure 3.- Variation of liquid rise in capillary tube as function of time in zero gravity.



(b) Tube diameter, 6.40 centimeters.

Figure 4.- Variation of liquid rise in annular space as function of time in zero gravity.

3.0 INTERFACE STABILITY

Covering liquid surface response and stability for changes in longitudinal and lateral acceleration, vehicle vibration, and rotational fields, including effects of surface tension interfaction and gas flow effects on liquid surfaces.

GAS-JET IMPINGEMENT NORMAL TO A LIQUID SURFACE
Labus, T.L., Aydelott, J.C., NASA-LeRC TN D-6368,
May 1971

OBJECTIVE. - Determine the characteristics of a gaseous jet impinging normally on a liquid surface in regions where both gravitational and surface tension forces are significant.

PERTINENT WORK PERFORMED. Both analytical and experimental (1-g and 0-g) work was accomplished using a 2.2 sec. drop tower. The analysis is based on the model presented in Figure 1. In the model, an incompressible, inviscid laminar gas jet with an initially parabolic velocity profile interacts with a liquid surface of infinite extent. An axisymmetric coordinate system was chosen with an origin located at the point 0 (Figure 1). The resulting theoretical equation, taking both gravity and surface tension into effect, was determined to be; $We_M/(h/d) = 0.57 + 0.5\ Bo_M$ when $H/d \leq 3$, where $We_M = \rho_g \bar{V}_j{}^2 d/\sigma$ and $Bo_M = \rho_\ell a\, d^2/\sigma$.

Testing was accomplished with a flat-bottomed, 10-cm-dia., cylindrical container with anhydrous alcohol (ethanol), trichlorotrifluoroethane, and distilled water. Nitrogen gas was passed through circular brass nozzles with inside diameter of 0.127, 0.191, 0.254, and 0.318-cm. located from 3 to 15 nozzle diameters above the liquid surface. Data was recorded with a 16-mm high-speed camera.

MAJOR RESULTS. -

1. $We_M/(h/d)$, from experiments at $H/d = 3$, showed a greater slope ($We_M/(h/d) = 0.57 + 0.9\ Bo_M$) than the theory. The difference between theory and experiment may be due to the employment of an inviscid analysis of the gas-jet-liquid interaction.
2. The data did correlate with: $We_M/(h/d) = K_1 + K_2\ Bo_M$ where K_1 and K_2 are constants which are functions of H/d as shown in Figures 2 and 3.
3. The following expression was found to predict gravity dominated penetration; $\frac{h}{d} = \frac{1}{K_2} \frac{\rho_g}{\rho_\ell} Fr_M$ where $Fr_M = \bar{V}_j^2/a\, d$. The form of this expression is similar to that obtained by previous investigators of gravity-dominated systems.

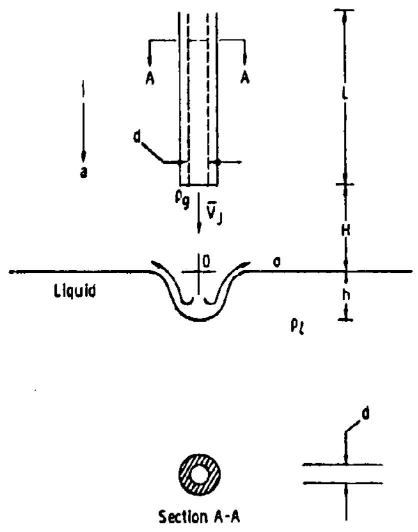


Figure 1. Defining Variables in Gas Impingement Study

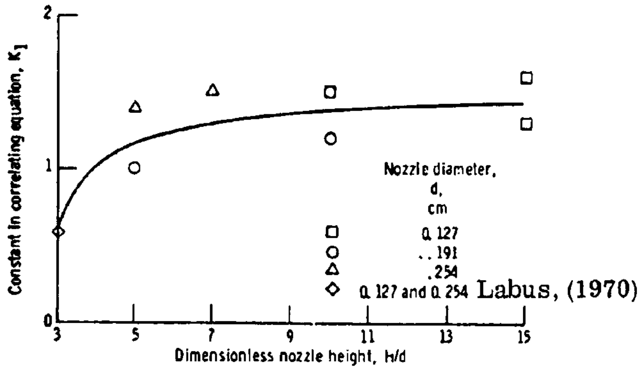


Figure 2 Effect of Nozzle Height on Penetration Depth in Zero Gravity

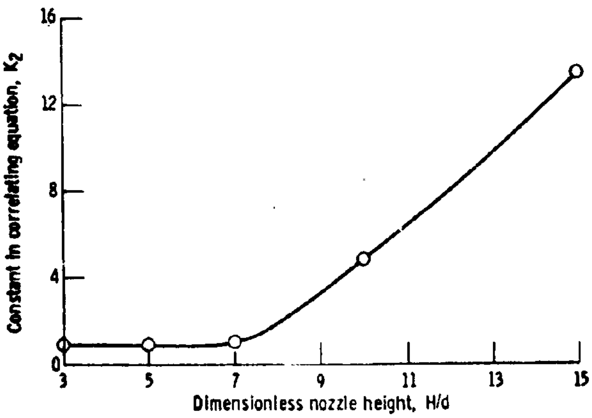


Figure 3. Variation of Constant K_2 with Nozzle Height

CAVITY STABILITY DURING GAS JET IMPINGEMENT ON LIQUID SURFACES IN WEIGHTLESSNESS
Labus, T. L., NASA-LeRC, TN D-5976, September 1970

OBJECTIVE. - Investigate gas jet impingement on a liquid surface during weightlessness with respect to correlation of the inception of bubble pinch-off with known system parameters.

PERTINENT WORK PERFORMED. Testing was accomplished in the LeRC 2.2-sec. zero-g facility. A flat-bottomed, 19-cm. - dia. transparent cylindrical container filled with distilled water was used. Circular brass nozzles with inside diameters of 0.127, 0.191, 0.254, and 0.318 cm. were located within three nozzle diameters above the liquid surface and at right angles to it. An ambient temperature laminar N_2 gas jet having a parabolic velocity profile was generated. The liquid-container-surface contact angle was maintained at 90° and thus the liquid-gas interface remained flat during weightlessness.

MAJOR RESULTS. -

1. The velocity at which the cavity becomes unstable (bubble pinch-off) decreases with increasing nozzle diameter (Figure 1).
2. An inviscid analysis was used to derive analytically a critical modified Weber number, $We_{Mcr} = \rho_g \bar{V}_j^2 d_o/\sigma_\ell$, where $\bar{V}_j$ is the average jet velocity and d_o is the nozzle diameter. This critical modified Weber number was experimentally shown to be a funcition of the Reynolds number and was empirically determined from the data (Figure 2) to be $We_{Mcr} = (Re^{0.8})/89$, where $Re = \rho_g \bar{V}_j d_o/\mu_g$.
3. No spraying of liquid droplets from the gas cavity was observed under weightless conditions over the range of variables tested. This is significant since spraying is a common occurrence under 1-g conditions.

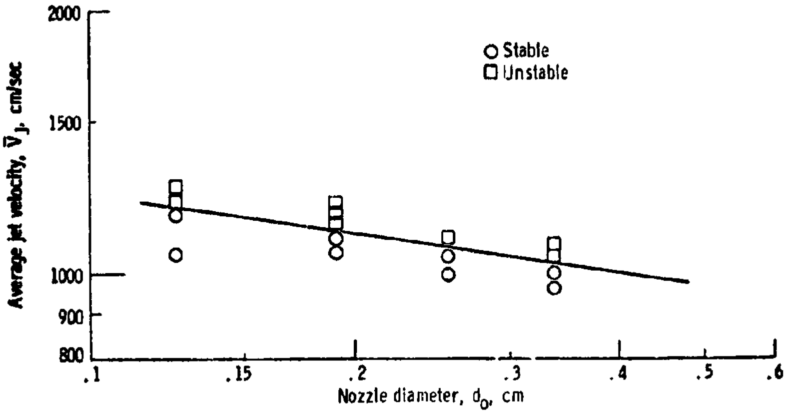


Figure 1. Stability Dependence on Average Jet Velocity and Nozzle Diameter

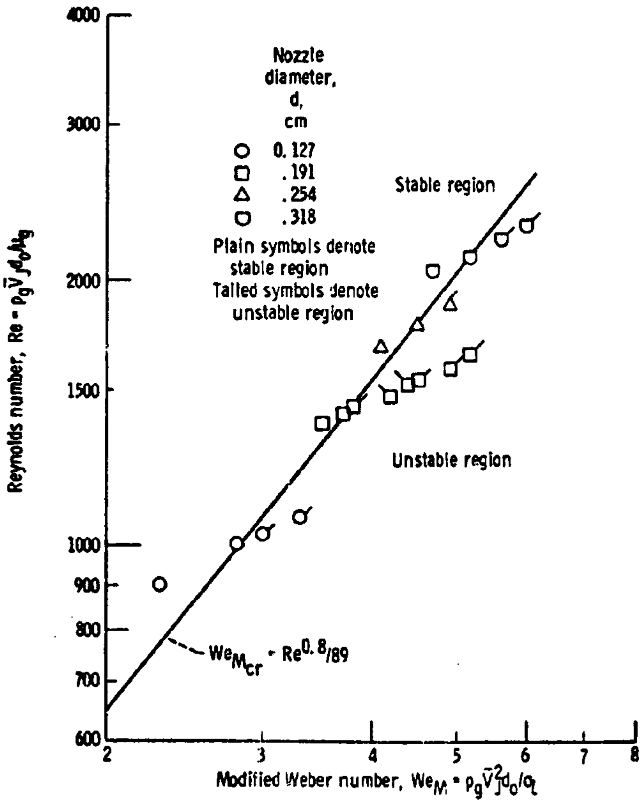


Figure 2. Dependence of Critical Modified Weber Number on Reynolds Number

PRESSURIZATION GAS FLOW EFFECTS ON LIQUID INTERFACE STABILITY

Blackmon, J.B., MACDAC, Proceedings of Low-G Seminar, DAC-63140, N71-13101, May 1969

OBJECTIVE. - To simulate the gas flow disturbances which affect stability in low-g pressurization and define methods or optimum diffusers to minimize surface disturbances.

PERTINENT WORK PERFORMED. - Analyses were performed of the interface instability phenomena which results from gas pressurization: cavity formation and globule formation. Cavity analysis was performed with the Bernoulli equation (Figure 1). Globule formation was approached as a Kelvin-Helmholtz instability which can be related to diffuser flow fields (Figure 2). The formulations were verified with one-g testing of 5 diffusers.

MAJOR RESULTS. -

1. The tests indicated the radial jet diffuser to cause the least 1-g disturbances, however, low-g disturbances would be greater. A nylon bag diffuser resulted in only causing interface ripples and would probably be satisfactory in low-g.
2. The cavity depth was correlated with Froude number; the results are shown in Figure 3 for three diffuser designs; the axial jet, the lateral jet, and the spray nozzle.
3. The heat and mass transfer rates are influenced by the interface area and the globule stripping due to a Kelvin-Helmholtz instability. A dimensionless group was found to correlate the data for the above three nozzle configurations in Figure 4.
4. The one-g tests provided qualitative information on the flow phenomena and afforded a ranking of diffusers for a one-g settled configuration. Techniques resulted for scaling one-g data to low-g.

COMMENTS. - The extension of the above results to low-g is only mentioned and not explained in sufficient detail, other than to trust in the one-g verification with a dimensionless number approach.

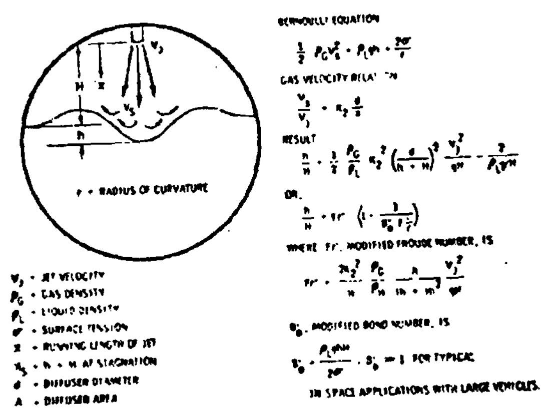


Figure 1. Analytical Model–Cavity Formation

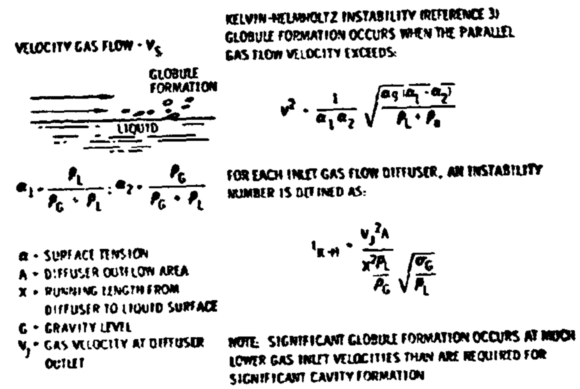


Figure 2. Analytical Model –Globule Formation

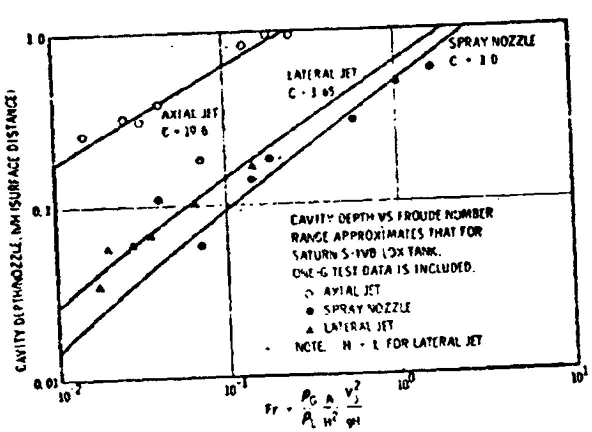


Figure 3. Cavity Depth vs Froude Number

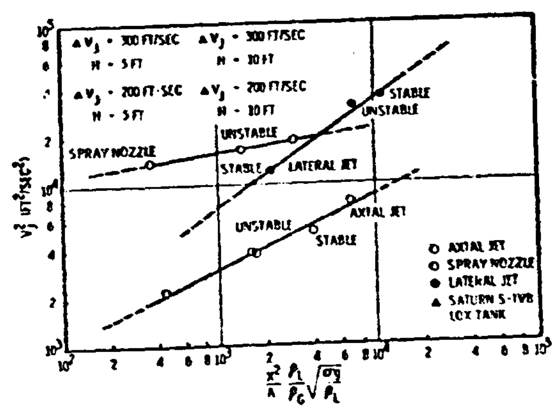


Figure 4. Dimensional Correlation of Kelvin-Helmoltz Instability

SURFACE DISINTEGRATION OF LIQUID IN
LONGITUDINALLY EXCITED CONTAINERS
Gerlach, C.R., SwRI, J. Spacecraft, Vol. 5, p. 553, May 1968

OBJECTIVE. - To develop and experimentally verify a theory to predict the liquid interface response in a cylinder which is excited longitudinally at higher frequency.

PERTINENT WORK PERFORMED. - A theoretical study was performed to modify earlier work in a rectangular tank to the cylindrical configuration under study here. An experimental effort was conducted in 9.5 and 24.8 cm tanks on a shaker with a liquid depth of 2.5 cm. Deeper liquids led to tank-liquid coupled compressibility effects. Frequencies covered a range 20 to 200 cps, the Bond numbers $\rho g d^2/\sigma$ were 1000 to 6000 for water, ethanol, water ethanol and water/glycerine. The observations were visual, photographic, and both a wave height transducer and a spray transducer were used.

MAJOR RESULTS. -

1. Excitation resulted in harmonic symmetric response with wavelets and spray for small excitation amplitudes, also response at 1/2 sub harmonics for larger amplitude excitations. In the latter case, spray actuated lower-mode phenomena occurred.

2. The surface disintegration (threshold of spray) conditions showed that the required input acceleration with the shaker increased proportionally to frequency and increased with increasing viscosity and surface tension. Below 50 cps, effects of surface tension and viscosity are small and gravity forces dominate.

3. The theory developed to predict surface disintegration was shown to be conservative in estimating the threshold of spray. The correlation for water is shown in Figure 1 where the spray threshold is correlated with frequency and input acceleration $\omega^2 x_0/g$ where ω is the wavelet oscillation frequency and x_0 the excitation amplitude. The stable and unstable response characteristics are indicated by the wave types shown in Figure 2. The generalized correlation for Bond numbers < 100 is shown in Figure 3. Points 50% above the curve indicate gross disintegration. Theory established at higher Bond numbers indicates one curve is valid in this region.

4. A unique correlation approach is indicated in Figure 4 where an excess input acceleration is defined which works with the surface droplet accelerations vice the input acceleration. The paper should be consulted for additional details.

COMMENTS. - This is a complex phenomena in which a significant advance in the state-of-the-art was made with this paper. Verification in full-scale cryogenic applications is lacking, however this represents a commendable experimental effort.

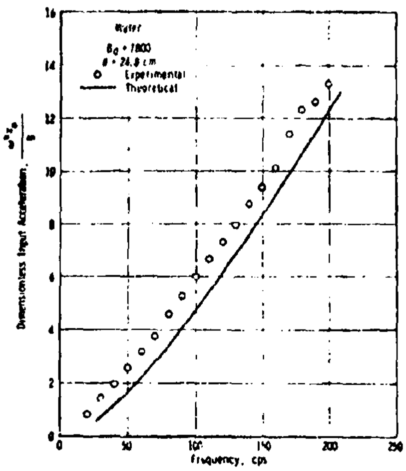


Figure 1. Comparison of Experimental Threshold of Spray for Water

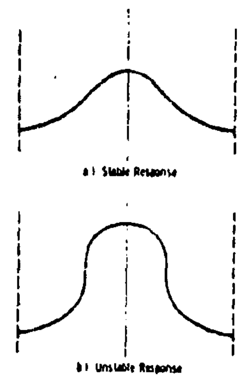


Figure 2. Mode Shapes for Stable and Unstable Large-Amplitude Wavelet Response

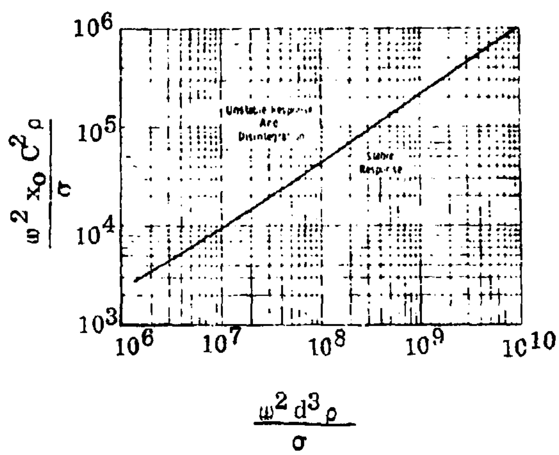


Figure 3. Dimensionless Threshold of Surface Disintegration Valid for Bond Numbers $B_d > 100$

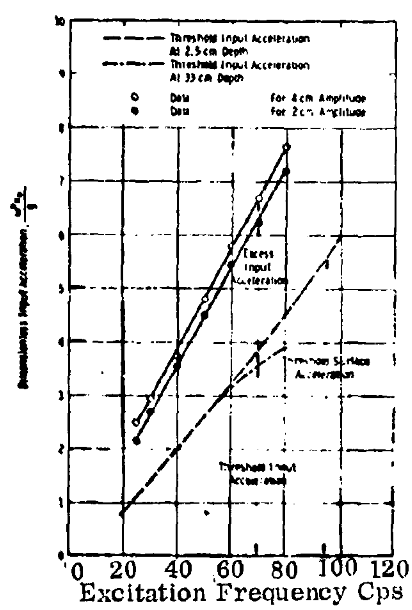


Figure 4. Dimensionless Input Acceleration (Threshold Plus Excess) Plotted as a Function of Excitation Frequency; 24.8 cm-diam. Container

EXPERIMENTAL INVESTIGATION OF LIQUID SURFACE MOTION IN RESPONSE TO LATERAL ACCELERATION DURING WEIGHTLESSNESS
Masica, W.J., NASA-LeRC, TN D-4066, July 1967

OBJECTIVE. - To determine large amplitude liquid-vapor interface motion and observed surface instabilities in cylinders in response to a constant lateral acceleration in a low-g axial field.

PERTINENT WORK PERFORMED. - A series of 2.3 sec drop tower tests were performed in cylinders of radii 0.317 to 3.17 cm. The zero-contact angle fluids used included ethanol, trichlorotrifluoroethane, methanol, carbon tetrachloride, butanol, 60% ethanol - 40% glycerol, and acetone. A brief period was allowed for formation of a low-g interface prior to application of the lateral acceleration which varied from 22.2 to 335 cm/sec^2 with lateral Bond numbers from 1 to 100. Lateral acceleration times were greater than the half-period of the fundamental interface oscillation. The test package afforded a lateral movement of 22 cm with the camera view. Stable interface conditions were defined for interface motion bounded in amplitude. Unstable interface behavior was unbounded but did not necessarily include interface instabilities of the Taylor or Helmholtz type or break-up of the steady flow. Both leading edge velocities and location and magnitude of maximum vapor penetration were defined.

MAJOR RESULTS. -

1. The descriptive configuration of the motion is shown in Figure 1 and the nomenclature is shown. For initially stable zero-g configurations, the interface motion was stable for all lateral Bond numbers less than 1.25 ± .05. The results are shown in Figure 2. The results are extended from earlier 1-g test data.

2. For the lateral Bond number range 1.25 to 3, the interface motion is generally non-steady with dominant viscous effects.

3. In the lateral Bond number range 3 to 100, steady interface motion exists for Re > 100; steady leading-edge velocities and vapor-penetration velocities were correlatable. The generalized velocity correlations corrected for viscous effects are shown in Figure 3 and vapor penetration distances are presented in Figure 4. The vapor phase penetration rate V_0 is given as
$$V_0 = 0.48\,(aR)^{1/2}\left[1 - (0.84/Bo)^{Bo/4.7}\right] \quad \text{for } Bo > 1$$
The leading edge of the interface accelerates $a_L = 3.8\, V_0^2/R$

4. When lateral accelerations were applied early in the drop while the low-g interface was forming, interface instabilities of the Taylor form occurred. For this type disturbance, no instabilities occurred for Bond numbers below 12.

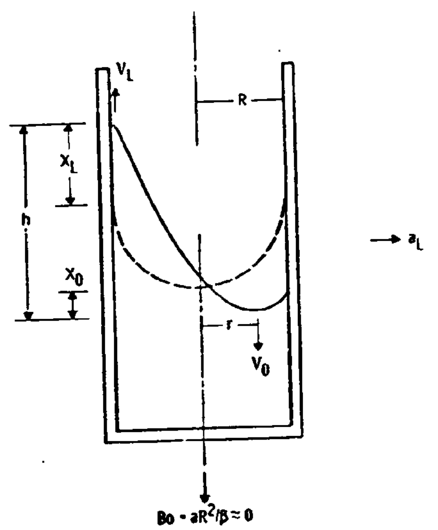


Figure 1. Interface Profile During Lateral Acceleration with Zero Axial Bond Number

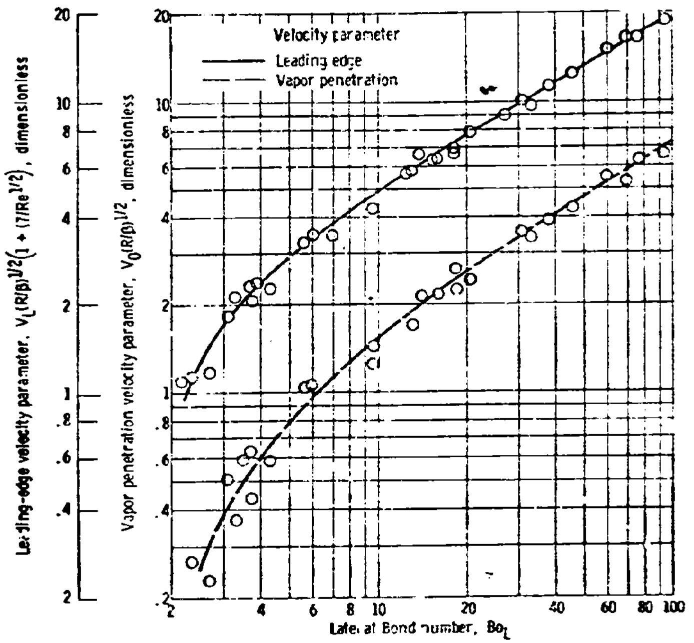


Figure 3. Interface Velocity Parameters as Function of Lateral Bond Number

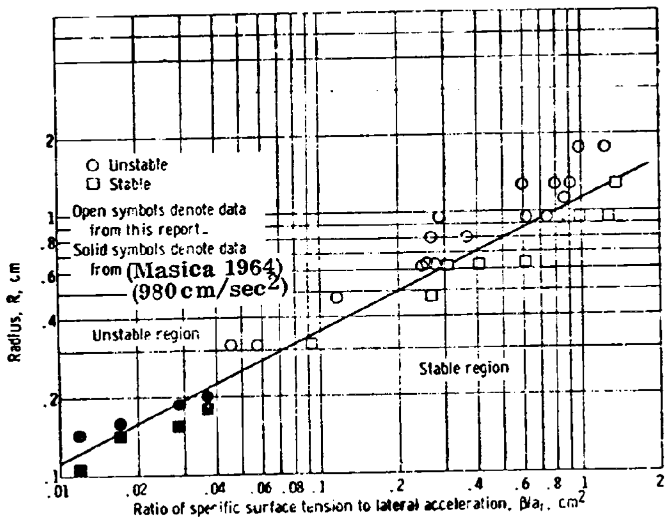


Figure 2. Interface Stability Delineated by Lateral Bond Number

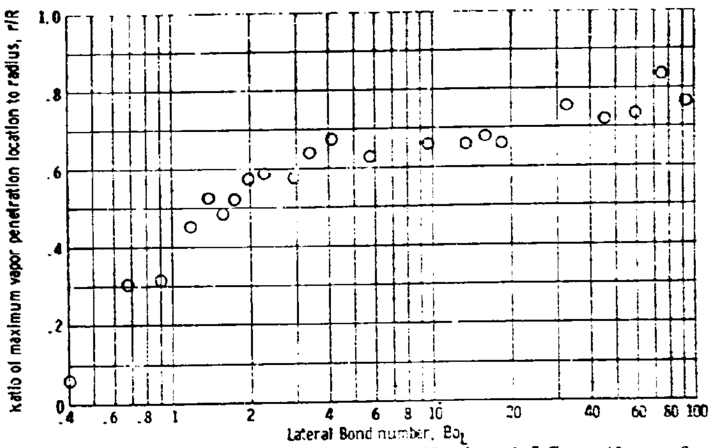


Figure 4. Average Steady-State Horizontal Location of Vapor Penetration Point

EXPERIMENTAL INVESTIGATION OF INTERFACIAL BEHAVIOR FOLLOWING TERMINATION OF OUTFLOW IN WEIGHTLESSNESS
Grubb, L.S., Petrash, D.A., NASA-LeRC, TN D-3897, April 1967

OBJECTIVE. - To investigate the behavior of the liquid-vapor interface following termination of outflow from a cylindrical tank in weightlessness.

PERTINENT WORK PERFORMED. - A series of drop tower tests were performed in the 2.2 sec tower to define the fluid behavior when outflow is terminated. The test tank configuration is shown in Figure 1; tank diameters were 2, 4 and 8 cm and tank lengths were 2 or 4 diameters. Any of six zero-contact angle liquids were used. Disturbances due to the valve closure were minimized. Test conditions were duplicated in zero and one-g environments. Pressurized outflow with an inlet baffle was used. Primary coverage was photographic The outflow rate and the $\Delta H/R$ when outflow is terminated were the primary two test variables.

MAJOR RESULTS. -

1. The primary variables influencing the geyser or non-geyser condition were the Weber number $\rho V_m^2 R/\sigma$ where V_m is mean velocity in tank and the ratio $\Delta H/R$ where ΔH is interface displacement due to velocity from the zero-g non-outflow interface shape. The occurrence of geysers was correlated and is summarized in Figure 2. For Weber number below 10 to 12, geysers did not occur. At larger Weber numbers, interface displacement determines geyser occurrence. When no geyser forms, the surface tension is strong enough to control the interface behavior.

2. A small effect on the Weber number value for geyser formation was attributable to kinematic viscosity. This effect is minor and is shown in Figure 3.

3. The effect of proximity to the tank bottom was considered and was found to be of no consequence. This eliminates outlet tube valve closure effects as a cause of the geyser.

4. The above results were obtained prior to vapor-ingestion occurring during outflow. For the distorted- interface cases, a geyser nearly always formed.

5. The appearance of geysers seems to be most predictable. Even when geysers formed, the amount of liquid reaching the tank top was small.

COMMENTS. - Sufficient design data is given to select conditions during which geysering will not occur. The vapor-ingestion geyser situation can probably be avoided by proper baffles, which were not considered in this analysis and are almost always present.

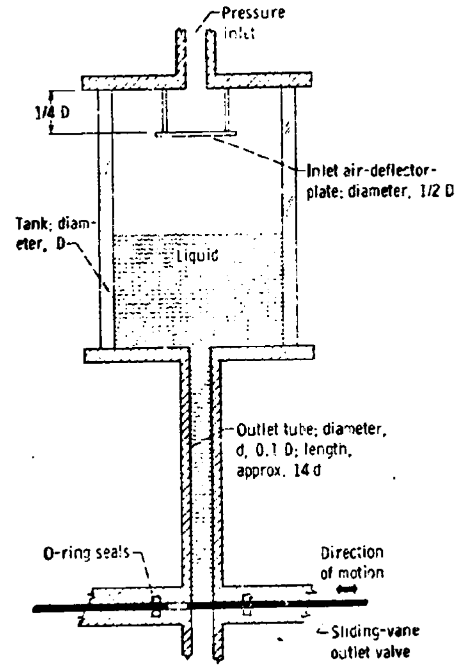


Figure 1. Schematic Drawing of Typical Test Tank

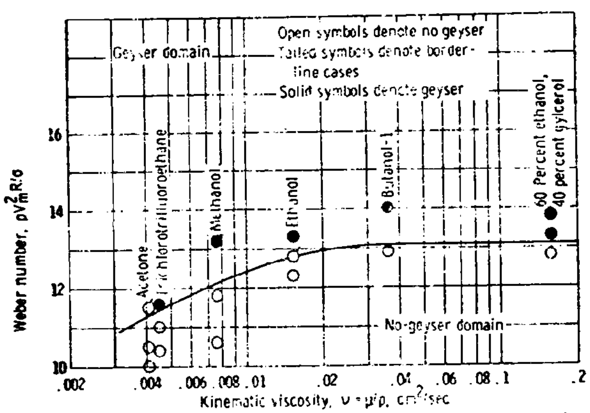


Figure 3. Geyser and No-Geyser Domains as Function of Weber Number and Kinematic Viscosity for Relative Interface Dispacements of Less Than 5

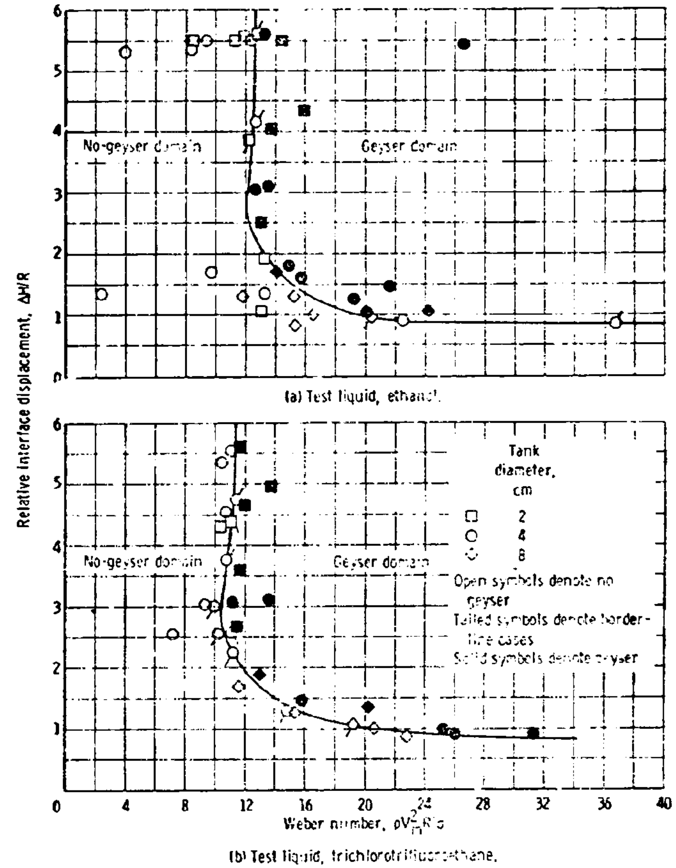


Figure 2. Geyser and No-Geyser Domains as a Function of Relative Interface Displacement and Weber Number

CRYOGENIC LIQUID EXPERIMENTS IN ORBIT VOLUME 1:
LIQUID SETTLING AND INTERFACE DYNAMICS
Bowman, T.E., MMC, NASA-MSFC CR-651, NAS8-11328, December 1966

OBJECTIVE. - To define analytically and confirm experimentally the dynamic response of a liquid surface to changes in axial or off-axis acceleration.

PERTINENT WORK PERFORMED. - Mathematical models are developed from potential flow theory to model small perturbations in liquid surface from a flat horizontal surface for small off-axis accelerations and 90° contact angle. The solutions are used to define the critical Bond numbers for the various axi-symmetric modes. Additionally, non-axial fundamental modes are determined and their critical Bond numbers defined. The geometric configuration is shown in Figure 1. The mathematical results are confirmed by drop tower experiments which start with initially flat surfaces.

MAJOR RESULTS. -

1. The analytical model was verified with drop tower results, however, limitations of the model were recognized. The initial perturbations were related to contact angle effects at the wall.

2. The axisymmetric modes are shown in Figure 2. None of the five modes are unstable to axial accelerations. A modified Bond number is defined $B_{\alpha R}$ equal to $\rho a R^2 \cos \alpha/\sigma$ where α is the acceleration angle to the axis and α_0 is the initial acceleration angle prior to step change.

3. Figures 3 and 4 indicate the analytical predictions for liquid motion with $B_{\alpha Ro} = 250$ and $B_{\alpha R} = -60$ at a time of $2\ (R/a)^{1/2}$. The fluid is initially displaced in Figure 4 and a large displacement occurs for initial acceleration. The contact angle was assumed to be 85°. The movement of the fluid in Figure 4 upon acceleration reversal indicates the complexity of the pattern. Experiments confirmed that for off-axis accelerations the fluid can move entirely up the side of the container.

COMMENTS. - The fluid contact angle in the analytical model is limited to near 90° whereas experimental fluids had contact angles near zero. Behavior in the vicinity of the wall would not necessarily be comparable; and the degree of comparison was not specifically addressed except to state that the axi-symmetric case had good qualitative agreement.

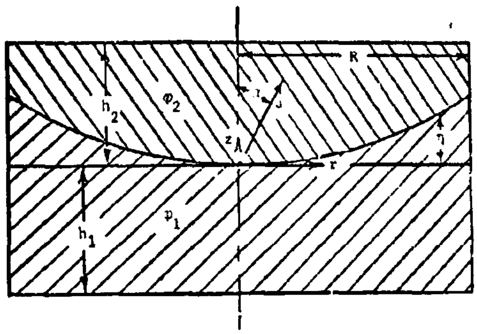


Figure 1. System of Interest

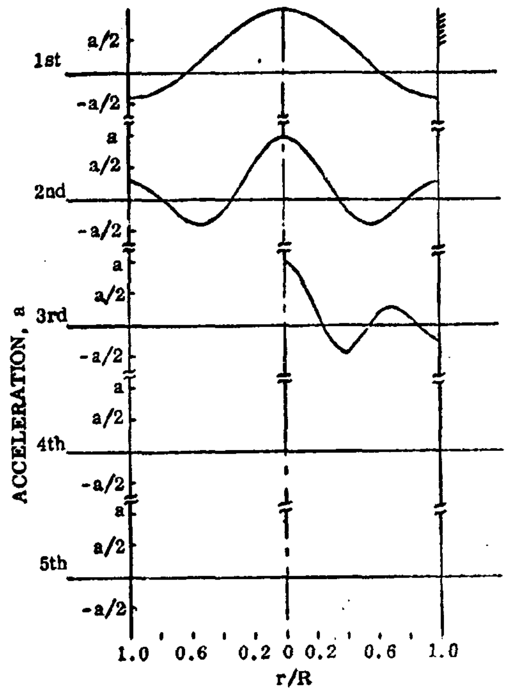


Figure 2. Axisymmetric Modes, Cross Section thru Axis

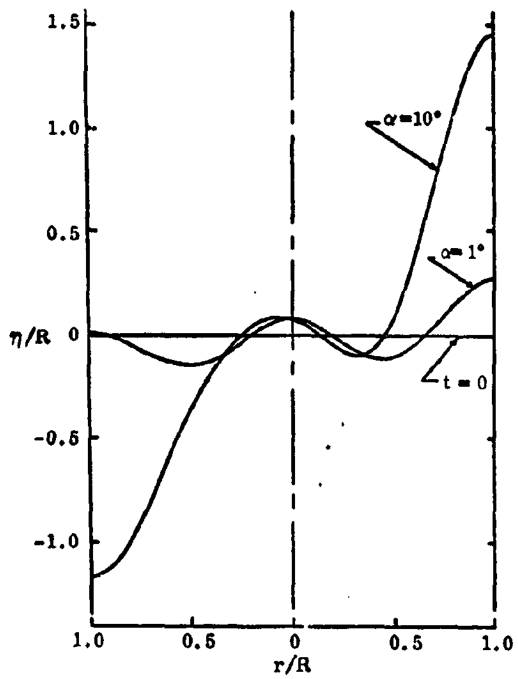


Figure 3. Analytical Results, $\alpha_o = 0$ deg

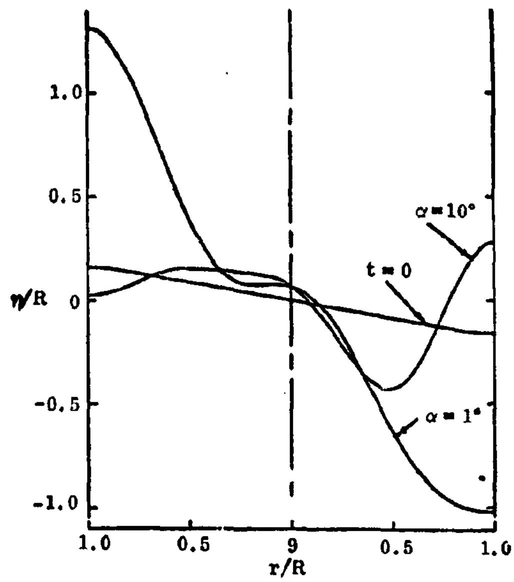


Figure 4. Analytical Results, $\alpha_o = 10$ deg

ANALYTICAL AND EXPERIMENTAL STUDY OF LIQUID-ULLAGE COUPLING AND LOW GRAVITY INTERFACE STABILITY
Hurd, S.E., et al, LMSC 2-05-66-1, NAS 8-11525, August 1966

OBJECTIVE. - To determine maximum surface velocities which still result in stable interfaces and to experimentally verify the results.

PERTINENT WORK PERFORMED. - An analytical model was developed which defines maximum Weber numbers (limiting velocities) for which the interface is stable. A computer solution was modified from a program defining meniscus shape to consider liquid motion. The radial surface velocities resulting from convective boundary layer flow were evaluated experimentally (Figure 1) in one-g and in drop tower experiments. The limiting values for Bond, Weber, and Froude number regimes were determined. The effects of ring baffles on interface jump and velocities was ascertained.

MAJOR RESULTS. -

1. The results of the test program are presented in Table 1 for one-g and reduced-g tests using the experimental configuration of Figure 1. The natural convection boundary layer theory gives velocities which are comparable with those which were simulated here and used in dimensionless numbers.

2. The results of the test program are shown in Figure 2. These curves are indicative of the radial velocity distributions. The results are further plotted as a function of dimensionless numbers in Figure 3. Stable operating regimes are defined as limiting Weber numbers. For a tank Bond number of zero, the stability criterion for the free surface is $We < 4$. The velocities are stabilized by gravity, therefore the constant 4 is modified to $We < 10\ (Bo)^{.35}$ for $.1 \leq Bo \leq 100$. For Bond numbers > 100, the jump height at the wall is ℓ where $\ell = 0.5R\ (Fr)$ where $Fr = U_s^2/gR$

3. The effectiveness of ring baffles on the wall were significant in stopping flow for $We < 50$ and resulted in only deflecting the flow for $We > 400$. Little distortion of the interface occurred for $Fr < 0.2$.

COMMENTS. - This series of tests and correlations provides some limiting conditions for maintaining a stable interface condition with minimal distortion caused by boundary layer flow which might arise during burns or boost.

Table 1. Summary of Interface Stability Test Conditions

Test Condition	Flow Rate gpm	Calculated Jet Velocity (cm/sec)		Acceleration Level	Bond Number	Weber Number			Froude Number
		u_{av}	u_m	g/g_o	Bo	We_m	We_{av}	We_δ	Fr_{av}
1	1.8	8.5	12.7	1	7350	115	51	5.9	0.007
2	2.9	13.8	20.5	1	7350	300	132	15.4	0.018
3	4.8	23.0	34.6	1	7350	855	378	44	0.051
4	6.6	31.0	46.6	1	7350	1550	687	80	0.093
5	8.0	37.6	56.5	1	7350	2280	1000	117	0.132
6	0	0	0	0	0	0	0	0	-
7	1.0	4.7	7.1	0	0	36	15.8	1.8	-
8	1.8	8.5	12.7	0	0	115	51	5.9	-
9	2.9	13.8	20.5	0	0	300	132	15.4	-
10	5.2	24.4	36.7	0	0	962	425	49.5	-
11	2.9	13.8	20.5	0.1	735	300	132	15.4	0.18
12	2.9	13.8	20.5	0.01	73.5	300	132	15.4	1.80
13	5.3	24.9	37.4	0	0	1000	443	51	-
14	1.8	8.5	12.7	0	0	115	51	5.9	-

$We_{av} = u_{av}^2 R \rho/\sigma$ $\quad We_\delta = u_m^2 \delta_{BL} \rho/\sigma$ $\quad We_m = u_m^2 R \rho/\sigma$

$R = 10.5$ cm $\quad \delta = 0.54$ cm $\quad \sigma/\rho = 14.7\ cm^3/sec^2$

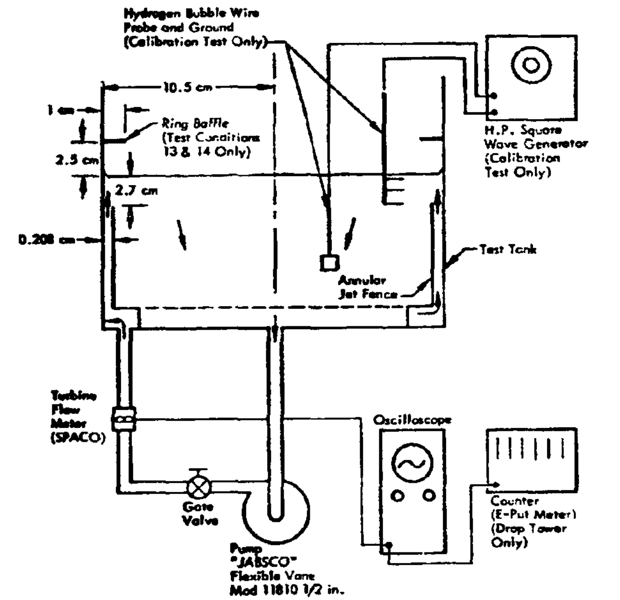


Figure 1. Schematic of Test Tank for Boundary Layer Breakthrough Studies

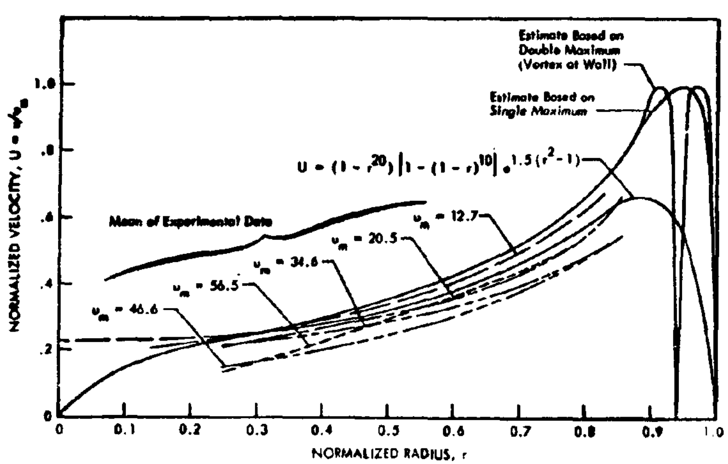


Figure 2. Normalized Radial Velocity Distributions

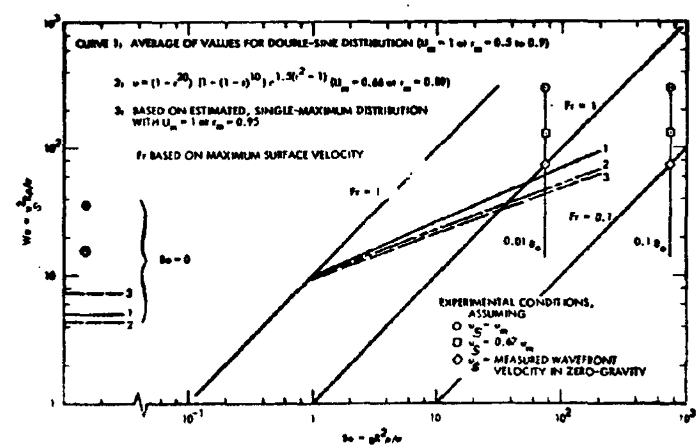


Figure 3. Limiting Weber Number Correlations

CONFIGURATION AND STABILITY OF A ROTATING AXISYMMETRIC MENISCUS AT LOW-G, Seebold, J. G., Reynolds, W. C., Stanford University, LG-4, NSF-GP-2720
March 1965

OBJECTIVE. - To define conditions for stability of the axisymmetric interface in a rotating cylindrical tank in a low-g environment.

PERTINENT WORK PERFORMED. - The indirect approach using Hamilton's principle - a mechanical system is in equilibrium at minimum potential energy - was used rather than a differential equation approach. A variational principle was used to obtain the static fluid solution, independent of viscosity. For non-rotating cylinders, the instabilities are Taylor-type and the critical Bond number for that case applies. Rotation changes the Taylor stability curve and stability depends on the contact angle as to direction of movement. A limiting stability occurs when the rotational speed throws the liquid to the outer wall. Tests were conducted with water and methanol in small cylinders to verify the rotational results. Drop tower tests were also conducted with rotating cylinders.

MAJOR RESULTS. -

1. For the non-rotating case, the first instability appears in an antisymmetric mode. The existance map for the stable region without rotation is shown in Figure 1.
2. The stability map for the rotating case is shown in Figure 2. Above the dotted line and above the Ω_c^2 curves, a stable interface exists. Below the dotted line but above the Ω_c^2 curves, no meniscus exists. Below the curve and below the dotted line, the meniscus which exists will exhibit Taylor instabilities.
3. Two special cases from Figure 2 are shown in Figure 3 and 4. In the former, the existence map for zero Bond number is shown. In Figure 4, the existence map at zero contact angle is presented. These are special cases of general interest for the rotating-cylinder interface.
4. This study indicated rotation makes wetting liquids more susceptible to Taylor instability and non-wetting fluids less susceptible than would occur for no rotation. The limit of stability for the meniscus in a rotating cylinder is non-existence, and is affected by contact angle.

COMMENTS. - The rotation of a transfer tank can be a positive factor in liquid location identification. Results here, which were verified, indicate viable operating regions.

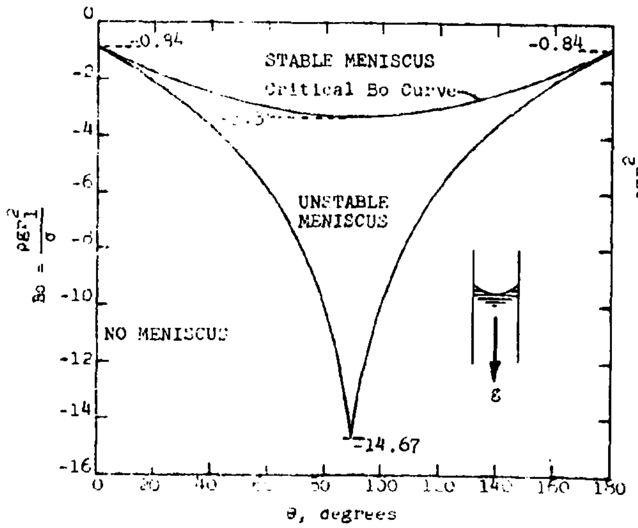


Figure 1. Existence Map (no Rotation)

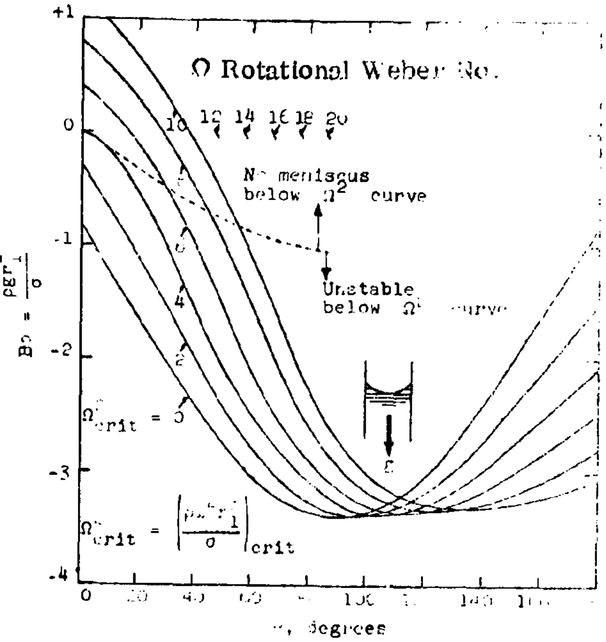


Figure 2. Stability Map

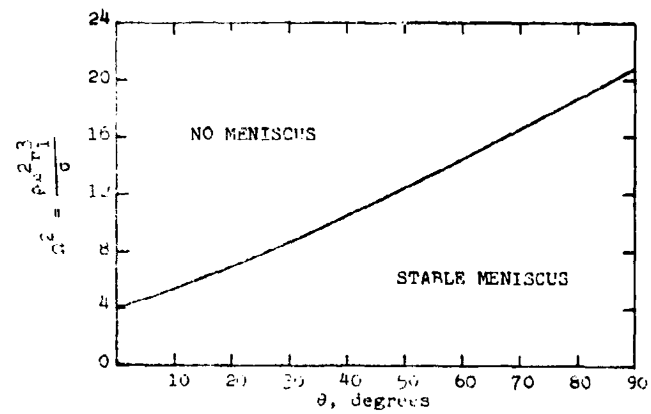


Figure 3. Existence Map (Zero Bond No.)

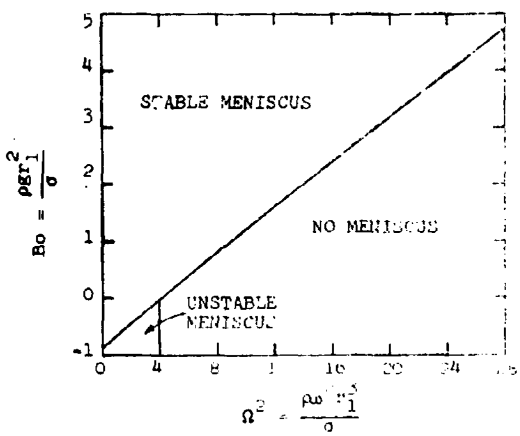


Figure 4. Existence Map (Zero Contact Angle)

CAPILLARY HYDROSTATICS AND HYDRODYNAMICS AT LOW-G, Reynolds, W. C., et al, Tech. Rpt. LG-3, Stanford University, NSF-G20090, September 1964

OBJECTIVE. - To provide data on stable liquid interface conditions for the design of space systems.

PERTINENT WORK PERFORMED. - A model was formulated using the calculus of variations to determine the critical Bond number for stability. Many geometric considerations were analyzed as to their influence on stability; this included annuli, parallel meniscus, and rotating axisymmetric meniscus.

MAJOR RESULTS. -

1. The results of the analytical model for critical Bond number are given in Figure 1 where $B_{crit} = f(r/r_w \sin\theta, \alpha)$. Maximum critical Bond numbers occur for flat interface ($\alpha = 90°$). The inverted meniscus is unstable at all Bond numbers if positive wall curvature exists.

2. The results from extensive experiments in slightly tapered tubes are shown in Figure 2. The tests support the analytical results.

3. The stability of annular menisci are presented in Figure 3 for a flat meniscus. A correction from Figure 2 is appropriate for other contact angles. For example with zero contact angle and $R_i/R_o = 1$, $B_{crit} = 1 \times 0.84/3.39 = 0.25$.

COMMENTS. - This rather basic and fundamental work provides working graphs which can be used for determining stability in capillary systems.

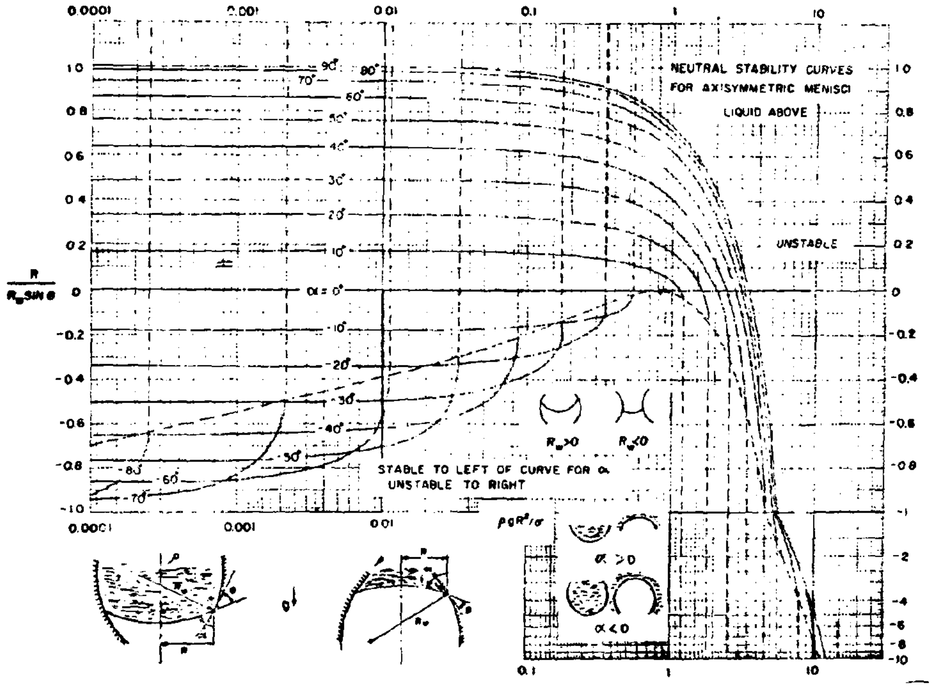


Figure 1. Neutral Stability Curves for Axisymmetric Menisci–Liquid Above

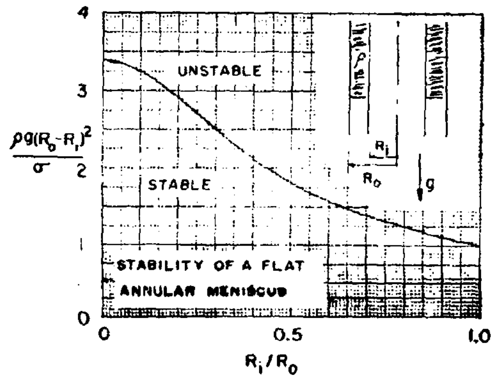


Figure 3. Stability of a Flat Annular Meniscus

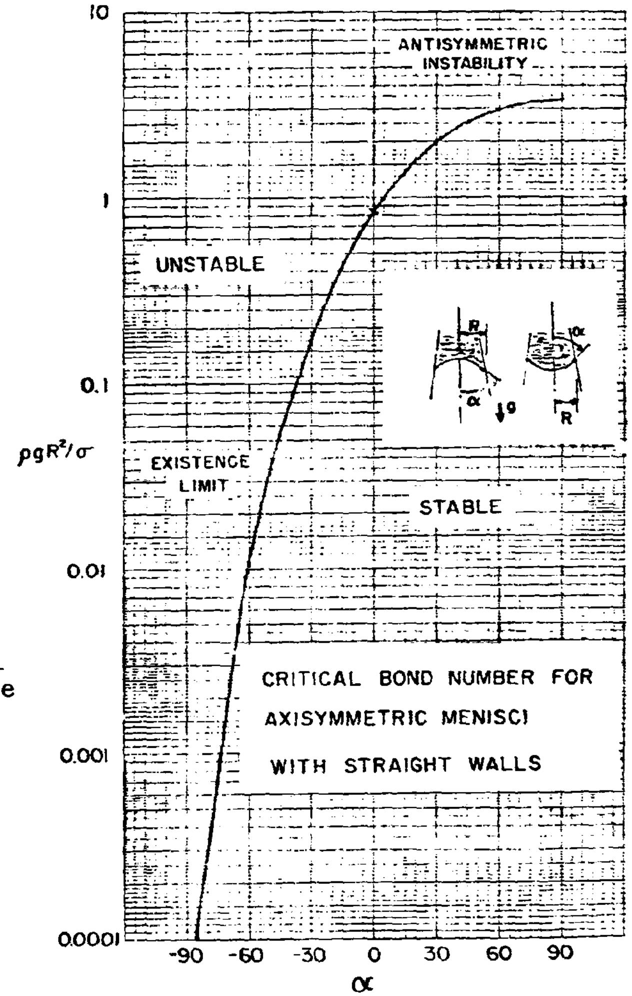


Figure 2. Critical Bond Number for Axisymmetric Menisci With Straight Walls

HYDROSTATIC STABILITY OF THE LIQUID-VAPOR
INTERFACE IN A LOW-ACCELERATION FIELD,
Masica, W. J., et al, NASA-LeRC TN D-2444, August 1964

OBJECTIVE. - To determine the hydrostatic stability of the interface in a right circular cylinder when subjected to axial accelerations in a low-g environment.

PERTINENT WORK PERFORMED. - This work extended the study of interface stability criterion Masica (TN D-2267) from 1-g to acceleration of 0.1- and 0.01-g. The tests were performed in the LeRC 2.2 sec drop tower in cylinders of 8 to 50 mm using four test liquids. A one-sec period in 10^{-5} g for the interface to form was followed by a similar period with thrustors-on to produce the desired g-level.

MAJOR RESULTS. -

1. The results from the earlier work in one-g are presented in Figure 1. Using the criteria of $Bo_{crit} = 0.84$ established there, tube diameters were selected for this study. The over-all results are presented in Figure 2 and confirm the established critical Bond number of 0.84 for the g-range 0.01 to 1.0. The liquid interface in a right circular cylinder will be stable until an adverse acceleration causing the Bond number to exceed 0.84 occurs.

2. The results for ethanol are extended to larger tank sizes in Figure 3 to indicate the order of magnitude of the g-level which will destabilize the interface. In typical tanks, destabilization will occur with g-fields of 10^{-6} or greater.

COMMENTS. - This is the work which established the critical Bond number concept for interfaces which is widely used in evaluating fluid orientation.

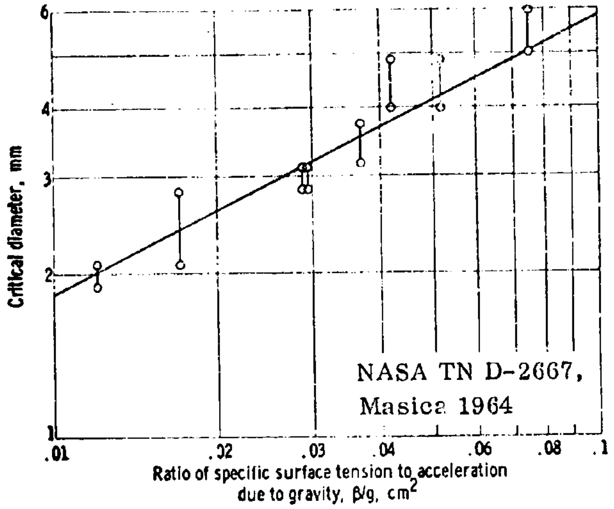


Figure 1. Stability Characteristics in Vertical Cylinder at 1g

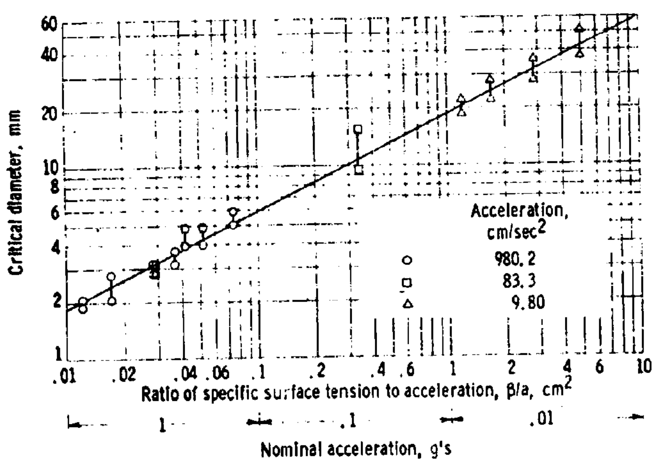


Figure 2. Interface Stability Delineated by Bond No. Criterion

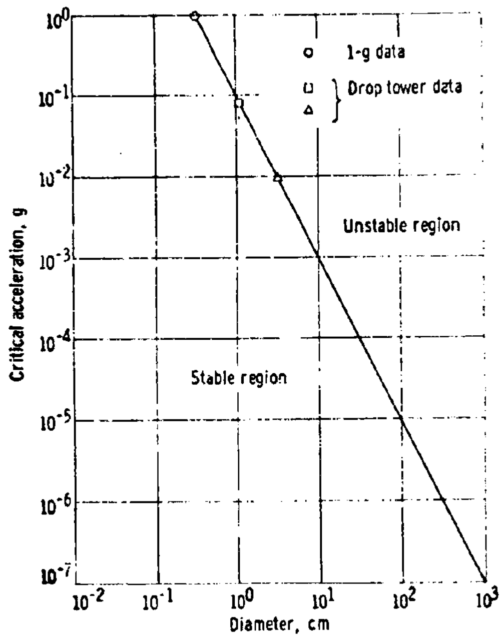


Figure 3. Interface Stability of Anhydrous Ethanol as Function of Acceleration. Specific Surface Tension, 28.25 cm Cubed per Second Squared

CAPILLARY STABILITY IN AN INVERTED RECTANGULAR TANK
Concus, P., LMSC, Advances in the Astronautical Sciences, Western Periodicals Co., No. Hollywood CA., Vol. 14, pp. 21-37 (1963)

OBJECTIVE. - To define static and dynamic stability for all contact angles for an incompressible inviscid fluid in an inverted rectangular channel.

PERTINENT WORK PERFORMED. - An analytical solution to the stability of the interface is derived considering the static and dynamic equations for all contact angles 0 to 90°. The configurations studied are shown in Figure 1 and 2. The static method was studied with a variational approach to the differential equation; this approach is from energy considerations. The dynamic approach considers the velocity potential and the amplitude of the normal modes as a function of time.

MAJOR RESULTS. -

1. The results are presented for contact angles 0 to 180° in Figure 3. For contact angles 90 to 180°, the equations are valid but must be modified slightly from the 0 to 90° solution. As in cylinders, the zero Bond number configuration is stable and it is only adverse accelerations which are unstable.
2. A configuration such as shown in Figure 2 where the radius of curvature changes sign is shown to never be stable.
3. The variations in the interface profile in the channel are shown for various Bond numbers in Figure 4. For a contact angle of zero degrees, Bond numbers greater than 0.718 are proven to be unstable.

COMMENTS. - This is an entirely theoretical work and there are no experimental data used to verify the theoretical effort. The configuration has potential application in propellant control devices.

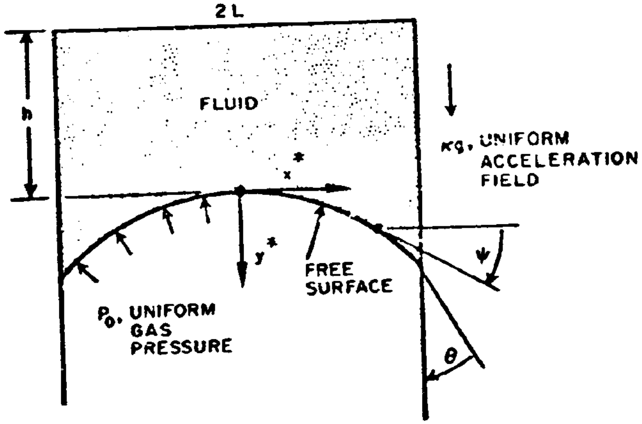


Figure 1. Equilibrium Fluid Configuration

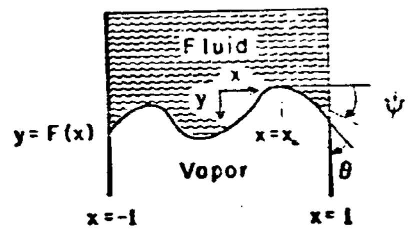


Figure 2. Geometric Configuration

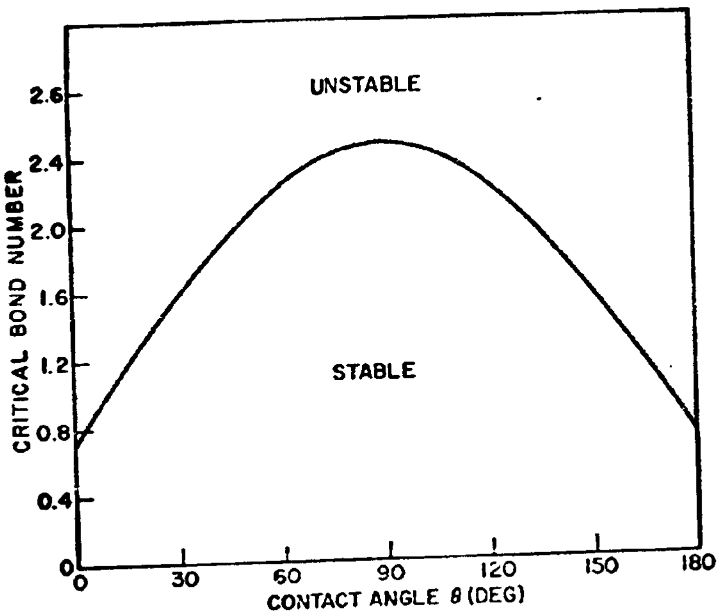


Figure 3. Critical Bond Number as a Function of Contact Angle

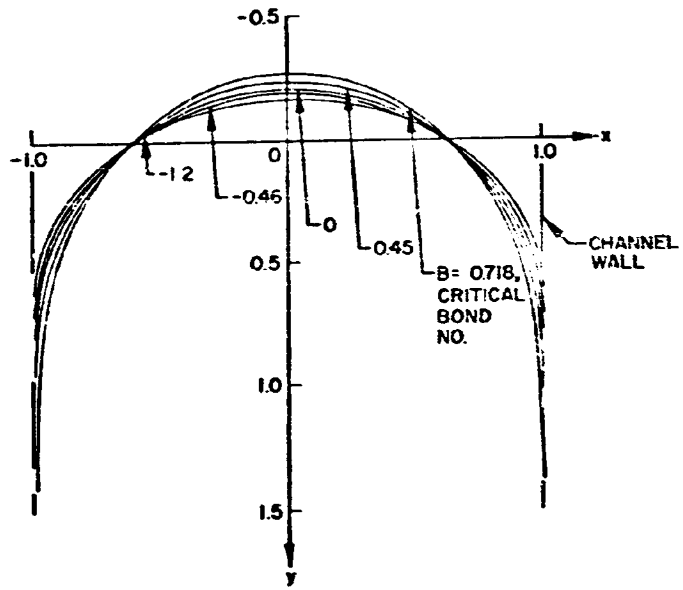


Figure 4. Equilibrium Interfaces for Various Bond Numbers With Contact Angle 0°, B = 0.718 is the Critical Bond Number

4.0 NATURAL FREQUENCY AND DAMPING

Covering lateral and longitudinal sloshing, slosh waves and tank elasticity effects, and slosh suppression by baffles and viscous damping.

RING-BAFFLE PRESSURE DISTRIBUTION AND SLOSH DAMPING IN LARGE CYLINDRICAL TANKS
Scholl, H.F., et al, NASA-LRC TN D-6870, December 1972

OBJECTIVE. - To determine the pressure loads and damping associated with rigid ring-baffles in large cylindrical tanks.

PERTINENT WORK PERFORMED. - The available theories were reviewed to predict the pressure loads and damping for single and double ring-baffle designs in large tanks. Tank diameter was 284 cm, one or two baffles were used in the cylindrical tank. The baffles were 14.2 cm wide and were below, at, or above the surface. The configuration and dimensions are shown in Figure 1. The test fluid was water. A plunger was used to manually apply vertical excitation at the fundamental slosh antinode. Baffle pressures and slosh frequency and amplitude were measured.

MAJOR RESULTS. -

1. The measured pressures at the baffles were a function of the liquid velocity. When the fluid is within 0.1 tank radius of the baffle, $d/r < 0.1$, the pressure is uniform over the baffle. Surface ampiitudes for velocity parameters and various liquid/ baffle depths are shown in Figure 2.
2. The baffle was most effective in slosh damping where $d/r < .5$; this condition also resulted in the highest baffle pressures. A typical baffle pressure correlation is given in Figure 3.
3. A second baffle located deeper in the liquid did not noticeably effect pressures on the upper baffle.
4. For submerged baffles, the theory based on oscillating flow developed in this report and NASA SP-8009 agree well with experimental results. Although not as precise for liquid at the level of the baffles, pressure predictions are adequate for design.
5. For exposed baffles, the submerged theory of this report predicts the magnitude and trend with fair accuracy and better than splash theory of NASA SP-8009.
6. The second baffle does not improve the situation by the sum of individual baffles. In fact, close spacing may be detrimental and baffle performance for damping may be less than the single baffle. The comparison of multiple baffles in damping is shown in Figure 4.

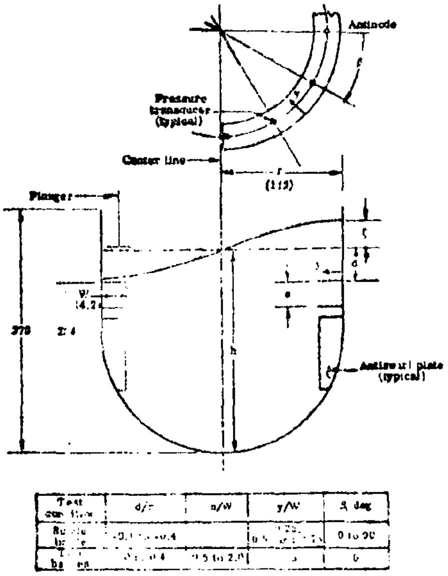


Figure 1. Slosh Tank Dimensions and Test Variables. Linear Dimensions Are in Centimeters

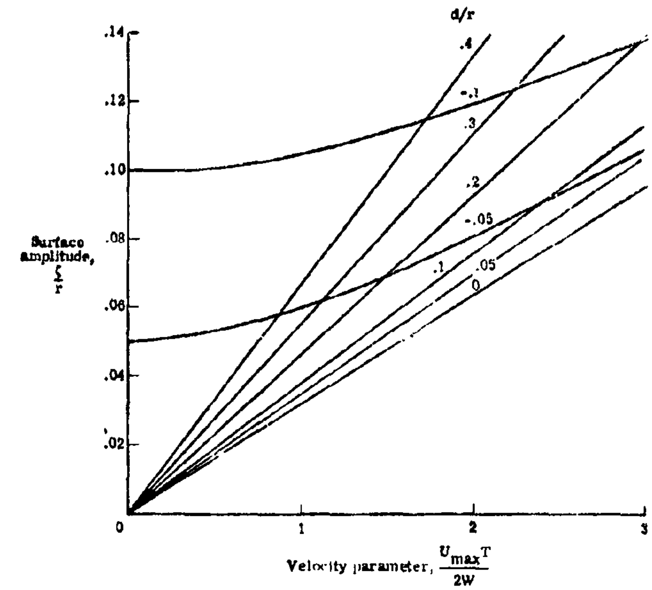
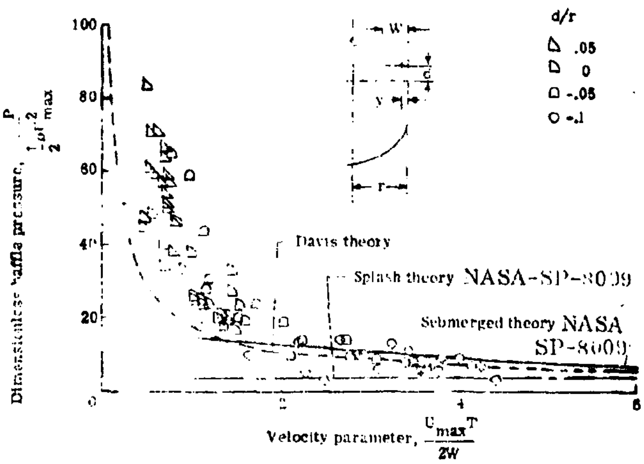


Figure 2. Variation of Surface Amplitude with Velocity Parameter for Various Baffle Depths



(a) y/W = 0.25.

Figure 3. Effect of Velocity Parameter on Baffle Pressure Parameter for a Range of Baffle Depths, Single Baffle, β = 0°

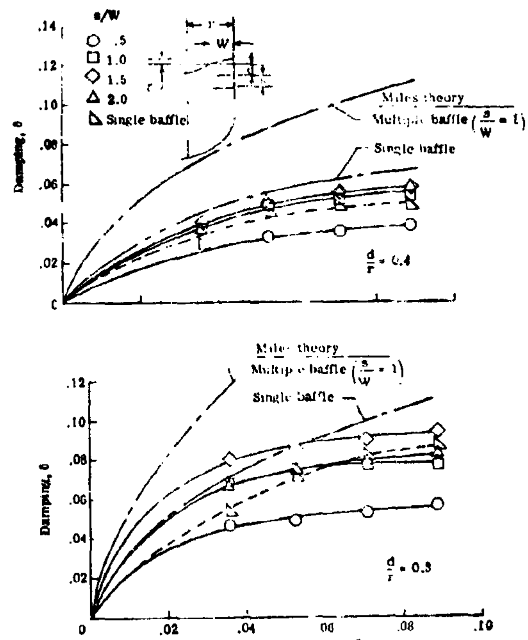


Figure 4. Effect of Surface Amplitude on Liquid Damping for a Range of Baffle Spacings and Depths

ENGINEERING STUDY OF FLEXIBLE BAFFLES FOR SLOSH SUPPRESSION

Dodge, F. T., SwRI. NASA CR-1880, NAS1-10074, September 1971

OBJECTIVE. - To determine the potential of flexible plastic baffles in a LO_2 flight system to provide high damping with lightweight baffles.

MAJOR WORK PERFORMED. - A study was performed to determine the available materials for this application. The selected list. whose properties are shown in Table 1, included plastics A (a polyester film), B (a polyimide film), C (a fluoronated ethylene propylane film), D (a polychlorotrifluoroethylene film), E (a polytetrafluoro ethylene film), and F (a polyvinylidene chloride film). Plastics A, B, and F were least compatible with LO_2, however, C. D, and E appeared suitable. The schematic of the flexible baffle is compared with the rigid baffle in Figure 1. Reuse tests of 100 cycles were conducted with LN_2 in a 30-inch tank.

MAJOR RESULTS. -

1. The damping ratio of flexible to rigid baffles is shown in Figure 2 for period parameter P which is a function of the slosh amplitude ζ_0, tank size, and the flexibility parameter F which is a function of the baffle size, properties and g-level.
2. Test results for 3 plastics are presented in Figure 3. The results indicate that these baffles are suitable for the LO_2 application. The optimum baffle developed from plastic has a large flexibility parameter of 0.1 to 0.2.
3. As indicated above, an improved damping factor results for a system of only 12 per cent the weight of a rigid baffle system
4. No structural or fatigue damage resulted after 100 reuse cycles. No problems of thermal shock for plastic baffles in aluminum tanks were experienced. The previous empirical correlations of damping as a function of period parameter and flexibility parameter were extendable to cryogenic temperatures.

COMMENTS. - Although not discussed in this CR, Dodge has indicated verbally that stainless steel in thin guages is now available to be used as flexible baffles.

Table 1. Properties of Candidate Materials

	ρ_B, kg/m³	α, m/m · °C	20°C σ_{yield}, newton/m²	20°C $\sigma_{ultimate}$, newton/m²	20°C E, newton/m²	-196°C σ_{yield}, newton/m²	-196°C $\sigma_{ultimate}$, newton/m²	-196°C E, newton/m²	$\rho_B E^{1/2}/(\sigma_{yield})^{3/2}$, kg/newton-m
Plastic A	1.40×10^3	2×10^{-5}	6.2×10^7	13.8×10^7	4.5×10^9	15.2×10^7	[illegible]	8.3×10^9	6.8×10^{-5}
Plastic B	1.42×10^3	2×10^{-5}	4.2×10^7	10.4×10^7	3.1×10^9	15.0×10^7	[illegible]	5.5×10^9	5.8×10^{-5}
Plastic C	2.15×10^3	8×10^{-5}	1.1×10^7	3.9×10^7	0.7×10^9	8.3×10^7	[illegible]	7.2×10^9	24.0×10^{-5}
Plastic D	2.20×10^3	5×10^{-5}	2.1×10^7	3.8×10^7	1.2×10^9	8.5×10^7	10.0×10^7	4.5×10^9	19.0×10^{-5}
Plastic E	2.10×10^3	5×10^{-5}	1.9×10^7	2.1×10^7	1.1×10^9	9.4×10^7	9.9×10^7	4.7×10^9	15.1×10^{-5}
Plastic F	1.65×10^3	20×10^{-5}	2.0×10^7	4.0×10^7	0.5×10^9	19.0×10^7	19.4×10^7	9.8×10^9	6.3×10^{-5}
1100(H14) Alum.	2.70×10^3	2×10^{-5}	14.5×10^7	25.5×10^7	69.0×10^9	16.5×10^7	30.0×10^7	79.0×10^9	43.0×10^{-5}

NOTE: 0.69×10^4 newton/m² = 1 lb/in².

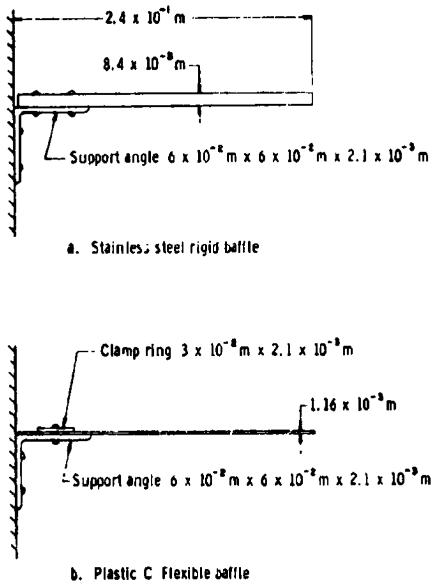


Figure 1. Simplified Baffle Support System

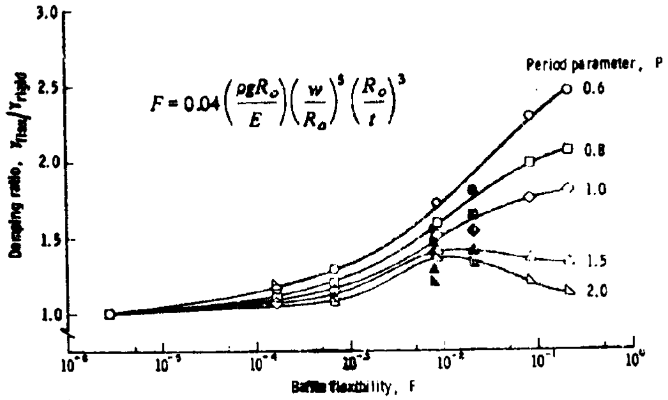


Figure 2. Relative Damping as a Function of Flexibility and Period Parameters (Stephens 1967)

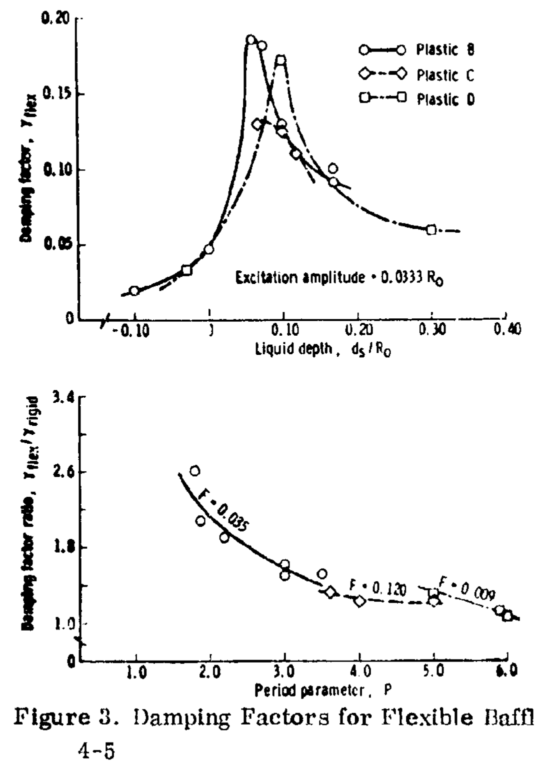


Figure 3. Damping Factors for Flexible Baffles

t baffle thickness, meter
w baffle width, meter
d_s baffle distance under free surface, meter

LATERAL SLOSHING IN OBLATE SPHEROIDAL TANKS
UNDER REDUCED AND NORMAL-GRAVITY CONDITIONS
Coney, T.A., Salzman, J.A., NASA-LeRC TN D-6250, March 1971

OBJECTIVE. - To measure the natural lateral sloshing frequency of liquid in oblate spheroidal tanks and compare the results with theory for high and low Bond numbers.

PERTINENT WORK PERFORMED. - A series of tests were conducted in the LeRC 5.1 sec drop tower to evaluate lateral sloshing in 2, 3, and 4 cm major axis oblate spheroids with eccentricities 0, 0.68, and 0.8. Four liquids with zero contact angle, carbon tetrachloride, ethanol, FC-78, and Freon TF were used at fill levels of 25 to 87.5 percent. Thrustors were used to achieve a Bond number range of 5 to 927. The natural frequency was determined with use of a film analyzer for analysis of the interface (Figure 1). A typical plot appears in Figure 2. The disturbance force was a 0.5 cm lateral movement of the container on a sliding platform.

MAJOR RESULTS. -

1. The measured natural frequencies are presented in Figure 3 and 4 for two fill levels. The natural frequency parameter Ω is defined $\omega\ (\beta/x^3 + a/x)^{1/2}$ where a is the acceleration, x is the semimajor axis (Figure 1), β is surface tension, and ω is the natural frequency. The measured natural frequencies compare well with theory of Concus 1969 at low Bond numbers and Rattayya, 1965 at higher Bond numbers. The transition between high and low Bond number theories is a function of fill level and eccentricity, however, it is generally in the region $60 < Bo < 100$.

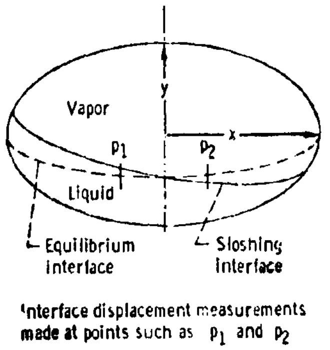


Figure 1. Test Geometry

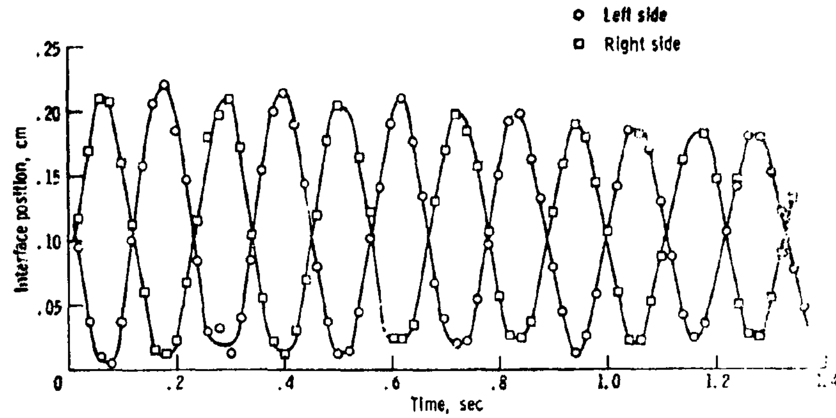


Figure 2. Sample Data Plot of Lateral Slosh. Bond Number, 514

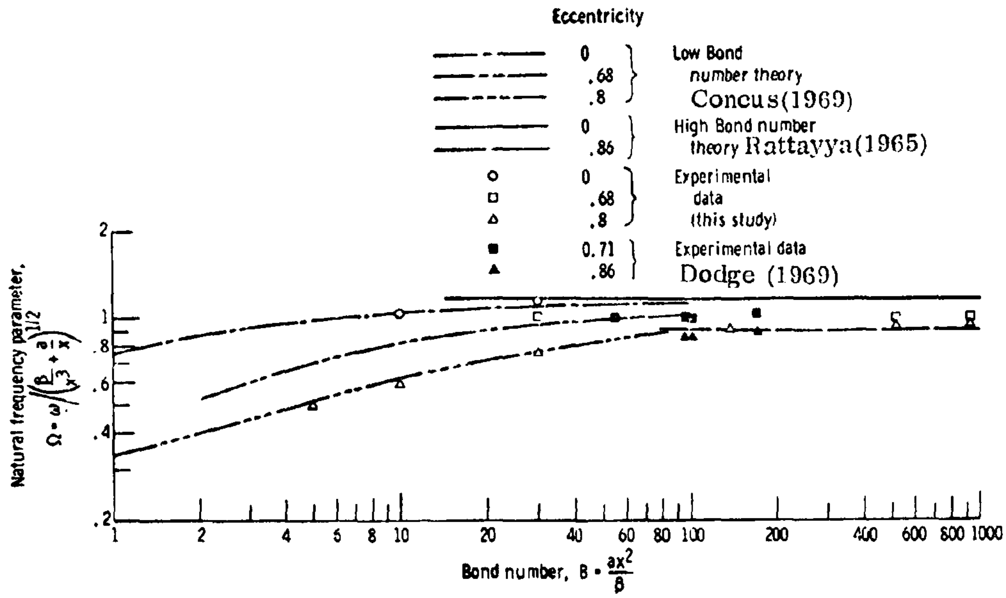


Figure 3. Comparison of Published Slosh Data, Filling, 25 Percent

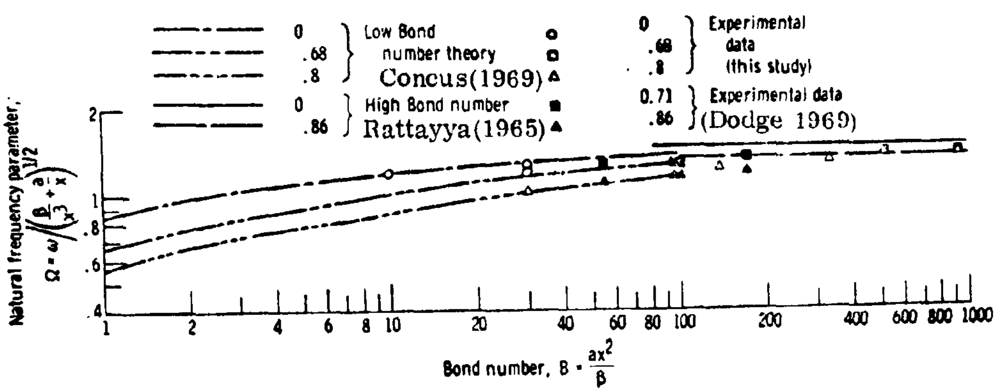


Figure 4. Comparison of Published Slosh Data. Filling, 75 Percent

STUDIES OF PROPELLANT SLOSHING UNDER LOW GRAVITY CONDITIONS, FINAL REPORT
Dodge, F. T., SwRI, Project 02-1846, NAS8-20290, October 1970

OBJECTIVE. - To study sloshing due to axial and lateral accelerations for 0° contact angle liquids in axisymmetric tanks under low-gravity conditions. To derive equivalent mechanical models of sloshing for use in stability and control analyses.

PERTINENT WORK PERFORMED. A series of sloshing tests were performed in either small containers or with magnetic fields to achieve low Bond number conditions. Variables included container shape, container size, and the fluids used. Both smooth wall-damping and rigid and flexible ring baffles were considered. Analytical modeling for defining slosh parameters was developed and verified with extensive small-scale test programs. This work was documented in ten technical reports whose abstracts are presented in this final report and which are generally available on microfiche and in six papers of which copies are included.

MAJOR RESULTS. -

1. Analytical results using an equivalent mechanical model for sloshing in rigid cylindrical tanks indicate the fundamental sloshing mass and natural frequency are smaller at low-g than high-g for zero contact angle fluids. Experimental verification from $10 < Bo < 200$ confirmed the proposed analytical model.

2. The damping factor in cylindrical tanks is affected by h/d in a manner similar to high-g results. Slosh damping increases as Bond number decreases. Low gravity natural slosh frequency can be predicted from high-gravity results, Figure 1. As Bond number decreases, the slosh mass decreases due to wall effects, Figure 2. A suggested empirical damping coefficient equation is derived:

$$\gamma_s = 0.83\, N_{GA}^{-.5} \left(1 + 8.20\, N_{Bo}^{-.6}\right) \quad \text{for Bo} > 10$$

3. In spherical tanks, increased interface curvature causes natural frequency to decrease with decreasing Bo, the opposite is true for cylinders.

4. The character of slosh force with excitation frequency for spherical tanks is shown in Figure 3. The natural frequency theory for sloshing of Concus, 1969 is verified with the experimental results presented in Figure 4. The equivalent spring-mass system has been used to define slosh force and moments for arbitrary axisymmetric rigid tanks for both pitching and translational oscillations in an effort paralleling that of Concus, 1967, 1969. Numerical examples compare favorably with theory and experiment.

COMMENTS. - This effort represents the most current in-depth effort in areas of low-gravity sloshing experimentation and correlations. The results are most pertinent for low-g transfer. However, Salzman, 1969 comments that these results can not be extrapolated to Bond numbers approaching zero; i.e. less than 10.

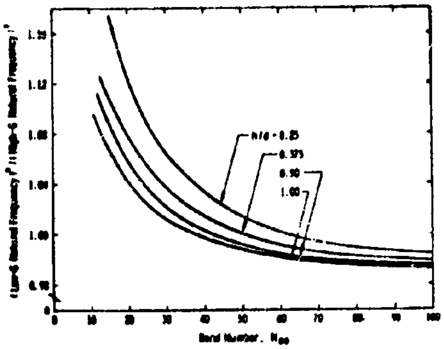


Figure 1. Variation of Slosh Natural Frequency with Bond Number in Cylindrical Tanks

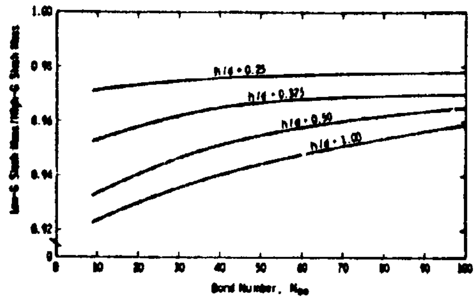


Figure 2. Variation of Slosh Mass with Bond Number in Cylindrical Tanks

x_o excitation amplitude

γ_s damping coefficient

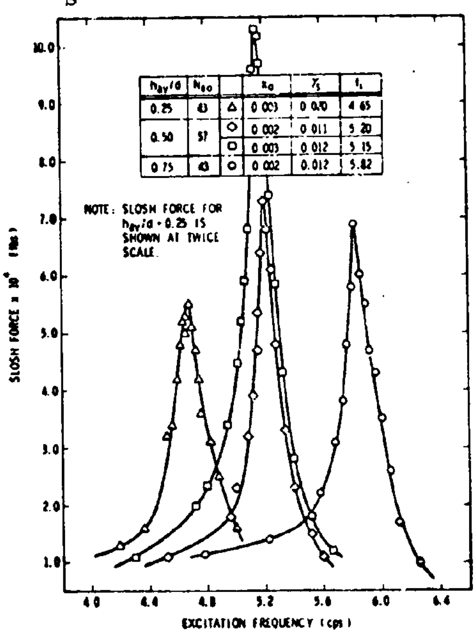


Figure 3. Typical Force Response for Spherical Tanks

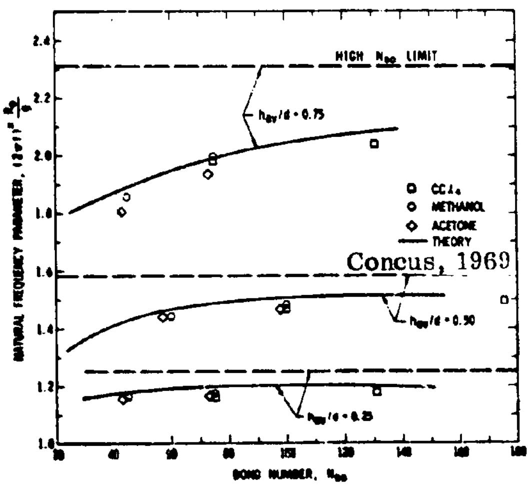


Figure 4. Variation of Natural Frequency with Bond Number for Spherical Tanks

EFFECTS OF VORTEX SHEDDING ON FUEL SLOSH DAMPING PREDICTIONS
Cole, Jr., H.A., NASA-Ames, TN D-5705, March 1970

OBJECTIVE. - To correlate a wide range of test data on fuel slosh damping with ring baffles in cylindrical tanks.

PERTINENT WORK PERFORMED. - Experimental measurements were collected from several investigations covering a range of tank sizes from 12 to 112 inches, oscillation amplitudes from 0.1 to 1.5 baffle widths, and baffle depths of 0.3 to 0.5 tank radius. An analytical study on the specific contributions (correction factors to Miles 1958 analysis) for wall damping, generalized mass change due to translation, and vortex shedding was conducted. Experimental studies on vortex shedding were conducted to better understand this phenomena.

MAJOR RESULTS. -

1. The assembled test results are shown in Table 1 where ζ is the damping ratio, A is the baffle double amplitude, and W is the baffle width, a is the tank radius, y_s is wave amplitude at wall, and d is the baffle depth to quiescent liquid. These results are plotted in Figure 1a per Miles method. The succeeding sequence indicates the improvement in the correlation as the correction factors are added. It is significant to note the improvement gained with the vortex shedding correction at low A/W.

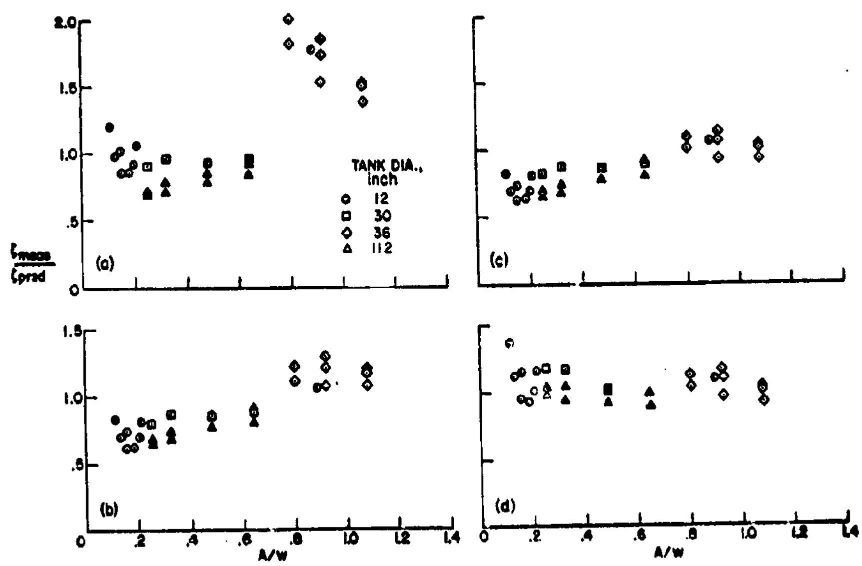
Table 1. Experimental Data

[Wave decay method]

Tank	2a (in.)	w/a	d/a	y_s	A/w	ζ_{meas}	ζ_o
Delaurier[a]	11.45	0.083	0.466	0.098	0.89	0.0145	0.0055
Reference	11.9	.125	.505	.032	.20	.0055	.0019[b]
(O'Neill, 1960)				.023	.15	.0052	
				.017	.11	.0052	
				.034	.21	.0065	
				.028	.18	.0047	
				.024	.15	.0044	
				.021	.13	.0047	
Reference	30	.1	.3	.0216	.25	.0083	.001[b]
(Stephens, 1967)				.0276	.32	.0099	
				.0415	.48	.0118	
				.0552	.64	.014	
Reference (Cole 1966)	36	.083	.33	.0834	1.08	.0165	.0035
t/w = 0 and 0.042						.018	
						.0183	
			.42		.92	.0123	
						.015	
						.014	
			.5		.8	.011	
						.010	
Reference 7	112	.1	.3	.0216	.25	.0062	.0003[b]
(Stephens 1967)				.0276	.32	.0073	
				.0415	.48	.0108	
				.0552	.64	.0135	
			.4	.026	.25	.0046	
				.0334	.32	.0056	
				.05	.48	.0070	
				.0667	.64	.0084	

[a]Unpublished Ames tests by James Delaurier.

[b]Estimated from reference (Stephens, 1962)



(a) Miles equation.
(b) Wall damping included.
(c) Wall damping and generalized mass factors included.
(d) Wall damping, generalized mass, and vortex shedding factors included.

Figure 1. Comparison of Predicted Damping by Miles' Equation with Measurements

NATURAL FREQUENCY OF LIQUIDS IN ANNULAR CYLINDERS UNDER LOW GRAVITATIONAL CONDITIONS
Labus, T.L., NASA-LeRC TN D-5412, September 1969

OBJECTIVE. - To determine the natural frequency of liquid sloshing in annular cylinders.

PERTINENT WORK PERFORMED. - An analytical investigation and experimental verification were performed to extend the natural frequency correlations for right circular cylinders to annular cylinders. A form of the equation was developed from earlier work in cylinders:

$$\Omega_A^2 \equiv \omega^2 R^3/\beta = f_2 (r/R) + f_1 (r/R) Bo$$

The constants were solved for using 0.63 to 2.05 cm radii cylinders with r/R of 0.09 to 0.74 for Bond numbers 0 to 200. Both the 2.2 and 5.1 sec towers at LeRC were used to provide the low-gravity Bond numbers; high Bond number tests were at 1-g. Four liquids were used which had nearly zero contact angle in the acrylic annular containers. The configuration is shown in Figure 1.

MAJOR RESULTS. -

1. The results did fit the equation form suggested. For zero Bond number (the natural frequency parameter for the annulus, $\Omega_A^2 = \omega_A^2 R^3/\beta$, was larger than the cylinder parameter for r/R up to 0.3, whereas above r/R of 0.4, the cylinder parameter was larger. Figure 2 indicates that at r/R of 0.2, the parameter Ω_A reached a maximum. In Figure 3, the results for the cylinder and annulus are compared and the frequency ratio varies only from 1.2 to 0.8 over the entire range of r/R.

2. The natural frequency at all Bond numbers was dependent on the annulus ratio r/R. To fit the equation above for Ω_A^2, the function f_2 was obtained from zero Bond number data and the function f_1 from high Bond number data where f_2 is unimportant. The verification of the method is shown in Figure 4.

COMMENTS. - This experimental verification supports the theoretical work of Abramson 1966 in SP-106, Bauer 1960, and Seebold 1967.

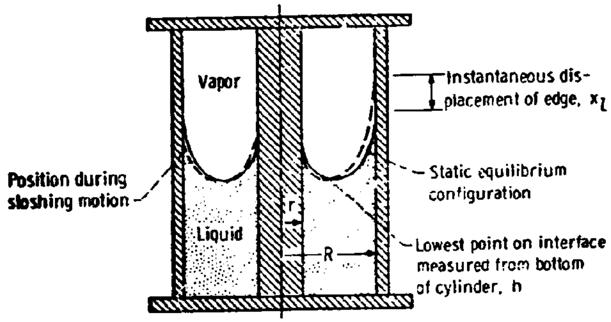


Figure 1. Typical Annular Cylinder Showing Interface Position During a Slosh Test

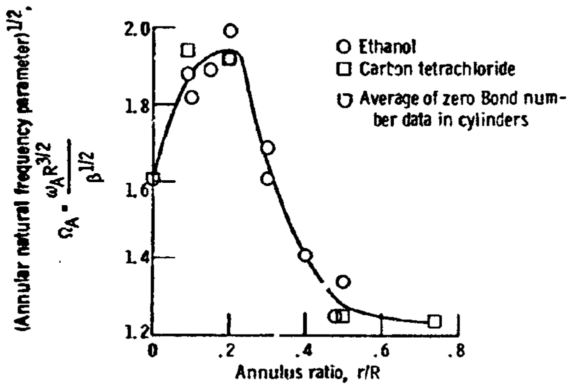


Figure 2. Natural Frequency in Annular Cylinders Under Zero Bond Number Conditions

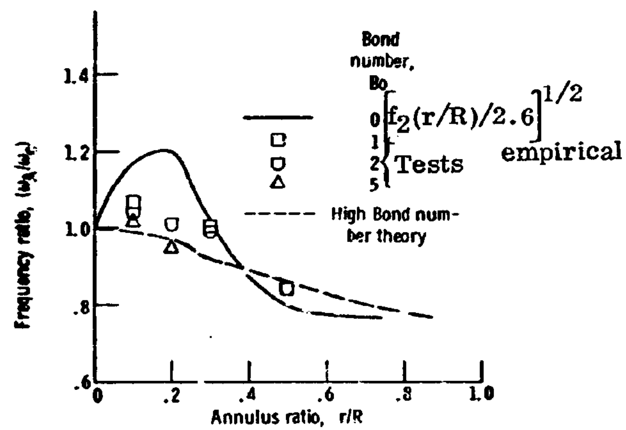


Figure 3. Natural Frequency Envelope for Annular Cylinders Under all Bond Numbers

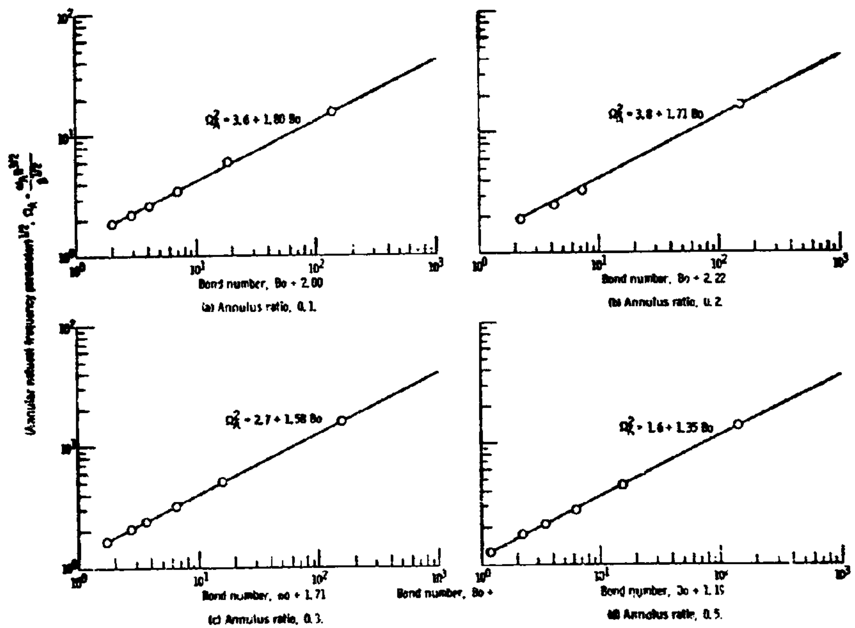


Figure 4. Correlation of Natural Frequency with the Bond Number

SLOSH SUPPRESSION
Abramson, H.N., SwRI, NASA-LRC, NASA SP-8031, May 1969

OBJECTIVE. - To present NASA guidelines for design of slosh suppression.

PERTINENT WORK PERFORMED. - The literature through early 1968 was reviewed and the information categorized into the steps for design required to include slosh suppression in the system. The various slosh suppression devices are discussed and their applications set forth. Slosh-suppression testing is discussed with extension to low-gravity sloshing. The design criteria are outlined; recommended practices are detailed.

MAJOR RESULTS. -

1. Some of the more important design correlations were included in the handbook. The wall damping ratio, ζ_{wd} is a function of the Galileo number, $a^{3/2} g^{1/2}/\nu$, where g is the longitudinal acceleration; ζ_{wd} = const. $G_A^{-1/2}$ for a non-baffled tank. A correction factor is multiplicative for low Bond numbers, i.e., ζ_{wd} = const. $G_A^{-1/2}$ (1 + const. $Bo^{-2/5}$). When baffles are used, wall damping may be neglected.

2. The effectiveness of ring-baffles is related to the baffle width, spacing, and depth of the top baffle beneath the surface. The damping ratio is plotted in Figure 1. For more than one baffle, superposition may be used.

3. The merits of compartmenting the tank to modify resonant frequencies and reduce the magnitude of the sloshing mass is illustrated in Figure 2. In low gravity conditions, the natural frequency is influenced by the Bond number.

4. In slosh-suppression testing at one-g, the Galileo number must be satisfied for similitude. For low-gravity simulation, Bond number scaling is also necessary.

COMMENTS. - Exception is taken to the super position concept in (2) above and useable data is presented by Scholl 1972 as the result of an extensive test program with baffles.

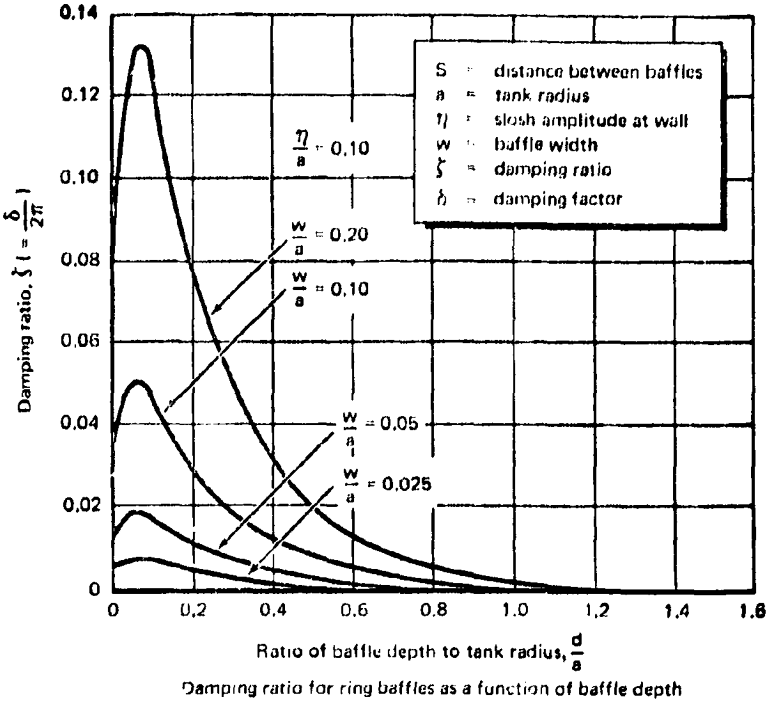


Figure 1. Ring-Baffle Damping in Cylindrical Tanks

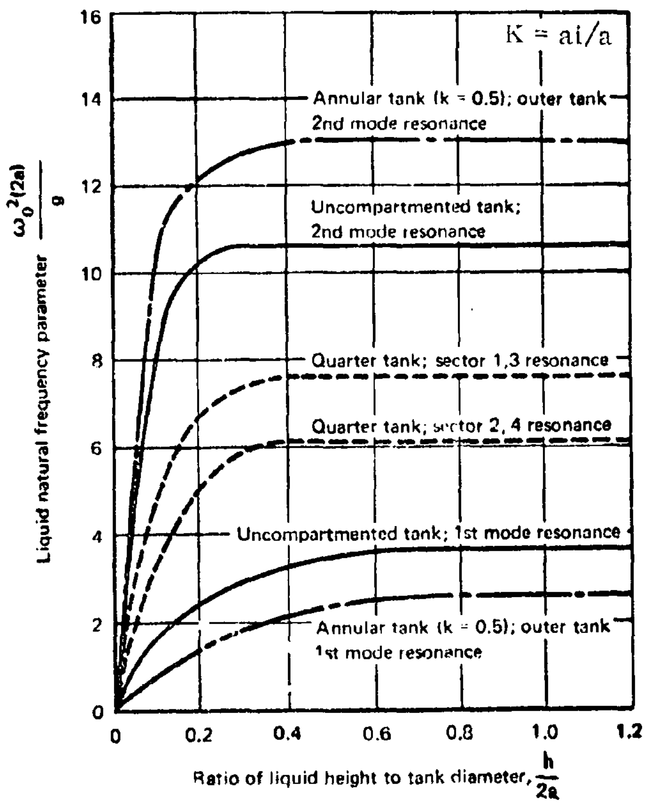


Figure 2. Variation of Liquid Natural Frequency with Liquid Height for Various Compartmented Cylindrical Tanks

SMALL AMPLITUDE LATERAL SLOSHING IN SPHEROIDAL CONTAINERS UNDER LOW GRAVITATIONAL CONDITIONS
Concus, P., et al, NASA-LeRC, CR-72500, LMSC A 944673, NAS3-9704, February 1969

OBJECTIVE. - To analytically define characteristic small-amplitude lateral sloshing in spheroidal tanks.

PERTINENT WORK PERFORMED. - The problem was formulated in a curvilinear coordinate system using a triangular mesh parallel to the low-g interface. Spheroids of eccentricity 0, 0.5, 0.68, and 0.8 were considered for fill levels of 1/8 to 7/8 for Bond numbers 0 to 100 defined on tank semi-major axis length; the contact angle was constant at 5°. At low fill levels and Bond numbers, the meniscus separates to leave dry spots on the top and bottom. The forced response to sinusoidal, square wave, and periodic pulse lateral perturbations were analyzed using a finite Fourier analysis to define the slosh frequencies.

MAJOR RESULTS. -

1. This report is noteworthy in a first attempt to predict lateral sloshing in spheroidal tanks. A restriction on the analytical method is that contact angle be non-zero.
2. The fundamental sloshing frequency was found to increase with increasing Bond number and liquid level. The fundamental sloshing frequency is near zero for zero Bond number. The trend with Bond number and liquid level is shown in Figure 1.
3. The eigenmode shapes for a spherical tank 1/2 full with a Bond number of 1 are shown in Figure 2 and are typical output of the analytical method.
4. An alternative data presentation is the liquid response to a square-wave-lateral perturbation shown for a two-circle liquid case in Figure 3. These data are developed from the Fourier analysis. When the first term is dominant, adequate engineering computations result from the spring -mass analog. Parameters for the latter analog for first mode sloshing are presented in the study.

COMMENTS. - This theoretical work on natural slosh frequency was verified in LeRC drop tower work (Coney, 1971).

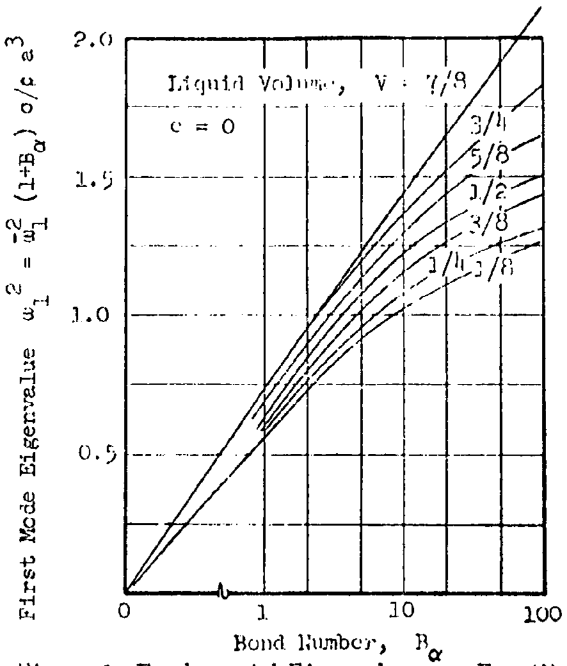


Figure 1. Fundamental Eigenvalue as a Function of B_α and V for Tanks of Eccentricity 0, 0.5, 0.68, and 0.8 (Two Circle Eigenvalues are Circled)

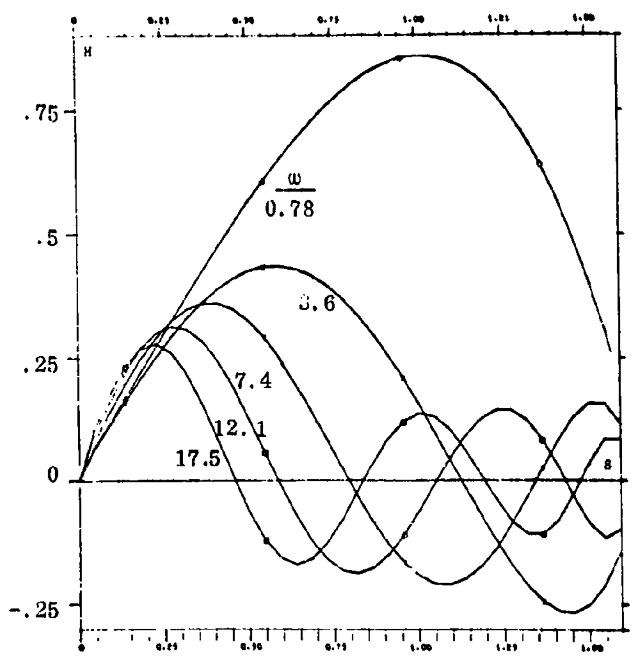


Figure 2. Eigenmode Shapes for $B_\alpha = 1$, V = 0.5 e = 0.

ω = frequency
H = $\bar{H}/a$ = normal coordinate of free surface
Z = $\bar{Z}/a$ = axial coordinate
R = $\bar{R}/a$ = radial coordinate

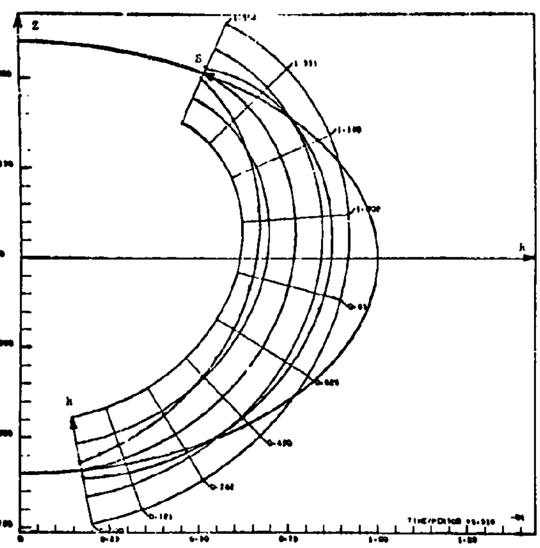


Figure 3. Liquid Response to Square-Wave Lateral Perturbing Acceleration for $B_\alpha = 1$, V = 3/8, and e = 0.8, for $\omega_0/\omega_1 = 0.7$

LATERAL SLOSHING IN CYLINDERS UNDER
LOW GRAVITY CONDITIONS
Salzman, J.A., Masica. W.J.. NASA-LeRC TN D-5058, Feb. 1969

OBJECTIVE. - To determine sloshing characteristics under low Bond number conditions in right circular cylinders.

PERTINENT WORK PERFORMED. - A series of tests were conducted in one-g and low-g to determine lateral liquid sloshing characteristics for six liquids with near zero contact angle. The 5.1 sec drop tower at LeRC was used, the Bond number range was 0 to 800 in 0.317 cm radius right circular cylinders with hemispherical bottoms. The primary method of data analysis was high-speed motion picture coverage. Results were correlated in terms of known system parameters. Results were compared with previous one-g slosh data.

MAJOR RESULTS. -

1. The fundamental slosh-mode shape exhibits a dependence of the Bond number just as the interface shape does. All sloshing after the initial wave occurred on surfaces wetted by the initial slosh wave. Variations in the contact angle (dynamic effects) were negligible.

2. The natural frequency, ω, for deeper liquids $h/R > 2$ was correlated by

$$\omega^2 = (2.6 + 1.84\ Bo)\,\sigma/\rho R^3 \qquad (1)$$

which confirmed earlier low-g studies (Salzman 1967). This expression reduces to the accepted high Bond number correlation. The correlation is shown in Figure 1.

3. For hemispherical-bottom cylinders with shallow liquid, $h/R < 2$, the results of the natural frequency data compared favorably with Concus 1967 at low Bond numbers and with Budiansky 1960 and Riley 1961 at high Bond numbers. The results for a single depth are shown in Figure 2.

4. A relation was developed for the logarithmic decrement damping factor $\delta = K_d (\nu/\omega R^2)^{1/2}$ where K_d is a nondimensional damping constant which is a function of Bond number. This study established the K_d value of 28.1 for Bo < 1 and supported earlier work at high Bond numbers > 100 for K_d of 6.1. The value of K_d as a function of Bond number is given in Figure 3. In the equation above ν is kinematic viscosity and ω the natural damping frequency.

5. A damping coefficient $\alpha = \delta\omega/2\pi$ is normalized by α at zero Bond number and is presented in Figure 4 as a function of Bond number.

COMMENTS. - This work extends the earlier work to low-g conditions and provides the needed verification of earlier work over a wide Bond number range. This report includes work of (Salzman, 1968) in TN 4458 which is not summarized.

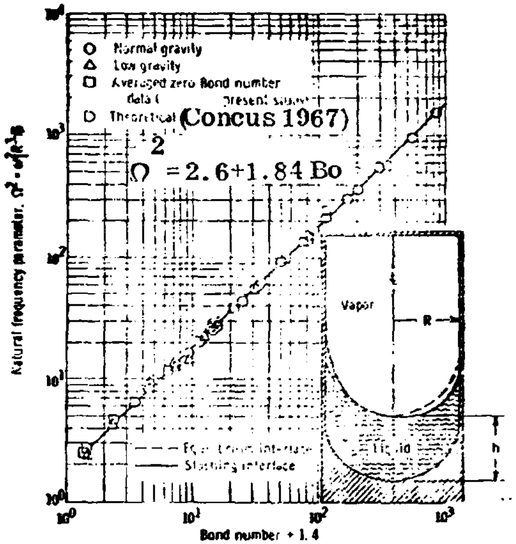


Figure 1. Correlation of Natural Frequency with Bond Number. Liquid Depth Ratio, > 2

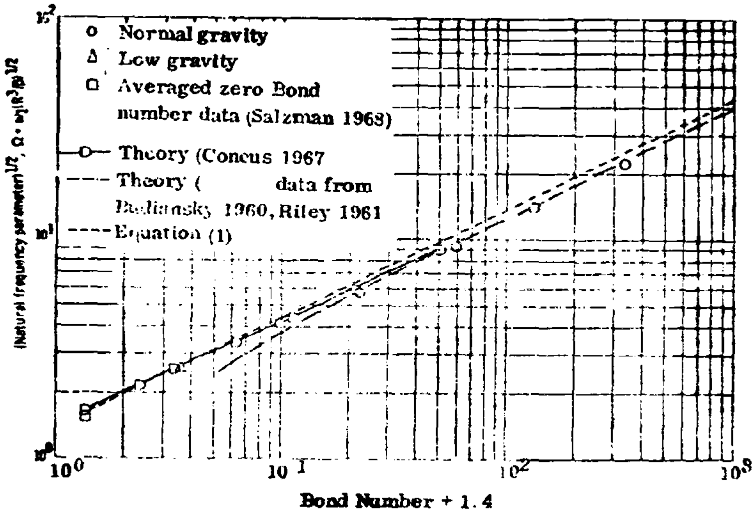


Figure 2. Natural Frequency Parameter as Function of Bond Number

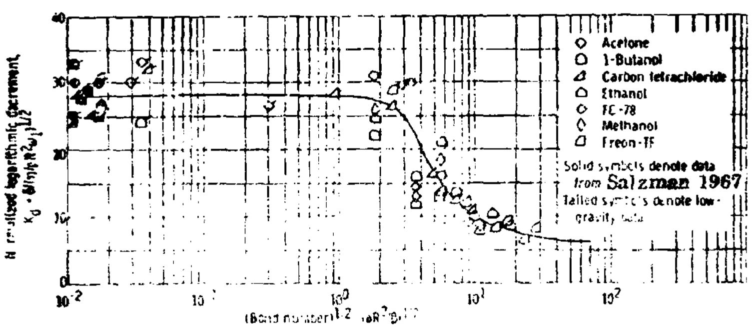


Figure 3. [illegible] Damping Data

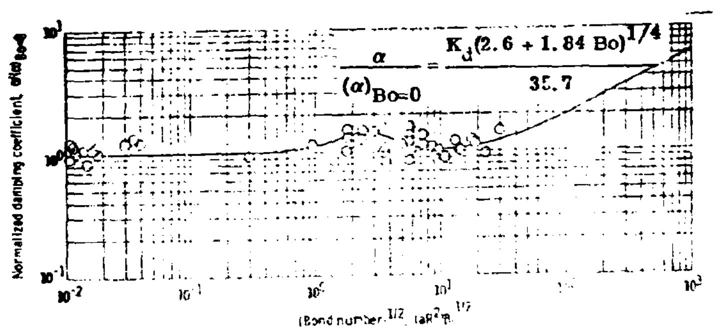


Figure 4. Damping Coefficient as Function of Bond Number

LARGE-AMPLITUDE MOTIONS OF A LIQUID-VAPOR
INTERFACE IN AN ACCELERATING CONTAINER
Perko, L.M., LMSC, J. Fluid Mechanics, Vol. 35, pp. 77-96 (1969)

OBJECTIVE. - To predict large amplitude symmetric and asymmetric irrotational motion of an inviscid incompressible fluid liquid-vapor interface in an accelerated container of revolution.

PERTINENT WORK PERFORMED. - A mathematical model was developed to predict fluid motion. A velocity potential which satisfies Laplace's equation for irrotational flow is prescribed. Surface tension and a constant contact angle are considered. The velocity potential is expanded in an infinite series. A flat-bottomed cylinder is assumed; both lateral and axial accelerations may be applied. Surface instabilities are seen to smooth out due to surface tension.

MAJOR RESULTS. -

1. An example of transverse sloshing resulting from a transverse impulse is shown in Figure 1. The impulse is brief compared to the total motion time. Traveling waves for successive time steps are illustrated.
2. In Figure 2, the time history of the surface shows a large amplitude asymmetric reorientation in which the liquid is being poured from the container with the container axis tilted 45° to the initial normal. Note that surface tension was inadequate to stabilize the final wave motion.
3. Finally, the three-dimensional aspects of the model are demonstrated in Figure 3. A liquid with a 45° contact angle is disturbed by an acceration at 45° to the container axis. The absence of surface tension dismisses the contact angle requirement. A Taylor instability terminates the problem.

COMMENTS. - The power of the method is demonstrated in these numerical examples.

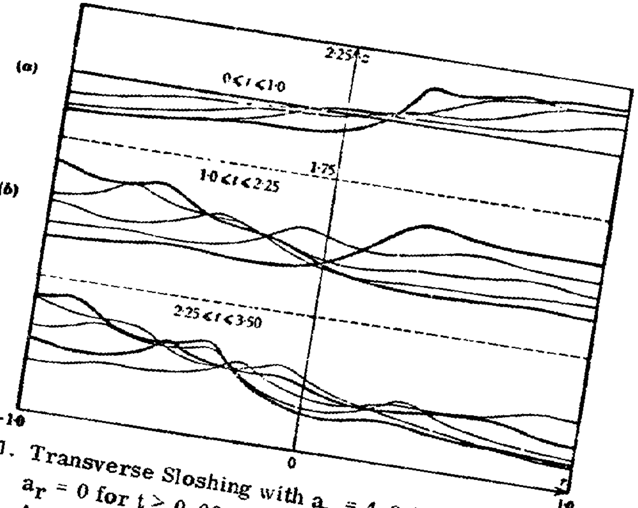


Figure 1. Transverse Sloshing with $a_r = 4.0$ for $0 \leq t \leq 0.05$, $a_r = 0$ for $t > 0.005$, $a_z = -2.0$, Bo = 25 Contact Angle = 90°

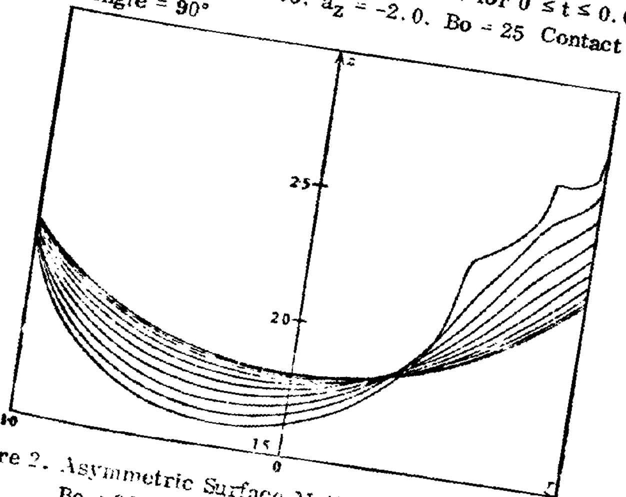


Figure 2. Asymmetric Surface Motion with $a_z = a_r = -1.0$, Bo = 20, $\Delta t = 0.08$ and Contact Angle = 45°

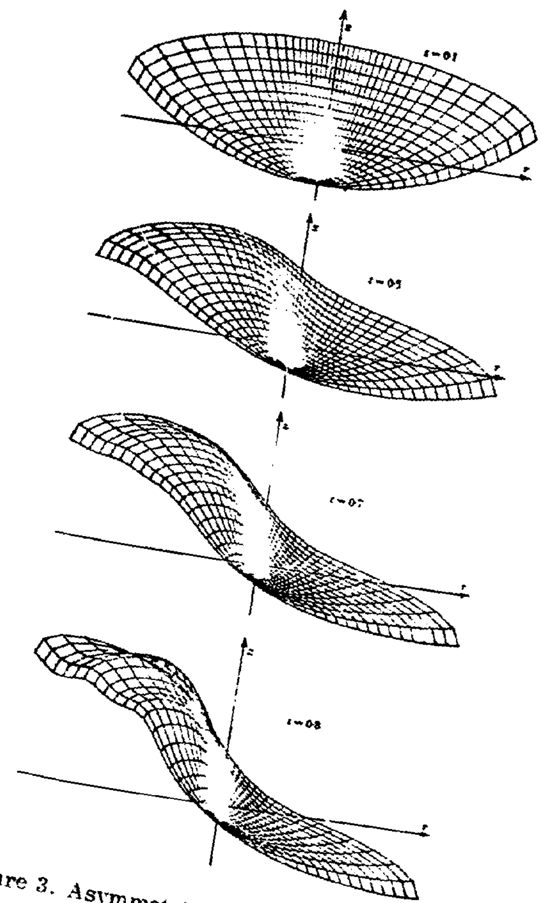


Figure 3. Asymmetric Surface Motion with $a_r = a_z = -1.0$, Bo = 0, Contact Angle = 45°

AN EXPERIMENTAL STUDY OF THE BEHAVIOR OF A SLOSHING LIQUID SUBJECTED TO A SUDDEN REDUCTION IN ACCELERATION
Toole, L.E., Hastings, L.J., NASA-MSFC-TM X-53755, August 1968

OBJECTIVE. - To investigate the behavior of an oscillating liquid column when subjected to a step change in axial acceleration.

PERTINENT WORK PERFORMED. - An experimental effort was conducted in the MSFC 4.3 sec drop tower to define fluid behavior in a model S-IVB fuel tank with and without ring baffles. The test range covered was $Bo \approx 12$ to 100 and $Fr = 0.03$ to 22. Scaling parameters were used to select variables for the test in a 3-inch radius model with petroleum ether. The liquid was sloshing before the drop and the thrustors were on from the start of the drop. Sloshing parameters were calculated and compared with other workers' correlations.

MAJOR RESULTS. -

1. The test results indicated that for the fundamental mode antisymmetric slosh wave following a sudden reduction in acceleration, the amplitude of the wave is uniquely dependent on the Froude number and equals

$$\Delta\zeta/R = 0.99\ Fr^{\,0.018\,\ln(Fr) + 0.177} \qquad (1)$$

   where $\Delta\zeta$ is (maximum liquid amplitude - amplitude at drop time).

2. The amplitude of the slosh motion was predicted without baffles to reach the top of the tank. A ring baffle was recommended for low gravity propellant control. Drop tower tests were made of the baffle; subsequent full-scale low-g tests confirmed the earlier tests and baffle effectiveness. For a non-baffled tank, the depth of the liquid at the wall below nominal was determined for various Froude numbers. Results are shown in Figure 1.

3. The logarithmic decrement for sloshing was determined as a function of the initial amplitude ratio; results are indicated in Figure 2.

4. Finally, the wave period for these tests was correlated with Bond number in Figure 3. Results were in very good agreement with the prediction for natural frequency by Satterlee 1964 in LG-2.

COMMENTS. - The experimental program presented here is a desirable task prior to flying the full-scale vehicle. Considerable information on operations was gained and model testing was justified. It appears the Δr variable correlated in Equation (1) with the Froude number may not provide a covenient design equation unless good data is available on amplitude and Froude number.

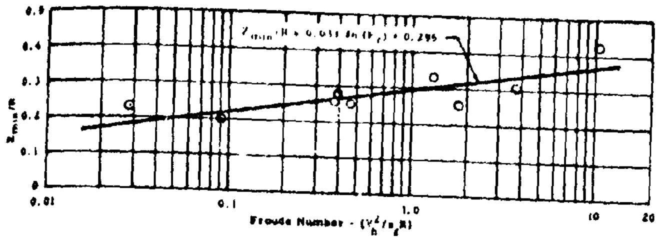


Figure 1. Maximum Depth of Liquid Vapor Interface Below Nominal Liquid Level When Liquid is at Peak Amplitude

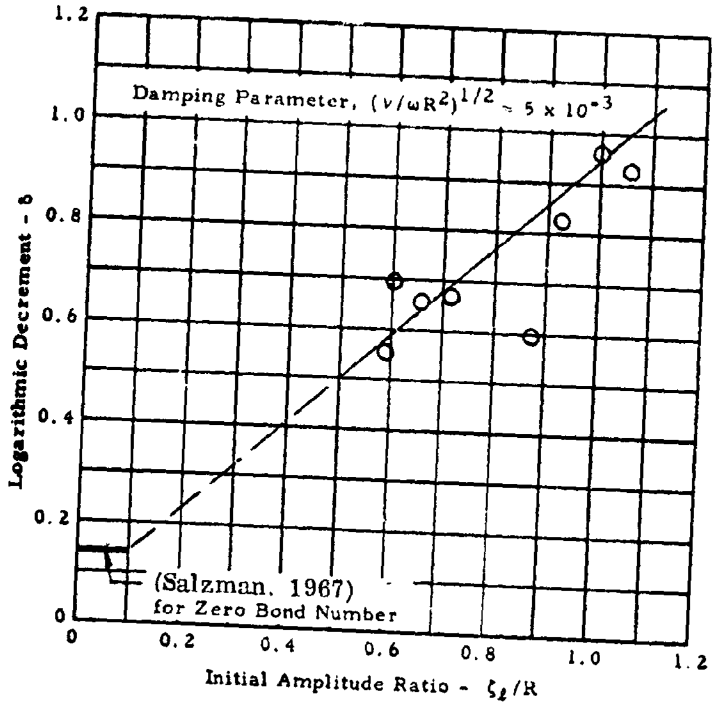


Figure 2, Variation of the Logarithmic Decrement with Initial Amplitude Ratio

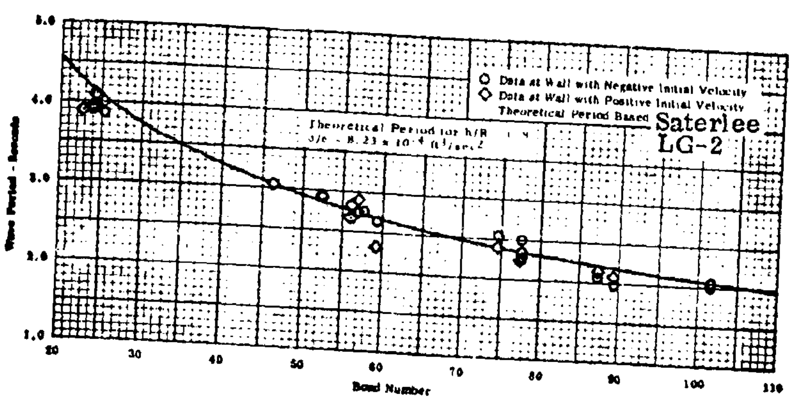


Figure 3. Measured Wave Period as a Function of Bond Number

LIQUID PROPELLANT BEHAVIOR DURING PERIODS OF VARYING ACCELERATIONS, Hollister, M.P., et al, LMSC-A874728, Code Y-87-67-1, NAS9-5174, June 1967

OBJECTIVE. - To develop analytical methods to define liquid propellant behavior under low gravity fields and to perform experiments to verify these models.

PERTINENT WORK PERFORMED. - Large amplitude sloshing motions are solved with a series solution with a separation of variables approach; the solution was characterized by instability in the velocity at the fluid high point. For small amplitude sloshing a linear analysis was performed which neglected viscosity. Slosh damping factors were analytically determined for cylinders and spheres. The potential flow function was defined and an energy decrement determined to define damping ratio. The liquid response to engine cut-off was analyzed. Experiments included lateral slosh tests in a 3-sec drop tower. Amplification tests were performed by dropping the package at maximum slosh kinetic energy. Bond numbers were 2 to 65 and Froude numbers 0.3 to 28. Liquid-liquid model tests in 1-g were used to consider damping, Figure 1, and effects of baffle placement beneath the surface. Finally, specific fluid examples were calculated for the Service Propulsion System and Lunar Module of Apollo, i.e. slosh damping in Figure 2.

MAJOR RESULTS. -

1. Axisymmetric motions result from reorientation and thrust changes. All lateral sloshing is asymmetric. Large amplitude lateral sloshing had non-linearities. Experimental verification of Concus, 1967, analytical method was performed but results in Figure 3 exceed theory by 25%. Boundary layers in small tanks and liquid viscosity effects on contact angle are possible explanations.

2. Experimental work was conducted to verify the slosh damping analysis. The logarithmic decrement as a function of baffle and liquid depth in the cylinde presented in Figure 4. This decrement is independent of Bond number; frequency increases with Bond number. Damping factors are functions of geometry and slosh amplitude.

3. The center of the sloshing mass was determined in experimental tests to calculate the wall forces during lateral sloshing.

4. The baffles analysis treated single submerged baffles and used the additive principle for more than one; only first mode lateral antisymmetric sloshing was considered. The additive principle is challenged by Scholl, 1972.

5. The static response of the walls at engine cut-off is considerably more important in slosh analysis than the dynamic response, however both structural responses are unimportant considerations in average fluid motion.

COMMENTS. - Pertinent areas here are expanded by Perko, 1969, Concus, 1967 and 1969, and updated by Salzman, 1969 and Scholl, 1972.

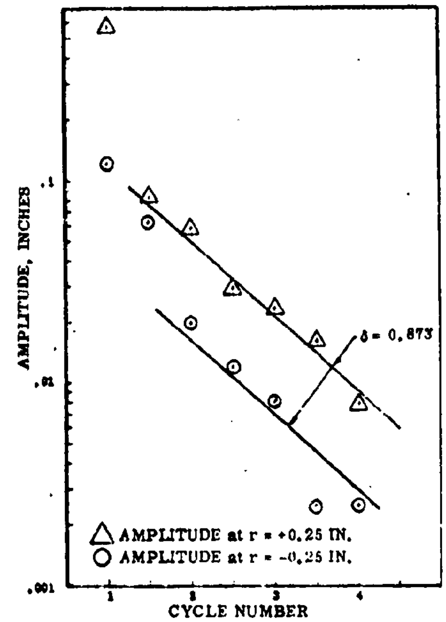


Figure 1. Damping of Interface Oscillations in Clean Tank

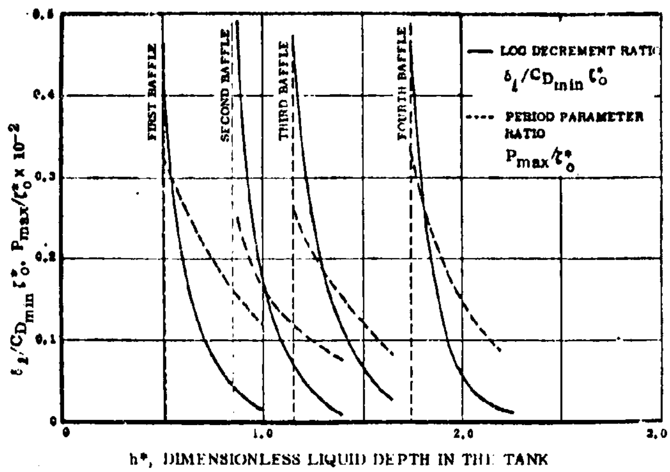


Figure 2. Slosh Damping in the LM Descent Tanks

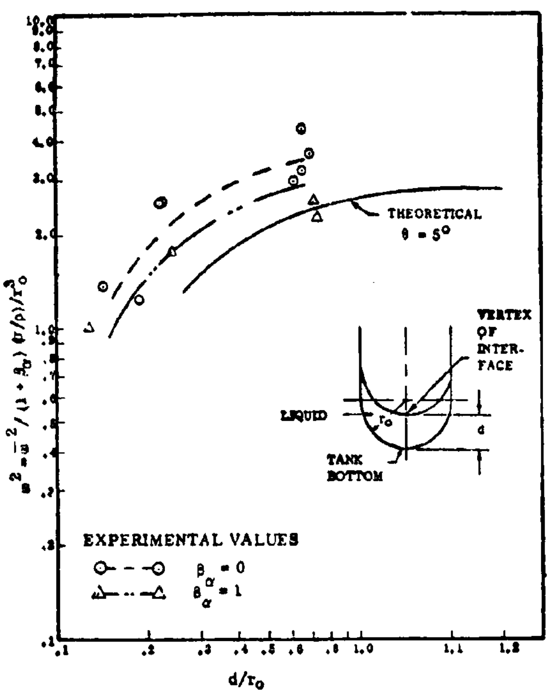


Figure 3. Slosh Frequency - Comparison of Prediction and Test Results

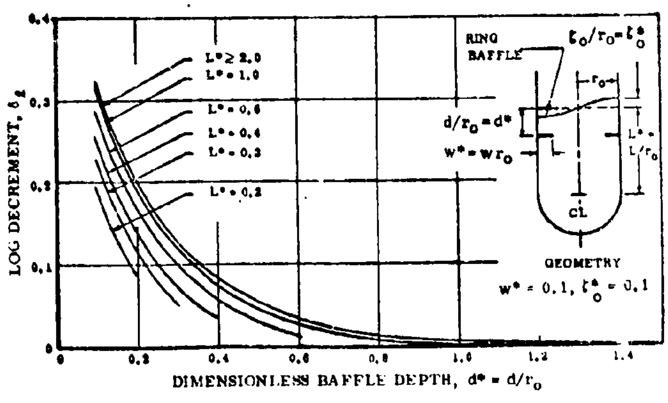


Figure 4. Effect of Baffle Depth on Log Decrement

SMALL AMPLITUDE LATERAL SLOSHING IN A CYLINDRICAL TANK WITH HEMISPHERICAL BOTTOM UNDER LOW GRAVITATIONAL CONDITIONS
Concus, P., et al, LMSC, NASA CR-54700, LMSC/A852007, Contract NAS3-7119, January 1967

OBJECTIVE. - To compute normal mode lateral sloshing in an axisymmetric configuration under positive low-g and small contact angle to demonstrate the analytical finite differences method's applicability.

PERTINENT WORK PERFORMED. - A finite difference technique utilizing an irregular triangular mesh and the Wielandt inverse iteration method was developed for sloshing computations. The method was applied to a cylindrical tank with a hemispherical bottom for Bond numbers 0 to 50, contact angle of 5°, and h/ro of 0.1 to 3. The methodology was confirmed with the proven spring-mass analog which is adequate when the first normal mode is dominant. Eigen values were calculated for lateral disturbances of periodic and sinusoidal accelerations to provide data on liquid rise heights at the wall.

MAJOR RESULTS. -

1. Extensive data is reported for the geometry specified above at lower contact angles than were earlier achievable. Although the model configuration here was cylindrical with hemispherical bottom, the method has application to any axisymmetric configuration. The method was verified with a comparison to the 90° contact angle, deep liquid,closed-form solution. Also the validity was checked with different mesh point sizes. The geometry and nomenclature appear in Figure 1.

2. The variation of the first mode (fundamental) Eigen value, ω^2, is shown in Figure 2 as a function of Bond number, B_α, and liquid depth, h_0. Note ω^2 is an increasing function with h_0 for all B_α; however, above a liquid depth $h_0/r > 1.5$, ω^2 decreases as B_α increases independent of h_0.

3. The effect of contact angle on the normalized first eigenmode, h_1, is shown in Figure 3 for the normalized radii. These results were fairly insensitive to liquid depth in the cylindrical section.

4. The first five eigenmodes are presented in Figure 4. The characteristics of the higher modes are their oscillatory nature, the existance of a region near the wall where their values are much larger than at other r, and the decrease in the size of this affected radial area with increasing mode number.

5. For a sinusoidal perturbation of $B_\alpha \sin \omega_0 t$, the maximum excursion at the wall occurs at $t = \pi/2\,\omega_0$. An equation is given in which this value provides the maximum rise in height at the wall.

COMMENTS. - The author mentions the complexity of the method and the magnitude of data handling to obtain reduced data.

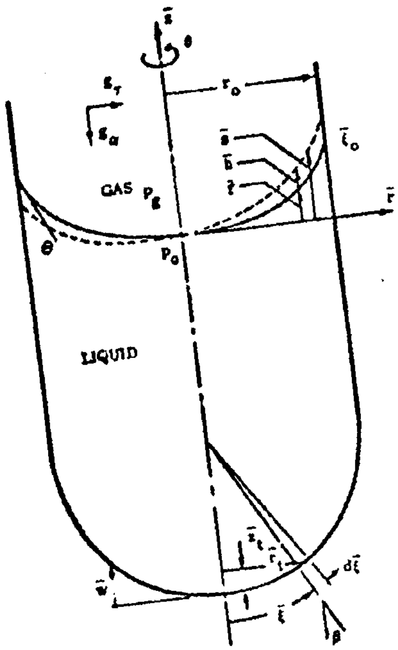


Figure 1. Container Geometry and Coordinate System

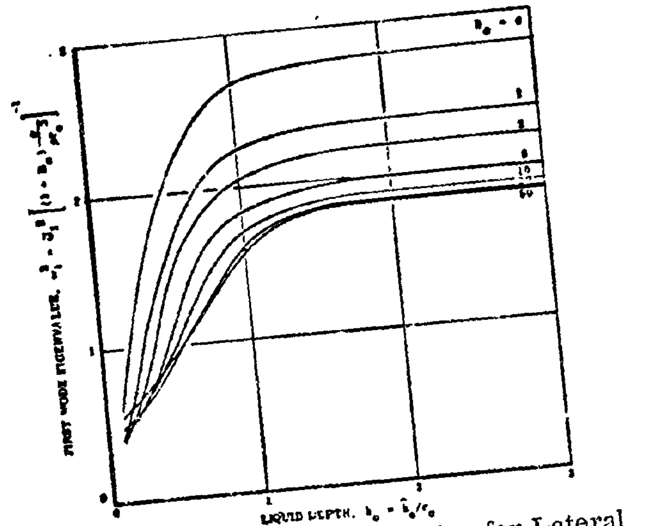


Figure 2. First Mode Eigenvalue for Lateral Sloshing in a Cylindrical Tank with Hemispherical Bottom $\theta = 5$ degrees

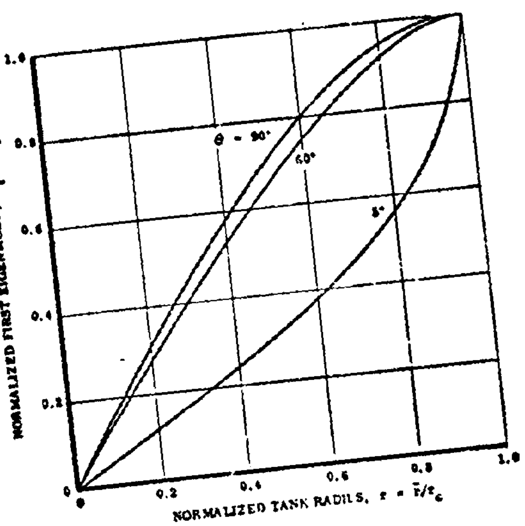


Figure 3. Effect of Contact Angle on the First Eigenmode $h_o = 3$, $B_\alpha = 0$

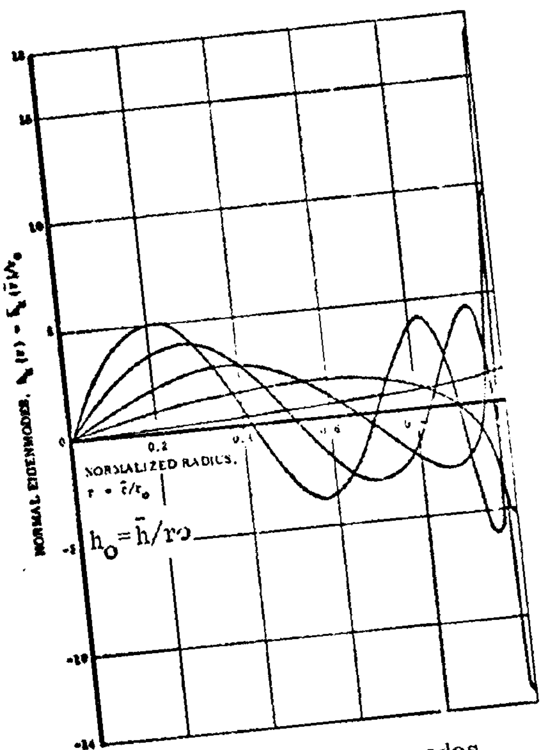


Figure 4. First Five Eigenmodes $B_\alpha = 0$, $\theta = 5$ Degrees, $h_o = 0.25$

MINIMIZATION OF SLOSH AMPLIFICATION AT ORBITAL INJECTION OF THE S-IVB/SATURN V BY AN OPTIMUM THRUST TERMINATION SEQUENCE
Curtis, H. S., Douglas Aircraft Space Systems, Proceedings of the Southeastern Symposium on Missiles and Aerospace Vehicles Sciences, Huntsville, AL, Paper 49, December 1966

OBJECTIVE. - To determine effects of thrust decay sequences on minimizing sloshing amplification for the S-IVB stage at boost termination.

PERTINENT WORK PERFORMED. - An analytical effort was performed to define the effects of various thrust decay histories on the amplification of boost sloshing. Step, ramp, and exponential decay curves were considered. Also, the timing of the application of the thrust and the length of time settling motors were used as a function of wave frequency were considered. The results with a linear sloshing model — spring, mass, and damper system — are compared with a non-linear model offerred by Bauer, 1965.

MAJOR RESULTS. -

1. The propellant sloshing amplitudes may be amplified by the reduction in vehicle acceleration which occurs at engine cut-off.

2. The magnitude of the slosh amplitude is dependent on the phasing of the thrust reduction with the natural slosh oscillation. The influence of this phase angle is shown in Figure 1. The slosh amplifications for an actual engine decay are shown in Figure 2.

3. Sloshing amplification during a period of thrust decrease can be greatly reduced if an intermediate thrust level with a duration of an odd number of quarter slosh periods is used.

4. Both the exponential and the ramp decrease sequence for thrust result in less slosh amplification than does a step thrust decrease. Both the exponential and ramp are normalized by the step function value and are shown in Figure 3. Amplification is further reduced for larger exponential time constants and longer ramp durations.

5. The optimum ullage intermediate-level thrust duration and resultant maximum slosh amplification given by the non-linear model and the linear model are nearly identical for small initial slosh amplitudes; this is shown in a comparison of Figures 2 and 4. However for larger initial slosh amplitudes, the non-linear model specifies significantly longer optimum intermediate-level ullage thrust durations.

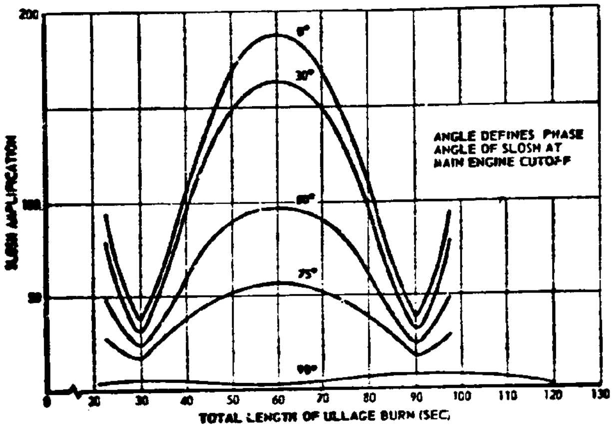


Figure 1. Slosh Amplification - Linear Slosh Model Step Thrust Changes

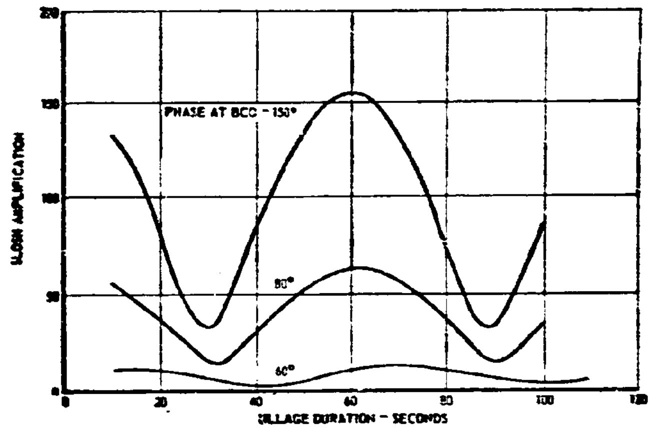


Figure 2. Slosh Amplification for Linear Slosh Model, Actual Thrust Decay

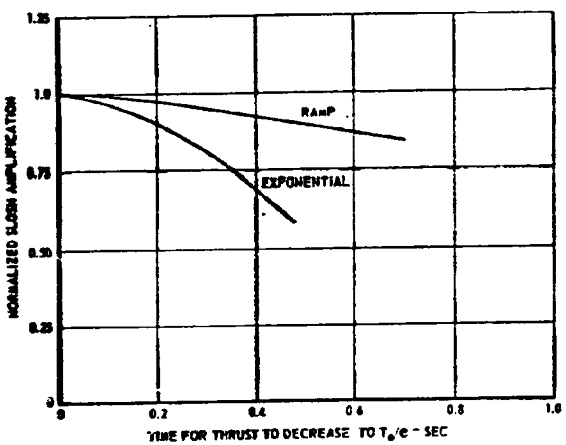


Figure 3. Effect of Thrust Tailoff on Slosh Amplification

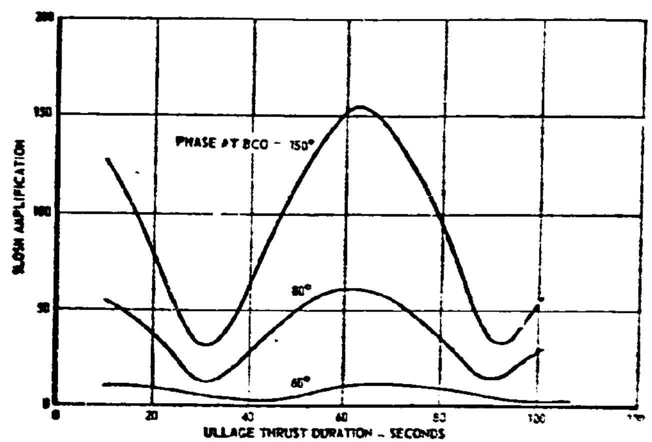


Figure 4. Slosh Amplification Nonlinear Slosh Model Initial Slosh 1 in.

THE DYNAMIC BEHAVIOR OF LIQUIDS IN MOVING CONTAINERS,
Abramson, H. N., SwRI, NASA SP-106, NASr-94(07), 1966

OBJECTIVE. - To evaluate the state-of-the-art for liquid behavior in moving containers. To summarize pertinent literature and present a synopsis of the technology.

MAJOR RESULTS. -

1. Lateral sloshing in cylindrical containers is well understood and theory and experiments agree quite well. In other shape containers experimental results depart from theory. Non-viscous theory is quite adequate to predict small amplitude lateral sloshing. A different numerical approach is used for spheres and ellipsoids versus cylinders; reasonable agreement is attained.

2. Nonlinear slosh theory explains deviations due to amplitude or surface instabilities. Swirl motion and rotary motion are nonlinear effects which have been considered analytically.

3. Slosh damping theory is developed on an energy basis. Experimentally slosh damping has been measured with the following methods: a ring force, a drive force, a wave amplitude response, a wave amplitude decay and an anchor force decay method. Damping may be accomplished by wall roughness, baffles, and floating objects. Classical work for the common fixed-ring baffle is by Miles (1958). Flexible baffles are attractive for weight-saving and effectiveness.

4. Extensive simulation testing has been accomplished. Some problems in sloshing lend themselves to simulation, others present more variables than can be simulated. Effective testing has been done and has resulted in meaningful correlations.

5. Considerable success has been achieved with a mechanical-mass, spring, damper-simulation of sloshing. The pendulum analogy for rotary sloshing is described.

6. Vertical excitation and the resultant interface break-up have received considerable attention. This motion frequency results in bubbles or spray which can affect engine performance. High frequency spray may induce low-frequency sloshing.

7. Liquid impact on tank bulkheads and longitudinal oscillations are two other areas given consideration. The former is a consideration in large amplitude sloshing.

8. A final chapter addresses the problem of modifying earlier work to the low-gravity environment. Reynolds and Satterlee extend their LG series work. The interface upon which sloshing is imposed must be defined at various static Bond numbers. Surface tension and contact angle effects complicate the definition of liquid behavior.

COMMENTS. - This SP is a significant document in the field, however most of it does not address low gravity correlations; it represents a significant departure point for extending correlations and identifying needed analytical and experimental work. Each result above is a chapter topic in the SP. Figures are abundant therefore the reader is referred to the original document.

5.0 LIQUID REORIENTATION

Covering fluid motion and collection caused by impulsive and sustained settling accelerations.

AN ANALYTICAL STUDY OF REDUCED GRAVITY PROPELLANT SETTLING
Bradshaw, R.D., Kramer, J.L., GD/C, NASA CR-134593
NAS3-16772, February 1974

OBJECTIVE. - Analytically predict full-scale propellant reorientation flow dynamics for the D-1T Centaur fuel tank.

PERTINENT WORK PERFORMED. - Previous studies have developed the Simplified Marker and Cell (SMAC) method, a numerical finite difference solution to the Navier-Stokes equations for incompressible viscous fluid flow. The method provided a time dependent solution for confined or free surface flow in either rectangular or cylindrical coordinates. Surface tension effects on surface cells and the use of straight or curved surfaces as boundaries were included in SMAC capability. In this study the SMAC code capability was increased, resulting in a new computer code, ERIE. ERIE was structured in overlay to reduce core storage and improve program efficiency. Variable grid capability was added to the code to permit increased resolution of thin boundary layer flow in corner areas and near walls and baffles. Capability was added for inputting time dependent acceleration in the axial direction for axisymmetric problems in cylindrical coordinates. Five propellant settling cases were simulated; three drop tower model cases and two full-scale D-1T Centaur fuel tanks. The first two unbaffled drop tower cases were run to check out the variable grid and time dependent gravity field capability, respectively. The third drop tower case was run to demonstrate the use of arbitrary boundaries to model baffles. Two full-scale Centaur LH_2 cases were run. Table 1 summarizes the fluid and property data for the five model cases. Figure 1 shows the full-scale and model dimensions.

MAJOR RESULTS. -

1. Drop tower test correlations successfully demonstrated the additions to computer code capability. Variable grid mesh capability improved geyser velocity predictions (previously too high). Convergence difficulties prevented checkout of the variable gravity capability. Surface pressures were not included in these runs because of erroneous surface pressure results with non-zero surface tension. Modelling of baffles was partially successful with the main flow over the baffle correctly simulated. Subsequent geysering near the tank centerline is greater in the tests than in the model predictions. Results were highly dependent upon initial interface conditions.

2. Full-scale case #4 and 5 shown in figure 2 and 3 indicated that liquid collection would occur within 120 seconds and approximately 155 seconds of thrust initiation, respectively. Some sloshing persists at these times, but damping is evident. Vent clearing occurs at 55 and 120 seconds respectively.

COMMENTS. - This method appears to have the greatest potential for predicting reorientation flow patterns and liquid collection time. Additional work appears to be required to check out model capabilities with test results and to reduce running time.

	Radius cm	Fluid	Baf- fles	Liq. %	Bond No., initial	Accelera- tion cm/sec^2	υ cm^2/sec	σ cm^3/sec^2
Case 1	7.0	FC-78[2]	No	20	10	-70.0	0.00477	0
Case 2	5.5	Ethanol	No	65	15	-73.5[1]	0.01520	0
Case 3	7.0	FC-78[2]	Yes	20	15	-69.6	0.00477	0
Case 4	152.4	LH_2	Yes	20	0	-0.643	0.00192	0
Case 5	152.4	LH_2	Yes	70	10	-0377	0.00192	0

Note 1: Acceleration set to 0.001 cm/sec^2 at 0.30 sec after impulsive settling.

Note 2: A fluorocarbon solvent registered by Minnesota Mining Mfg. Co.

Table 1. Fluid and Property Data for Five Model Cases

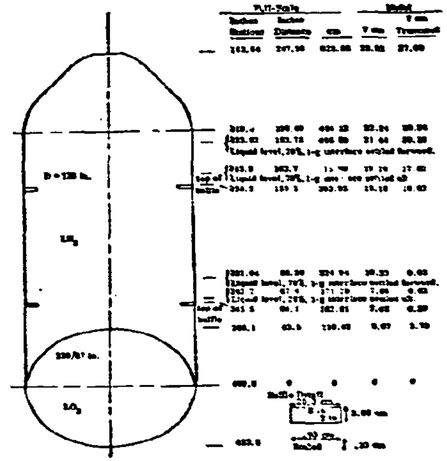


Figure 1. D-1T Tank Configuration With Full Scale and Model Dimensions

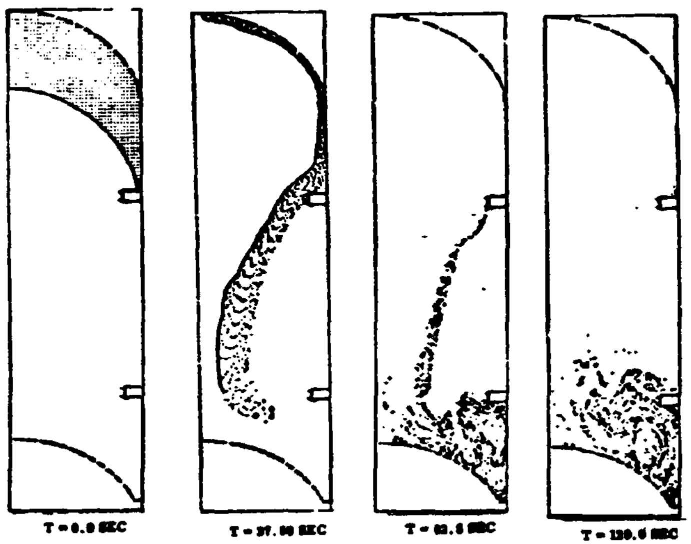


Figure 2. Marker Particle Plots for Full-Scale D-1T Simulation - Case 4

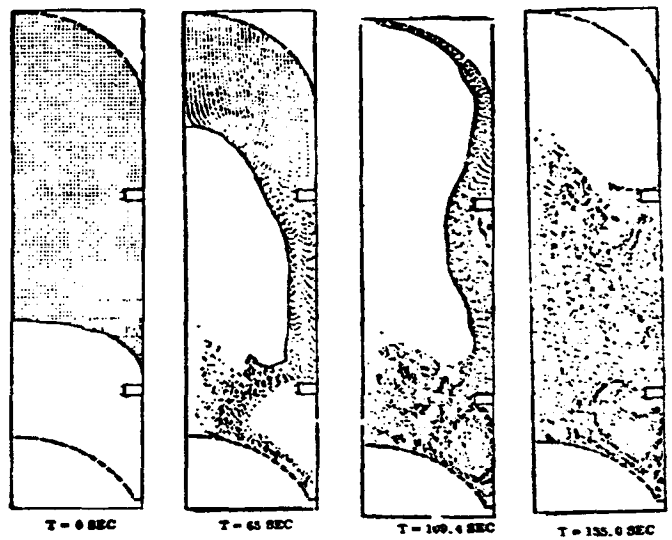


Figure 3. Marker Particle Plots for Full-Scale D-1T Simulation - Case 5

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

Salzman, J.A., et al, NASA-LeRC, TN D-7168, February 1973

OBJECTIVE. - To experimentally 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.

PERTINENT WORK PERFORMED. - Scale model Centaur LH_2 tanks of 5.5 and 7.0 centimeter radius, with and without ring baffles and liquid fill levels of 20 and 70 percent, were used. Reorientation Bond numbers were 200 and 450 with a Bond number of 15 stabilizing the liquid at the top of the tank before reorientation. Test fluids were FC-78 and Freon TF. Ring baffles were 0.15 R (radius) wide and 0.05R thick, located at 1.3R and 2.7R from the tank bottom (Figure 1). Tanks were fabricated of II UVA acrylic plastic. Data were obtained by both a high speed photography system and telemetry using the 155m long x 6.1m diameter, Lewis Zero Gravity Facility to obtain 5 seconds of free fall time.

MAJOR RESULTS. -

1. High amplitude oscillations of the liquid-vapor interface, occurring during the transition from normal gravity to the desired Bond number of 15, had a significant effect on the flow during the reorientation process. An interface that is flat or convex near the tank centerline produces a Taylor instability resulting in a dome or spike near the centerline, as well as flow near the walls. A concave interface resulted in only flow along the tank walls.

2. Results agreed with previously published LeRc results. Table I shows how to compute reorientation time estimates. Nomenclature is given in Table 2. Total liquid reorientation time and liquid collection rates are not predicted because of the dependence of geyser growth and decay, interface breakup and liquid reservoir depletion. Results can be used for predicting when venting can occur.

3. No vapor entrainment due to wall flow was observed. High bubble concentrations did occur due to entrapment, leading-edge flow, breakup and turbulence.

4. Baffling of the tanks changed the reorientation flow patterns but resulted in only minor differences in the time required to clear the top of the tank of liquid. More bubbles were observed in the baffled tanks.

COMMENTS. -

Results of other investigations have repeatedly shown Taylor instabilities during the reorientation process. These results indicate that for interface conditions representative of orbital coast periods the most likely reorientation pattern is wall flow alone.

NOMENCLATURE

- 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

Table 1. - 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

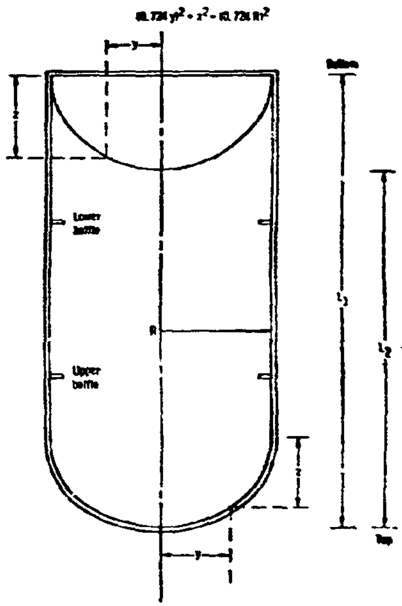


Figure 1. Geometry of liquid container

LIQUID REORIENTATION IN SPHERES BY MEANS OF LOW-G ACCELERATIONS, Labus, T. L., Masica, W. J., NASA-LeRC, TM X-1659, October 1968

OBJECTIVE. - Determine the reorientation flow patterns in spheres subjected to low-g acceleration.

PERTINENT WORK PERFORMED. - The Lewis Research Center 2.3 second drop tower was used to test acrylic plastic spherical tanks ranging in radius from 2.1 to 3.1 centimeters. The range of liquid volume was from 30 to 80 percent. The reorientation Bond number range was from 1.6 to 23.3. Anhydrous ethanol and Trichlorotrifluoroethane (Freon TF), forming zero contact angle surfaces on their containers, were used as the test fluids. Reorientation acceleration was imposed on the experiment by means of a high response, gaseous thrust system. All data were recorded photographically and corrected for optical refraction. Initial conditions at reorientation were either a flat interface or a spherical interface with the ullage bubble in the center of the tank.

MAJOR RESULTS. - Results were qualitative in nature.

1. Liquid reorientation in spheres was axisymmetric under both initial interface conditions.
2. Geysering increases with increasing reorientation Bond number although geyser occurence appears to depend more explicitly on the flow velocity at the collected interface.
3. The collection rate increased with increasing reorientation acceleration (other variables being equal).
4. Percent liquid volume determined the collected equilibrium interface configuration and influenced the geyser formation and character of the large amplitude collected interface oscillations about the equilibrium position.
5. Collecting fluid from an initially spherical interface was qualitatively the same as collecting from an initially flat interface.
6. Drop tower results agreed with Aerobee data previously obtained.

PROPELLANT SETTLING
Blackmon, J. B., et al, MACDAC,
DAC-62263, May 1968

OBJECTIVE. - Analytically and experimentally determine propellant reorientation times and auxiliary propellant weights for achieving engine restart, vapor venting and propellant transfer.

PERTINENT WORK PERFORMED. - Settling was broken up into four different liquid flow fields: (1) Time for the liquid to reach the bottom of the tank or for the ullage to reach the top of the tank, (2) Turbulent dissipation time after impact on the tank bottom, (3) Laminar dissipation time (sloshing) and (4) Bubble formation and rise time. Analytical expressions for each period were derived and total settling time obtained by selecting the greater of 1, 2 and 3 or 1, 2 and 4. Many of the analytical expressions required empirical constants for their solution that were determined using normal gravity tests in transparent model tanks, (Figure 1). Diaphragms were stretched across the top of the tanks to hold liquid. Puncturing of the diaphragm initiated the settling process which was recorded photographically. Sample cases were computed for the S-IVC and Nuclear Stage.

MAJOR RESULTS. -

1. Analytical expressions were obtained for all regimes of flow, (Figures 2, 3 and 4). Transition amplitude between turbulent and laminar motion was assumed to be 0.5 R. A constant turbulent dissipation rate was assumed.

2. Bubble formation was found to be proportional to dynamic Bond number. For Bond numbers of 1000 or higher, extensive bubble formation results. For dynamic Bond numbers of 7,000 to 20,000, bubble volume is a significant percentage of liquid volume and bubbles found are small and densely packed. The bubble velocity as a function of Reynolds number of the bubble was given for the Stokes, Harmathy and spherical cap regimes.

3. Experimental study results were from 15 to 60% higher than analytical predictions of reorientation time for the three cases cited.

COMMENTS. - The report has many logical, innovative ideas. The test technique, while producing Taylor instabilities, does give long enough test times to evaluate reorientation time. Empirical coefficients needed to evaluate the equations presented are not obtainable from the data as presented; e.g., γ_T, γ_L, η_i/η_f. If possible, methods for evaluating these variables as a function of known conditions should be determined.

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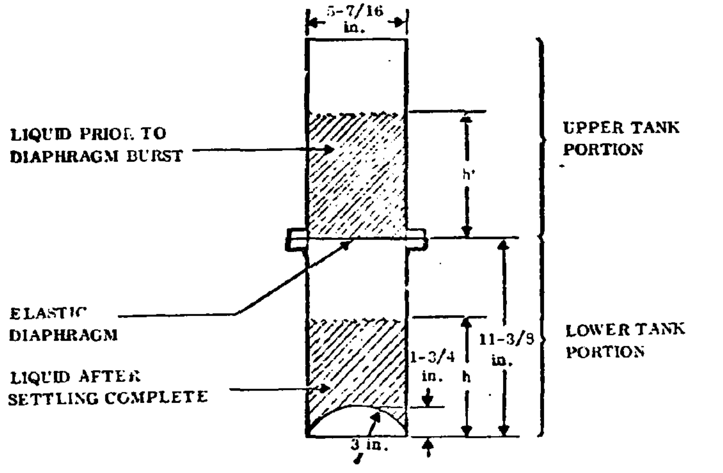


Figure 1. Plexiglas Inverted Tank Dome Model

a_i	initial acceleration of vehicle	n	ratio of bubble volume to ullage volume
a_f	final acceleration of vehicle	n'	ratio of bubble volume to liquid volume
a_L	leading edge acceleration	r	bubble radius
B_o	Bond number, $\rho g R^2/\sigma$	R	tank radius
B'_o	modified or dynamic Bond no., $\rho g h_{mL} V_L/\sigma R^2$	R_e	Reyno[illegible], $(2r\ u)/2$
C_D	drag coefficient, $(8/3)\ (r\ g/u^2)$	V_L	liquid volume
h_{mL}	distance between CG of liquid in initial and final states	V_o	ullage gas velocity
h_{mV}	distance between CG of ullage gas in initial and final states	V_T	total tank volume
		W_e	Weber no., $(2r\ \rho u^2)/\sigma$
k	wave number	γ_L	laminar damping ratio
m	fraction of impact kinetic energy transformed to bubble surface free energy	γ_t	turbulent damping ratio
		η	wave amplitude
M	$\mu^4 g/\rho\sigma^2$, dimensionless parameter	ω	slosh wave frequency

Figure 3. Nomenclature

INITIAL SETTLING TIME LIQUID FALLING

$$t_{liq} = \frac{\sqrt{L}}{0.662\sqrt{a_i}\,[1-(0.84/B_o)^{B_o/4.7}]}$$

ULLAGE GAS RISING

$$t_{ullage} = \frac{h_{MV}}{0.48\sqrt{a_i R}\,[1-(0.84/B_o)^{B_o/4.7}]}$$

TURBULENT DISSIPATION TIME

$$t_{turb} = \frac{1}{2\gamma_T[k\,a_f\tanh(kh)]^{1/2}}\log\left[\frac{4a_i\,h_{mL}V_L}{a_f\pi R^2[1-(kR)^{-2}]\eta_i^2}\right]$$

LAMINAR DISSIPATION TIME

$$t_{lam} = \frac{\log_e(\eta_i/\eta_f)}{\omega\gamma_L}$$

$$\gamma_L = \gamma_{wall} + \gamma_{baffle}$$

Figure 2. Flow Regimes

I STOKES REGIME

$C_{D_1} = 24/Re_1$ $\quad u_1 = \frac{2}{9}\frac{r^2 g\rho}{\mu}$ $\quad Re_1 < 3.7$

II TRANSITION REGIME

$C_{D_2} = 18.5/Re_2^{4/5}$ $\quad u_2 = 0.317\,r^{3/2}g^{5/6}(\rho/\mu)^{2/3}$ $\quad 3.7 < Re_2 \le 8.8M^{-0.139}$

III HARMATHY REGIME

$C_{D_3} = 0.37M^{1/4}Re_3$ $\quad u_3 = 1.5\,(\sigma g/\rho)^{1/4}$ $\quad 8.8M^{-0.139} < Re_3 \le 7M^{-1/4}$

IV SPHERICAL CAP REGIME

$C_{D_4} = 2.6$ $\quad u_4 = \sqrt{gr}$ $\quad 7M^{-1/4} < Re_4$

$$\left.\begin{aligned} C_{D_i} &= \frac{8}{3}\frac{r\,g}{u_i} \\ Re_i &= \frac{2\rho\,r\,u_i}{\mu} \end{aligned}\right\}\quad i = 1, 2, 3, 4$$

Figure 4. Representative Bubble-Velocity Equations

LIQUID PROPELLANT BEHAVIOR DURING PERIODS OF VARYING ACCELERATIONS, Hollister, M. P., et al, LMSC, A874728, Code Y-87-67-1, NAS9-5174, June 1967

OBJECTIVES. - Experimentally investigate reorientation flow in baffled and unbaffled tanks subjected to impulsive and sustained axial accelerations. Experimentally investigate geysering, rebound and ullage gas entrainment that results from a reorientation flow.

PERTINENT WORK PERFORMED. Drop tower tests (Table 1) were run using lucite cylindrical tanks with tank radii, r, of 1.30, 1.84, 3.48 and 4.12 cm. Tank length was eight times the radius. Two antislosh baffles having annular widths of 0.11 r and thickness of 0.017r and a circular screen disk of 70% porosity were used. Two tanks had single baffles installed at 1.57R and 3.34R from the bottom of the tank and a third tank a screen at 3.34R. Impulsive acceleration tests were conducted with the 1.30 cm radius tanks. Standard gravity tests were used to evaluate propellant rebound (Figure 1). A total of 15 test runs were made using carbon tetrachloride and isopropyl alcohol. Data was recorded on high speed motion picture film.

MAJOR RESULTS. -

1. Capillary response time for reorientation to the zero g interface, assuming no oscillations, agreed fairly well with the data of Siegert, TN D-2458, (Figure 2).

2. Test data on the motion of the ullage bubble in reaching the top of the tank during the reorientation process was compared to analytical predictions (Figure 3).

3. Liquid leading edge acceleration was found to be only 0.64 to 0.72 of the induced acceleration. (NASA/LeRC has reported fractions of about 0.90). Viscosity effects at low Reynolds numbers tend to slow the wall wave during reorientation at low liquid fill levels, when the wall wave is thin. For impulsive accelerations, at Weber number less than 3.5 the wall wave returned to the bottom of the tank during the test period. For $9 < We < 22$ a portion of the wave was pinched off and separated from the main body of liquid. For $55 \leq We \leq 90$ more liquid was reoriented toward the top of the tank. The baffles and the screen generally caused liquid to flow toward the center of the tank. Baffles tend to increase turbulence in the reoriented fluid (normal gravity tests) reducing liquid collection time while simultaneously increasing entrained vapor. The report suggests using 3 times the free fall time as the settling time, but no justification is given for this.

COMMENTS. - Several "adjustments" to the data are not explained adequately. Clearer data presentation would have enhanced the usefulness of the report. Diaphragm tests of Blackmon et al, 1968, are better suited to normal gravity testing than the apparatus shown in Figure 1.

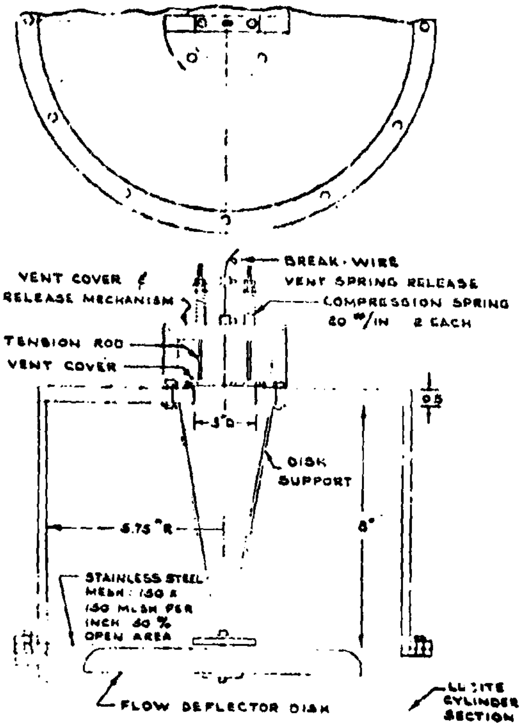


Figure 1. Reservoir and Liquid Release Mechanism

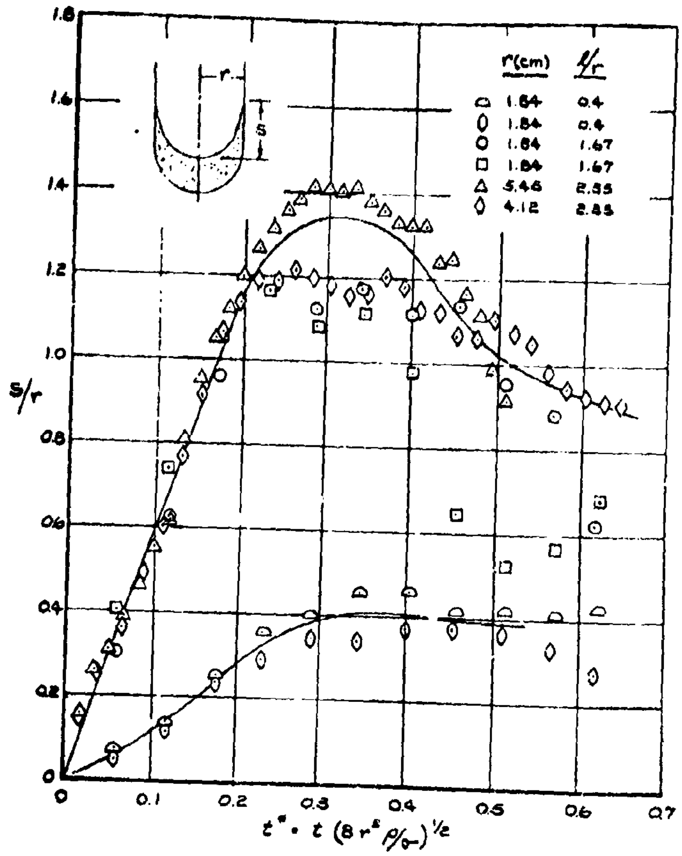


Figure 2. Zero Gravity Response

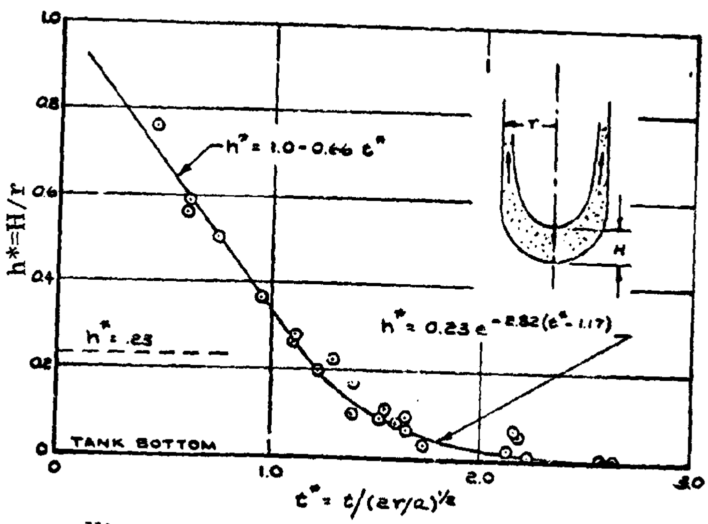


Figure 3. Liquid Depth Approaching Tank End

Tower Height	186 ft
Drop Test Height	144 ft
Zero-g Test Time	2.9 sec
Drag Shield Length (overall)	19 ft 1 in
Drag Shield Diameter	54 in
Drag Shield Mass	1300 lb
Test Module Dimensions	38 in D by 44 in L
Test Module Mass	300 lb
Acceleration Range (in both directions parallel to the drop axis)	0.3 g_o to 10^{-2} g_o
Instrumentation	High speed motion pictures 400 frame/sec
Power	On board batteries and umbilical cable prior to release
Release Mechanism	Jaw and tang - pneumatic operated

Table 1.

EXPERIMENTAL INVESTIGATION OF LIQUID-PROPELLANT REORIENTATION
Salzman, J. A., Masica, W.J.
NASA-LeRC, NASA TN D-3789, January 1967

OBJECTIVE. - To experimentally determine the criteria for predicting liquid reorientation from an initially highly curved interface by low-level accelerations.

PERTINENT WORK PERFORMED. - The experimental investigation utilized both scale model Centaur liquid hydrogen tanks and hemispherically ended models ranging in radius from 1.27 to 5.16 centimeters. Length to diameter ratios were generally 2. Liquids chosen for testing were trichlorotrifluoroethane, carbon tetrachloride, methanol and ethanol. Data were obtained photographically in the 2.3 second zero gravity drop tower facility.

A curved liquid vapor interface configuration was allowed to form prior to imposing a reorientation acceleration parallel to the longitudinal axis directed positively from the vapor to the liquid phase (Fig. 1). Geysering, liquid rebounding, and subsequent recirculation during reorientation were studied. Corrections had to be made to leading edge velocity data to account for the lack of a completely quiescent zero gravity configuration prior to reorientation.

MAJOR RESULTS. -

1. Weber number, based on leading edge velocity was found to be a convenient scaling parameter for predicting the magnitude of geysering. Leading edge velocity may be calculated using the leading edge acceleration as discussed in Masica, W. J. and Petrash, D. A., 1965. As shown in Figure 2, at We (Weber Numbers) of 4 or greater, surface forces are not large enough to completely inhibit rebound flow momentum. Geyser flow was classified into four regimes, as shown in Fig. 3, delineated by the Weber number.

2. Expressions were given for collection velocity for the different Weber no. regimes. Ullage velocity, $V_o = 0.48\ (aR)^{1/2}\ [1-(0.84/Bo)^{Bo/4.7}]$, see Nomenclature. For We < 4, geysering will not occur, collection velocity, $V_c=V_o$, and reorientation time can be obtained directly if the amount of liquid in the tank is known. For We > 30, the data showed that $V_c=V_o[1 - 2.76K(X_L/R)^{1/2}]$ where K decreases with increasing Weber number. Because of the recirculation occurring at high Weber numbers, these collection velocities cannot be used to predict reorientation time.

3. Comparison of collection Bond numbers showed that if geysering can be eliminated by using low-reorientation Bond numbers, impulse requirements for attaining complete reorientation can be minimized.

COMMENTS. Means of determining K are not given in the report.

Table 1. Nomenclature

a	system acceleration, cm/sec^2
a_L	interface leading-edge acceleration, cm/sec^2
Bo	Bond number, $Bo = aR^2/\beta$
D	tank diameter, cm
K, K'	nondimensional constants
L	tank length, cm
R	tank radius, cm
r	geyser radius, cm
t	time, sec
V_c	collected liquid velocity (fig. 2(b)), cm/sec
V_g	geyser tip velocity or growth rate (fig. 2(b)), cm/sec
V_L'	instantaneous leading-edge velocity at impingement or convergence at tank bottom (fig. 2(a)), cm/sec
V_L''	instantaneous leading-edge velocity in convex-bottomed models measured at end of cylindrical portion of tank (fig. 2(a)), cm/sec
V_o	ullage velocity, cm/sec
We	Weber number. $We = (V_L')^2 R/\beta$
X_c	collected liquid depth (fig 2(b)), cm
X_g	geyser tip displacement (fig. 2(b)), cm
X_L	interface leading-edge displacement from initial 0-g configuration to convergence or impingement, cm
β	specific surface tension, σ/ρ, cm^3/sec^2
ρ	liquid density, g/cm^3
σ	surface tension, dynes/cm

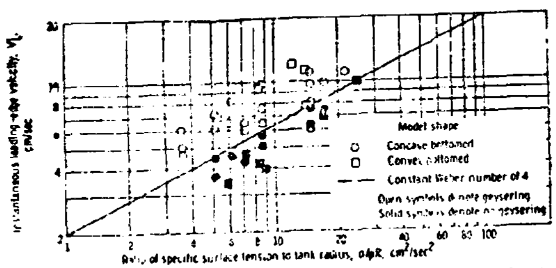


Figure 2. Geyser formation delineated by Weber number criterion

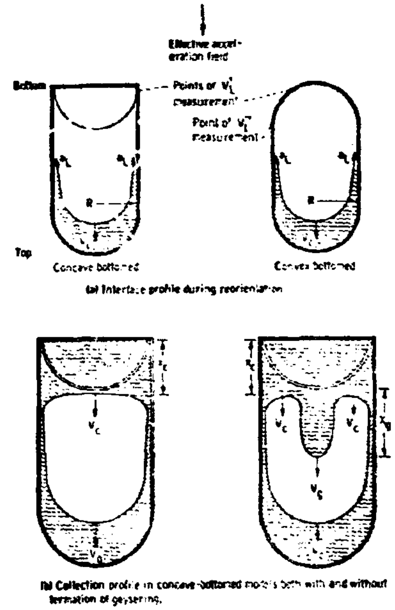


Figure 1. Basic reorientation profiles

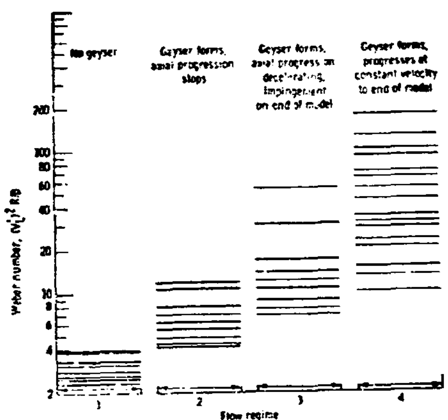
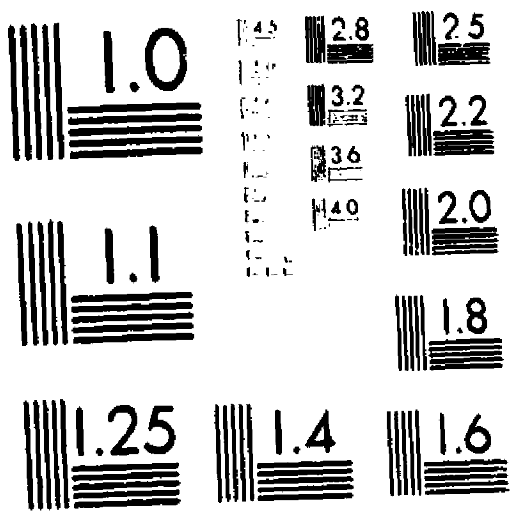


Figure 3. General classification of observed geyser flow in concave-bottomed models. Length to diameter ratio, 2.



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EXPERIMENTAL INVESTIGATION OF LIQUID IMPACT IN A MODEL PROPELLANT TANK.
Stephens, D.G., NASA-LeRC, NASA TN D-2913, October 1965

OBJECTIVE. - To experimentally determine the effect of liquid impact on structural loads in booster and space vehicle propellant tanks.

PERTINENT WORK PERFORMED. - A partially filled 21.6 cm diameter cylindrical tank with hemispherical ends was subjected to sudden reversals in axial acceleration. As shown in Figure 1, the tank (36% full by volume) was accelerated upward by dropping a weight attached to the tank by a cable. The deceleration of the tank when the weight hit the ground was controlled by an elastic cable in order to simulate the history of a vehicle experiencing a thrust termination. Data was recorded photographically and with an accelerometer, force transducers and pressure cell. Previous analysis indicated that peak pressure would be proportional to tank deceleration and would be greater for tanks and thrusts inclined to the vertical. Preliminary analysis utilizing a spring mass model indicated that possible damaging stress levels could occur due to thrust termination. A test program, incorporating tank acceleration, initial condition of the liquid free surface, baffle configuration and fluid properties (water at several temperatures) as variables, was therefore conducted to study liquid impact phenomena. The test tank was either unbaffled or contained screen baffles or simulated "Z ring" baffles. Initial liquid conditions of the fluid at the time of tank arrest were quiescent or asymmetric sloshing.

MAJOR RESULTS. -

1. Impact force data, shown in Figure 2, indicate that force increases with tank acceleration and is not appreciably influenced by initial liquid free surface conditions. If the surface is initially quiescent, a series of particles and streamers leave the surface and travel to the opposite bulkhead. If the surface is oscillating, the liquid travels up one wall, around the dome and back down the opposite wall.

2. Screen baffles produced approximately 30 percent less force for a given acceleration than the unbaffled tank. The "Z-ring" baffles produced no significant reductions in force.

3. Liquid property variations did not influence impact forces.

4. Peak pressures at the center of the dome are about twice as high as the value obtained from dividing the average force by the projected area.

5. The ratio of impact load to hydrostatic load is less than 1 for all values of tank deceleration greater than 1g. Tanks can therefore be designed to hydrostatic loads resulting from tank deceleration (greater than 1g).

C 2

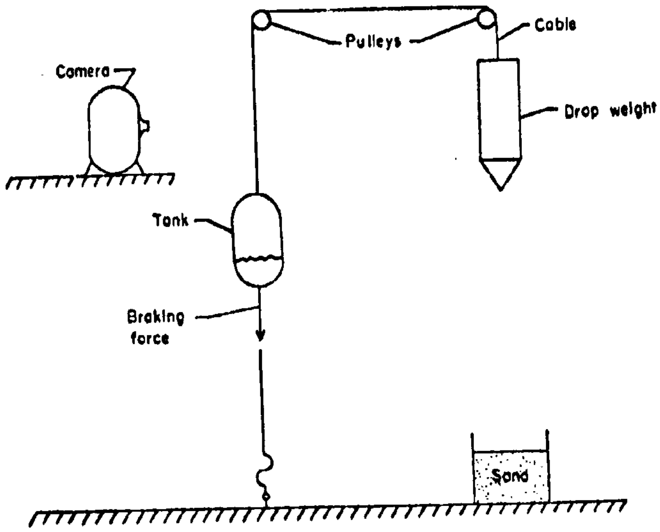


Figure 1. - Schematic representation of impact simulator.

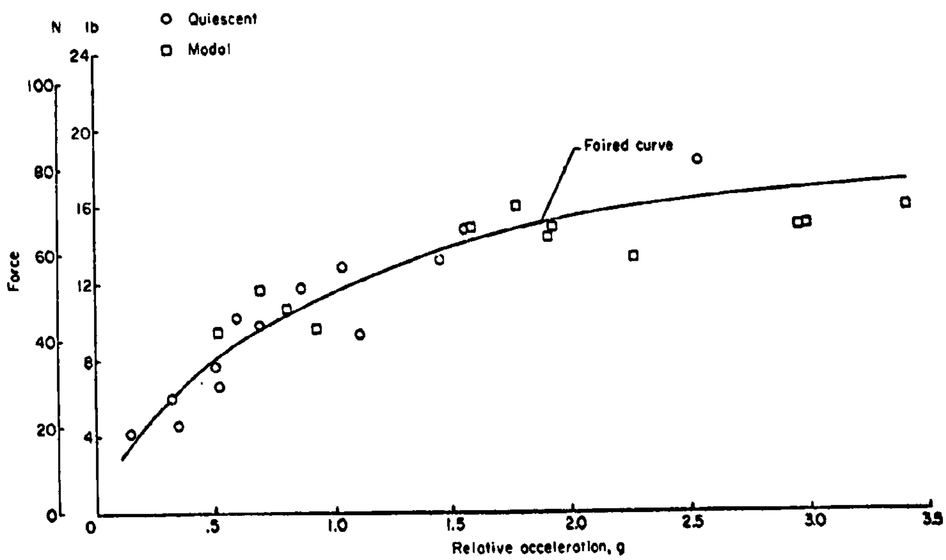


Figure 2. Variation of impact force with tank acceleration. Smooth-wall tank.

MOTION OF LIQUID-VAPOR INTERFACE IN RESPONSE TO IMPOSED ACCELERATION, Masica, W. J., Petrash, D. A., NASA-LeRC, NASA TN D-3005, September 1965

OBJECTIVE. - Determine the motion of the liquid-vapor interface in a cylindrical container in response to a constant translational acceleration.

PERTINENT WORK PERFORMED. - The Lewis Research Center (85 ft) Drop Tower was used to test Borosilicate glass cylinders containing Trichlorotrifluroethane and anhydrous ethanol. Two cylinders (1.27 cm and 2.03 cm diameter) were tested simultaneously using the same test fluid. After an initial period of zero g interface formation, an acceleration was applied parallel to the longitudinal axis, directed positively from the vapor to the liquid phase. Normal gravity testing with glass tubing at Bond numbers from 349 to 1870 was conducted to determine the velocity of bubbles ascending in a liquid.

MAJOR RESULTS. -

1. Previous studies indicated that: For $Bo > 10$, Taylor's inviscid potential theory showed that $V_o = 0.464\ (aR)^{1/2}$, where V_o is the ullage velocity, a is the acceleration and R is the tank radius. For $Bo > 1.75$ an empirical correlation employing Taylor's theory indicated that;

$$V_o = 0.51\ (aR)^{1/2} \left[1 - \frac{1.12}{Bo} \right] f\ (Re)$$

2. The present study found that $V_o = 0.48\ (aR)^{1/2}$ was applicable for $Bo > 12$ and that

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

represents the data for Bond Numbers greater than 0.84. Comparison between this equation and LeRC normal gravity, published and LeRC drop tower data is shown in Figures 1, 2, and 3.

3. Leading edge acceleration, a_L, may be expressed as

$$a_L = \frac{3V_o^2}{R} \text{ for } Bo > 1.75 \text{ and } a_L = 0.87a \text{ for } Bo > 12$$

4. The liquid vapor interface profile assumed the form predicted by the inviscid potential theory of Taylor.

COMMENTS. - For higher Bond numbers, geysering and recirculation have a significant effect on fluid reorientation and bubble motion.

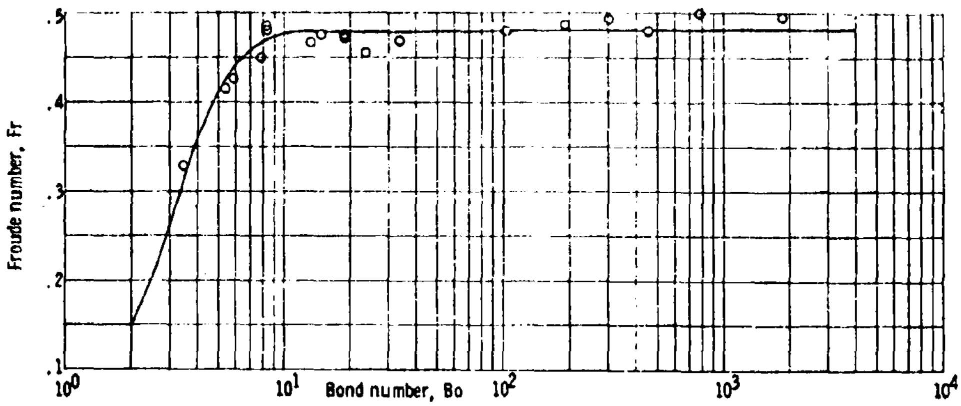


Figure 1. Results of Normal-Gravity Investigation. Liquid Viscosity, 0.7 to 1.2 Centipoise

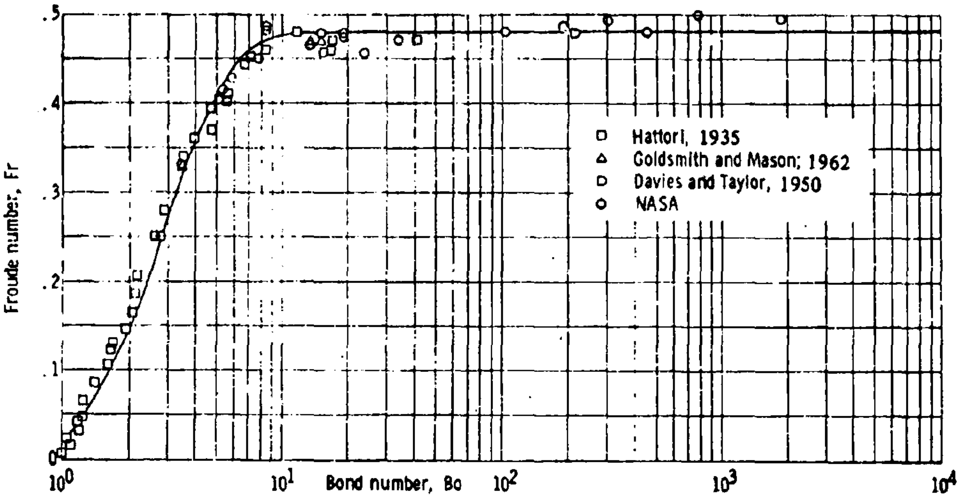


Figure 2. Correlation of Published Data. System Acceleration, 980 Centimeters per Second Squared; Liquid Viscosity, 0.25 to 5.6 Centipoise.

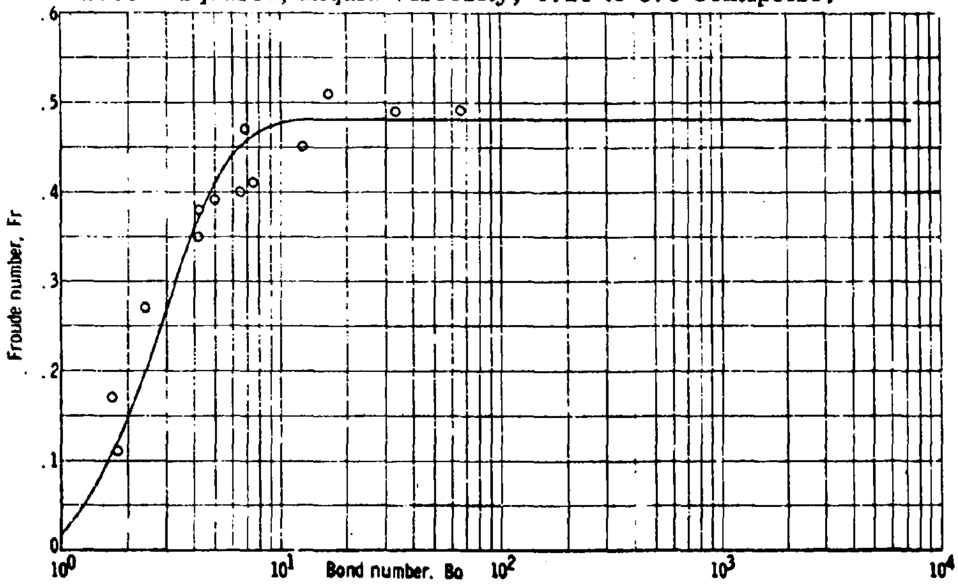


Figure 3. Bubble Velocity as Function of Bond No. for Drop-Tower Data. System Acceleration, 0.01 to 0.08 g.

LIQUID SETTLING IN LARGE TANKS
Bowman, T. E., MMC, Symposium on
Fluid Mechanics and Heat Transfer Under Low
Gravitational Conditions, June 1965

OBJECTIVE. - Experimentally determine the flow characteristics of the fluid reorientation process when settling from an initially flat interface configuration.

PERTINENT WORK PERFORMED. - Nine transparent cylinders, 2.3 cm to 29.2 cm diameter were tested in a 75 foot drop tower using carbon tetrachloride, chloroform, trichlorotrifluorethane and methanol as test fluids. Fluid in the bottom of the tank was reoriented towards the top of the tank by acceleration of from 0.002g to 0.027g. Bond numbers ranged from subcritical to 390. Data were recorded using a Milliken camera operating at 213 frames per second. A theoretical description of the type of reorientation flow anticipated was included. Waves on the liquid vapor interface were expected to grow; forming a liquid spike along the tank centerline, a broader, rising liquid dome in the center of the tank or even a number of concentric hollow cylinders. In addition to these Taylor instability generated flows, wall flow will occur for wetting fluids. Helmholz instability can also occur, tending to break up the spike into discrete masses of liquid as a result of the surface pinching in at regular intervals. Asymmetry in the moving spike can cause a major portion of the tank flow to occur along the side of the tank toward which the spike moved.

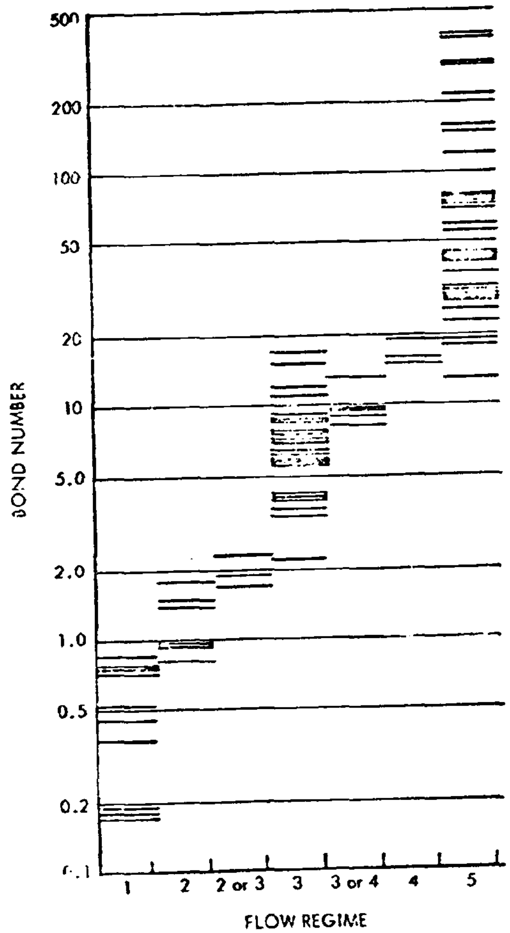
MAJOR RESULTS. -

1. Flow regimes were delineated by Bond number as shown in Figure 1. Liquid filling level was found to have no influence.

2. Features of the central flow observed for cases where the dome or cylinder forming in the center hits the opposite tank wall or joins the wall flow are shown in Figure 2.

COMMENTS. -

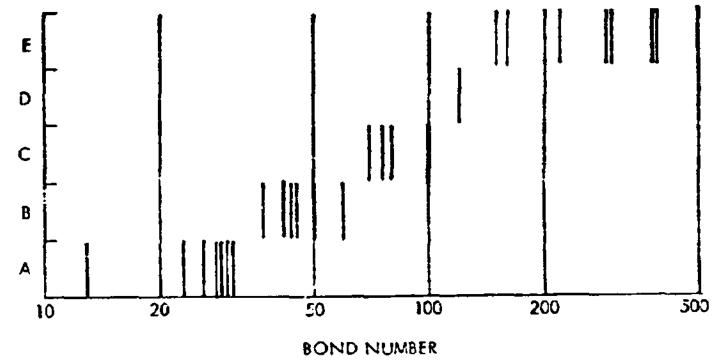
Results are applicable to the case of a large supply tank in low earth orbit, subject to an aerodynamic drag flattening the interface. Results are also applicable to cases where Taylor instabilities may occur, such as for an oscillating interface prior to reorientation. Test results do not allow collection rates to be determined quantitatively.



FLOW REGIMES

1. No flow.
2. Flow along the walls only.
3. Dome of liquid forms in the center, then recedes.
4. Dome forms in the center, grows to a certain size, then stops growing and remains virtually stationary until the liquid below is depleted due to flow along the walls.
5. Dome or cylinder forms in the center, continues to grow until it hits the top or joins the flow along one wall.

Fig. 1. Summary of Test Results; General Classification of the Observed Flows



A. The liquid dome grows into a thin spike which eventually extends to the top of the tank. Effects of Helmholtz instability are seen if the spike L/D becomes large enough.

B. A small depression forms in the center of the upper surface of the dome. Shortly after its formation, the depression "turns inside out," becoming a small protuberance on the top surface of the dome. The protuberance grows rapidly in amplitude and diameter relative to the original dome until the two cannot be distinguished from each other. Together they form a column up the center of the cylinder, as in A.

C. A depression forms in the center of the upper surface of the dome, similar to the depression observed in B but somewhat larger. The depression is present only temporarily, leaving behind a bubble or cavity inside the dome. No protuberance is seen to form following the breakup of the depression.

D. In its formative stages, the cylinder has a complex upper surface characterized by concentric waves whose amplitudes become large with time. The eventual result is a broad dome with protuberance growing on its upper surface as in B.

E. Same as D, except that the eventual result is a hollow cylinder.

Fig. 2. Summary of Test Results; Additional Features of the Central Flow Observed in Certain Regime 5 Flows

INVISCID FLUID FLOW IN AN ACCELERATING
CYLINDRICAL CONTAINER
Moore, R. E., Perko, L. M., LMSC, J. Fluid Mech., Vol. 22, pp. 305-320, 1965

OBJECTIVE. - Numerically evaluate the problem of fluid motion in a cylindrical container subjected to a time-varying acceleration in connection with the study of the dynamics of a liquid rocket propellant.

PERTINENT WORK PERFORMED. - Free surface behavior of the fluid was numerically determined by solving the Eulerian equations utilizing a Fourier series representation for the velocity potential with time dependent coefficients. Free surface motion was computed by following individual fluid particles on the surface using the method of characteristics. Surface tension was included as a smoothing term.

Two types of cases were numerically evaluated for a right circular cylinder; (1) acceleration of lg tending to settle the liquid to the opposite end of the container and (2) acceleration of lg tending to keep the fluid in the bottom of the container. Eight cases were run, with different contact angle, surface tension and interface shape. A hemispherical initial interface shape was assumed for 7 of the cases, (Table 1).

MAJOR RESULTS. -

1. For the reorientation case presented in Figures 1 and 2, breakers, or perturbations forming on the liquid surface, were very sensitive to small changes in the initial interface shape. A 2% deviation from the hemispherical shape of Figure 1 at two or three points caused a 20% decrease in the time at which breakers occurred. Surface tension had a smoothing effect that tended to eliminate breakers, as shown in Figure 3.
2. An initially flat interface produced breakers quickly (No Taylor instability was predicted.)
3. Cases tending to flatten the interface toward the bottom of the tank, produced geysering and splashing that increased from case to case as the surface tension was decreased and the free surface increased (lower contact angle).

COMMENTS. - Nomenclature and dimensions are not clear for system geometry. The study illustrates the importance of initial conditions on the accurate modelling of reorientation flow.

Figure no.	$\alpha(t)$	β	Initial shape	H	θ_0	$\Delta t/r_0^{1/2}$	$t_{final}\, r_0^{1/2}$
2	+1.0	0	Hemispherical	2.0	45°	0.0177	0.195
—	+1.0	0	Hemispherical	2.0	22.5°	0.0177	0.14
—	+1.0	0	Hemispherical	0.4	45°	0.0266	0.16
5	+1.0	0.005	Hemispherical	2.0	45°	0.0177	0.16
6	+1.0	0.05	Flat with meniscus	2.0	0°	0.0350	0.49
7	−1.0	0	Hemispherical	2.0	45°	0.0266	0.40
8	−1.0	0.05	Hemispherical	2.0	45°	0.0266	0.48
9	−1.0	0.05	Hemispherical	2.0	15°	0.0266	0.48

Table 1. Summary of the cases studied

α (t) = acceleration
β = surface tension
H = initial liquid height assuming a flat interface
θ_o = initial contact angle
Δt = time (seconds)
r_o = tank radius (feet)

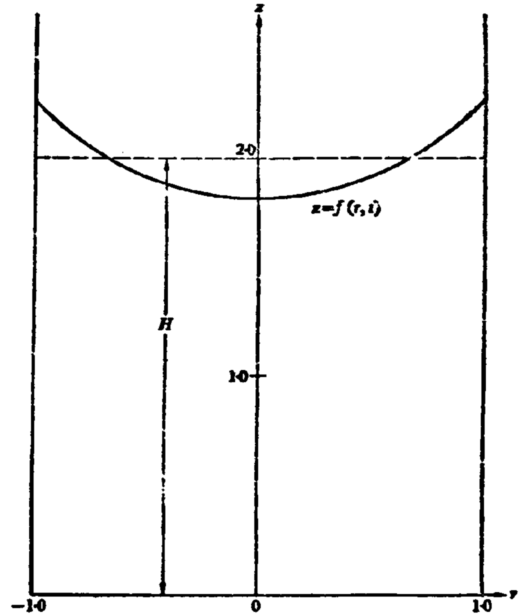


Figure 1. Coordinate system and hemispherical initial shape with H = 2.0 and r_o = 1.0

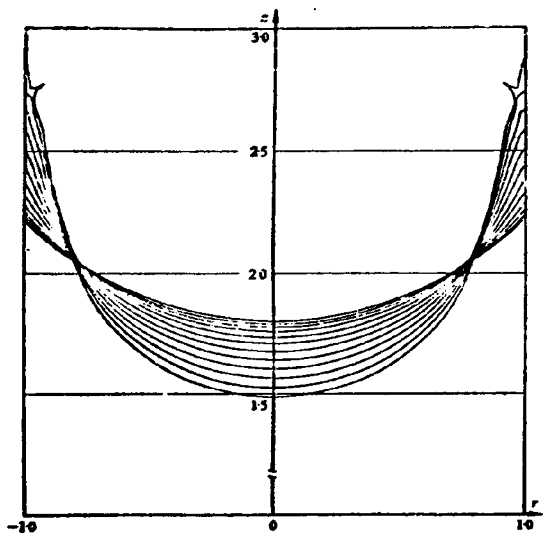


Figure 2. Hemispherical initial shape with H = 2.0, α(t) = +1, β = 0, θ_o = 45° and Δt = 0.0177 $r_o^{1/2}$ sec.

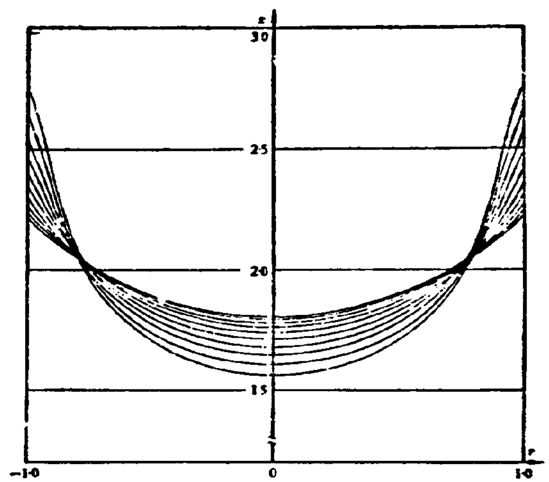


Figure 3. Hemispherical initial shape with H = 2.0, α(t) = 1+, β = 0.005, θ_o = 45° and Δt = 0.0177 $r_o^{1/2}$ sec.

6.0 BUBBLES AND DROPLETS

Covering bubble growth and coalescence, low-g shape, and motion of bubbles and droplets not at a surface.

UNSTABLE BUBBLE MOTION UNDER
LOW-GRAVITATIONAL CONDITIONS
Haggard, J.B., Jr., NASA-LeRC, TN D-5809, May 1970

OBJECTIVE. - Examine fundamental aspects of the nonrectilinear motion of single noncondensable bubbles under low-g conditions.

PERTINENT WORK PERFORMED. - Both 1-g and low-g ($0.03 \leq a/g \leq 0.05$) testing was accomplished using the LeRC 2.2-sec drop facility. Bubble radii ranged from 0.17 to 0.87-cm. Liquids were 1-butanol, methanol, carbon tetrachloride, trichlorotrifluoroethane, and FC-78. The test tank was acrylic plastic, octagonal, 19 cm. high and 13.96 cm between faces. Each face was 5.78 cm wide. This shape minimized light refraction as well as liquid volume. The normal-gravity test tank had a square cross section 5.6 by 5.6 cm by 17.8 cm. high. In both cases the tanks were large enough so that wall effects were negligible. Bubble velocity, bubble size, and path measurements (frequency and amplitude) were typically obtained from motion picture film of each test during the last second of the drop. Unstable bubble motion at terminal velocity was characterized by either zig-zag motion (oscillation in a plane that contains the axis of symmetry of the tank) or helical motion (spiral on an imagined cylinder having a radius much smaller than the tank). The amplitude of oscillation in the case of zig-zag motion was the maximum displacement from the axis. For helical motion, the amplitude was the radius of the spiral.

MAJOR RESULTS. -

1. The approximate bubble size above which unstable motion will occur for low-viscosity fluids was found to be given by the empirical relation; $r_{eq} = 0.4\ (\beta/a)^{1/2}$, where r_{eq} = radius of spherical bubble with same volume as observed bubble.
2. Either a critical Weber number or a critical Bond number criterion is sufficient to predict the onset of unstable bubble motion, implying that for distorted bubbles hydrodynamic forces are a simple function of the acceleration imposed on the system (Figures 1 and 2). v is the terminal velocity of the bubble.
3. Unstable bubbles appeared to oscillate with a frequency directly proportional to the square root of the acceleration, while the amplitude appeared to be inversely proportional to the square root of the acceleration.

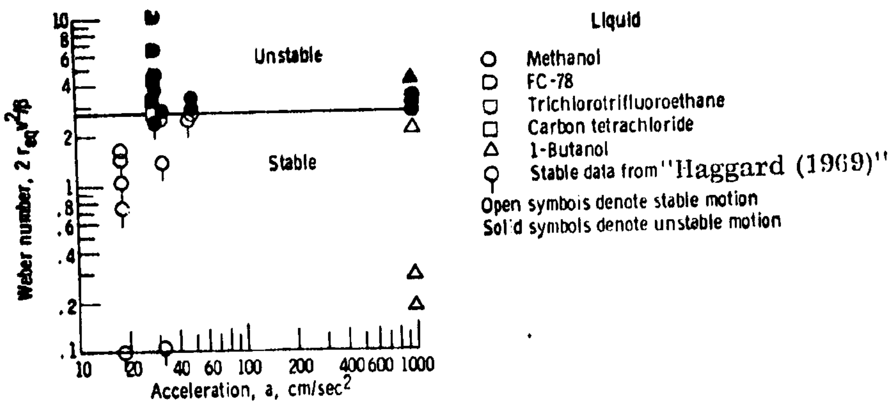


Figure 1. Dependence of Type of Bubble Motion with Weber Number. Critical Weber Number, 2.7.

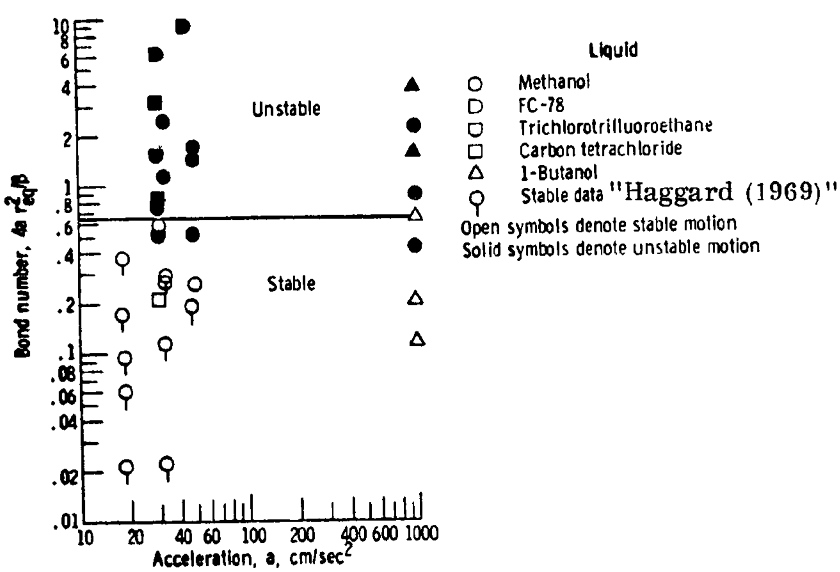


Figure 2. Dependence of Type of Bubble Motion with Bond Number. Critical Bond Number, 0.64

MOTION OF SINGLE BUBBLES UNDER
LOW GRAVITATIONAL CONDITIONS
Haggard, J.B., Masica, W.J.,
NASA-LeRC, TN D-5462, October 1969

OBJECTIVE. - Examine single, noncondensable bubble motion under low-gravity conditions.

PERTINENT WORK PERFORMED. - Testing was accomplished at 1-g and at low-g ($0.005 < a/g < 0.05$) in the LeRC 2.2 sec. drop tower. Terminal velocity and shape of single air bubbles of radii 0.07 to 0.43 cm. were determined using a high speed camera. The Reynolds number ($2\,r_{eq}\,v/\nu_{\ell}$) varied from 12 to 1030, where r_{eq} is the equivalent radius of a spherical bubble of the same volume as the observed bubble and v is the terminal velocity. The test liquids were 1-butanol, anhydrous ethanol, and methanol. Both the low-g and 1-g test tanks were large enough, (tank dia.)/(bubble dia.) ≥ 10, such that wall effects were negligible.

A theory proposed by Moore was used to correlate the data. This theory uses the M number ($\mu^4\, a/\rho_{\ell}\sigma^3$) as a correlating parameter and appears to be the most complete theory available in the distorted gas bubble regime. This theory, which is applicable to liquids and test conditions where the M number is less than 10^{-8}, extends from Reynolds numbers greater than 50 to the point where the bubble is distorted such that the ratio of the major axis to minor axis of the bubble equals 4. This ratio is the distortion parameter $\chi = r_h/r_v$, where r_h = semimajor axis perpendicular to direction of the bubble motion and r_v = semiminor axis parallel to the bubble motion.

MAJOR RESULTS -

1. Only rectilinear bubble motion was observed in the low-g tests. This is different from normal gravity results, where at Reynolds numbers above several hundred, helical motion is normally observed.

2. As expected, the terminal velocity of a bubble in low-g was reduced over that at 1-g, the percent reduction varying with bubble size. Due to this reduced velocity, the bubble distorted from spherical at much larger bubble radii at low-g than at 1-g (Figure 1).

3. Using Moore's solution as representative of a class of theoretical descriptions of bubble motion within the Reynolds number regimes studied, it was found that this solution was in fair agreement with the test data when the solution was scaled by the M number. That is, it is possible to predict the terminal velocity and shape of a bubble, given the liquid properties and the applied gravity field. Drag coefficients are shown typically in Figure 2 as functions of Reynolds and M numbers.

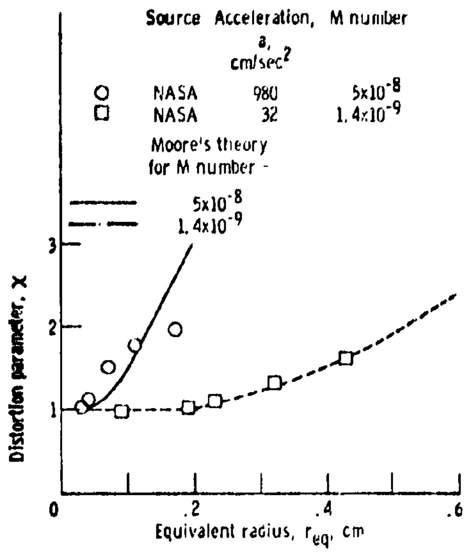


Figure 1. Typical Amount of Distortion to an Oblate Ellipsoid as Function of Bubble Size. Test Liquid, 1-Butanol

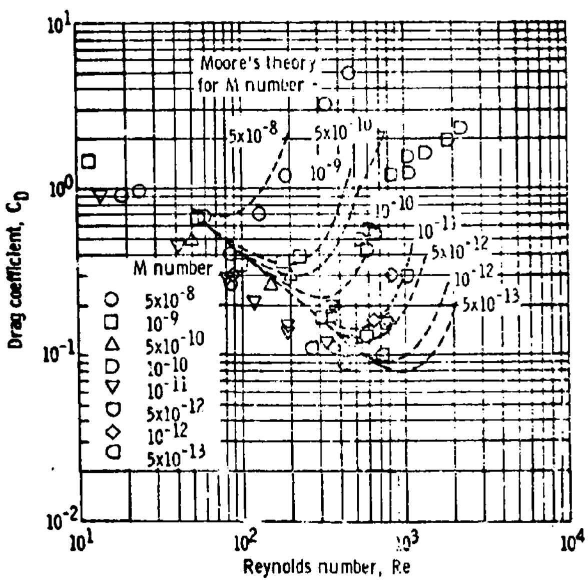


Figure 2. Experiment Results Showing M-Number Trend on Drag Coefficient for Various Liquids and Gravity Fields

GROWTH RATES OF FREE VAPOR BUBBLES IN LIQUIDS AT UNIFORM SUPERHEATS UNDER NORMAL AND ZERO GRAVITY CONDITIONS
Florschuetz, L. W., et al, Arizona State Univ., Int. Journal Heat Mass Transfer, April 1969

OBJECTIVE. - To study growth rates of vapor bubbles in bulk liquid (away from solid surfaces) at both 1-g and zero-g.

PERTINENT WORK PERFORMED. - Experimental data were obtained with a 1200 frames/sec camera using water, ethanol, and isopropanol at 1-g and in water and ethanol at near 0-g employing a 9-ft drop tower. In each case, bubbles grew under essentially constant superheat, obtained by suddenly decreasing the pressure of a saturated liquid contained in a 6 in. dia. by 10 in. high closed container. Superheats studied were from 2.2 to 4.9°C. The nominal pressure was 1 atm. Observation times were up to 140 m sec for 1-g data and up to 450 m sec for near 0-g. In these tests no foreign material was injected to start bubble nucleation; rather nucleation started from microscopic bubbles originating from natural sites. Only bubbles isolated by at least one diameter were chosen for analysis. For data analysis, an equivalent bubble radius was determined from an average of the major and minor axes.

The data obtained were compared to an exact solution for spherically symmetric heat transfer controlled growth (Scriven, 1959), which predicts a bubble radius growing according to: $R = 2\beta(\alpha_\ell t)^{1/2}$, where the growth constant, β, is given by $f(\epsilon, \beta) = Ja$, where $\epsilon = 1 - (\rho_v/\rho_\ell)$, Ja = Jakob number, $\rho_\ell C_{P_\ell} \Delta T_{superheat}/\rho_v h_{fg}$, and $f(\epsilon, \beta)$ is a complicated function containing integrals which cannot be evaluated in closed form; however, Scriven (1959) has presented tabular values. It is noted that for cases of interest here, ϵ may be taken as 1 and $f(\epsilon, \beta) \simeq \beta \simeq Ja$.

MAJOR RESULTS. -

1. In zero-g, bubble growth was essentially spherical over the entire test time and agreement with Scriven's theoretical prediction was very good, as shown typically in Figure 1.

2. At 1-g, bubbles departed from spherical at times between 30 and 50 m sec, with increased growth rates and a deviation from prediction, as illustrated in Figure 2. Analysis indicated that this was due to buoyancy causing translation effects.

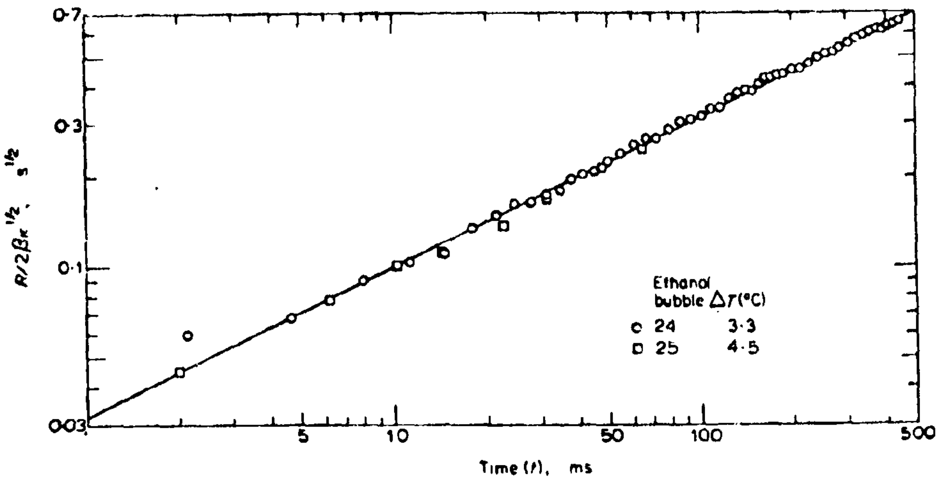


Figure 1. Comparison of present ethanol data for zero gravity to Scriven's theoretical result.

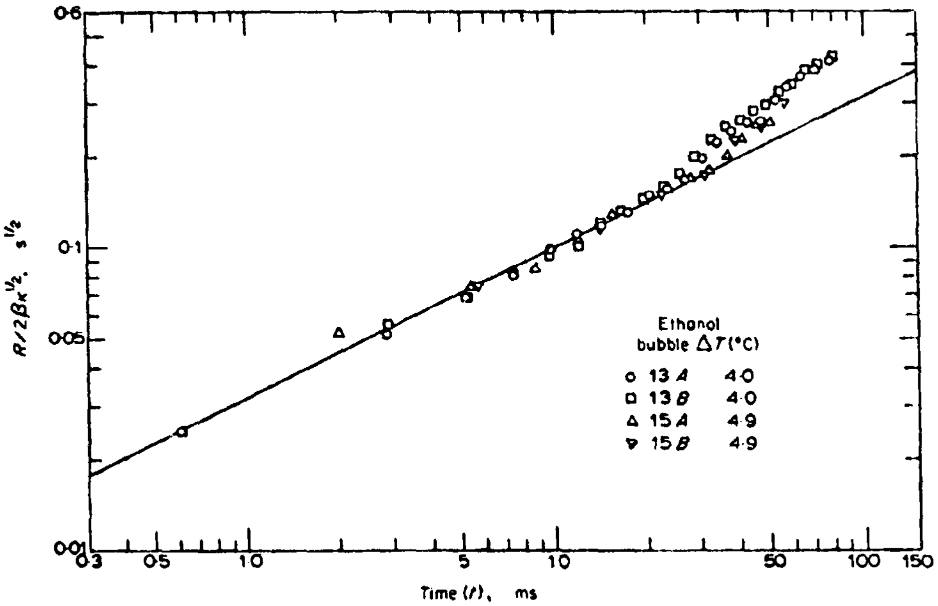


Figure 2. Comparison of present ethanol data for normal gravity to Scriven's theoretical result.

7.0 FLUID INFLOW

Covering tank and baffle geometry and fill-level effects on inlet flow patterns, wall impingement and childown.

EFFECT OF BAFFLES ON INFLOW PATTERNS IN SPHERICAL CONTAINERS DURING WEIGHTLESSNESS
Labus, T. L., et al, NASA-LeRC TM X-2670, November 1972

OBJECTIVE. - To determine the degree of wall wetting during inflow, the amount of liquid vented, and the preferred inflow-baffle configuration for reduced-gravity filling of spherical containers.

PERTINENT WORK PERFORMED. - A series of tests were conducted in the 2.2 sec LeRC drop tower to investigate inflow into a 10 cm diameter sphere with unbaffled and baffled inlets. The geometric configuration with the inlet at the bottom and two symmetric vents at the top is shown in Figure 1. The specific test conditions are detailed in Table I; only air drag for an acceleration field of 10^{-5} g's was present. The results were evaluated from movie coverage. The degree of wall-wetting was the key issue, however, liquid vented out the vent was also a variable of interest. Three tests in the unbaffled tanks indicated that the lowest Weber number, which was 680, resulted in the most severe liquid venting overboard condition. By extending the vents inward, this liquid-loss could be corrected. The wall-wetting was satisfactory in all three tests. The baffled tests listed in Table I were run at the determined worst Weber number condition of 680 using the various baffles shown in Figure 2.

MAJOR RESULTS. -

1. For unbaffled tanks less liquid escaped at higher Weber number conditions.
2. The flat plate baffle resulted in little liquid loss, however, the wall-wetting was not very uniform.
3. The solid hemispherical baffle resulted in poor wall-wetting and considerable liquid loss.
4. The hemispherical screen baffles did not disperse the flow and were unsatisfactory. Although coarser screens were more effective, wetting patterns were not uniform and liquid losses occurred.
5. Final tests with a perforated hemispherical baffle resulted in more rapid wall-wetting than the unbaffled tanks and in complete wall-wetting. Liquid loss was minimal and was zero for internally extended vent ports.
6. Moreover, in all tests, extending the vent inlet inward through the wall film avoided liquid loss.
7. Although these tests were isothermal and noncryogenic, a baffle was selected which resulted in excellant wall-wetting for a wide range of Weber numbers.

Table 1. Summary of Parameters

[Tank radius, 5 cm.]

Type of inlet baffle	Liquid	Specific surface tension,[a] β, cm^3/sec^2	Volumetric flow rate, Q, cm^3/sec	Inlet radius, R_I, cm	Weber number, $We = \frac{Q^2}{\pi^2 \beta R_I^3}$
Unbaffled	Anhydrous ethanol	28.3	39	0.20	680
Unbaffled	Trichlorotrifluoroethane	11.8	52		2 900
Unbaffled	FC-78[b]	7.7	84		11 600
Unbaffled; vents extended internally	Anhydrous ethanol	28.3	39		680
Circular flat plate					
Circular flat plate; vents extended internally					
Solid hemisphere					
Hemispherical screen (200 × 200 mesh)					
Hemispherical screen (120 × 120 mesh)					
Hemispherical screen (80 × 80 mesh)					
Perforated hemisphere				.50	46
Perforated hemisphere	FC-78[b]	7.7	82	.50	710
Perforated hemisphere; vents extended internally	FC-78[b]	7.7	82	.50	710

[a]At 20° C.
[b]Minnesota Mining and Manufacturing Co. registered trademark for fluorocarbon solvent.

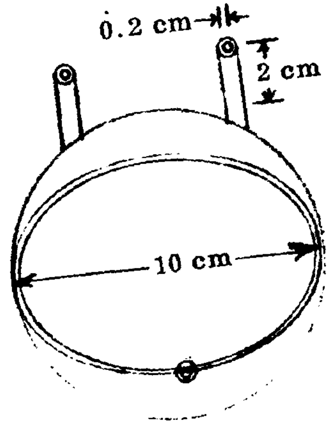


Figure 1. Test Container

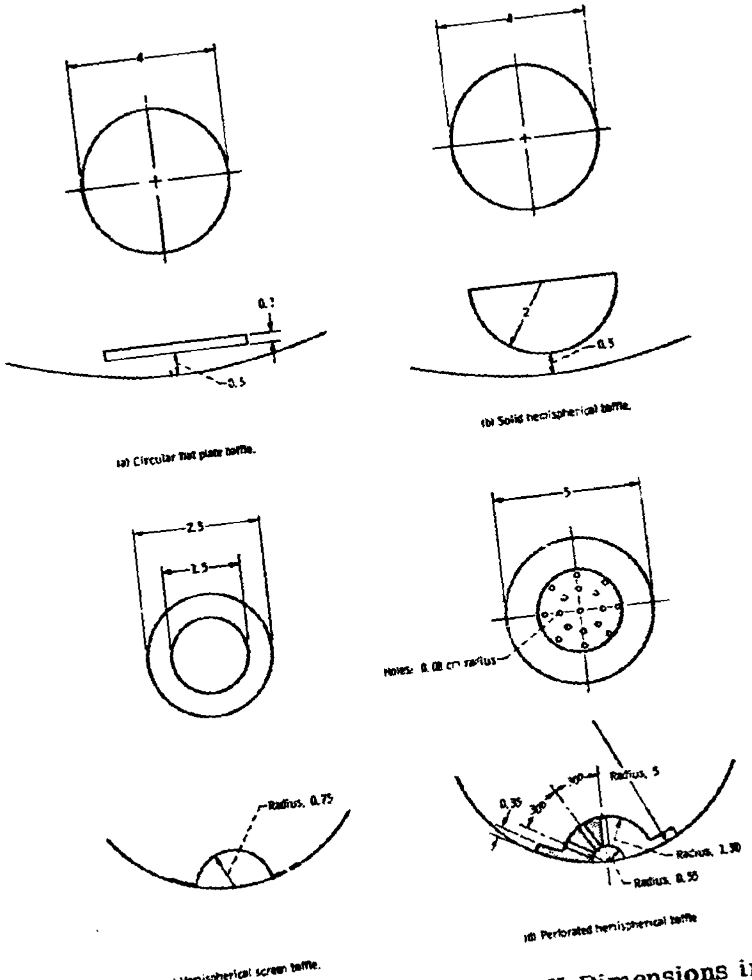


Figure 2. Schematic of Baffles. (All Dimensions in cm Unless Indicated Otherwise)

LIQUID INFLOW TO INITIALLY EMPTY CYLINDRICAL TANKS IN LOW GRAVITY

Spuckler, C. M., NASA-LeRC TM X-2613, August 1974

OBJECTIVE. - To determine the characteristics of liquid inflow to initially empty cylindrical tanks in a low gravity environment.

PERTINENT WORK PERFORMED. - A series of tests were performed in the LeRC 5.1 second drop tower to investigate liquid inflow. The tank sizes are shown in Figure 1. The fluids were anhydrous ethanol and trichlorotrifluoroethane with properties: density 0.79 and 1.58 g/cm^3, viscosity 0.012 and 0.007 g/cm-sec, and specific surface tension 28.3 and 11.8 cm^3/sec^2. Acceleration levels of 0.003 to 0.015 g resulted in a Bond number (ar_l^2/β) range of 0.059 to 2.80. Data was taken primarily by movie evaluation. Various inflow rates were used to vary Reynolds number (Vd_l/μ) from 1415 to 9870. Data measurement consisted of an evaluation of the jet stability and the jet height; the tests conducted and the reduced data are given in Table I. The correlation with a nondimensional jet height parameter of $We/(h/r_l) = V_l^2/h\beta$ (note inversely proportional to height) was made versus Bond number.

MAJOR RESULTS. -

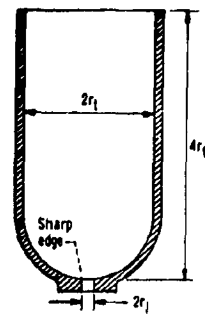
1. The fact that the Weber number rather than the Froude number correlated the results indicates the domination of surface tension in this flow regime.
2. The results of the tests for the two flow regimes, laminar-transition for Re < 4000 and turbulent Re > 4000 are presented with separate correlations in Figures 2 and 3.
3. In Figure 3, the overlapping regions of the correlation are shown. The jet height h is lower for the turbulent region.
4. Although earlier work — Symons (1970) — determined some cases to result in unstable jets, no instabilities were detected in this work.

COMMENTS. - This comprehensive series of tests are convincing that low-gravity filling can be accomplished in a controlled manner using conditions defined by this study. The absence of instabilities — jets breaking up and continuing to increase in height — were not explained.

Table 1. Summary of Low-Gravity Data

Tank radius, r_t, cm	Inlet radius, r_l, cm	Test liquid	Bond number, Bo $\frac{a\,r_l^2}{\beta}$	Weber number, We $\frac{V^2 r_l}{\beta}$	Ratio of maximum jet height to inlet radius, h/r_l	Flow regime
7.5	0.75	Ethanol	0.059	5.31	29.6	Laminar
			.137	6.67	25.1	Laminar
			.214	12.3	30.1	Transition
			.293	7.65	14.9	Laminar
		TCTFE[a]	0.140	3.44	7.13	Transition
			.327	4.58	7.87	↓
			.327	8.98	14.2	↓
			.514	4.58	7.08	↓
			.514	16.0	15.0	Turbulent
			.701	6.59	6.91	Transition
			.701	12.7	11.0	Turbulent
			.701	18.3	15.3	Turbulent
15	0.75	Ethanol	0.098	5.31	25.1	Laminar
			.176	12.3	39.9	Transition
			.234	13.6	35.8	Transition
			.293	13.6	29.2	Transition
		TCTFE[a]	0.140	3.44	9.09	Transition
			.327	8.98	13.6	Transition
			.514	4.58	6.95	Transition
			.701	12.7	11.1	Turbulent
15	1.5	Ethanol	0.390	7.06	9.15	Transition
			.546	8.04	8.30	↓
			.858	9.59	7.99	↓
			1.17	10.2	7.15	↓
		TCTFE[a]	0.561	4.49	3.37	Turbulent
			.934	5.69	3.65	↓
			.934	10.4	7.12	↓
			1.31	10.4	6.33	↓
			1.31	13.9	6.74	↓
			1.87	11.4	5.87	↓
			1.87	18.6	8.26	↓
			2.06	23.0	7.74	↓
			2.43	12.5	5.79	↓
			2.43	18.4	6.80	↓
			2.43	26.5	8.54	↓
			2.80	16.3	5.08	↓
			2.80	27.0	8.27	↓

[a] Trichlorotrifluoroethane.



Tank radius, r_t, cm	Inlet-line radius, r_l, cm
15	1.5
15	.75
7.5	.75

Figure 1. Experiment Tanks

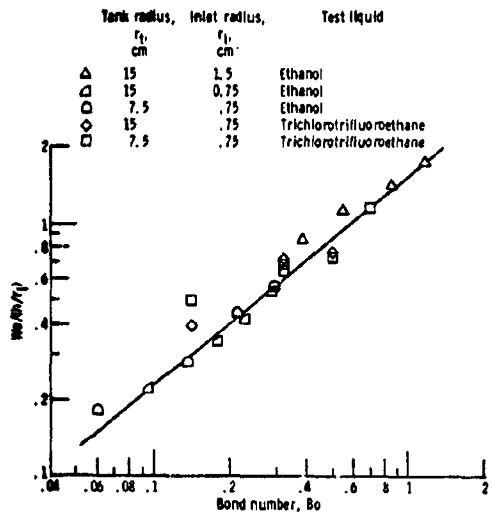


Figure 2. Dependence of Jet Height on System Parameters with Liquid Flow in the Laminar and Transition Regimes Reynolds Number, 4000

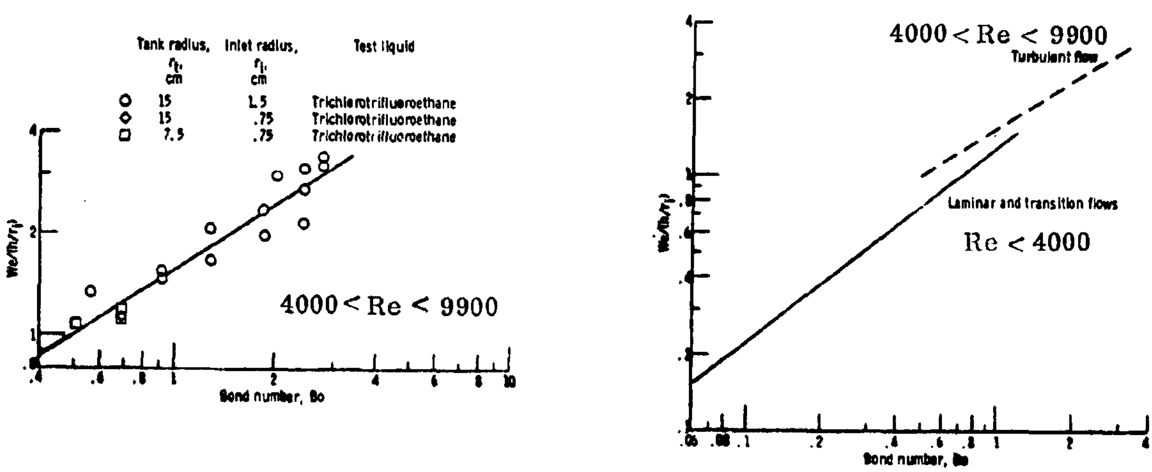


Figure 3. Dependence of Jet Height on System Parameters and Flow Regimes

LIQUID INFLOW TO A BAFFLED CYLINDRICAL TANK DURING WEIGHTLESSNESS
Staskus, J. V., NASA-LeRC TM X-2598, August 1972

OBJECTIVE. - To determine the increase in the stable inflow velocity range provided by various baffle configurations in a low-gravity environment.

PERTINENT WORK PERFORMED. - Early work in an unbaffled 2 cm radius cylindrical tank was extended to study what improvements can be gained with inlet baffle configurations. The test series was conducted in the LeRC 2.2 sec drop tower, the acceleration field was 10^{-5} g's.

The inlet in the hemispherical-bottomed tank was 0.2 cm and the test fluid was ethanol. The six inlet baffles tested are shown in Figure 1. The results were a determination of the inlet velocity at which instability occurred; so defined as geyser-like, globular, or sheet flow up the walls or tank center region. Movie coverage was used to evaluate results; velocities were compared as a ratio of the velocity at which the instability onset occurred in baffled tanks to an unbaffled tank. A qualitative description of test results are presented in Table 1.

MAJOR RESULTS. -

1. The notable increase in inlet velocity prior to onset of instability is shown in Figure 2. Increases from three-fold to twelve-fold occurred for various baffles. A pattern of wall-flow with little accumulation was the typical onset of unstable filling.

2. Perforated plates and stacked disks, with sloshing, both exhibited unstable globular flow. Vapor entrainment in the collected liquid was also present for perforated plates and the 180° redirection baffle.

3. The use of inlet baffles increased the inlet pressure drop. The maximum was for the perforated plate; a 16 percent higher pressure was required to maintain the same flow rate as an unbaffled inlet.

4. The results were most encouraging that inflow times can be substantially reduced using baffles which permit many fold increases in inlet velocities (Figure 2).

COMMENTS. - A later work in low-gravity spherical tanks (Labus, 1972) indicates the merits of a filling rate such that the walls are initially wetted and chilled, the perforated plate is indicated to be quite effective. Similarly (Spuckler, 1972) seems to permit geyser-like flow and still considers it a stable filling process in unbaffled tanks. It appears the stability criteria may need to be reviewed as to what degree of fluid motion can be accepted.

Table 1. Data Summary for Baffled Inflow

Baffle	Inflow velocity, cm/sec	Interface stability
None[a]	20.0	Stable, liquid geyser height remains constant
	20.4	Unstable, geyser height slowly increases
	21.0	Unstable, geyser height increases more rapidly
	22.4	Unstable, geyser strikes cylinder wall
Stainless steel disk	32	Stable, hemisphere fills slowly
	42	Stable, hemisphere fills more rapidly
	43	Stable, hemisphere fills more rapidly
	61	Marginal, flow up cylinder wall before filling beneath disk
	70	Unstable, more rapid flow up cylinder wall
	118	Unstable, sheet flow up wall
	143	Unstable, sheet flow up wall
	174	Unstable, all flow is up cylinder wall
	390	Unstable, very rapid flow up cylinder wall
Fluorocarbon resin disk	50	Stable, hemisphere fills
	55	Unstable, geyser forms around disk
	61	Marginal, flow up cylinder wall before filling hemisphere
	65	Marginal, flow up cylinder wall before filling hemisphere
	70	Stable, hemisphere fills before rise up cylinder
	75	Unstable, sheet flow up wall and globules break off from disk
Disk and ring	60	Stable, slow hemisphere filling
	75	Stable, liquid passes ring before filling hemisphere
	83	Unstable, almost no accumulation in hemisphere
	93	Unstable, considerable flow along cylinder wall
180°	70	Stable, trapped bubbles circulating beneath baffle
	79	Unstable, considerable flow along cylinder wall
135°	64	Stable, hemisphere fills beneath baffle
	70	Marginal, developing sheet flow along wall
	80	Unstable, considerable flow up wall
Perforated plate	78	Stable, small droplets strike wall and bubbles circulating beneath baffle
	80	Marginal, increasing flow up cylinder wall
	86	Unstable, rapid flow up wall and large globules moving up tank center
	96	Unstable, rapid flow up wall and large globules moving up tank center
Stacked disks	138	Stable, slow, uniform, hemisphere filling
	148	Stable, increasing flow up wall
	160	Unstable, large liquid volume flows up wall
	175	Unstable, flow along wall with droplets up center
Stacked disks and ring	175	Stable, hemisphere fills before liquid passes ring
	185	Stable, hemisphere fills before liquid passes ring
	199	Stable, hemisphere nearly full before liquid passes ring, interface distorted, small drops break away
	220	Stable, hemisphere nearly full before liquid passes ring, interface distorted, small drops break away
	239	Marginal, more rapid rise up wall, bubbles being trapped
	244	Unstable, large globules move up center, many bubbles trapped
	260	Unstable, large geyser strikes wall

[a] From Symons, 1971

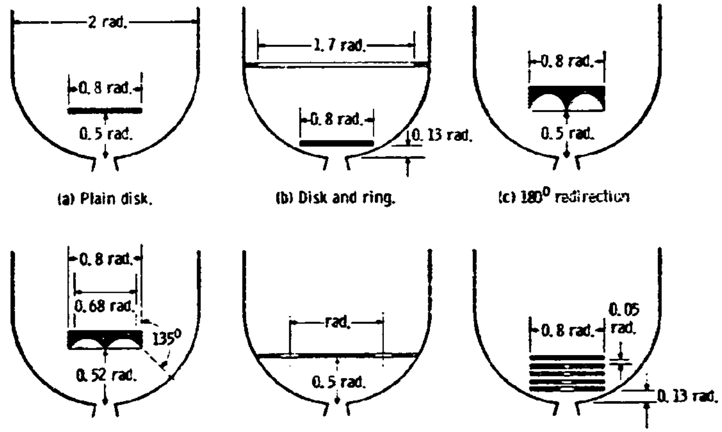


Figure 1. Inflow Baffle Cross Sections

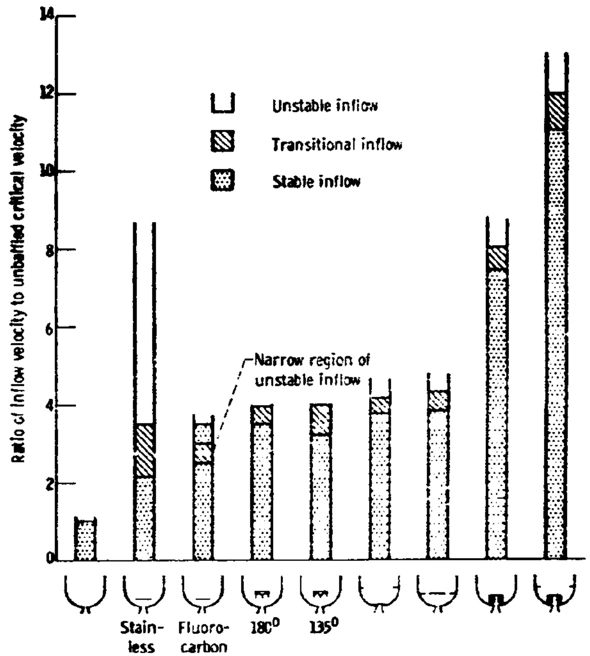


Figure 2. Comparison of Inflow Baffle Effectiveness

EXPERIMENTAL INVESTIGATION OF AN AXISYMMETRIC FREE JET WITH AN INITIALLY UNIFORM VELOCITY PROFILE
Labus, T. L., Symons E. P., NASA-LeRC TN D-6783, May 1972

OBJECTIVE. - To determine experimentally the flow characteristics of a circular free helium jet having an initially uniform velocity profile.

PERTINENT WORK PERFORMED. - An experiment was performed with a 0.254 cm diameter nozzle with a 30° convergent section to study free jet parameters; this nozzle resulted in uniform velocity profiles. The flow media and controlled environment (0.2 psig) into which the jet emerged were helium. Centerline velocity decay was measured to 25 nozzle diameters downstream for a range of $\rho U_{max} D_j/u$ of 155 to 5349 while extensive velocity profiles (0 3, 6, 10, 15, 20 nozzle diameters from the exit) were measured at Reynolds number (Re) of 1027 and 5471. Static and total head pressure measurements were made: the resolution on dynamic pressure was 0.115 n/m^2 (0.000017 psia). Although these tests were of a gas jet the results have applicability to any media under the same Re with an environment equal to the jet fluid density. In addition to velocity profiles, jet spreading angle and mass entrainment were calculated.

MAJOR RESULTS. -

1. Typical jet profile measurements for Re of 1027 are shown in Figure 1. The convergent nozzle is effective in obtaining the uniform profile. Profiles at higher Re of 4571 spread approximately double the rate pictured here.

2. The potential-core length (defined $U_{CL}/U_{max} > .95$) was a function of jet Re number. It was a maximum of 20 for Re of 1500 and decreased to near 4 at Re > 5000 as shown in Figure 2. Centerline velocities are shown in Figure 3.

3. The half angle of spread was 2° to 7° to the end of the potential-core and 2° to 11° in the region of established flow, being highest at high Re.

4. Their results for length of potential-core and half-angle spread are in agreement with previous investigations.

5. The entrained mass flux is a significant variable in mixing, if not for inflow. The fluxes at two Re are presented in Figure 4.

6. The axial jet momentum flux remained essentially constant for a given Re at the various distances downstream as determined from a velocity profile integration. If M_o is the outlet momentum based on U_{max}, the M/M_o was 0.999 for Re of 4751 but only 0.786 for Re of 1027, the constants indicating the departure from the initial totally uniform velocity profile.

COMMENTS. - Some of the results were used in liquid inflow studies by Symons (1971) (NASA TM-X-2348) for definition of jet spreading. Results here compliment similar work on the full-developed laminar profile free jet by Symons (1971) NASA (TN D-6304).

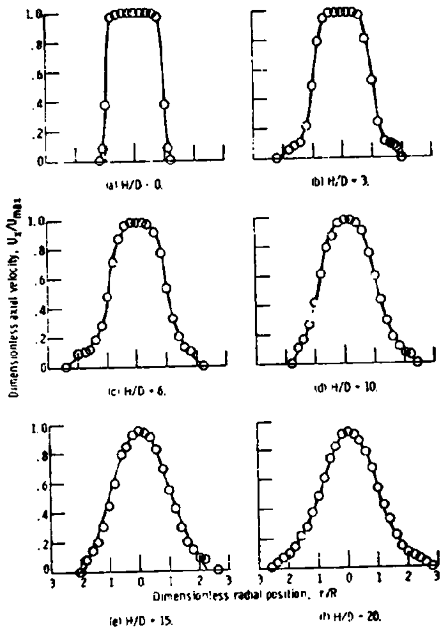


Figure 1. Velocity Profiles Downstream of Nozzle Jet Reynolds Number, 1027. (H/D is Ratio of Axial Distance from Nozzle to Internal Diameter of Nozzle.)

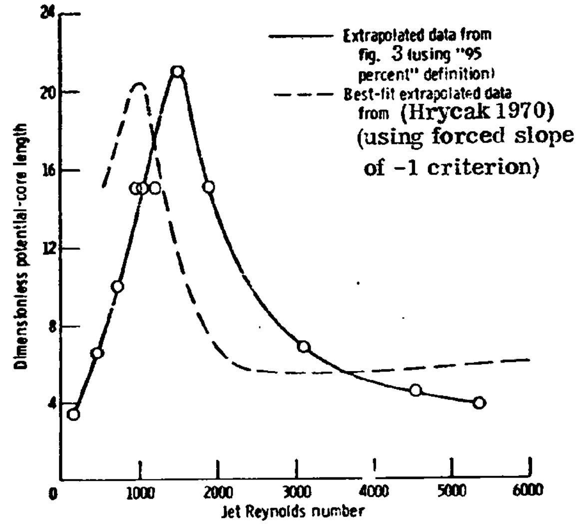


Figure 2. Dependence of Potential-Core Length on Jet Reynolds Number

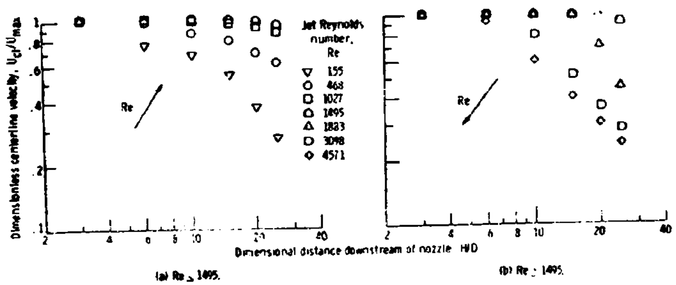


Figure 3. Dependence of Centerline Velocity Decay on Jet Reynolds Number

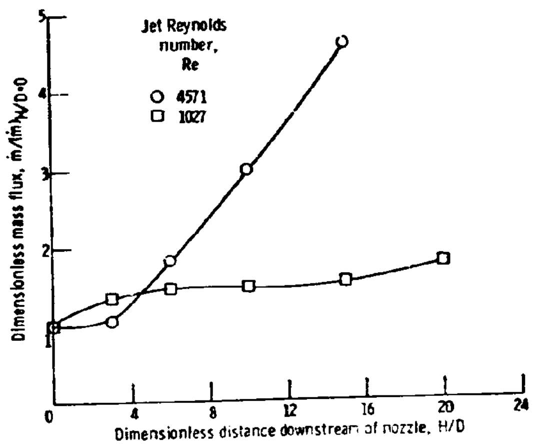


Figure 4. Dependence of Entrained Mass Flux on Jet Reynolds Number

INTERFACE STABILITY DURING LIQUID INFLOW TO PARTIALLY FULL, HEMISPHERICAL ENDED CYLINDERS DURING WEIGHTLESSNESS
Symons, E.P., Staskus, J.V., NASA-LeRC TM X-2348, August 1971

OBJECTIVE. - To define stable and unstable operating regions for liquid inflow in low gravity in cylindrical tanks.

PERTINENT WORK PERFORMED. - A series of tests to study inflow were performed in a 4 cm diameter cylindrical tank (Figure 1) in the Lewis 2.2 sec drop tower. The test liquids were ethanol, carbon tetrachloride, and tricholotrifluorethane in a single size tank. Tests were formed for selected initial liquid levels; a period was given for the low-g configuration to form prior to inflow. In particular, the effects of a uniform velocity jet rather than the parabolic velocity profile (Symons, 1969) were investigated. The uniform profile was achieved with a 30° convergent nozzle inlet. Movie coverage to provide analysis of the jet was the primary data source. A stable jet is one in which the geyser does not increase in height with time, whereas the unstable jet grows in height and may neck down and break up in globules or droplets which move toward the top vent.

MAJOR RESULTS. -

1. A Weber number for the parabolic jet is $2\ V_{i,av}^2\ R_i^2/3\beta R$, whereas the uniform jet is $V_{i,av}^2\ R_i^2/2\beta R_j$ where $V_{i,av}$ is the inlet velocity and R_j the jet radius. Test results indicated the critical Weber number of 1.5 to be a valid value for any velocity profile shape; the range had been 1.3 to 1.7 dependent on profile. In defining the Weber number, the jet R_j is required. Formulae for gas jets were used for liquid jet spreading.

$$R_j = R_i + H_i \tan 7° \cong R_i + 0.12\ H_i \qquad H_i \le 12.4\ R_i$$

$$\left.\begin{aligned} R_j &= R_i\ [1 + 12.4\ (\tan 7° - \tan 11°)] + H_i \tan 11° \\ &\cong 0.11\ R_i + 0.19\ H_i \end{aligned}\right\} \qquad H_i > 12.4\ R_i$$

2. The uniform velocity profile significantly increases the height at which the jet goes unstable over previous parabolic profile test results which are taken from Symons TM X-1934 (1969) and given in Figure 2. These results for the uniform velocity profile are shown in Figure 3 for comparison.

3. The critical Weber number increases with liquid height as is expected. This trend is shown in Figure 4. A change in slope occurs as H_i increases, which is caused by a change in the spread angle of the jet. The liquids correlate differently because of the Re number regime, 500 to 750 for ethanol and 1400 to 2500 for the other two liquids.

COMMENTS. - The work is significant in defining filling rates; improved performance of uniform profiles over parabolic profiles is shown. Additional work is required to generalize the correlations and definitely identify effects of Reynolds number and spreading angle. Note that Figure 2 is height h_i, whereas Figures 3 and 4 are dimensionless height h_i/D_i.

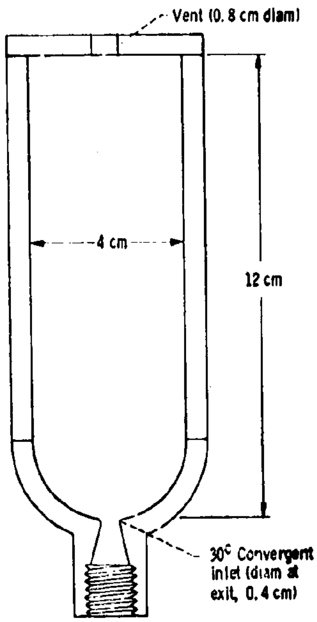


Figure 1. Experiment Tank

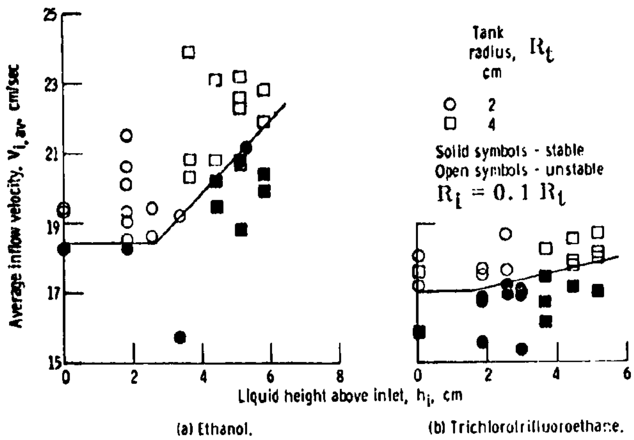


Figure 2. Effect of Initial Liquid Height on Critical Inflow Velocity
From TM X-1934 Symons (1969)

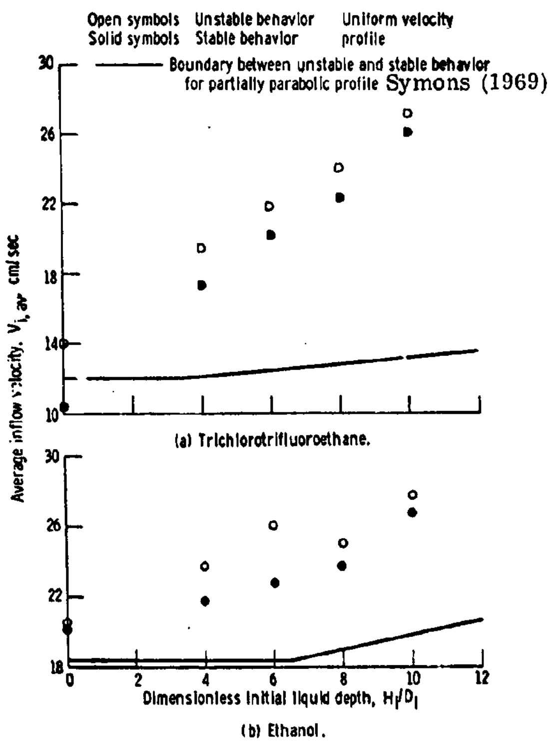


Figure 3. Effect of Initial Velocity Profile and Initial Liquid Depth on Critical Inflow Velocity

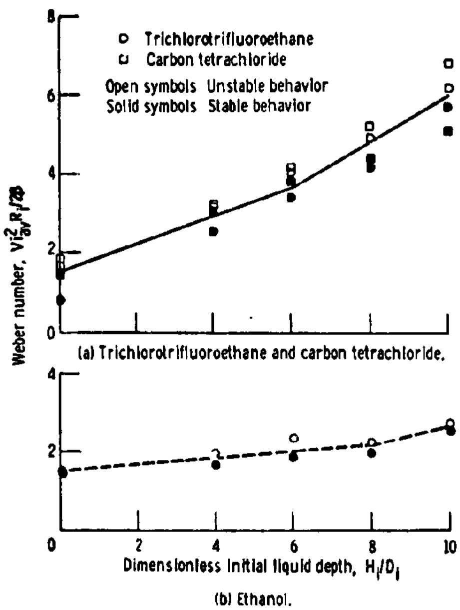


Figure 4. Weber Number as Function of Dimensionless Initial Liquid Depth

EXPERIMENTAL INVESTIGATION OF AN AXISYMMETRIC FULLY DEVELOPED LAMINAR FREE JET
Symons, E.P., Labus, T.L., NASA-LeRC TN D-6304, April 1971

OBJECTIVE. - To experimentally determine dynamic characteristics of a circular, fully developed, laminar free jet.

PERTINENT WORK PERFORMED. - A series of experiments were performed to evaluate the properties of a laminar free helium jet in an environment of helium at 0.2 psig. The nozzle was a straight tube 0.254 cm in diameter. Complete velocity profiles were measured at 0, 3, 6, 10, 15, and 25 nozzle diameters downstream at Reynolds number (Re) of 437 and 1839. Centerline velocity decay data and angle of jet spreading were measured for Re of 225 to 1839. Total and static pressure measurements were made.

MAJOR RESULTS. -

1. The velocity profile for Re equal 1837 is compared with the prediction from $U_x/U_{max}=1 - (r/R)^2$ in Figure 1. Downstream $U_x/U_{max} = (U_{c\ell}/U_{max}) \exp(-r^2/2\sigma^2)$ where σ is the r value at which $U_x = 0.605\ U_{c\ell}$. Reasonably good agreement with these equations were obtained.

2. Centerline velocity decay rates are shown in Figure 2. At three nozzle diameters some decay had occurred, making it impossible to define a potential core $\equiv (> .95\ U_{max})$. Initial velocity profiles, uniform or parabolic, do influence the velocity decay and potential core values.

3. Beyond 4 nozzle diameters, centerline velocity decay increases fastest at lower jet Re.

4. A half-angle of jet spread of 2° to 3° was determined for the jet Reynolds number range investigated. This jet spread is pictured in Figures 3 and 4 at two Re.

5. The dynamic jet behavior was determined to depend upon the initial profile of the jet. Differences from uniform velocity jets were detected.

COMMENTS - A similar study using the same hardware is reported for uniform velocity jets by Labus (1972) in NASA TN D-6783. The definition of the jet spreading complimented LeRC inflow tests at low-g.

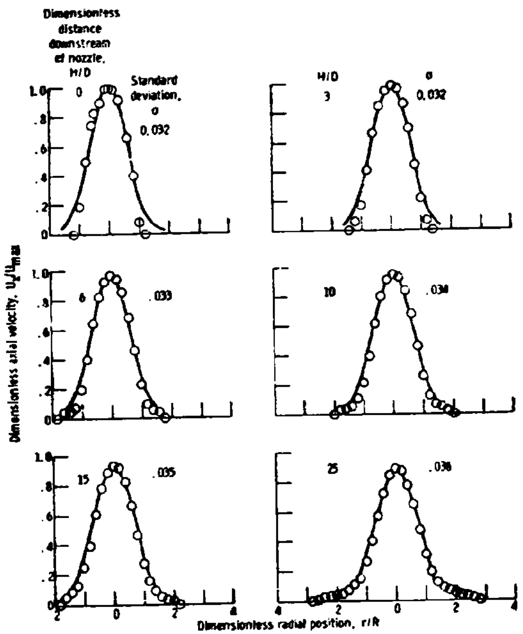


Figure 1. Velocity Profiles Downstream of Nozzle. Reynolds Number, 1839

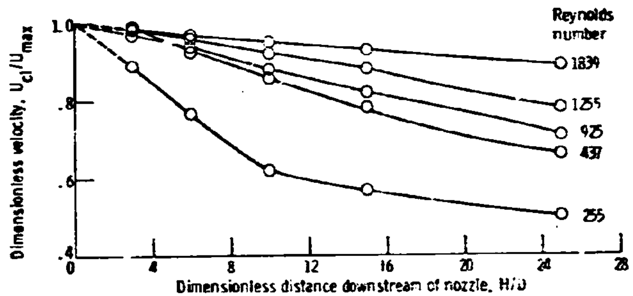


Figure 2. Dependence of Centerline Velocity Decay on Jet Reynolds Number

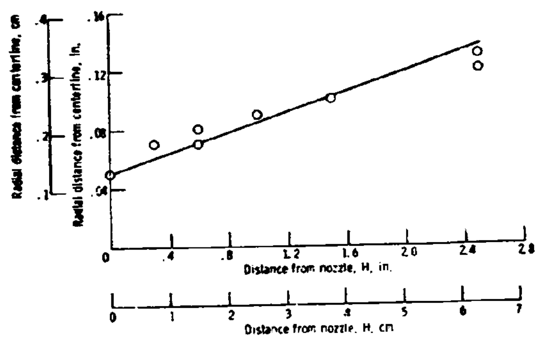


Figure 3. Jet Radius as Function of Distance from Nozzle Exit. Reynolds Number, 437; Half-Angle of Spread θ, Approximately 2°, Tan θ, Approximately 0.034

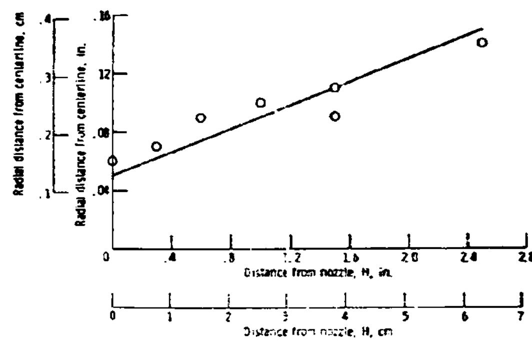


Figure 4. Jet Radius as Function of Distance from Nozzle Exit. Reynolds Number, 1839; Half-Angle of Spread θ, Approximately 2°; Tan θ, Approximately 0.034

INTERFACE STABILITY DURING LIQUID INFLOW TO INITIALLY EMPTY HEMISPHERICAL ENDED CYLINDERS IN WEIGHTLESSNESS
Symons, E. P., NASA-LeRC TM X-2003, April 1970

OBJECTIVE. - To define a Weber number criteria for determining stable/unstable filling conditions in initially empty hemispherical-ended cylindrical tanks in a low-gravity environment.

PERTINENT WORK PERFORMED. - A series of tests were performed in LeRC 2.2 and 5.2 sec drop towers with 10^{-5}g acceleration to evaluate stable inflow conditions. The first series of tests were reported in TN D4628 (Symons, 1968), however, the results are included here in Figure 1. The earlier tests with R_t of 2 to 4 cm and R_i of 0.005 0.1, and 0.2 R_t were extended to larger tanks as indicated in Figure 2; configurations were geometrically similar. Stable filling meant a geyser may form but does not grow, also liquid collects at the inlet. Unstable filling entails a geyser which continues to grow or may break up, a condition where little liquid collects, with probable vent impingement at the top of the tank. Properties of liquids used are shown in Table 1.

MAJOR RESULTS. -

1. A critical Weber number is developed as a ratio of the disturbing force of the inlet velocity momentum flux to the resistive force of surface tension.

$$We_{crit} = \frac{F_{mf}}{F_{st}} = \frac{V_{i,\,avg}^{\;2}\, R_i^{\,2}\, \pi \rho}{2\,\pi\, R_i\, \sigma} = \frac{V_{i,\,avg}^{\;2}\, R_i}{2\beta}$$

   The correlation line for a critical Weber number of 1.3 is shown (Figure 1) to correlate all the earlier data and define a clear zone of stable versus unstable inlet velocities.

2. This same correlation is shown in Figure 3 to correlate the data in the larger 7.5 and 15 cm radii tanks.

3. This critical Weber number indicates that in large tanks, typically 10 feet (304.9 cm) with R_i of 0.5 feet (15.2 cm), the fill time would approach 48 hours. This indicates a need for baffled inlet flow to permit higher fill rates. Conversely, small tanks of R_t of 6 inches (15.2 cm) could be filled in a reasonable 10 minute period.

4. The range of tank sizes and fluids indicated correlation independence of tank size and fluid viscosity.

COMMENTS. - Later work at LeRC correlated the jet height as a function of Bond number TM X-2613 (Spuckler, 1972); identified a dependence on velocity profile which increased the Weber number to 1.5 for uniform profiles in TM X-2348 (Symons, 1971); and determined stable velocities as much as 12 times greater for baffled tanks in TM X-2598 (Staskus, 1972).

Table 1. Properties of Test Liquids

[Contact angle with cast acrylic plastic in air, 0°]

Liquid	Surface tension at 20° C, σ, dynes/cm	Density at 20° C, ρ, gm/cm^3	Viscosity at 20° C, μ, gm/cm-sec	Specific surface tension, β, cm^3/sec^2
Anhydrous ethanol	22.3	0.789	1.2×10^{-2}	28.3
Trichloro-trifluoro-ethane	18.6	1.579	0.7×10^{-2}	11.8
Butanol	24.6	0.809	2.9×10^{-2}	30.4

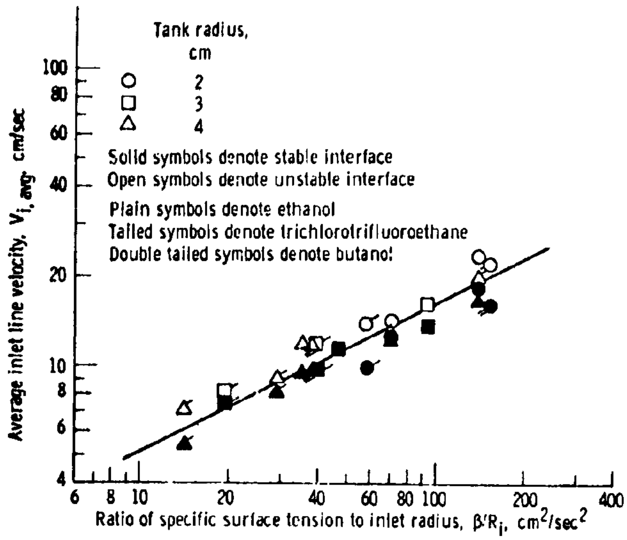


Figure 1. Stability of Liquid-Vapor Interface Delineated by Weber Number

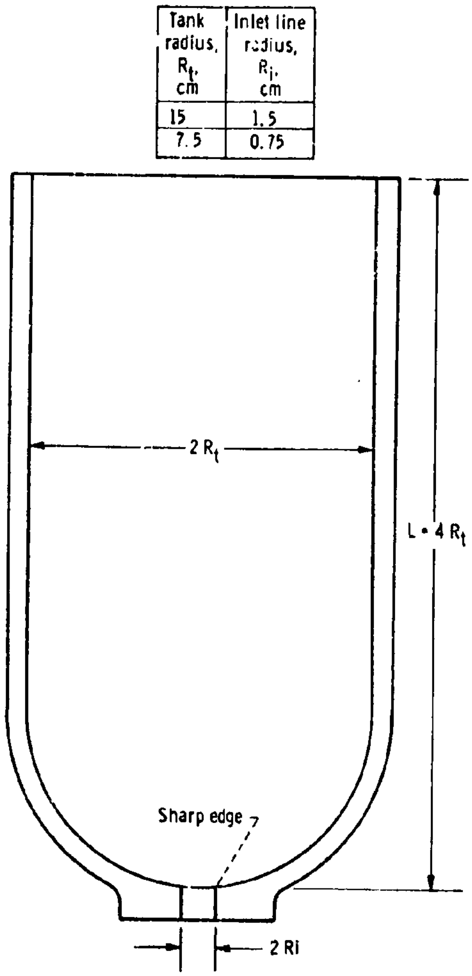


Figure 2. Experiment Tanks

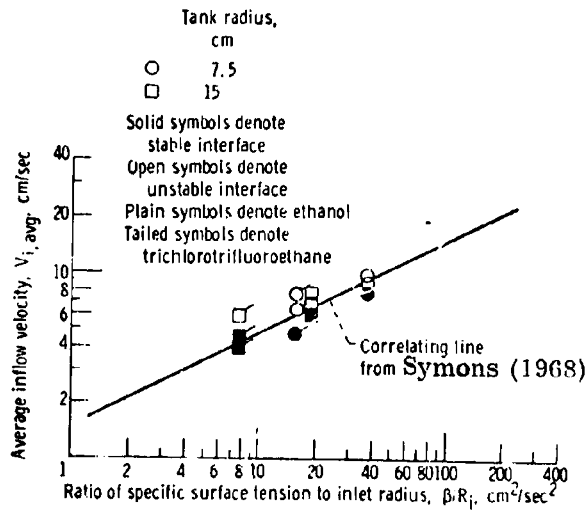


Figure 3. Delineation of Interface Behavior by Weber Number Criterion

OBSERVATIONS OF INTERFACE BEHAVIOR DURING INFLOW TO AN ELLIPTICAL ENDED CYLINDER IN WEIGHTLESSNESS

Symons, E. P, Nussle, R.C., NASA-LeRC TM X-1719. January 1969

OBJECTIVE. - To experimentally investigate fill operations in low-g for a scaled Centaur-model fuel tank.

PERTINENT WORK PERFORMED. - A series of tests were performed in the LeRC 2.2 sec drop tower with liquid ethanol to investigate effects of line size and fluid velocity on the fluid behavior during filling operations at 10^{-5}g. The geometric configuration is shown in Figure 1 of a Centaur hydrogen tank model 4 cm in diameter. The size and length of the fill line and the fluid velocity were primary variables. The tank was initially empty. The main data source was photographic coverage. A peculiarity in this configuration was the side-filling laterally onto the elliptical bulkhead.

MAJOR RESULTS. -

1. The observed flow regimes can be divided into (a) stable where the fluid moves up, wetting the walls symmetrically, (b) stable but distorted where the flow accumulates on the opposite side of the elliptical bulkhead from the inlet, and (c) unstable in which the liquid moved up the opposite wall toward the upper bulkhead and vent area.

2. In the 4 cm diameter tank with a 0.4 cm inlet, the 14.7 cm/sec inlet velocity was stable. the 22.5 to 29.7 cm/sec velocities resulted in distorted stable conditions, while 41.5 cm/sec was unstable. The latter velocity still uniformly wetted the bulkhead area rather than rebound off of it in a spraylike manner as might be expected.

3. As the inlet diameter was changed from 0.2 to 0.8 cm or 1/20 to 1/5 of tank diameter, the maximum velocity at which stability occurred dropped from 67.5 to 7.9 cm/sec.

COMMENTS. - A summary table of the test conditions or a graphical correlation are not included. The velocities in Result (3) above seem to depart from the expected critical Weber number definition for stability, i.e., they are not proportional to a $V_i^2 R_i$ relationship. Methods for scaling these results to a full-scale Centaur were not discussed.

Tank Dimensions

Tank Diameter, D, cm	Tank Length, L, cm	Inlet Line Diameter, d, cm
4	8	0.2
4	8	0.4
4	8	0.8

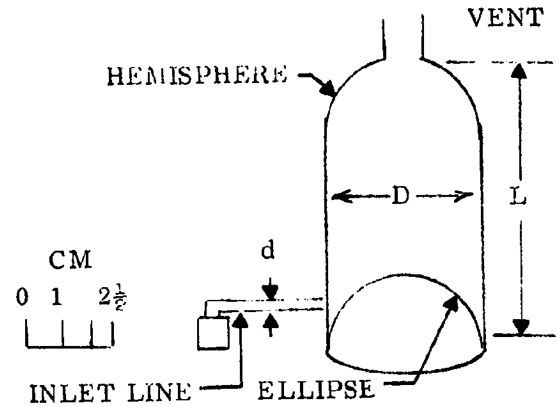


Figure 1. Test Tank Details

AN EXPERIMENTAL STUDY OF LIQUID FLOW INTO A BAFFLED SPHERICAL TANK DURING WEIGHTLESSNESS
Andracchio, C.R., Abdalla, K.L., NASA-LeRC
TM X-1526, April 1968

OBJECTIVE. - To determine stable inflow velocities for a baffled spherical tank with various initial fill levels, including empty, in a low-gravity environment.

PERTINENT WORK PERFORMED. - A series of tests were conducted in the Lewis 2.3 sec drop tower facility with a spherical baffled tank as shown in Figure 1. Tests were run with and without the spherical baffle and with and without the baffle deflector shown. Water was used as a partially wetting liquid, contact angle ~70° and ethanol as a total wetting liquid of contact angle zero. The two liquids exhibited different behavior as the correlations below indicate. In tests with initial fill, the static equilibrium interface was allowed to form before inflow started and flow stopped at 90% fill or at the end of the drop. Stable flow was defined as no liquid reaching the vent.

MAJOR RESULTS. -

1. In an unbaffled tank, the region of stable flow was defined with water for the initial fill range indicated in Figure 2. Tests were performed to define the critical inlet velocity for each fill level. Tests could not be performed with the ethanol which was wetting at any finite velocity. The effectiveness of the baffle is clearly indicated by the five to nine-fold increase in stable velocities. The log plots underemphasize the considerable improvements which were gained.

2. Similar results for baffled tests with ethanol are presented in Figure 3. Recall no stable conditions occurred for an unbaffled tank with ethanol; the flow was surface tension dominated. The deflector resulted in considerable improvements at the lower fill levels.

3. The effects of wettability are clearly illustrated in Figure 4. Two of the curves indicate the critical velocity for the same geometric configuration, a spherical baffle without deflector. Stable velocities with water are generally double those with ethanol. At lower fill levels, the deflector (middle curve) results in significant improvements for ethanol, approaching the water velocities.

4. The tests series indicated the significant improvements gained with baffles and the stable conditions attainable even for zero contact angle fluids.

COMMENTS. - Later work (Symons 1968) with cylindrical containers without baffles did not encounter this difficulty in attaining stable velocities with ethanol, a wetting fluid. The aspect ratio of jet height to tank diameter affords longer runs in cylindrical tanks; however, the results here are still surprising in view of several later LeRC investigations.

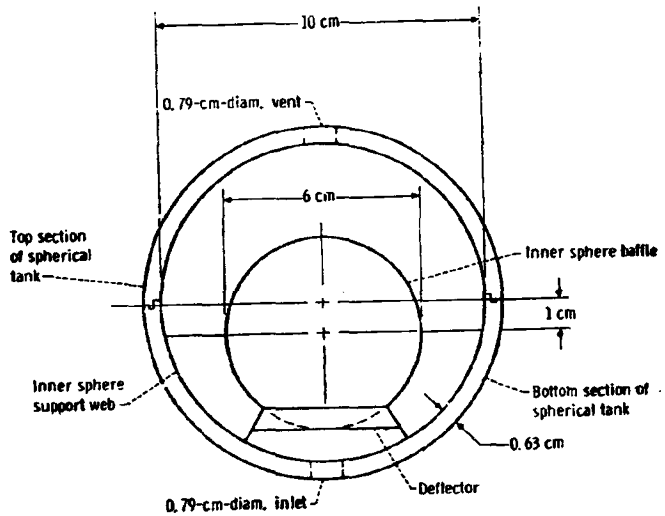


Figure 1. Tank Dimensional Sketch

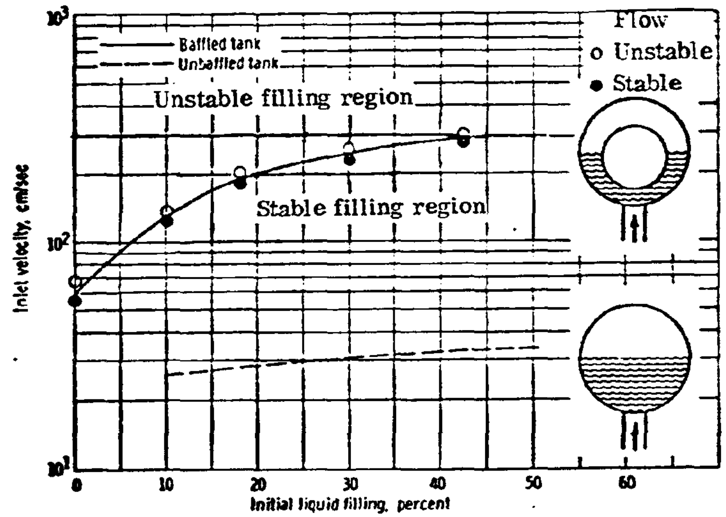


Figure 2. Baffled Tank Effectiveness in Weightlessness With Water as Test Liquid

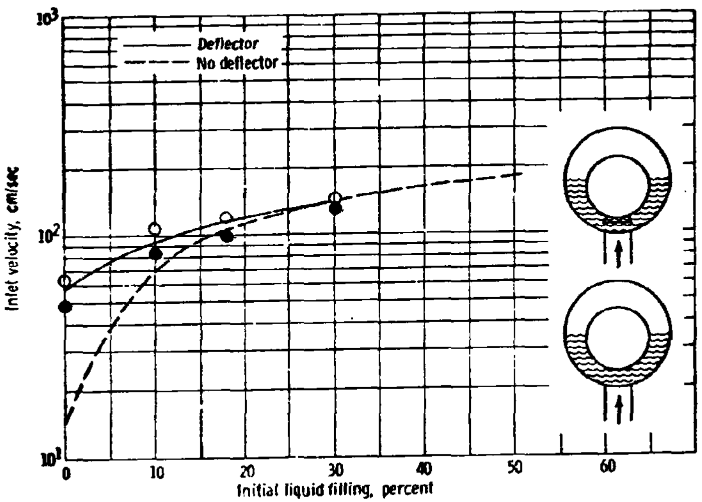


Figure 3. Inflow Deflector Performance in Weightlessness With Ethanol as Test Liquid

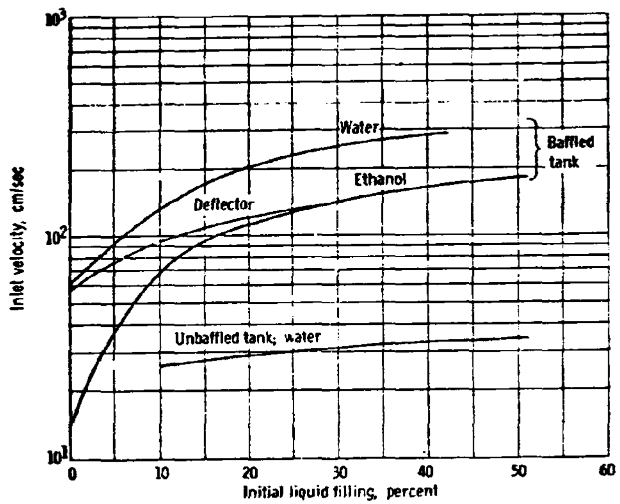


Figure 4. Effect of Wettability on Stable Inflow With and Without Surface Tension Baffle

A STUDY OF CRYOGENIC CONTAINER THERMODYNAMICS DURING PROPELLANT TRANSFER,
Vernon, R. M., Brogan, J. J., LMSC K-14-67-3, NAS8-20362, Nov 1967.

OBJECTIVE. - Provide analytical and empirical descriptions of transient phenomena in cryogenic receiver tanks during initial filling. Work was also accomplished on the transfer line alone, which is covered in another summary.

PERTINENT WORK PERFORMED. - Work consisted of both analysis (development of a computer model) and test to verify the model and develop empirical constants. The analytical model divides the tank into three vapor regions (Figure 1), with bottomed liquid and dispersed liquid (droplets) superimposed, except that no liquid can exist in the top region. Incoming liquid is dispersed in the jet region with no mixing between the jet and surrounding gas, except at the top of the jet (H_j-D/2). Evaporation of the liquid occurs only upon entering the bottom ullage region or upon contacting the wall. Venting can be from the top region only. Each fluid in each region is assumed to be ideal and at constant temperature. Testing was accomplished in a 2' diameter spherical plexiglas tank with LN_2 and a 5' diameter tank with LN_2 and LH_2. A total of 41 tests were run. Void fraction (nucleonic gage) and visual observations were made at tank inlets. Test duration covered only the first few seconds of chilldown. A straight inlet was tested and also a screened and a baffled inlet to investigate implosion phenomena.

MAJOR RESULTS. -

1. Average droplet size of the liquid entering the tank, as used in the analytical model, had a significant effect on the models ability to correlate with the test data (Fig. 2).
2. A correlation for characteristic droplet diameter (D'_D) was made using only the LN_2 data (Fig. 3). Using D'_D from Figure 3 the model prediction for LN_2 was within ±0.15 psi on pressure and ±5% on ullage vapor temperature.
3. The smaller the droplets entering the tank, the slower the pressure rise, or the more the tendency for implosion (Figure 4).
4. Agreement of the analytical model with baffled inlet test data was poor.

COMMENTS. - The receiver program presented in Vol. IV is in error. As presented, heat transfer to the dispersed liquid can be greater than that to vaporize the total coming in. This is corrected in the combination program presented in Volume V. As it stands, the program has not been checked out for other than initial inflow, before wall chilldown starts and/or liquid begins to accumulate. Existing problems are that tank wall C_p is assumed constant over the full range of chilldown and heat transfer between the wall and fluid is not properly modelled.

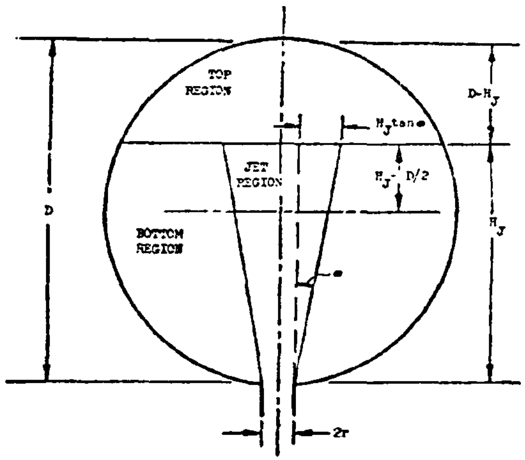


Figure 1. Tank and Jet Geometry

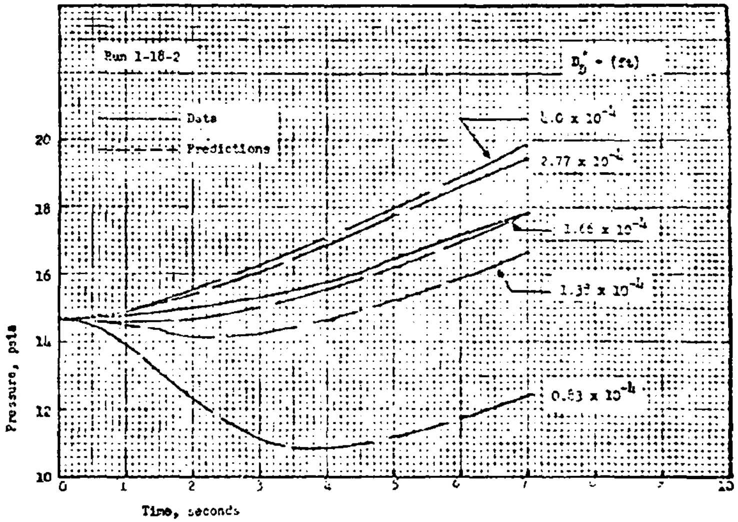


Figure 2. Comparison of Pressure Data with Predictions --- Two-ft Transparent Tank

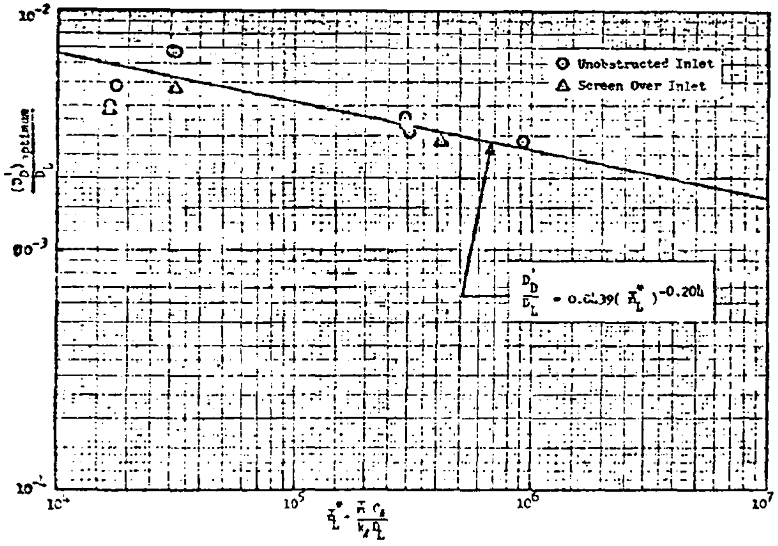


Figure 3. Optimum Values of Characteristic Droplet Diameter vs Dimensionless Mass Flowrate

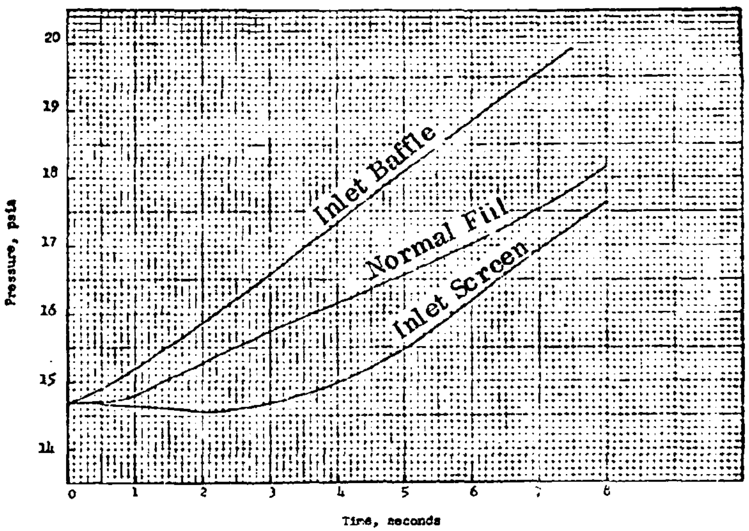


Figure 4. Comparison of Measured Pressure Responses With Low Inlet Flowrates

RAPID, LOW-LOSS LIQUID HELIUM TRANSFERS

Szara, R.J., University of Chicago, Chicago,Illinois: Advances in Cryogenic Engineering, Vol. 13, pp. 232-236, 1967.

OBJECTIVE. - To determine a method for low-liquid loss transfer of liquid helium in laboratory dewars.

PERTINENT WORK PERFORMED. - An analytical investigation of the thermodynamic and heat transfer aspects of liquid helium transfer in laboratory-size dewars was conducted. It was hypothesized that transfer tube heat losses and flash losses due to a change of a few psi in pressure would not account for losses of 15%;however,thermal equilibration of pressurant gases and hydrodynamic losses in the receiver would be major factors. A series of tests in a 100ℓ container to fill 50 and 25ℓ containers were conducted with insulated transfer lines and over pressures of 1-1/2, 2, and 3 psi.

MAJOR RESULTS. -

1. The use of flashing helium in the supply tank is very inefficient. Pressurized transfer using heated helium is most effective. Figure 1 indicates the absence of heat transfer between the warm ullage and the helium bulk. The subcooling of the delivered helium reduces line losses and results in a closed jet which enters the receiver tank with minimal losses. The absence of interaction between the inflow and the vented vapor is important to efficient transfer. Short transfer times in large tubes reduce thermal losses.
2. Results from 8 tests are shown in Table 1. The losses average only 2.25%; considerably below typical operating conditions for this size dewar.

COMMENTS. - The procedures suggested here result in minimization of losses for liquid helium transfer and suggest methods for optimal transfer of other cryogens.

Table I. Experimental Results

Type of dewar received	Liq. He received, liters	Transfers into Supairco N_2-shielded dewars, liters	Total transferred, liters	Loss, %
Cryenco gas-shielded	97	47, 45.5	92.5	4.6
Cryenco gas-shielded	95	43.5, 44, 6	93.5	1.6
Cryenco gas-shielded	89	21, 48.5, 18.5	88	1.1
Linde gas-shielded	104.25	46.5, 48.5, 5.5	100.5	3.6
Cryenco gas-shielded	95	43, 48.5, 2.5	94	1.0
Cryenco gas-shielded	88	48, 38	86	2.3
Cryenco gas-shielded	95	17.5, 29, 27, 21	94.5	0.5
Hofman nitrogen-shielded	93	43, 23.5, 23.5	90	3.2

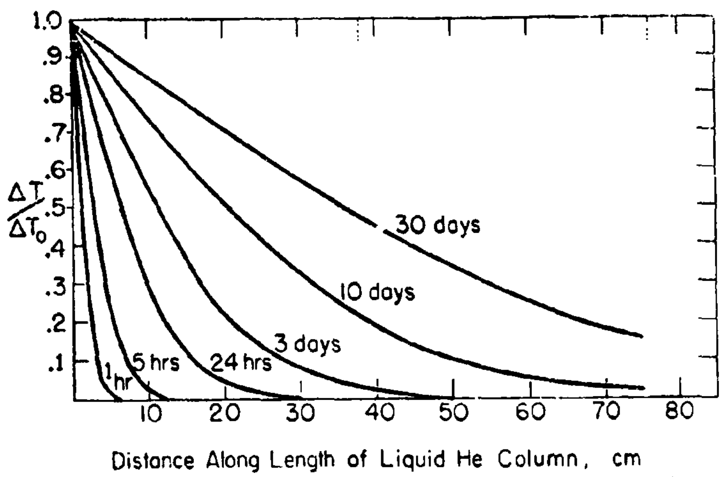


Fig. 1. Temperature penetration into a semi-infinite column of liquid helium as a function of time

$$\Delta T = \Delta T_0 [1 - 2/\pi^{\frac{1}{2}} \int_0^{x/2(\mathcal{K}t)^{\frac{1}{2}}} e^{-\zeta^2} d\zeta]$$

$\mathcal{K}$ = temperature diffusivity
x = distance from origin in column
t = time
$\zeta = x/2(\mathcal{K}t)^{\frac{1}{2}}$

8.0 FLUID OUTFLOW

Covering draining with and without pullthrough suppression devices and with and without flow throttling.

EFFECT OF THROTTLING ON INTERFACE BEHAVIOR AND LIQUID RESIDUALS IN WEIGHTLESSNESS
Symons, E.P., NASA-LeRC, NASA TM X-3034, May 1974

OBJECTIVE. - Experimentally evaluate vapor ingestion in a flat bottomed cylindrical tank following a single-step throttling in outflow rate in a weightless environment.

PERTINENT WORK PERFORMED. - The Lewis Research Center Zero Gravity Research Facility was used to obtain the experiment data for this investigation. A typical experiment test tank is schematically shown in Figure 1. The tanks were flat bottomed right-circular cylinders 2 and 4 centimeters in radius and machined from cast acrylic plastic. Outlet radius was either 1/10th or 1/20th of the tank radius. Outlet lines had a run of at least 15 outlet line diameters prior to entering the throttle valve. Test liquids were anhydrous ethanol and trichlorotrifluoroethane.

During a drop, a predetermined time increment was allotted to allow the liquid-vapor interface to reach its low point in the first pass through its equilibrium configuration. After this time increment, outflow was initiated and continued until vapor ingestion into the tank outlet was imminent. At this time the throttle valve was actuated to reduce the outflow rate. In all tests the ratio of the final Weber number to the initial Weber number was 1:10. Liquid-vapor interface data was recorded photographically.

MAJOR RESULTS. -

1. The throttling process excited a large-amplitude symmetric slosh.

2. Depending upon the initial Weber number (before throttling), the sloshing produced a liquid vapor interface that was either flattened, formed in a stable geyser which eventually receded into the bulk liquid, or formed in an unstable geyser which broke into one or more droplets which moved to the tank end opposite the outlet line. The Weber numbers delineating these regimes were found to be similar to those found in Grubb and Petrash, 1967.

3. Throttling reduced liquid residuals. For Weber number greater than 0.5 and less than 4, liquid residuals were adequately predicted by assuming that draining occurred at the final Weber number. For Weber number greater than 5, residuals were lower than this predicted value.

4. Step throttling appeared to be useful in reducing residuals in those cases where the initial Weber number was sufficiently high to produce significant interface distortion during throttling (see Figure 2).

COMMENTS. - Step throttling also allows reductions in transfer time compared to draining continuously at the final Weber number.

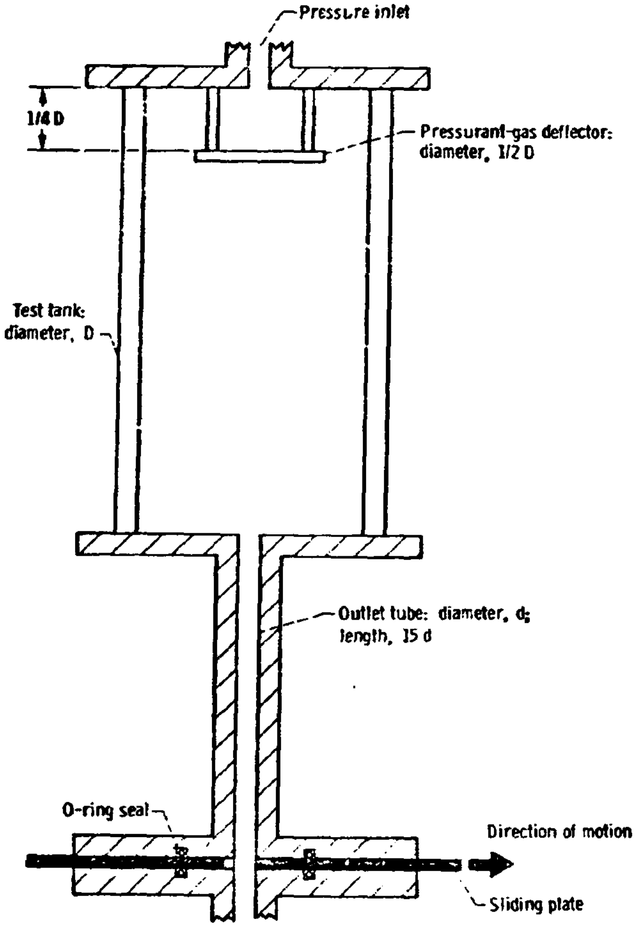


Figure 1. Schematic drawing of typical test tank.

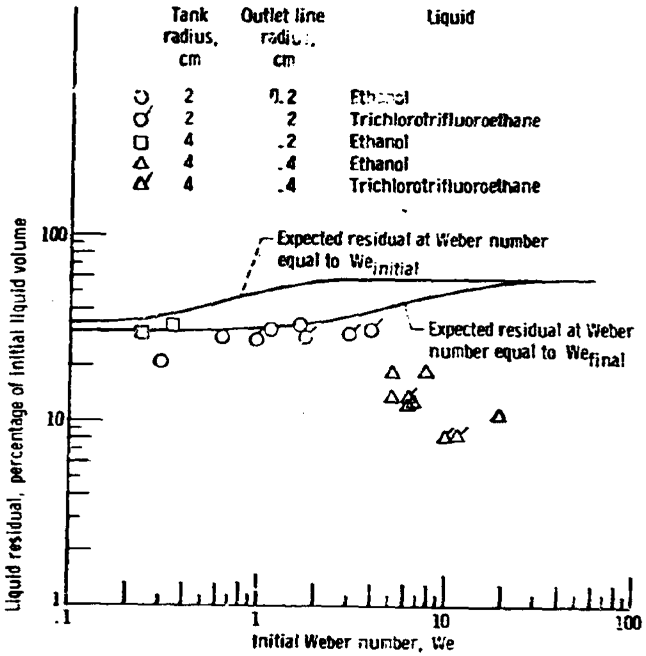


Figure 2. Percentage of liquid residual as function of initial Weber number. Ratio of final Weber number to initial Weber number, 1:10.

VAPOR INGESTION IN A CYLINDRICAL TANK WITH A CONCAVE ELLIPTICAL BOTTOM
Klavins, A., LMSC, LMSC/D386845, NAS3-17798.
February 1974

OBJECTIVE: - Analytically estimate the propellant residual in the Centaur LH_2 tank during draining.

PERTINENT WORK PERFORMED. - Residual estimates were made based on the approximate analysis of Lubin and Hurwitz 1966 extended to low g conditions in Satterlee and Hollister 1967. The Bernoulli equation was written for a surface streamline between a point on the drain centerline and a point far from the drain. The fluid velocity at the centerline of the drain was expressed in terms of the flow rate, and the pressure drop along the streamline due to surface tension was expressed in terms of the surface curvature.

Other work at LMSC suggested that vapor ingestion data at all acceleration levels may be correlated in terms of the group $W/(1+B)$ where W is the Weber number, $(\rho Q^2/\pi^2\sigma a^3)$ and B is the Bond number $(\rho g a^2/\sigma)$ where a is the tank radius. Approximations are made for Centaur tank geometry to obtain the control area to be considered and the surface curvature function for possible outflow conditions. These conditions included high Bond number and low Bond number draining for cases where the free surface height away from the drain is both large and small relative to the semi-minor axis of the intermediate bulkhead. The analysis was not correlated with experimental data. Flow conditions of Table 1 were examined using the computational method of Table 2. Figure 1 defines the fluid and tank geometry and nomenclature.

MAJOR RESULTS. -

1. Figure 2 shows the fluid height at which vapor ingestion may be expected to occur for a given $W/(1+B)$. Residual volumes assume that the liquid surface away from the drain is flat $(B_o \longrightarrow \infty)$.
2. Table 1 conditions were evaluated using the results of Figure 2. On the basis of these calculations, vapor ingestion was predicted to occur after the liquid level dropped below the top of the sump region.

COMMENTS. - Correlating results on the basis of $W/(1+B)$ is consistent with previous investigations that have found the Weber number to be the significant correlation parameter for pullthrough at low acceleration levels (B small relative to 1) and the Froude number to apply at high acceleration levels $(B \gg 1$, since $Fr = W/B)$.

Table 1. Summary of Flow Conditions

Propellant: liquid hydrogen, $\sigma/\rho = 26.6\ \mathrm{cm^3/sec^2}$

Initial vehicle weight $W_o = 14{,}024\ \mathrm{lb_m}$

Initial propellant loading $= 27.4\% \approx 350\ \mathrm{ft^3}$

Acceleration levels, based on W_o:

Thrust $T = 24\ \mathrm{lb_f}$	$B = 1.47 \times 10^3$	Settling
$T = 100\ \mathrm{lb_f}$	$B = 6.13 \times 10^3$	Settling
$T = 30{,}000\ \mathrm{lb_f}$	$B = 1.84 \times 10^6$	Main Engine

Flow rates:

Time sec.	Q $\mathrm{ft^3/sec.}$	W/(1+B) $T = 0$	$T = 24\ \mathrm{lb_f}$	$T = 100\ \mathrm{lb_f}$	$T = 30{,}000\ \mathrm{lb_f}$
10	.214	3.96×10^{-2}	2.69×10^{-5}	6.46×10^{-6}	—
[illegible]	.927	7.43×10^{-1}	4.37×10^{-4}	1.21×10^{-4}	—
29.95	3.275	9.28	6.31×10^{-3}	1.51×10^{-3}	—
30.35	2.675	6.64	4.57×10^{-3}	1.08×10^{-3}	3.36×10^{-6}

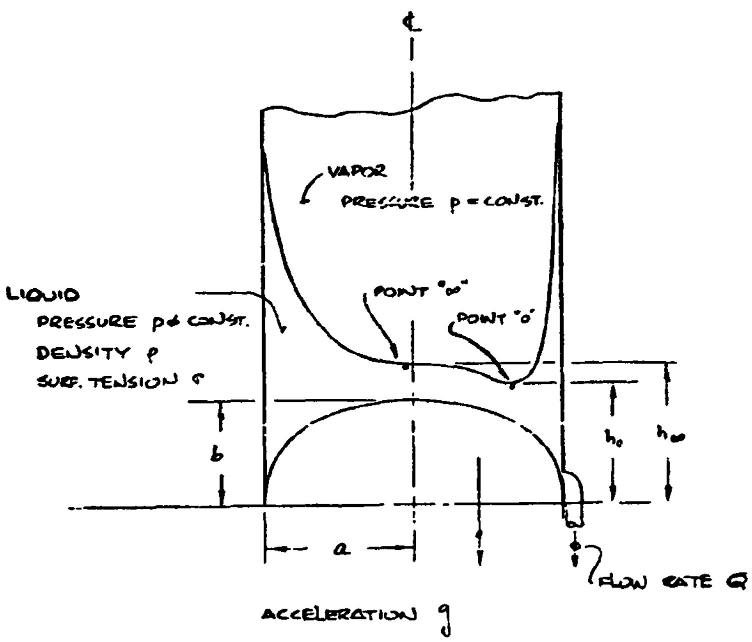


Figure 1. Low-g Tank Draining Definition of Terms

Table 2. Computation Sequence

(i) Pick Bond number and choice of A and f, where f is the curvature function and A is the control area

(ii) Pick $H_o = h_{oc}/b$

(iii) Evaluate $A(H_o)$ and $f(H_o)$

(iv) Evaluate the derivatives

$$\frac{\partial A}{\partial h_o} \approx \frac{100}{b}\left[A\,(H_o + .01) - A(H_o)\right],$$

$$\frac{\partial f}{\partial h_o} \approx \frac{100}{b}\left[f\,(H_o : .01) - f(H_o)\right].$$

(v) Substitute the results of (iii) and (iv) into $h_{\infty c} - h_{oc} =$

$$\left[\frac{2}{A}\frac{\partial A}{\partial h_o} - \frac{1}{1+Bf}\,\frac{1}{f}\,\frac{\partial f}{\partial h_o}\right]_o^{-1}$$ to obtain $(h_\infty/h_o)_c$

(vi) Substitute the results of (iii) and (v) into $\frac{W}{1+B} =$

$$\frac{2}{g^2 a^5}\,\frac{A^2}{f}\,\frac{1+Bf}{1+B}$$ to obtain $(W/(1+B))$

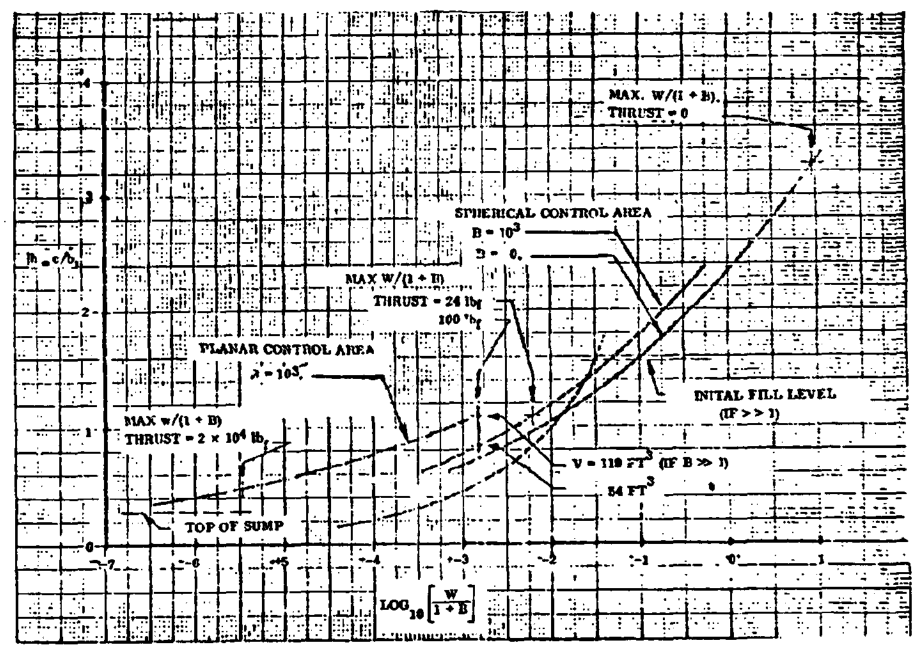


Figure 2. Vapor Ingestion Height as a Function of (W/(1 + B)

OUTLET BAFFLES - EFFECT ON LIQUID RESIDUALS FROM ZERO-GRAVITY DRAINING OF HEMISPHERICALLY ENDED CYLINDERS
Symons, E.P., NASA-LeRC, TM X-2631,
September 1972

OBJECTIVE. - To experimentally investigate the relative effectiveness of various outlet baffles in reducing liquid residuals resulting from the draining of hemispherically ended cylinders in a weightless environment.

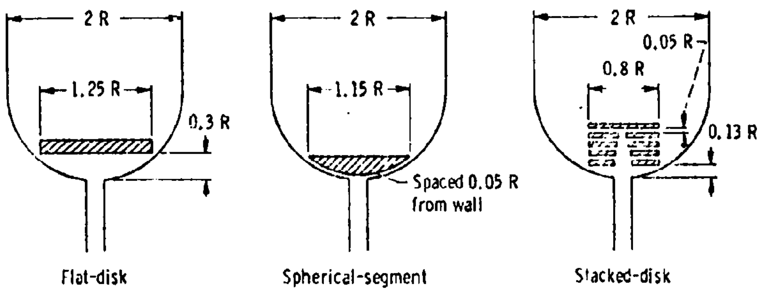
PERTINENT WORK PERFORMED. - A 2 cm radius hemispherically bottomed cast acrylic cylinder (Figure 1) was used with three outlet baffle configurations; a flat disk baffle, a spherical segment baffle and a stacked disc baffle (Figure 1). For the spherical segment baffle, total open area was approximately equal to the tank outlet cross section area, A_T. For the stacked disk and flat disk baffles, flow area was approximately $4A_T$ and $10A_T$ respectively. A flat disk baffle was employed to prevent interface deformation due to pressurant inflow. The axisymmetric outlet had a radius of 0.2 cm. Normal gravity tests were used to calibrate pressure vs outflow rate. Trichlorotrifluorethane and anhydrous ethanol were used as the test fluids, with draining initiated after allowing time for the zero-g interface to form. Data was recorded photographically in order to compare interface shapes and residuals at vapor pull through. Runs were made for the flat disk baffle at two fill levels, 2R and 3R from the tank bottom.

MAJOR RESULTS. -

1. Baffles reduced residuals from the unbaffled cases (Figure 2). Due to the highly curved liquid vapor interface and the shape of the tank bottom, as much as 45% of the initial liquid volume in the tank is residual, even with the best baffle configuration.
2. The most effective baffle in reducing residuals was the flat disk baffle.
3. Residual fraction was independent of initial filling over the range of parameters investigated.

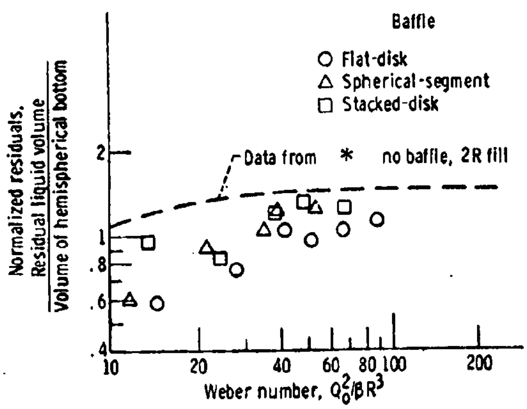
COMMENTS. - In order to fairly compare the different baffle configurations employed, equal flow areas should probably be used.

(a) Tank components and outlet baffles.



(b) Sketches showing relative locations and sizes of baffles.

Figure 1. Experiment Tank and Outlet Baffles



* Berenyi and Abdalla, 1969

Figure 2. Comparison of Performance of Baffles

UNSTEADY AXISYMMETRIC FLOWS OF A LIQUID DRAINING FROM A CIRCULAR TANK
Chow, C.Y., Lai, W.M., Rensselaer Polytechnic Institute,
AIAA Journal, Vol. 10, No. 8, Aug. 1972.

OBJECTIVE. - Analytically study the problem of unsteady axisymmetric flow from a flat bottomed circular cylinder with a centrally located drain using nonlinear boundary conditions at the free surface.

PERTINENT WORK PERFORMED: - The same model as Easton and Catton, 1970 was used. The method employed was based on the nondimensionalization and application of the Gram-Schmidt orthonormalization scheme to determine some of the coefficients in the resulting equation. The velocity potentials were computed and the liquid remaining in the tank at a given time was integrated numerically by the trapezoidal rule on the free surface. Results were compared to the experimental work of Gluck, et al 1966 and the analysis of Easton and Catton, 1970. A contact angle of 90° was assumed in both this work and that of Easton and Catton.

MAJOR RESULTS. -

1. Computed results compare favorably to the experimental data of Gluck et al, 1961. In Figure 1, H_c, the critical height divided by tank radius, is plotted as a function of the mean surface velocity, drain radius and gravitational acceleration.
2. Hc, dimensionless critical height (h_c/r) increases with increasing dimensionless initial fill level (h_s/r) (Figure 2).
3. An experimental expression by Harleman, et al, 1959, $F_{cr} = Q_c/(gh_c^5)^{1/2} = 0.51\pi$ where Fr_{cr} is the critical Froude number delineated by the asymptotic region in Figure 1, Q_c is the critical volumetric discharge rate, g is the gravitational acceleration and h_c is the critical height, agrees quite well with the numerical computations.
4. This study predicts much earlier inception of dip formation and hence more residual volume then predicted by Easton and Catton. Monotonically decreasing slopes are predicted during draining compared to the reversal in slopes predicted by Easton and Catton (Figure 3). Initial rate of decrease of the free surface and the center line are much steeper than that of Easton and Catton.

COMMENTS. - Results of this study agree more closely with the data of Gluck and yield more logical surface shapes than the results of Easton and Catton.

Nomenclature

$A_m^{(n)}$	= coefficients
a	= radius of the drain
$\bar{a}$	= drain radius ratio a/r_o
B_o	= Bond number $\rho g(2r_o)^2/T$
$B_m^{(n)}$	= coefficients
C	= a constant
$f^{(m)}(\xi)$	= functions of ξ
F	= Froude number $U^2/(gr_o)$
F_{cr}	= critical Froude number $Q_c/(g'h_c^5)^{1/2}$
F_r	= Froude number $V_m^2/(2ga)$
g	= gravitational acceleration
g'	= effective gravitational acceleration $g(\rho_2 - \rho_1)/\rho_2$
$h(\xi, \tau)$	= shape of the free surface
h_c	= central height of the liquid at critical flow
h_o	= initial height of the liquid in the tank
h_w	= height of the free surface on the wall
$h^{(m)}$	= terms of expansion of $h(\xi, \tau)$ on τ
H_s	= initial height ratio h_s/r_o
$H(0, \tau)$	= center height ratio $h(0, \tau)/r_o$
H_c	= critical height ratio h_c/r_o
H_w	= dimensionless height of the free surface on the wall h_w/r_o
$J_0(k)$	= Bessel function of the zero order
$J_1(k)$	= Bessel function of the first order
k	= constant
k_m	= positive mth root of $J_1(k_m)$
Q	= constant rate of discharge through the drain
Q_c	= critical rate of discharge
r, z	= cylindrical coordinates
r_o	= radius of the tank
t_c	= critical time
t	= time
$\bar{t}$	= time parameter $t/(\rho r_o^3/T)^{1/2}$
T	= surface tension
$u_m(\xi)$	= orthonormalized functions of ξ
U	= constant discharge velocity through the drain
$v_m(\xi)$	= functions of ξ
V_m	= average velocity of the liquid in the tank $U\bar{a}^2$
W	= Weber number $r_o\rho U^2/T$
W_e	= Weber number $2\rho r_o V_m^2/T$
ξ, η	= dimensionless cylindrical coordinates $\xi = r/r_o$, $\eta = z/r_o$
Φ	= velocity potential
π	= pi
$\varphi = \varphi(\xi, \eta, \tau)$	= dimensionless velocity potential Φ/Ur_o
$\varphi^{(m)}$	= dimensionless velocity potentials
$\varphi^{(m)}(\xi, \eta)$	= dimensionless velocity potentials
τ	= dimensionless time $tUa^2/(h_s r_o^2)$

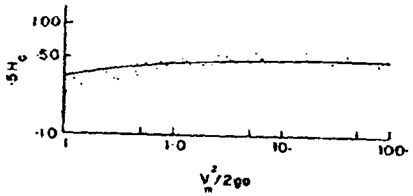


Figure 1. Comparison of Computed Results (Solid Line, Based on $H_S = 1.2$, $\bar{a} = 0.312$, $W = \infty$) and Experimental Data (Dots Taken from Gluck, et al, 1966

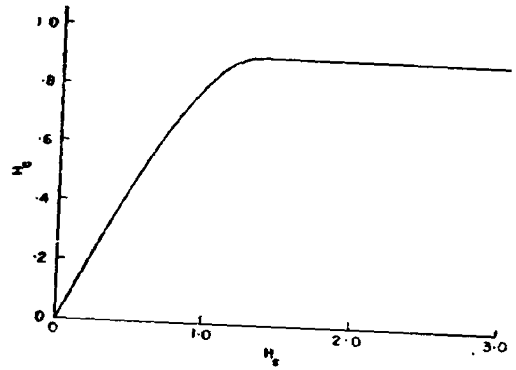


Figure 2. Dimensionless Critical-Height Vs Dimensionless Initial-Height; $\bar{a} = 0.312$, $F = 10^4$, $W = \infty$

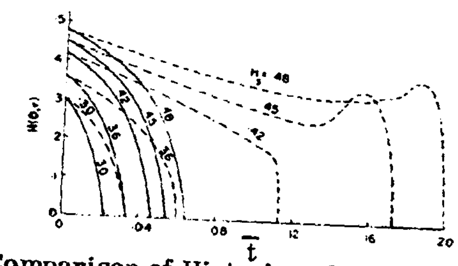


Figure 3. Comparison of Histories of Dimensionless Central Height of Free Surface for Various Dimensionless Initial Heights. Solid Lines are Present Results, Dashed Lines are Results of Easton and Catton, 1970

IN-SPACE PROPELLANT LOGISTICS
Sexton, R. E., et al, NAR, SD 72-SA-0053,
NAS8-27692, June 1972

OBJECTIVE. - Definition of a representative in-space propellant logistics system and its operation.

PERTINENT WORK PERFORMED. - Work included determination of in-space propellant requirements in support of the NASA space program plan (Fleming Model), definitions of propellant logistics system concepts to meet these requirements, cost analyses and maintenance, and manned support requirements analysis. This work is reported in five volumes; (1) executive summary, (2) technical report, (3) trade studies, (4) project planning data, and (5) cost estimates. A systems safety analysis was also accomplished and is reported in another three volumes under report number SD 72-SA-0054.

In general, the work reported here is based on existing technology or work which is summarized elsewhere. However, a few pertinent notes of current interest are presented below.

MAJOR RESULTS. -

1. The connected ullage concept shown in Figure 1 was selected as the baseline system for receiver tank thermodynamic control on the basis of minimum propellant loss, system simplicity, and compatibility with the expulsion subsystem selected. Liquid acquisition is accomplished with linear acceleration.

2. Pullthrough data developed in another study (Chen and Zukoski, 1968) was used to compare a variety of tank outlet shapes. Residuals versus Froude number are shown in Figure 2 for various tank geometries. Data from Chen and Zukoski, 1968, indicated that residuals would be two to four times greater than predicted by Berenyi and Abdalla, 1970. The selected configurations employed flow rate throttling of 10:1 to reduce residuals.

COMMENTS. - Chen and Zukoski, 1968, was not obtained in time to be included in the literature review.

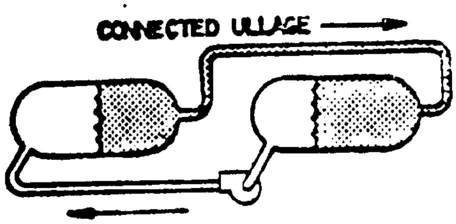


Figure 1. Connected Ullage

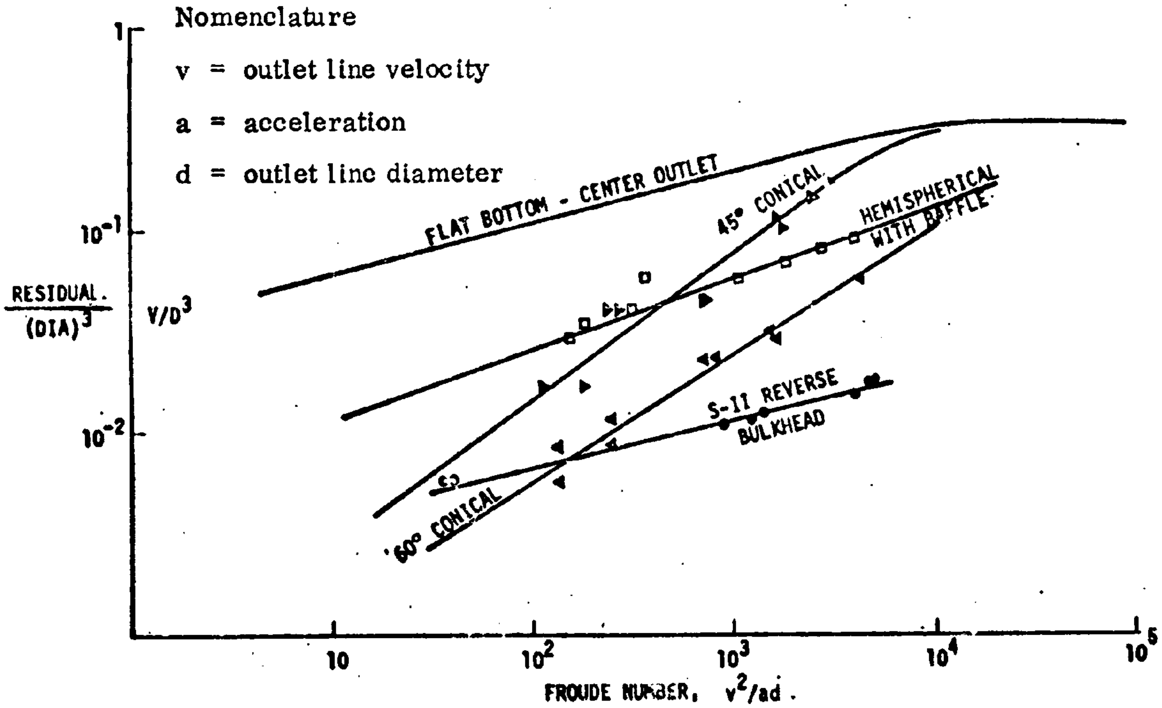


Figure 2. Residual Versus Froude Number for Various Tank Geometries

NONLINEAR FREE SURFACE EFFECTS IN TANK DRAINING
AT LOW GRAVITY
Easton, C.R. Catton, I., MACDAC, AIAA Journal, Vol. 8
No. 12, December 1970

OBJECTIVE. - Analytically develop solutions for low gravity draining, retaining all of the nonlinear terms in the free surface boundary conditions.

PERTINENT WORK PERFORMED. - Low Bond number draining was not addressed because no means are available for expressing the transient surface shape in a form that permits accurate spatial derivatives of the surface shape to be calculated.

Work of previous investigators have limitations, in assuming small surface deformations or in yielding empirical relationships, that do not permit residuals to be determined or the time history of the outflow to be followed. In this paper, the full nonlinear dynamic and kinematic boundary conditions were used. The effect of surface tension was included. The basic equations formulated were solved in a stepwise manner until pullthrough occurred, using an Adams-Bashforth differencing method. A 90° contact angle was imposed, using an initially flat interface impulsively started in motion at the mean tank velocity, V_m.

MAJOR RESULTS. -

1. Computation time and accuracy were found to be strongly dependent upon the number of terms in the Fourier expansion (Figure 1).

2. Nonlinear theory agreed quite well with the experimental data on vapor ingestion (Gluck, 1966 and Lubin and Springer, 1967) over the range of Weber numbers considered (Figure 2). Several points in Figure 2, obtained from Marker and Cell program results (Madsen, 1970), also agreed with the experimental data.

3. Linear theory predicted too low a critical height at all Weber numbers with increasing error for smaller Weber number (Figure 2).

4. Bond number was varied from 10 to 1000 without a significant effect on the calculations.

COMMENTS. - The linearization assumption used in obtaining the results discussed in 3. is not stated.

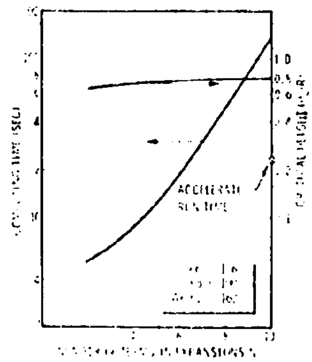


Figure 1. Sensitivity of Solution and Run Time
To Number of Terms in Expansions

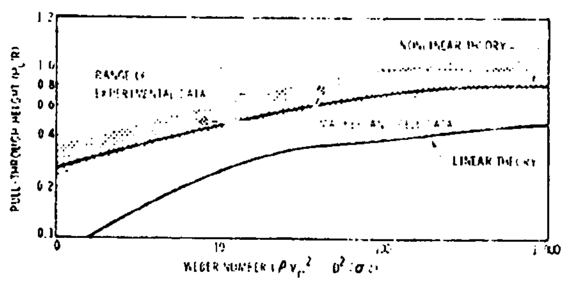


Figure 2. Correlation of Linear and Nonlinear
Theories to Experiments on Pull-
Through Height

EFFECT OF PRESSURANT INLET CONFIGURATION ON LIQUID OUTFLOW IN WEIGHTLESSNESS.

Berenyi, S. G., NASA-LeRC, TM X-2109, October 1970

OBJECTIVE. - To experimentally investigate the effect of various pressurant inlet configurations on the draining process during liquid outflow from a cylinder in weightlessness.

PERTINENT WORK PERFORMED. - Normal gravity tests were conducted in an acrylic plastic 15 cm diameter cylinder with a pressure regulator, and supply pressure gauge using filtered air as the test fluid. Mass flow was measured at 0.5 cm increments across the entire tank with a constant temperature anemometer and a hot film sensor. Normal gravity draining tests were used to determine pressure vs liquid flow rate calibrations. A liquid outflow rate of 2050 cm^3/sec at 20 psi tank pressure was chosen for the test. Drop tower draining tests were conducted in the 5 to 10 second facility using the same test tank with ethanol as the test fluid.

Four of the six pressurant inlet configurations (Figure 1) used in normal gravity were used in the drop tower tests (Table 1). The initial location of the liquid vapor interface, for the normal gravity test, was 3.75 in. below the exit of the pressurant inlet device. Before outflow was initiated, a period of time was allowed to reach the zero g equilibrium interface configuration.

MAJOR RESULTS. -

1. In normal gravity, three types of distributions were obtained. These distributions were central peaked, wall peaked, and nearly uniform,and were obtained with pipe and cones, a flat plate and a porous plate, respectively. (Figure 2)
2. Residual fractions in weightlessness ranged from 1.93 for the central peak profile to 0.96 for the uniform profile (Table 1). There is a clear advantage to maintaining a uniform pressure distribution over the surface.

Table 1. Liquid Residuals in Weightlessness

Pressure Profiles	Pressurant Inlet Configuration	Residual Fraction*
Central Peak	1.25-cm-diam pipe	1.93
	30° Cone	1.81
Wall Peak	Flat Plate	1.09
Uniform	Porous Plate	0.96

* Residual fraction = (Residual volume)/(reference volume or $(2/3)\,\pi R^3$).

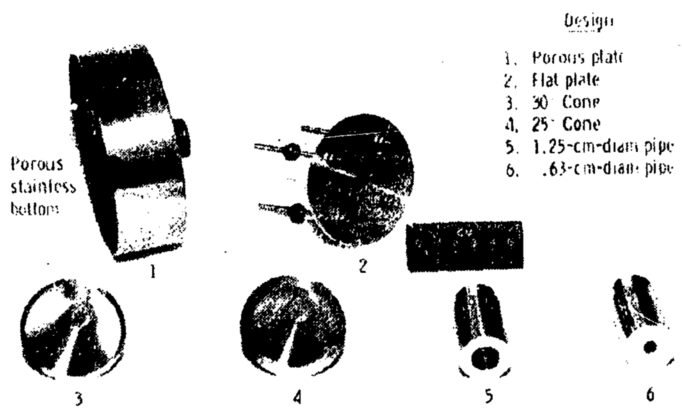


Figure 1. Inlet Configurations Tested

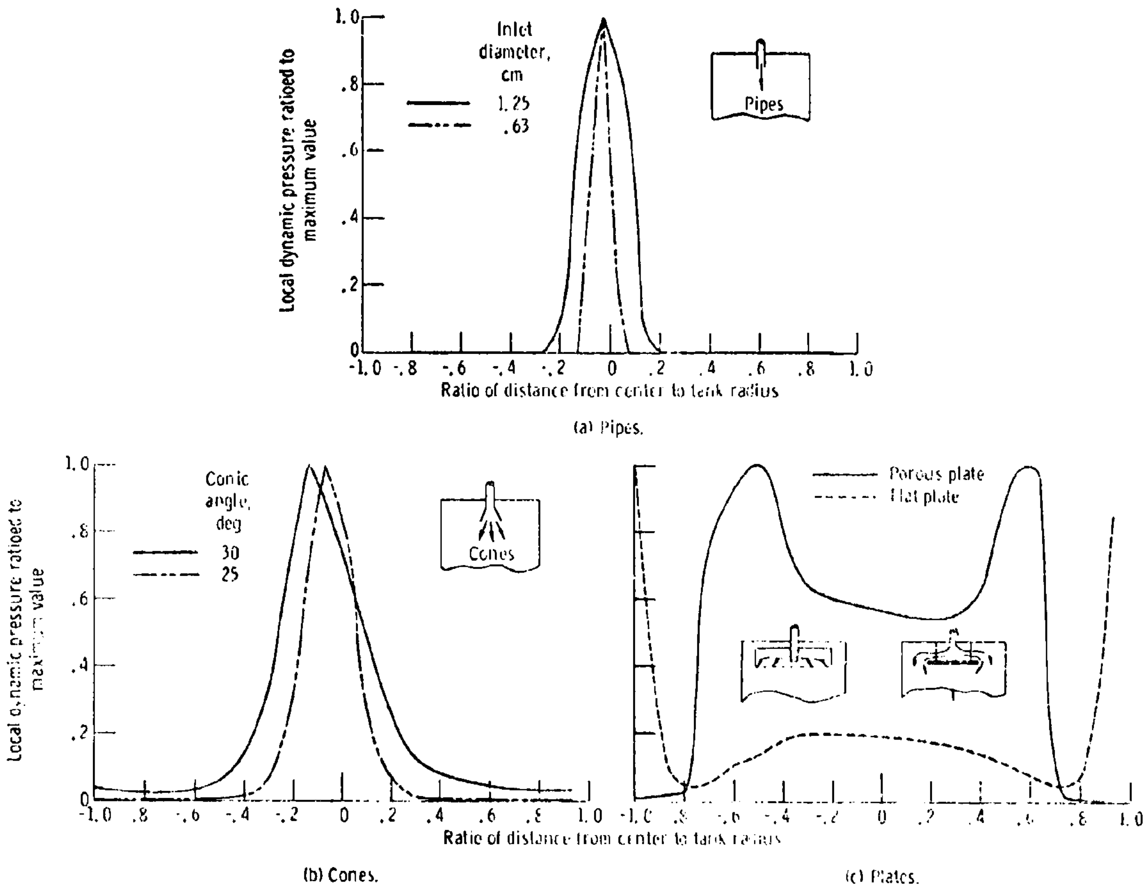


Figure 2. Dynamic Pressure Distributions in Normal Gravity

LOW GRAVITY DRAINING FROM HEMISPHERICALLY BOTTOMED CYLINDRICAL TANKS

Bizzell, G.D., et al, LMSC, NASA CR-72718, LMSC-A903128, NAS3-11526, June 1970

OBJECTIVE. - Utilize an irregular triangular mesh with a finite difference technique to analytically study tank draining in low gravity.

PERTINENT WORK PERFORMED. - The draining of inviscid, incompressible, irrotational liquids from hemispherically bottomed axisymmetric cylinders was studied by analytical and numerical methods. The solid-liquid contact angle was assumed constant at 5°.

Low gravity free surface shapes are strongly dependent upon the nonlinear terms in the Bernoulli equation, namely the surface tension and velocity squared terms. Consequently linearization limits the applicability of the results. A near 90° contact angle makes linearization more reasonable but these physical situations are rare. The equilibrium free surface condition of the liquid was formulated from surface tension forces and the boundary conditions at the centerline and tank wall. The initial volume of the liquid was computed based on the shape of the free surface. A constant outflow velocity was initiated instantaneously, producing a uniform surface velocity over the outlet. An auxiliary potential at the drain was used to eliminate the mesh refinement otherwise needed in this area. The solution was restricted to the neighborhood of the free surface. A cubic spline interpolation permitted accurate calculation of the surface tension term in the Bernoulli equation. The method used, employing both Lagrangian and Eulerian equations was compared favorably to the LINC and MAC methods. The LINC method (Hurt, et al 1970), using a completely Lagrangian mesh, was downgraded for its poorer representation of surface tension. The MAC method (Marker and Cell, Bradshaw and Kramer, 1974) was criticized for being more complicated than the current method in dealing with the fluid away from the free surface.

MAJOR RESULTS. -

1. Liquid residuals increase with Weber number and decrease with Bond number.
2. For certain ranges of Bond number and Weber number, axisymmetric slosh can be induced.
3. Drain size does not influence residuals at high Weber numbers.
4. Vapor ingestion times tend to correlate with W/(1 + B) where W is the Weber number and B is the Bond number.
5. Computed results predict higher centerline height as a function of time than experimental data (Figure 1). h_c is the height of the surface at the center and r_o is the orifice or outlet radius.

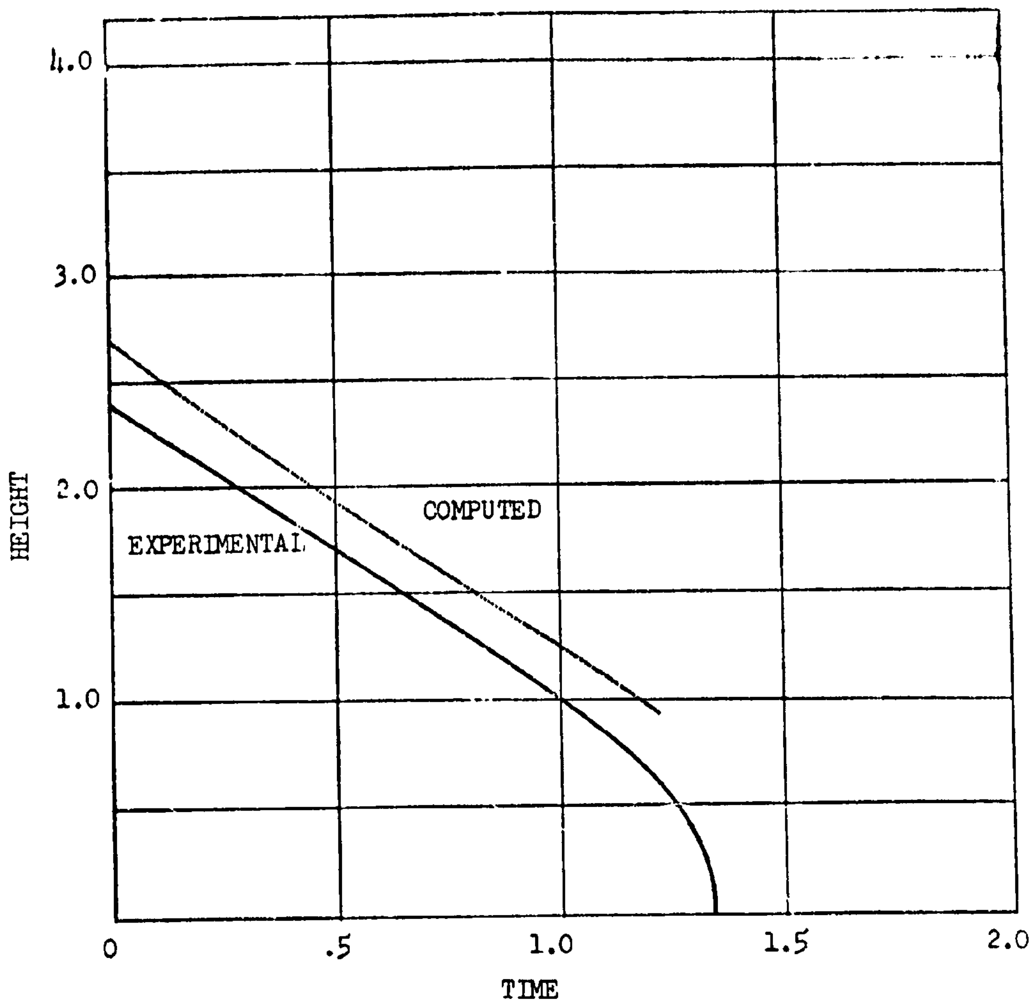


Figure 1. Comparison of computed and experimental values of centerline height during draining for case D3: B=0, W=36.06, h_c=2.6704, r_o=1/10; experimental data furnished by NASA-Lewis Research Center.

EFFECT OF OUTLET BAFFLING ON LIQUID RESIDUALS
FOR OUTFLOW FROM CYLINDERS IN WEIGHTLESSNESS
Berenyi, S.G., NASA-LeRC, NASA TM X-2018, May 1970.

OBJECTIVE. - To experimentally study the effect of outlet baffles in reducing liquid residuals for outflow from cylindrical cylinders in weightlessness.

PERTINENT WORK PERFORMED. - The experimental study utilized a flat bottomed right circular cylinder acrylic plastic test tank, 4 centimeters in radius. A flat disk pressurant inflow baffle was used with four different outflow baffles (Figure 1). Three flat baffles with baffle to tank radius ratios B/R of 0.485, 0.635 and 0.980 were tested as well as a perforated flat plate with a B/R of 1 containing 10 equally spaced 0.127 cm diameter holes on a 2 centimeter-radius circle. Baffles were placed at either 1 or 2 outlet radii above the tank bottom (0.4 or 0.8 cm). Anhydrous ethanol was used for all tests. Normal gravity pressurized outflow yielded average outflow velocity correlations which were used to interpret tests conducted in the 2.2 second Zero Gravity Facility. Tests were conducted with an initial fill level of one diameter. Data was visually recorded.

MAJOR RESULTS. -

1. No difference in residuals was found between placing the flat disk baffle (B/R = 0.485) at one radius or two radii above the outlet. This baffle reduced residuals from the unbaffled case (Figure 2).

2. The largest flat disk baffle (B/R=0.98, with an open area equal to the outlet cross-sectional area) had the lowest residuals of the three flat disk baffles tested (Figure 3). This occurred because, for the initial hemisphere interface shape, the drain was effectively moved to an area of higher liquid depth away from the centerline with this baffle. The flat disk baffles did not require an appreciable increase in tank pressure for comparable flow-rates compared to the unbaffled case.

3. The flat plate baffle (B/R = 0.90) was more effective in reducing residuals over the unbaffled case than the perforated baffle. The perforated baffles had 6 to 7 times greater pressure drop for the same flow rates compared to the unbaffled case.

4. Although residuals were reduced 60% from the unbaffled case with the best baffle tested, almost half the tank volume remained at vapor ingestion with the baffles.

COMMENTS. - Improved pullthrough suppression devices are needed to reduce residuals to acceptable levels during low gravity draining.

Figure 1. Tank Parts With Various Outlet Baffles

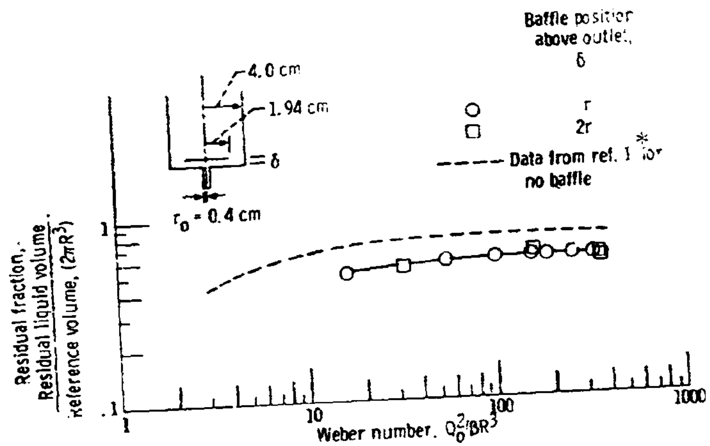


Figure 2. Effect of Baffle Position Above Outlet on Liquid Residuals for Flat Plate Baffle. (Baffle-to-tank-Radius Ratio B/R = 0.485).

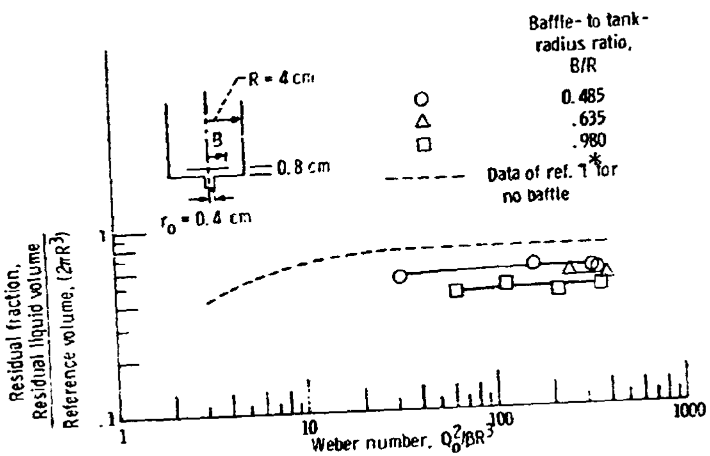


Figure 3. Effect of Baffle-to-tank-Radius Ratio on Residuals for Flat Plate Baffle

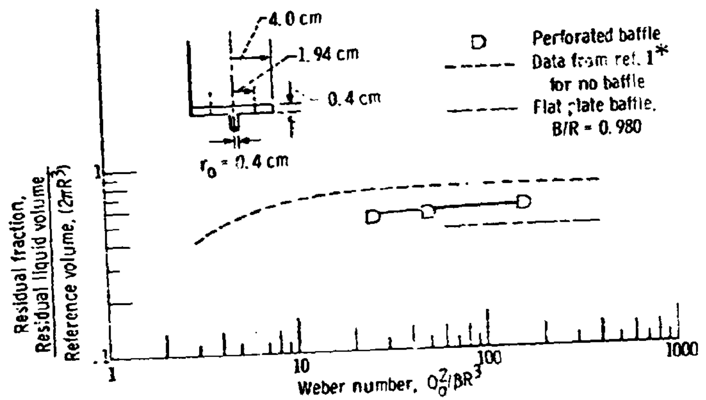


Figure 4. Effect of Perforated Baffle on Liquid Residuals

* Ref. 1. Abdalla, K. L., and Berenyi, S. G., 1969

VAPOR INGESTION PHENOMENON IN HEMISPHERICALLY BOTTOMED TANKS IN NORMAL GRAVITY AND IN WEIGHTLESSNESS

Berenyi, S.G., Abdalla, K.L., NASA-LeRC,
NASA TN D-5704, April 1970

OBJECTIVE. - Experimentally study vapor ingestion during liquid outflow from hemispherically bottomed cylinders in normal gravity and in weightlessness.

PERTINENT WORK PERFORMED. - The 2.2-second Zero Gravity Facility was used to test 2- and 4-centimeter radius, hemispherically bottomed cylindrical tanks fitted with outflow lines having radii of one-fifth, one-tenth and one-twentieth the tank radius. Normal gravity tests were used to obtain flow rate calibrations. Data was visually recorded using anhydrous alcohol as the test fluid. Initial filling levels of both two and three tank radii were used.

Literature review and qualitative evaluation of vapor ingestion in normal gravity and weightlessness were conducted. A Froude number criteria was meaningful for normal gravity outflow with a flat interface. In weightlessness, the Weber number appeared to be the important parameter in determining critical height at vapor pullthrough. Critical height (Figure 1) is the height of the liquid vapor interface at incipience of vapor ingestion, measured at the centerline of the tank.

This work is compared to results for flat bottomed tanks contained in Berenyi and Abdalla, TN D-5210, May 1969.

MAJOR RESULTS. -

1. Vapor ingestion height in normal gravity may be scaled by the Froude number (Figure 2). Nomenclature are presented in Table 1. Vapor ingestion heights were approximately 10% higher than those predicted in TN D-5210 for flat bottomed tanks.
2. In weightlessness, critical height above the drain may be scaled by the Weber number (Figure 3). Critical heights were higher than for flat bottomed tanks.
3. Residual liquid fraction increases with Weber number up to a Weber number of 40, after which it remains essentially constant.
4. Initial liquid height did not affect residuals.

Table 1. Nomenclature

a	acceleration, cm/sec^2
g_o	acceleration due to gravity, 980 cm/sec^2
h_{cr}	critical height, cm
h_i	initial liquid height, cm
h_{vi}	vapor ingestion height, cm
Q_o	outflow rate, cm^3/sec
R	tank radius, cm
R/r_o	radius ratio
r_o	outlet radius, cm
t	time, sec
V_o	average outflow velocity (velocity in outlet line), cm/sec
V_T	average liquid velocity in tank, cm/sec
We	Weber number, $V_o^2 r_o/\beta$ or $Q_o^2/\beta R^3$
β	specific surface tension, σ/ρ, cm^3/sec^2
μ	absolute viscosity, g/(cm-sec)
ρ	density, g/cm^3
σ	surface tension, dynes/cm (or 10^{-5} N/cm)

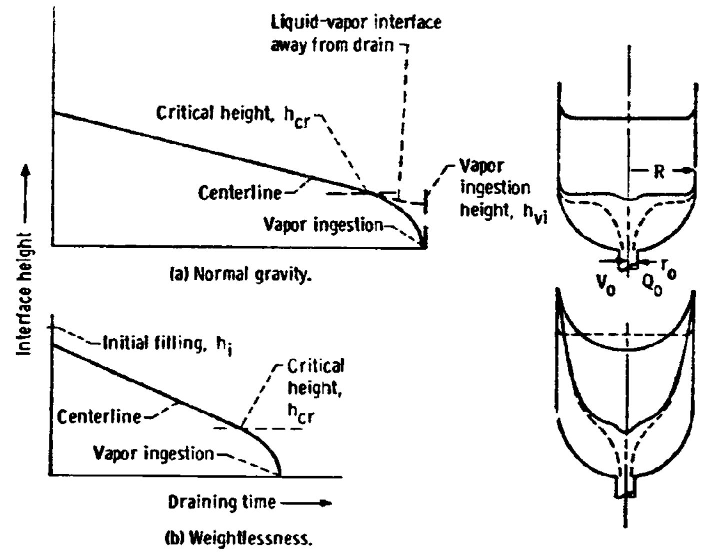


Figure 1. Vapor Ingestion Phenomenon

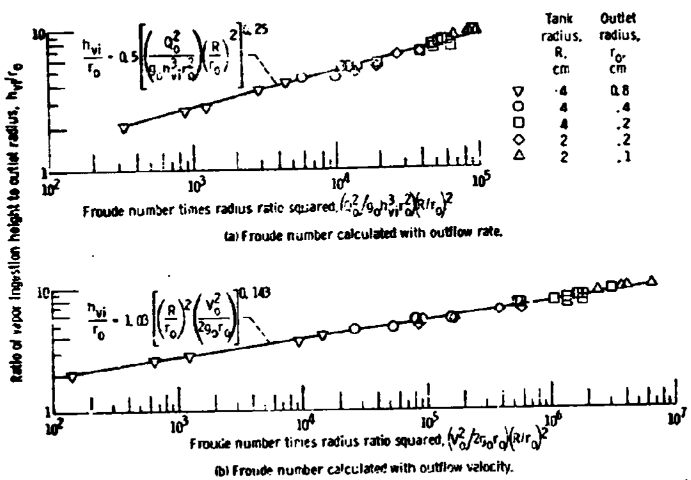


Figure 2. Vapor Ingestion Heights in Normal Gravity With Froud Number.

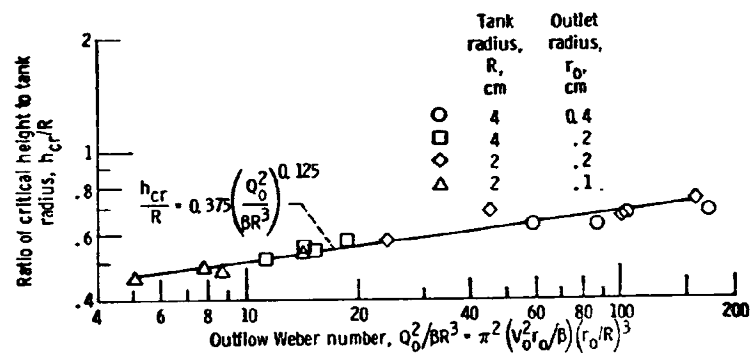


Figure 3. Incipience of Vapor Ingestion in Weightlessness as Function of Outflow Weber Number

THE LIQUID-VAPOR INTERFACE DURING OUTFLOW
IN WEIGHTLESSNESS

Berenyi, S.G., Abdalla, K.L., NASA-LeRC

NASA TM X-1811, June 1969

OBJECTIVE. - Experimentally determine the effect of outflow from a tank on the behavior of the liquid vapor interface during weightlessness.

PERTINENT WORK PERFORMED. - The 5- to 10-second Zero Gravity Facility was used to extend the data presented in Derdul, et al, TN D-3746, 1966 to larger tank sizes. Two tank bottom shapes were used: hemispherical with a center outlet and inverted elliptical with a side outlet. Test tanks were 4, 7.5 and 15 centimeter radius cylinders machined from acrylic plastic. Pressurant inflow flat disc baffles were used. Test fluids were anhydrous ethanol and trichlorotrifluoroethane. Tank outlets had radii equal to 1/10 tank radius (R) and length equal to the tank radius. Initial liquid levels of 2R, 2.5R and 3R were used. Total free fall test time was 5.16 seconds. Sufficient zero gravity interface formation time was allotted in order for the interface shape to reach its low point in the formation cycle except for the 15 cm radius tank. For this tank the formation time was too great, causing a compromise to be reached in using the time when the low point of the liquid vapor interface was stationary. Data was recorded photographically in order to determine interface shapes and incidence of vapor ingestion. Outflow rate vs pressure was obtained both from normal gravity calibration and flowmeter readings. The two methods agreed within 1%.

MAJOR RESULTS. -

1. Interface distortion during outflow was reduced as initial filling level increased (Figure 1, Table 1).
2. A limiting value of 0.27 was reached for the distortion parameter similar to that obtained by Derdul, et al, TN D-3746, 1966 (Figure 2).
3. The distortion parameter correlation with Weber Number (Figure 2) was extended to larger tank sizes in the high outflow velocity flow region.
4. Insufficient test time was available to obtain distortion data in the 15 centimeter radius tanks.

Table 1.

h	centerline distance from liquid-vapor interface to outlet, cm
R	tank radius, cm
V	liquid-vapor interface velocity in weightlessness, cm/sec
V_m	mean liquid velocity, cm/sec
We	Weber number, $We = \rho V_m^2 R/4\sigma$
β	specific surface tension, cm^3/sec^2
μ	viscosity, g/cm-sec
ρ	liquid density, g/cm^3
σ	surface tension, dyne/cm

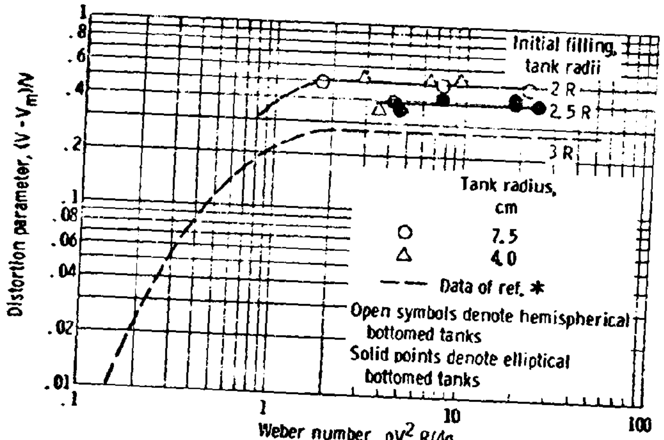


Figure 1. Effect of initial filling on distortion of liquid-vapor interface in cylindrical tanks during outflow.

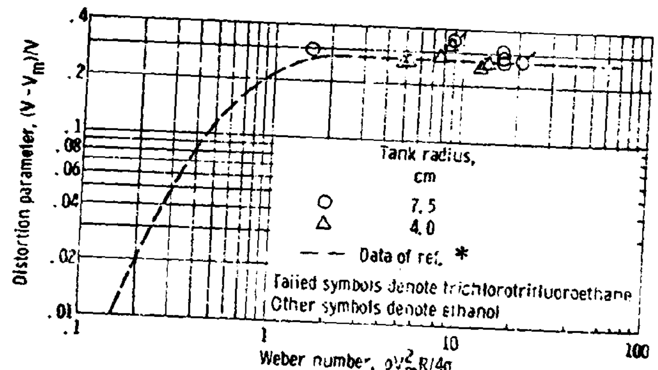


Figure 2. Effect of outflow on distortion of liquid-vapor interface in hemispherical bottomed cylindrical tanks at initial filling of 3 tank radii.

* Derdul, et al, 1966

VAPOR INGESTION PHENOMENON IN WEIGHTLESSNESS

Abdalla, K. L., Berenyi, S.G., NASA-LeRC,

TN D-5210, May 1969

OBJECTIVE. - To experimentally determine the criteria for predicting vapor ingestion during draining from flat-bottom, cylindrical tanks in weightlessness.

PERTINENT WORK PERFORMED. - The experimental investigation utilized two flat-bottom, cylindrical tanks, 2 and 4 centimeters in radius. Each tank was fitted with cylindrical outlet lines equal to one-tenth and one-twentieth of the respective tank radii. The initial liquid filling level prior to draining ranged from 2 to 7 tank radii. Outflow velocities were varied from 200 to 2500 cm/sec in the outlet line. Three liquids were chosen for this study with specific surface tensions ranging from 11.8 to 28.3 cm^3/sec^2, and viscosities from 0.7 to 15.4 cP. Outflow was achieved by gas pressurization. Data were obtained in the 2.2-sec Zero Gravity Facility.

Motion picture records were made for each draining test. Therefore, the shape of the liquid-vapor interface during draining, as well as the liquid height on the tank centerline were obtained (Figure 1). In weightlessness the interface prior to draining was a curved surface and during draining distorts from this initially curved surface. The interface centerline height moved at constant velocity, as it did in normal gravity, until incipience of vapor ingestion and then accelerated into the outlet. The liquid-vapor interface height at incipience of vapor ingestion was defined as the critical height.

MAJOR RESULTS. -

1. In weightlessness, the critical liquid height, defined as the liquid-vapor interface centerline height at the incipience of vapor ingestion, was correlated (Figure 2) by the Weber no. relation $Q_0^2/\beta R^3 = 4000 (h_{cr}/R)^8$, where Q_0 was the outflow rate, β was the specific surface tension, R was the tank radius, and h_{cr} was the critical height.

2. The critical height in weightlessness was generally higher than the vapor ingestion height in normal gravity for identical conditions (Figure 3).

3. The liquid residuals (Figure 4), at the time of vapor ingestion after draining in weightlessness, were considerably higher than the residuals in normal gravity, for the same conditions.

4. The vapor ingestion phenomenon either in normal gravity or in weightlessness was apparently unaffected by a change in initial liquid height ranging from 2 to 7 radii.

5. Increasing the viscosity from 0.7 to 15.4 cP showed no noticeable effect on vapor ingestion.

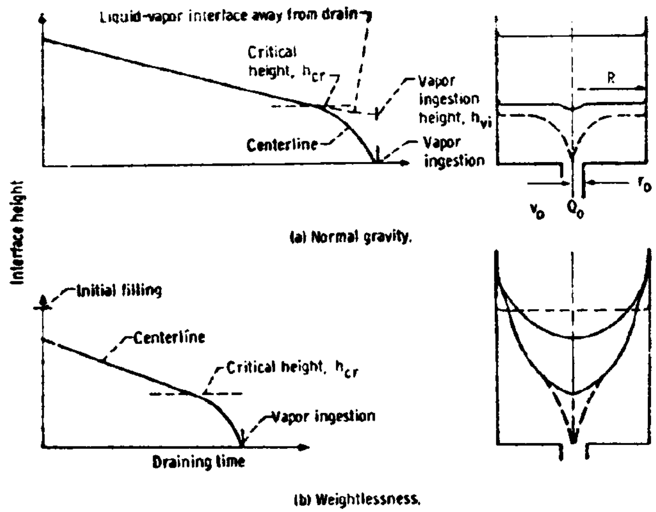


Figure 1. Vapor Ingestion Phenomenon

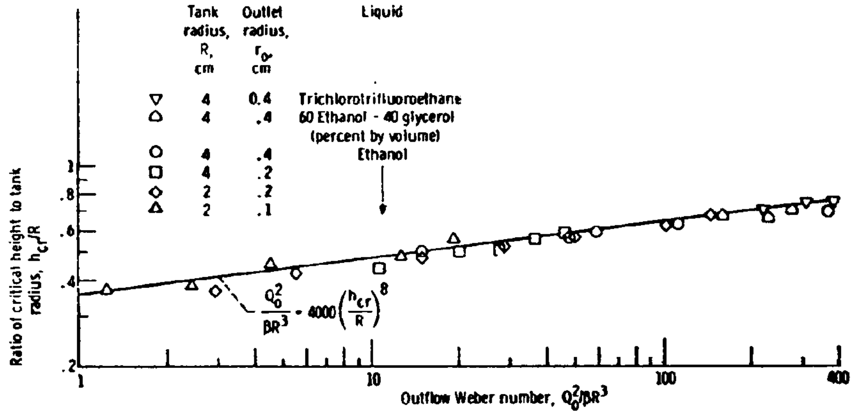


Figure 2. Prediction of Incipience of Vapor Ingestion in Weightlessness by Outflow Weber Number. Initial Liquid Height, 2 Tank Radii.

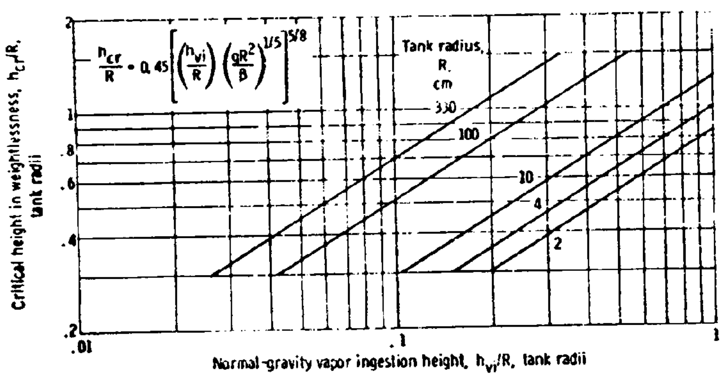


Figure 3. Vapor Ingestion Comparison Calculated for Various Tanks Filled to a Level of 2 Tank Radii With Liquid Hydrogen

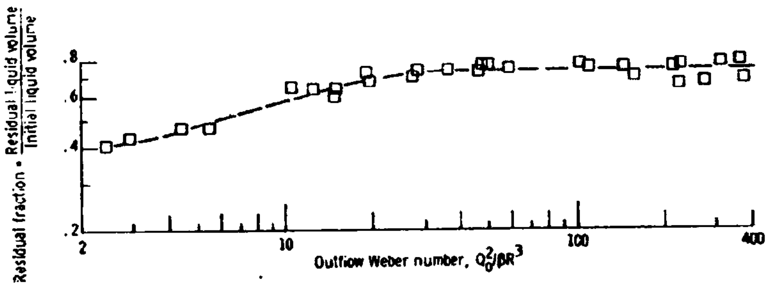


Figure 4. Residual Fractions in Weightlessness. Initial Fill Height, Two Tank Radii

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF OUTFLOW RESIDUALS IN INTERCONNECTED SPHERICAL TANKS
Kasper, H.J., Boyle, R.J., NASA-LeRC, NASA TN D-4828, September 1968

OBJECTIVE. - Analytically and experimentally determine the liquid residuals during outflow from four interconnected equal volume spherical tanks.

PERTINENT WORK PERFORMED. - A theoretical analysis of liquid residuals in multiple tank systems with and without crossflow lines was compared to experimental data. The analysis, based on continuity, conservation of mass, volume vs height relationships, and line pressure drop, determined the volumetric flow between tanks for a given piping system and total outflow rate from all tanks. Examples were presented for three cases where the four tanks are interconnected by crossflow lines: 1. All four of the tank outflow lines meet at a common junction, 2. Two tanks have outflow lines that meet at a common junction, two tanks have no outflow lines and just crossflow lines, 3. The outflow lines from each pair of tanks are joined to form two common junctions. These common lines are then joined to give a single line crossing the system boundary. A fourth order Runge-Kutta numerical integration procedure was used to solve the differential equations formulated.

The experimental apparatus consisted of four 32 inch diameter plexiglass spheres with sumps. Configurations similar to case one were fabricated with equal and unequal outflow lines. Tanks were filled to equal or unequal levels, outflow was initiated by opening ball valves and flow rate and liquid level were monitored. Water was used as the test fluid. Cruciform antivortex baffles were provided at the sump inlets. Relative residuals were compared between tanks when pullthrough first occurred in one of the tanks.

MAJOR RESULTS. -

1. For the test configuration shown in Figure 1, 0.33% relative residuals were experienced with crossflow lines closed due to asymmetry caused by manufacturing tolerances. Opening the crossflow lines during outflow reduced residuals to 0.03 per cent of the four tank volumes (not including sump volume).
2. Figure 2 illustrates comparisons between data and analysis for tank 3 initally full and the other three tanks 50% full and 20% full.
3. Data was obtained and compared to analytical predictions for unequal length lines, equal length lines with dip tubes and for various crossflow line loss coefficients.
4. Crossflow lines were recommended for reducing residuals. Sizing of the lines can be accomplished using the theoretical analysis.

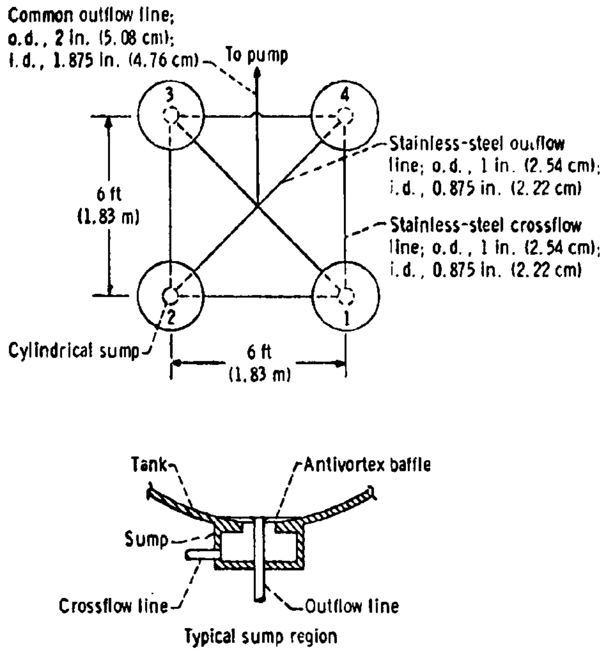


Figure 1. Four Tanks With Equal-Length Outflow Lines

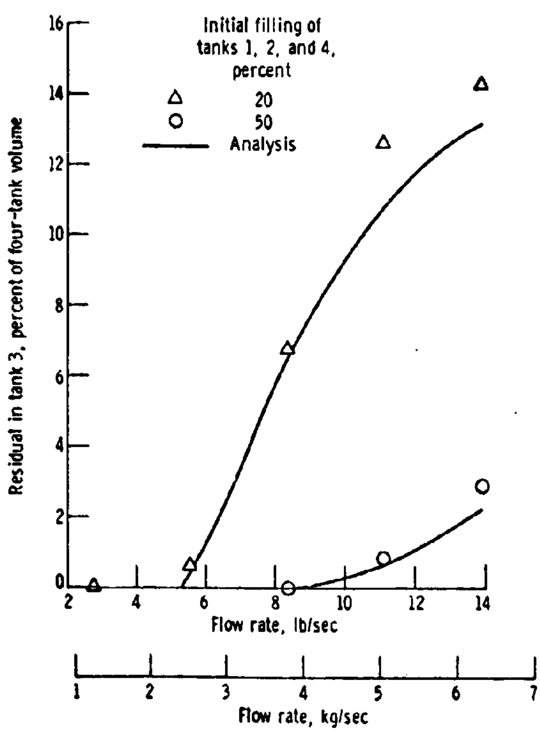


Figure 2. Residual in the Full Tank (Tank 3) of the Equal Length Outflow Line System as Function of Flow Rate for Two Different Initial Conditions. Crossflow Lines Open

FREE SURFACE BEHAVIOR DURING PROPELLANT WITHDRAWAL,
Saad, M. A., Univ. of Santa Clara, Joint AIAA/Aerospace Corp.
Symposium, "Low Gravity Propellant Orientation and Expulsion,"
May 1968

OBJECTIVE.- Experimentally and analytically determine the average height of liquid in a tank during draining when gas is first ingested.

PERTINENT WORK PERFORMED. - Linearized potential theory was used to formulate an equation for the velocity potential of the free surface of a draining tank in terms of the gravity, inertia and surface forces. For low surface forces, the Froude number becomes most important. Solutions of Saad and Oliver 1964 indicate that modelling parameters can be used to simulate the displacement of the free surface of liquids. A correlation of the form $h_c/D = f\ (V^2/gd,\ D/d,\ h_o/d)$ was indicated (Table 1). The critical h_c is the average height when vapor ingestion first occurs. Experiments were designed and run based on this functional dependence.

Three transparent tank configurations were tested (Figure 1) using water as the test fluid and a high speed camera to visually record the draining data. Outflow rate was computed from the motion pictures using graph paper marking the liquid level and timing marks on the film. Six different tank diameters ranging from 2-1/4" to 8-7/16" were tested. D/d ratios covered the range between 2.67 and 10. Bond number varied from 44 to 615 and Reynolds number varied from 6800 to 73000. Since both these ranges were high, the effects of surface tension and viscosity were considered minor.

MAJOR RESULTS. -

1. Initial liquid level in the tank (for $h_o \gg h_c$) did not significantly affect h_c.
2. Critical height is a function of Froude number under high g draining conditions. Figure 2 and 3 show the correlations for a flat bottomed tank with an axisymmetric and asymmetric outlet respectively.
3. Critical height in a hemispherically bottomed tank was less than in a flat bottomed tank at identical Froude number.

D	tank diameter
d	outlet diameter
g	gravitational acceleration
h	height along z coordinate
h_c	critical height
Subscripts	
(c)	critcial value
(o)	initial value

Table 1. Nomenclature

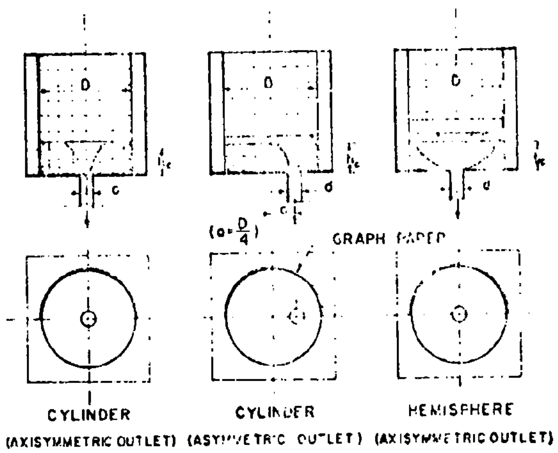


Figure 1. Types of Tanks

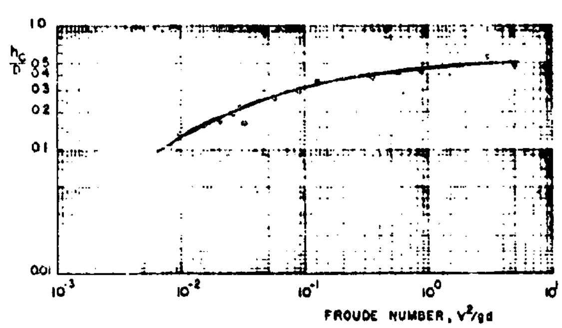


Figure 2. Dimensionless Critical Height as a Function of Froude Number - Cylindrical Tank with Axisymmetric Outlet

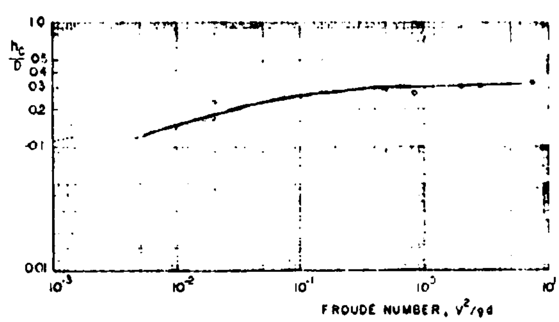


Figure 3. Dimensionless Critical Height as a Function of Froude Number - Cylindrical Tank with Asymmetric Outlet

EXPERIMENTAL INVESTIGATION OF VAPOR INGESTION IN THE CENTAUR LIQUID HYDROGEN TANK
Lacovic, R. F., Stofan, A.J., NASA-LeRC,
TM X-1482, March 1968

<u>OBJECTIVE</u>. - To experimentally determine the criteria for predicting vapor ingestion during draining of a Centaur liquid hydrogen tank.

<u>PERTINENT WORK PERFORMED</u>. - All tests were conducted at normal gravity using 1/3.67 and 1/38 scale model lucite Centaur LH_2 tanks. High pressure air was used to expel water from the 1/38 scale model tank while a pump was used to expel water and ethyl alcohol from the 1/3.67 scale model tank. (Figure 1 shows the geometry of a full scale Centaur tank). Tests were run to simulate "deadhead" pumping conditions and main-engine flow conditions. Data was recorded photographically. An analysis was performed using Bernoulli's equations applied at the incipience of vapor ingestion.

<u>MAJOR RESULTS</u>. -

1. The analysis indicated that critical liquid height was related to the Froude number by the expressions;

$$h_c = h_{0c}\left[1 + \frac{h_{0c}^2 + r_0^2}{2\,(2h_{0c}^2 + r_0^2)}\right] \text{ and } \frac{2\,h_{0c}^3\,(h_{0c}^2 + r_0^2)^2}{(2\,h_{0c}^2 + r_0^2)\,r_0^5} = Fr\left[\frac{\rho_1}{\rho_1 - \rho_2}\right]$$

   where $Fr = V^2/aD$. (See Table 1 for Nomenclature).

2. Analysis, compared to experimental data in Figures 2 and 3, showed good agreement for the higher Froude number range (low vehicle acceleration) where inertia forces dominate.

<u>COMMENTS</u>. - The method of analysis is useful for the regime where gravitational and inertial forces predominate over the viscous and surface tension forces.

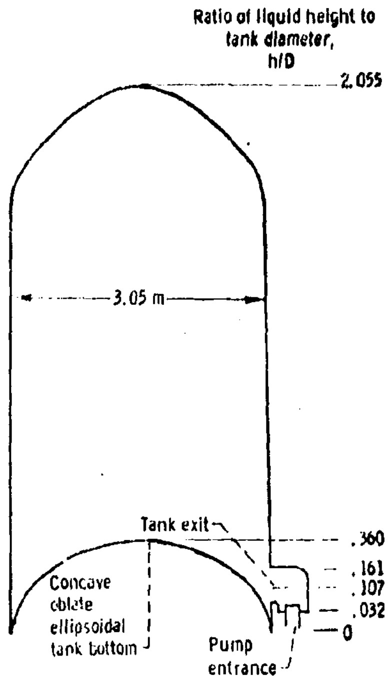


Figure 1. Centaur Liquid Hydrogen Tank

Table 1. Symbols

a	fluid acceleration, m/sec^2
D	diameter of tank outlet, m
g	acceleration due to gravity, m/sec^2
h	liquid height at tank wall, m
h_c	liquid height at tank wall at which vapor ingestion occurs, m
h_{ec}	liquid height at Centaur tank wall at which vapor ingestion occurs, m
h_0	liquid height above tank outlet perimeter, m
h_{0c}	liquid height above tank outlet perimeter at which vapor ingestion occurs, m
P_T	pressure at liquid surface at tank wall, kg/m^2
P_0	pressure at liquid surface above tank outlet perimeter, kg/m^2
Q	volumetric tank outflow rate, m^3/sec
r_0	radius of tank outlet, m
t	time, sec
U_0	stream velocity normal to hemispherical surface constructed over tank outlet, m/sec
V	tank outflow velocity, m/sec
ρ	fluid density, kg/m^3

Subscripts

1	fluid 1
2	fluid 2

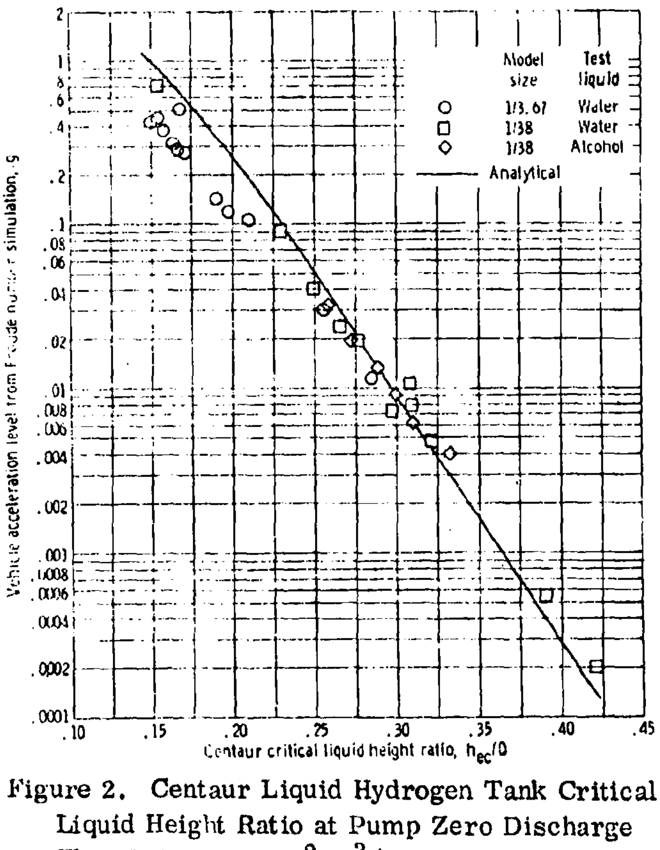


Figure 2. Centaur Liquid Hydrogen Tank Critical Liquid Height Ratio at Pump Zero Discharge Flow Rate (2.5×10^{-2} m^3/sec)

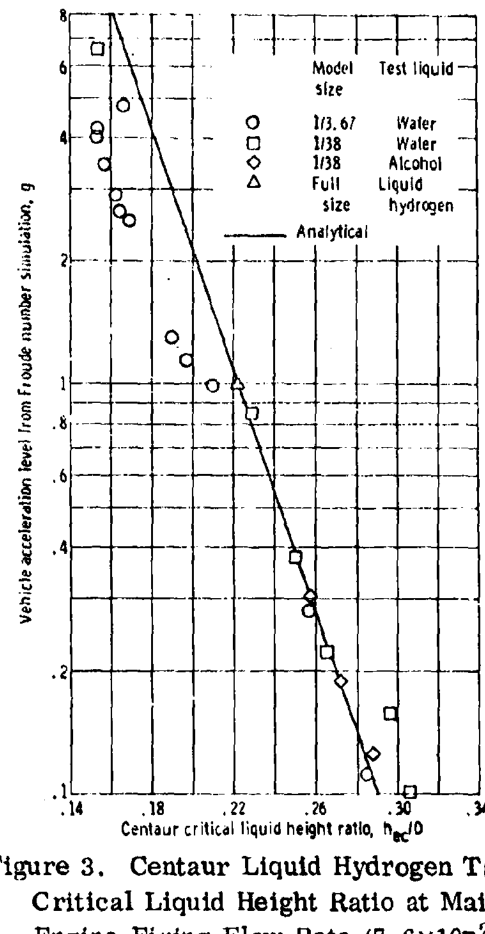


Figure 3. Centaur Liquid Hydrogen Tank Critical Liquid Height Ratio at Main Engine Firing Flow Rate (7.6×10^{-2} m^2/sec)

SURFACE DEFORMATIONS IN A DRAINING CYLINDRICAL TANK
Marshall, F.L., California Institute of Technology,
No. 67-6969, Ph.D. Thesis, December 1967

OBJECTIVE. - Analytically evaluate the problem of draining of a liquid from a cylindrical tank through a hole in the bottom.

PERTINENT WORK PERFORMED. - Irrotational flow was assumed and free surface boundary conditions were linearized. The liquid surface was initially flat and drained at a uniform velocity. The shape of the free surface was determined at constant mass flow rate. Equations were linearized with respect to the surface displacement. The linearized analyses thus does not apply to the case of extreme surface deformation associated with actual gas ingestion.

MAJOR RESULTS. -

1. When Froude number is not large, surface tension influences the surface shape slightly as indicated by the dependence of surface deformation on the Bond Number.
2. For large Froude numbers, the assumption that the velocity terms in the Bernoulli equation can be neglected (Saad and Oliver, 1964) is invalid.
3. Surface oscillations present in the solution appear to be caused by unrealistic initial conditions and in reality would be of little physical significance.
4. Any attempt to find the surface profile when the flow is started from rest must properly take into account the surface deformation that occurs during the starting transient.
5. The dimensionless surface deformation is a weak function of the drain radius to tank radius and varies with the Froude Number to an asymptotic value at Froude Number near one. These results agree with those determined experimentally by Gluck, et al, 1966.

LOW-G LIQUID PROPELLANT BEHAVIOR,
ENGINEERS HANDBOOK -
Satterlee, H. M., Hollister, M. P.,
LMSC, LMSC-A874831, NAS 9-5174, May 1967

OBJECTIVE. - Evaluate the problems of vortex formation and pressurant blow-through in draining tanks under low-g.

PERTINENT WORK PERFORMED. - Experimental observations of vortex formation were discussed. Vortex formation under reduced gravity conditions was examined analytically.

The pullthrough analysis of Lubin and Hurwitz, 1966, was extended to include the influence of surface tension on draining of a propellant tank. Bernoulli's equation was applied to the surface streamline in the vicinity of the tank drain. A hemispherical control volume was employed as shown in Figure 1. The curvature in the dip region was estimated in order to evaluate surface forces. Pullthrough occurs when the free surface over the outlet moves at much greater velocity than the surface away from the outlet. Expressions were derived for critical height much greater than the drain radius and for critical height much less than the drain radius. Results of previous investigators were reviewed and compared. An equation was derived for a baffle over the outlet.

MAJOR RESULTS. -

1. For $h_c \gg r$, $(h_c/r_o)^5 = 1.5\ (V_d^2/r_o g)$ (Equation 1) at high g and $(h_c/r_o)^5 = [(0.76\ \rho\ V_d^2 d\ r_o)/\sigma]\ (R/r_o)^2$ for zero g, where V_d is the drain velocity, R the tank radius, and g the gravitational acceleration, r_o the drain radius, σ is the surface tension and h_c is the liquid free surface height at pullthrough.

2. For $h_c \ll r$, $(h_c^3/r_o) = 1.9\ (V_d^2/r_o g)$ (Equation 2) at high g and $(h_c/r)^3 = 0.95\ [(\rho\ V_d^2\ r_o)/\sigma]\ (R/r_o)^2$ for zero-g.

3. Present results are compared with the results of other investigators in Figure 2 for gravity dominated draining. $h_c/r_o = 0.86$ tank $[1.3\ (V_m^2/2g\ r_o)^{0.29}]$ (Equation 3) is that of Gluck, et al 1966, where V_m is the mean free surface velocity away from the drain.

4. For baffled draining at $h_c \ll r$, $(h_c/r_o)^3 = 0.83\ (V_d^2/g\ r_o)\ (r_o^2/r_b)$ (Equation 4) where r_b is the baffle radius. This equation is compared to unbaffled draining in Figure 2 to illustrate the significant residual reductions made possible by employing baffles.

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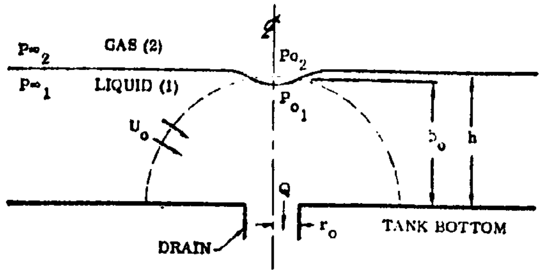
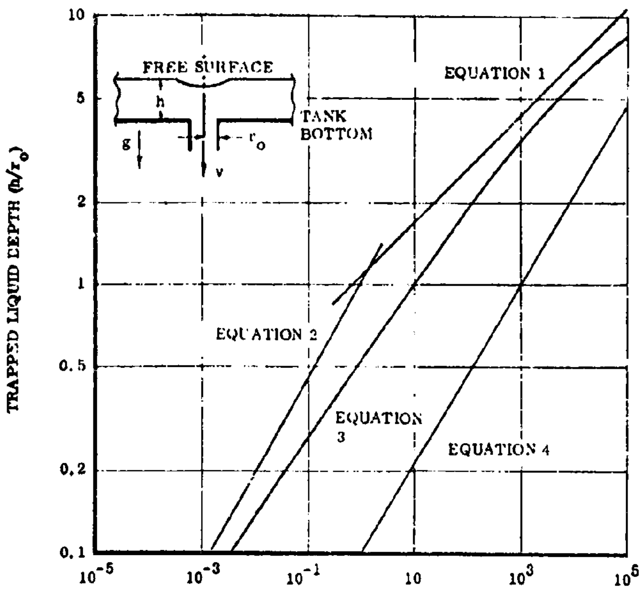


Figure 1. Pullthrough Analysis



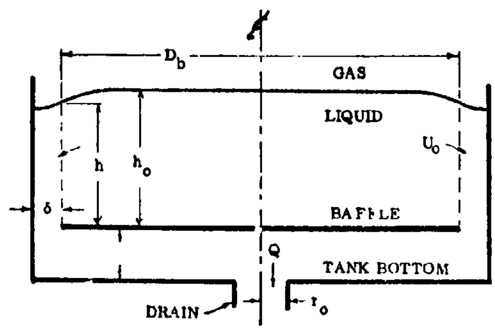


Figure 2. Pullthrough Criteria for Baffled Draining

THE FORMATION OF A DIP ON THE SURFACE OF A LIQUID DRAINING FROM A TANK

Lubin, B. T., Dynatech, Springer, G.S., MIT, J. Fluid Mech, Vol. 29 part 2, pp. 385-390, 1967

OBJECTIVE. - Experimentally and analytically evaluate the formation of a dip on the surface of an initially stationary liquid draining from a cylindrical tank through an axisymmetrically placed circular orifice.

PERTINENT WORK PERFORMED. - Two flat bottomed Plexiglas cylinders (Figure 1) were used to conduct outflow tests in order to determine the height of the liquid in the tank at vapor pullthrough. A scale was used to visually measure the height, H, of the liquid free surface at the outer radius of each tank. The volume flow rate, Q, was measured with a graduated cylinder and timer. Tests were performed both with water and with other fluids on top of the water to determine the effect of fluid properties on the experimental data. Several hours of quiesence prior to draining ensured that there was no liquid motion that could cause fluid vortexing. All data were obtained at large tank radius to outlet radius ratios (see Figure 1 for dimensions). Initial liquid levels were 1 in., 1-1/2 in. and 2 in.

An inviscid analysis was performed neglecting surface tension for steady flow, assuming that pullthrough occurs instantaneously with surface dip formation. Conservation of mass for a hemispherical control volume over the outlet combined with the Bernoulli equation written for a streamline just below the interface resulted in an expression

$$\frac{H_c}{a} = 0.69\left[\frac{Q^2}{(1 - \rho_2/\rho_1)\, g a^5}\right]^{1/5}$$

where H_c is the liquid free surface height at pullthrough, a is outlet radius, ρ_1 is the density of the bottom fluid and ρ_2 is the density of the top fluid floating on the water.

MAJOR RESULTS. -

1. Critical height was independent of the initial height of the liquid in the tank.
2. The experimental data was correlated with the above equation and good agreement was obtained (Figure 2).

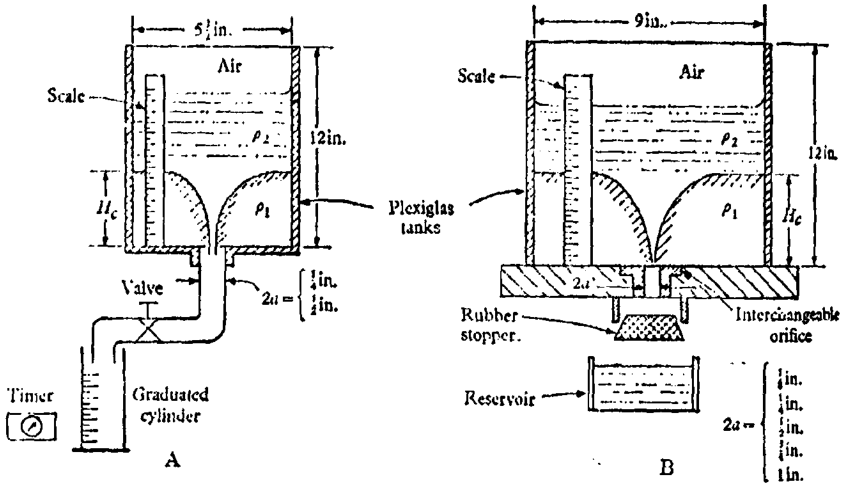


Figure 1. Schematic diagram of experimental apparatus

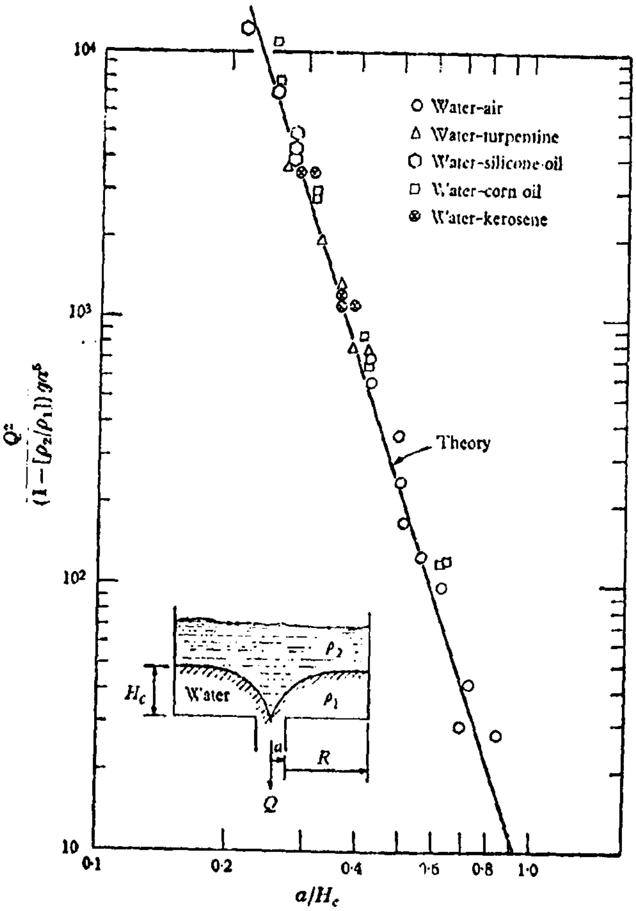


Figure 2. Critical height. Comparison between experimental data and theory

EXPERIMENTAL INVESTIGATION OF LIQUID OUTFLOW FROM CYLINDRICAL TANKS DURING WEIGHTLESSNESS
Derdul, J.D., et al, NASA-LeRC, TN D-3746, Dec. 1966

OBJECTIVE. - To experimentally determine the behavior of the liquid-vapor interface during draining in weightlessness.

PERTINENT WORK PERFORMED. - Cylindrical tanks of cast acrylic plastic 1, 2, 4, and 8 cm in radius, R, and a 0.5 cm radius flat bottom tank constructed of borosilicate glass tubing (Figure 1) were used. Square edged outlets with tank radius to outlet radius of 10 were used in all cases except for the 2 cm radius tanks where a ratio of 5 was used. Inflow baffles minimized distortion of the liquid-vapor interface due to pressurant inflow. For each data point,normal gravity and weightless runs were made. The normal gravity runs, at the same pressure and fill level as the weightless runs were used to determine interface velocity. Test fluids were trichlorotrifluoroethane, carbon tetrachloride, 1,1,1 tricloro-ethane, 60% anhydrous ethanol + 40% glycerol (by volume), anhydrous ethanol and anhydrous methanol. Data was taken photographically. After allowing sufficient weightless time for the interface to reach its lowest point in its first oscillation, outflow was initiated.

MAJOR RESULTS. -

1. A distortion parameter $(V-V_M)/V$ (Table 1) increases with increasing Weber number (Figure 2). Scatter in the data is attributable to oscillations about the equilibrium zero g position prior to outflow initiation.
2. The shape of the bottom of the tank, outlet location, tank size and ratio of tank to outlet radius had no effect on the distortion parameter (Figure 2).
3. The distortion parameter increased as the liquid level decreased, (Figure 3). Scatter for the 7 radii filling points is due to the relatively small difference between V and V_M.

COMMENTS. - Useful information is presented, however the format does not lend itself to direct prediction of residuals. The data can be used to get a feeling for what parameters are useful in predicting residuals.

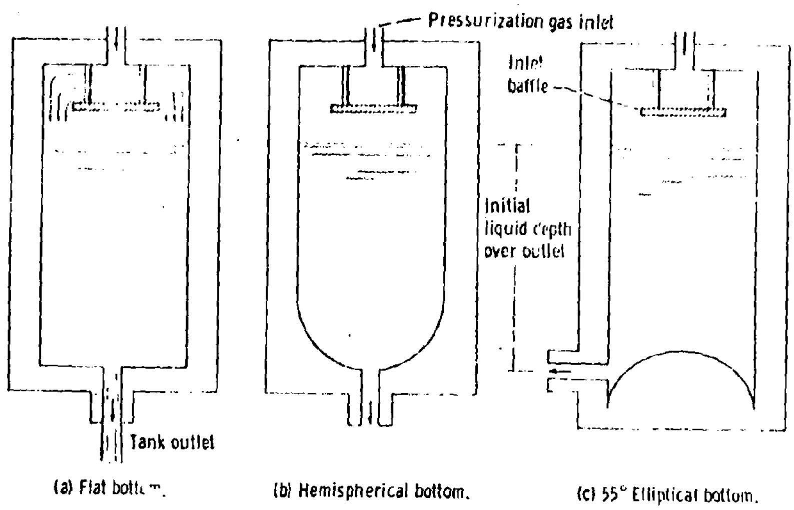


Figure 1. Schematic Drawings of Tank Geometries

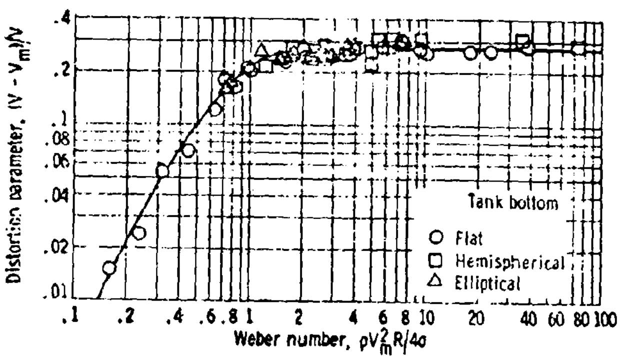


Figure 2. Effect of Outflow on Distortion on Liquid-Vapor Interface in Cylindrical Tanks at Initial Filling of 3 Radii

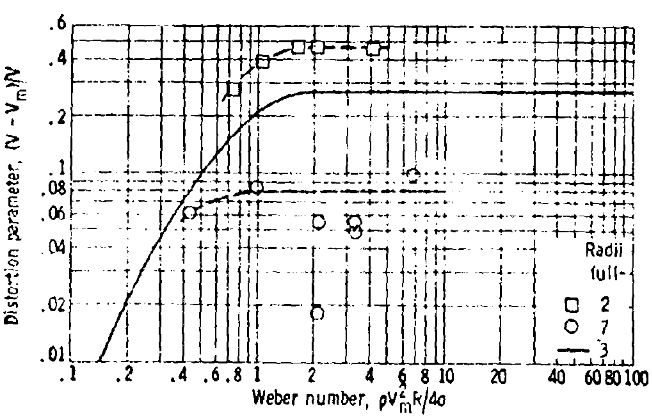


Figure 3. Effect of Initial Filling on Distortion of Liquid-Vapor Interface During Outflow From Flat-Bottom Cylindrical Tanks

Table 1. Symbols

A_o	cross-sectional area of outlet, cm^2
A_t	cross-sectional area of tank, cm^2
F_c	capillary forces, dynes
F_p	pressure forces, dynes
R	cylinder radius, cm
V	liquid-vapor interface velocity at centerline of tank in weightlessness, cm/sec
V_m	mean liquid velocity in weightlessness, A_oV_o/A_t, cm/sec
V_o	outlet velocity in weightlessness, cm/sec
We	Weber no., We = $\rho V_m^2 R/4\sigma$
ρ	liquid density, g/cm^3
σ	surface tension, dynes/cm

DISTORTION OF A FREE SURFACE DURING TANK DISCHARGE
Gluck, D. F., et al, NAR,
J. Spacecraft, Vol. 3, No. 11, November 1966

OBJECTIVE. - Experimentally determine the height of the liquid surface at vapor ingestion in normal gravity using flat bottomed cylindrical tanks with right cylindrical outlets.

PERTINENT WORK PERFORMED. - Over 100 tests using flat bottomed plastic cylinders were conducted using nitrogen pressurant gas and water and hexane as the test fluids. One inch and two inch diameter cylinders with tank diameter to outlet diameter ratios of 3.2 to 20.0 used. Inlet baffles prevented distortion due to pressurant inflow. Fluid motion prior to outflow was noted in order to assure that liquid circulation was not present and therefore that vorticity was not responsible for the observed vapor ingestion. The velocity of the liquid-gas interface was measured from photographic data. The independent variable in the data correlations was the normalized liquid height at vapor ingestion. This height was the liquid height, outside the meniscus region, measured from the bottom of the tank at the time of vapor ingestion, divided by the tank diameter.

MAJOR RESULTS. -

1. Free surface distortion can be expressed as a function of the tank diameter (D) to outlet diameter ratio and the Froude number (Figure 1). The correlating equation is $\frac{h}{D} = 0.43$ tank $(1.3\ FR^{0.29})$ where $\frac{h}{D}$ = normalized liquid height and FR = Froude number (V^2/ad) where V is the undistorted interface velocity, a the acceleration, and d the outlet diameter. h/D reaches an asymptotic value of 0.43 at FR greater than 2.0.
2. When surface tension forces or viscous forces are large, the influence of Bond number or Reynolds number becomes important.
3. In the limiting case of $D \gg d$, gas ingestion height is independent of tank diameter and $\frac{h}{d} = 0.43\ (v^2/ad)^{1/4}$ (where v is the outline line velocity) is suggested to be most useful at low Froude numbers.
4. Initial liquid level did not affect h for initial levels greater than h.
5. No influence was found due to tank Reynolds number for $10^2 < Re < 10^5$ and due to tank Bond number for $90 < Bo < 900$. Tests run at low Bond number indicated that, for Bond number less than 5, interface curvature may become important.

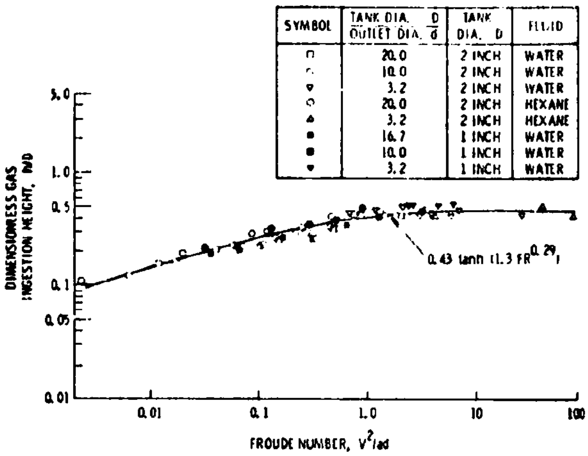


Figure 1. Dependence of gas ingestion height on Froude number for various diameter ratios.

AN ANALYTICAL STUDY OF LIQUID OUTFLOW FROM CYLINDRICAL TANKS DURING WEIGHTLESSNESS .

Koval, L.R. , Bhuta, P.G., TRW, NASA CR 54796, NAS3-7931, June 1966

OBJECTIVE. Analytically determine the configuration of the liquid-vapor interface during liquid outflow from a flat-bottomed cylindrical tank under conditions of weightlessness.

PERTINENT WORK PERFORMED: A linearized solution assuming inviscid, incompressible, irrotational flow was used as an engineering approximation to the nonlinear, viscous flow. Axisymmetric draining in a symmetrical container was considered. The linearization assumption was that the slopes of the free-surface waves and the radial component of the free surface velocity were small. These assumptions cause the results to be invalid in the region of vapor ingestion.

The boundary value problem involving the free surface motion and the velocity potential were solved using Bessel functions and an expansion into a Fourier-Bessel series. The free surface was initially approximated as a hemisphere prior to draining. Equations were nondimensionalized and solved numerically. Criteria were set up for vapor ingestion, and the volume of fluid remaining in the tank at vapor ingestion was computed. No experimental correlations were made.

MAJOR RESULTS. -

1. Scaling parameters for draining problems are Weber Number, initial fill depth to tank radius ratio and outlet radius to tank radius ratio.

2. Free surface oscillations occur during tank draining that are more pronounced at low Weber number. Pullthrough is directly influenced by these oscillation

9.0 CONVECTION HEAT TRANSFER

Covering free and forced convection in single phase fluids including supercritical fluids.

NATURAL CONVECTION IN LOW-G ENVIRONMENTS
Grodzka, P.G., LMSC, Bannister, T.C., NASA-MSFC
AIAA Paper No. 74-156, February 1974

OBJECTIVE. - To review the findings to date in the area of low-g natural convection.

PERTINENT WORK PERFORMED. - Convections driven by steady low-g accelerations, g-jitter (varying g-levels), thermal volume expansions, surface tension, interfacial tension (liquid/liquid interface), electric fields, and liquid/solid phase change are covered. Existing 1-g data and analyses are discussed in connection with data obtained from special experiments aboard Apollo 14 and 17 and Skylab 3, as well as data from the Apollo supercritical cryogenic storage tanks. The work reported here is oriented toward space manufacturing, however, some of the data presented is of general interest and will be discussed herein. Two special low-g ($a/g < 3 \times 10^{-6}$) experiments of interest here were conducted aboard Apollo 14 and 17: (1) heating of argon gas by a center post in a 6.35 cm dia. by 2.5 cm high container to obtain radial temperature gradients and (2) flow pattern determination, where a thin layer of oil in an open pan (7.3 cm dia.) is heated from below. In both cases photographic coverage was included.

MAJOR RESULTS. -

1. Data from the Apollo cryogenic gas storage tanks showed that convection was sufficient to obviate the need for forced mixing, and rotations of 3 rpm and 1 rpm increased this convection.

2. Data from the Apollo 14 and 17 experiments and the Apollo 15 cryogenic tanks showed that g-jitter can result in significant convection even in small containers. Quantitative evaluation, however, was difficult since the only measurement of the magnitude of g-jitter was the gyroscope, which did not appear to give accurate measurements at the experiment location. Results of the radial heating experiments were compared with a theoretical analysis based strictly on conduction and radiation (Figure 1). As seen, the flight curve deviates considerably from the theory, indicating g-jitter convection. Using the analysis of Gebhart (1963) an attempt was made to account for g-jitter (Figure 2). Better agreement is obtained but the curve shapes are still significantly different. Not having precise vibration data was likely one of the problems. Apollo 17 data agreed well with the conduction-radiation analysis. When coupled with a steady g-field a damping effect on g-jitter fluid motions seemed to occur.

3. Apollo 14 data showed conclusively that cellular convection can be caused by surface tension alone and that, as in 1-g, a critical value of the temperature gradient must be exceeded before cellular convection occurs. It was also shown that surface-tension driven cellular convection occurs at lower temperature gradients in low-g than in 1-g. From Apollo 17 data both rolls and cells were observed, which is at variance with the somewhat general belief that rolls and cells are associated respectively with gravity and surface tension driven convection.

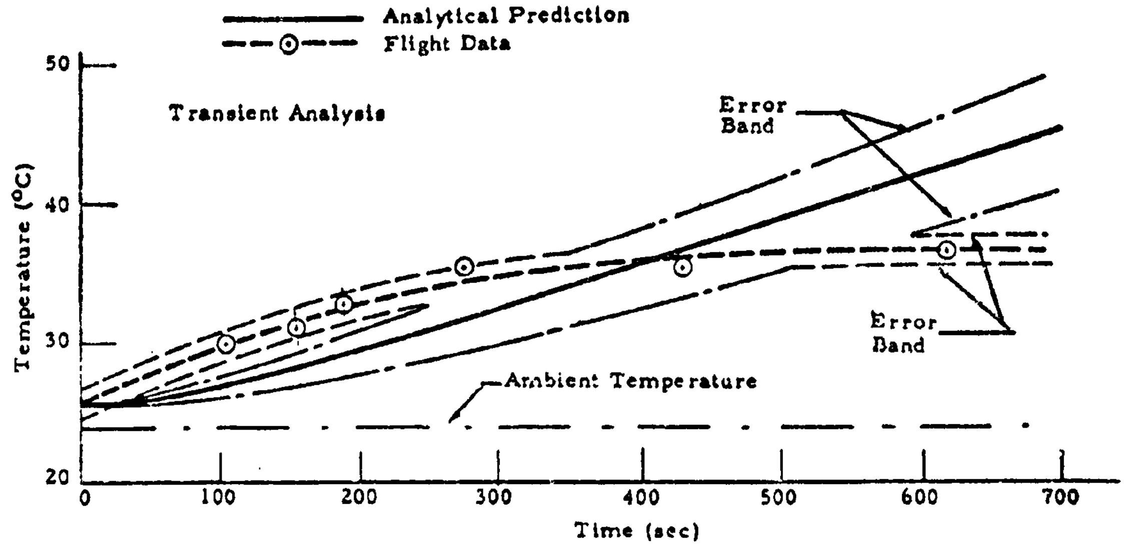


Fig 1. Typical time-temperature curve at a point obtained in Apollo 14 radial heating experiment

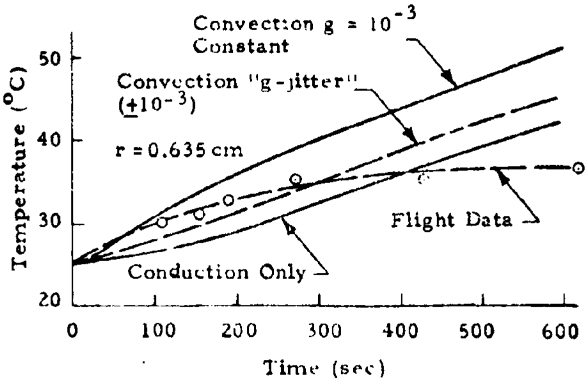


Fig. 2. Curves calculated by assuming various g-levels and Apollo 14 radial cell data

CONVECTION IN THE TANKS OF A ROTATING SPACECRAFT
NASA-Ames, NASA TR R-386, June 1972

OBJECTIVE. - To study convection and mixing of a stratified fluid in a rotating tank with specific application to the Apollo supercritical O_2 system.

PERTINENT WORK PERFORMED. - An analysis was developed which is based on a set of approximate equations for the Navier-Stokes description of fluid convection with small density variations. The problem is set up to include the effects of body forces due to temperature stratification (caused by a heater) and arbitrary time-dependent rotation of the container about a noncentral axis. The analysis includes the Coriolis term. A highly efficient numerical finite-difference scheme was developed for the computation of the convection of vorticity and energy in a two-dimensional square tank. Special procedures were developed for analysis of the thermodynamic states of supercritical oxygen for use in the program.

Calculations were made to determine the effectiveness of vehicle maneuvering as a means for mixing the Apollo oxygen tanks. The effects of a reversal in rotation after a prolonged period of constant rotation and of spin up after a prolonged period at zero-g were investigated.

MAJOR RESULTS. -

1. The levels of potential pressure decay to be anticipated,according to the calculations, are in reasonable agreement with previous estimates from Apollo 12 data and stratification analyses.
2. Considerable mixing or reduction in the potential for pressure decay can occur in a fairly short time from rotation reversal and spin up, as shown in Figures 1 and 2.

COMMENTS. - The Navier-Stokes convection problem was also formulated for a circular-tank configuration (NASA TR R-392, Martin et al, 1972) and calculations were made for comparison with the square-tank results reported here. The result was that the square-tank calculations were confirmed.

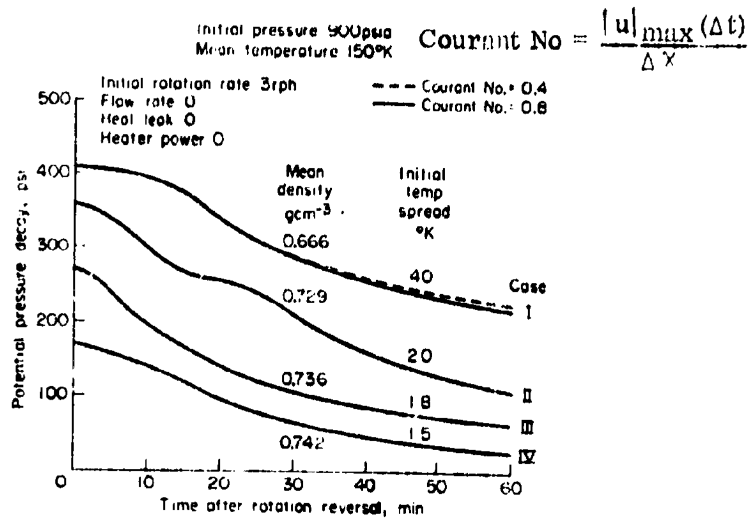


Figure 1. Potential Pressure Decay After Rotation Reversal

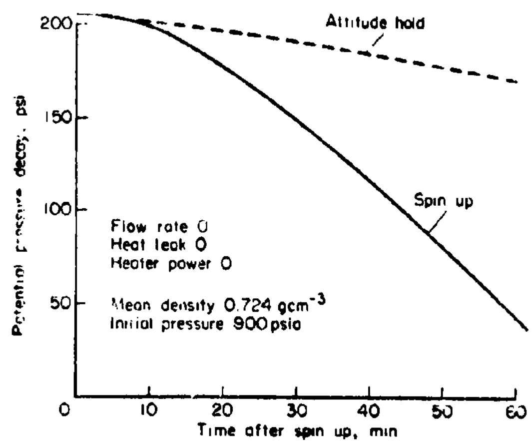


Figure 2. Reduction in Potential Pressure Decay Due to Spinup.

APOLLO OXYGEN TANK STRATIFICATION ANALYSIS
Barton, J.E., et al Boeing, NASA-CR-115143 (Vol. I), CR-115400 (Vol. II), NAS9-11576, August 1971 (Vol. I), January 1972 (Vol. II)

OBJECTIVE. - Develop analytical methods suitable for prediction of Apollo supercritical oxygen tank performance (temperatures and pressure) at low-g without mechanical mixing.

PERTINENT WORK PERFORMED. - Calculations were made using a math model originally developed by Forester, et. al, (1970). Comparisons were made with Apollo 12, 14 and 15 flight data. Modifications were also made to the model to improve the simulation accuracy and reduce computer time. The stratification math model simulates the tank performance by a finite difference solution of the two dimensional equations for the convection flow field in the tank (Figure 1). The current model has a variable grid capability and uses the General Elliptic Method (GEM) to solve the conservation equations. The basic assumptions are: (1) pressure terms in the energy and momentum equation are not coupled, which is valid for low velocity flows in which acoustic waves do not contribute significantly to the fluid energy, (2) two dimensional rectangular geometry, (3) radiation neglected, (4) acceleration body forces are constant throughout the tank, and (5) viscous energy dissipation and kinetic energies neglected.

A simplified method for heater temperature predictions was also developed using a modified Rayleigh No. convection equation. This simplified method predicted heater temperatures within 50°F of the Apollo 14 flight data.

MAJOR RESULTS. -

1. A stratification math model was developed which accurately simulates supercritical O_2 tank low-g flight performance (tank pressure and heater temperature) for all flight conditions with the exception of conditions where pitch and yaw maneuvers cause fluid rotation. Typical non-rotating data are presented in Figure 2 where AET is Apollo Elapsed Time.

2. The two dimensional model cannot accurately simulate the effects of vehicle rotation which is thought to cause three dimensional flows (Figure 3).

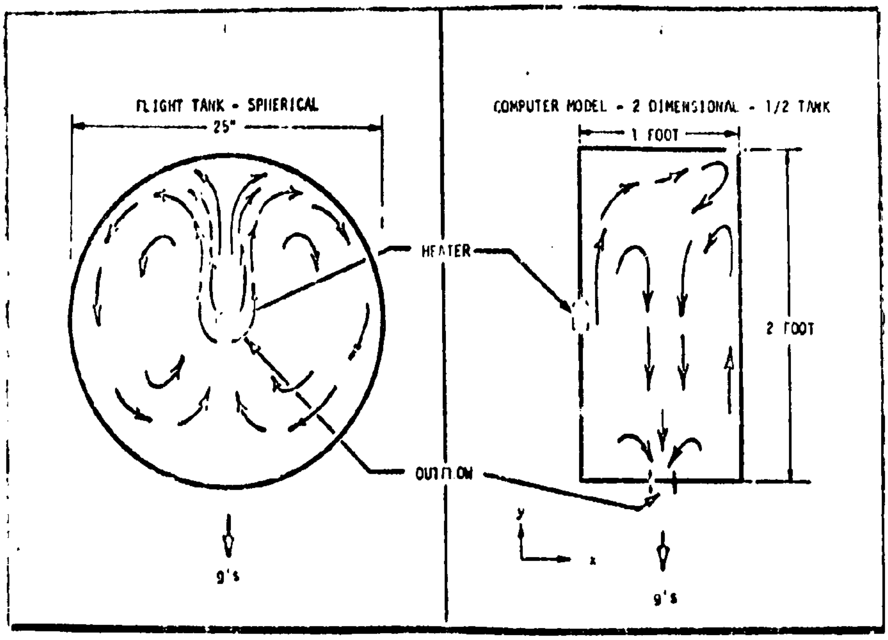


Figure 1. Analytical Approach - Model Description

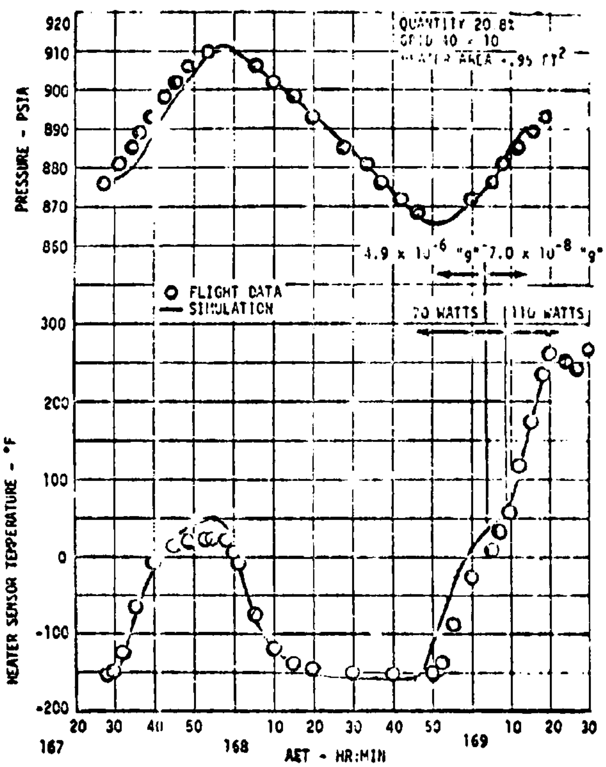


Figure 2. Tank 3 Test Simulation

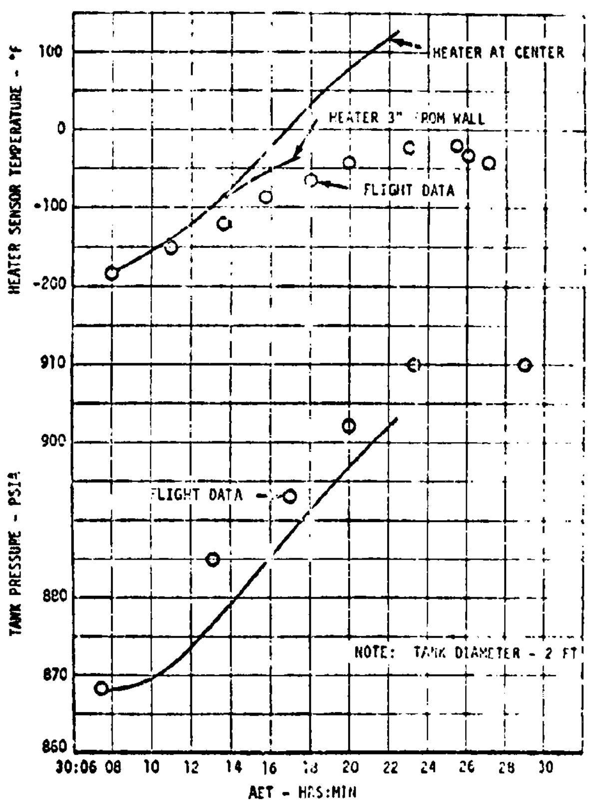


Figure 3. Rotation Simulation-Flight Data Comparison

EFFECTS OF REDUCED GRAVITY ON HEAT TRANSFER
Siegel, R., NASA-LeRC, Advances in Heat Transfer,
Vol. 4, 1967

OBJECTIVE. - To review and summarize low gravity heat transfer information up to about November 1966.

PERTINENT WORK PERFORMED. - Data and/or discussions are presented on free convection, pool and forced flow boiling, condensation in stationary vapor and in forced flow, and combustion. The major result of the study is the handy consolidation of data and the conclusions which resulted, highlights of which are presented below.

MAJOR RESULTS. -

1. In the area of free convection there is a lack of data. A difficulty is that such boundary layers have a relatively slow time response so that tests cannot be conducted with convenient facilities such as drop towers or airplane flights.

2. Both analysis and experiment indicate that nucleate pool boiling heat flux is insensitive to gravity, while the peak nucleate and minimum film boiling heat fluxes were found to vary reasonably well as $g^{1/4}$. In laminar film boiling the heat transfer coefficient depends on $g^{1/4}$, while for a turbulent film the exponent may be 2/5 to 1/2.

3. Photographic studies of reduced-g pool boiling for saturated conditions show that; (a) vapor tends to linger near the heater surface and collect new bubbles being formed, thus helping their removal, (b) bubble growth rate is insensitive to gravity, and (c) departure diameters of slowly growing single bubbles depend on $g^{-1/2}$ (buoyancy causes departure), while for rapidly growing bubbles departure size is relatively insensitive to gravity (inertia causes departure).

4. For reduced gravity forced-convection boiling, little experimental information is available, however, isothermal two-phase flow visualization tests with air-water mixtures indicate that cross-sectional bubble distribution in a vertical tube at earth gravity is very similar to that in zero gravity.

5. For condensation without forced flow, no experimental results were found in the literature. For forced flow condensation in tubes, low gravity tests have been performed with nonwetting mercury, with the result that (a) pressure drop was insensitive to gravity for the conditions tested, (b) stability of the vapor-liquid interface was indicated from the Taylor type of instability theory, and (c) low gravity conditions aid in the trapping of noncondensable gas.

6. The experimental evidence to substantiate the above conclusions is mostly from tests of short duration. Additional experimental work is needed with longer testing times. This is especially true at very low gravities; for example, it has not been conclusively demonstrated that the critical heat flux does go to zero as exactly zero gravity is approached.

10.0 BOILING HEAT TRANSFER

Covering transition, nucleate, peak, minimum and film boiling, including transient and steady state conditions and bubble dynamics and other characteristics associated with boiling at a solid surface. Both pool and forced flow boiling are considered.

POOL BOILING HEAT TRANSFER TO LIQUID HELIUM AND LIQUID NITROGEN IN A NEARLY ZERO GRAVITY ENVIRONMENT
F. J. Edeskuty, et al, Los Alamos Scientific Laboratory, 5th International Cryogenic Engineering Conference, Kyoto, Japan, May 1974

OBJECTIVE. - To obtain steady state data on nucleate boiling heat transfer to liquid helium and liquid nitrogen in a nearly zero gravity environment.

PERTINENT WORK PERFORMED. - A boiling experiment was flown in a 9-in. Nike-Tomahawk rocket providing 5-1/2 minutes of nearly zero gravity ($a/g < 0.001$). Helium was the primary test fluid of interest since the bubble Froude number for helium, calculated using an equation from Clark (1968), was found to be only 0.02 at 1-g, as compared to several hundred for other cryogenic fluids such as LN_2, LH_2 and LO_2 which have been tested at low g. The LN_2 provided thermal shielding for the LHe as well as a comparison with previous LN_2 low-g data. Both cryogenic fluids had five heat transfer surfaces oriented both parallel and perpendicular to the rocket axis. Each consisted of a 6 mm dia. cylindrical Cu. rod insulated on the sides and one end. Q/A values were chosen for each fluid to cover the nucleate boiling region. Each vessel had a two-liter capacity. The interior of each vessel contained baffles to isolate the heat transfer surfaces and minimize residual fluid motion after rocket despin. A constant 1 atm. pressure was maintained during flight. At launch both vessels were approximately 90% full. LHe temperature varied between 4.1°K and 4.25°K while the N_2 temperature was constant at 77°K. Comparison tests were accomplished at 1-g.

MAJOR RESULTS. -

1. In the nitrogen case, the 1-g maximum nucleate heat flux was 20 W/cm^2 at a ΔT of 12°K, while under low-g it was 9 W/cm^2 (55% reduction) at a ΔT of 8.5°K.

2. In the case of helium, low-g nucleate boiling data were obtained only at the lowest two heat fluxes (0.12 and 0.07 W/cm^2), the maximum heat flux being exceeded at all higher values. This implies that the maximum heat flux at zero-g lies between 0.12 and 0.25 W/cm^2 at a ΔT between 0.15 and 0.20°K. At 1-g the maximum flux was 1 W/cm^2 at a ΔT of 0.5°K. Insufficient data were obtained to comment on the effect of gravity in the nucleate boiling region.

FORCED CONVECTION PEAK HEAT FLUX ON CYLINDRICAL HEATERS IN WATER AND REFRIGERANT 113
Cochran, T. H., et al, NASA-LeRC, TN D-7553, February 1974

OBJECTIVE. - To study the burnout of cylindrical heaters in the crossflow of a saturated liquid as a function of free stream velocity.

PERTINENT WORK PERFORMED. - Testing was accomplished with distilled water and Refrigerant 113 with heaters of 0.049 to 0.181 cm diameter over a fluid velocity range of 10.1 to 18.1 cm/sec. Photographic observations were included. The heater sizes were chosen to be in the low Bond number range, to attempt to simulate the heat transfer characteristics larger heaters would experience at low g.

MAJOR RESULTS. -

The water data, at high flow rates, was adequately correlated by the prediction of Vliet and Leppert (1964), Equation 1 below. At low flow rates this was not true and under these conditions a model (Equation 2), based on a superposition of Lienhard's (1973) pool boiling prediction plus single phase forced convection, was applied successfully. The correlations obtained are illustrated in Figure 1.

$$q_{max},\ W/m^2 = 30.8 \times 10^4 \frac{(u_\infty,\ cm/sec)^{1/2}}{(D,\ cm)^{0.15}} \qquad \text{(Equ. 1 Water)}$$

$$q_{max} = 2.45 \times 10^4 \frac{u_\infty^{1/2}}{D^{0.15}} \qquad \text{(Equ. 1 Refr. 113)}$$

$$q_{max} = \frac{1}{2}\left(B^2 + 2q_{PB} + B\sqrt{B^2 + 4q_{PB}}\right) \qquad \text{(Equ. 2)}$$

where; $B = \bar{h}_c \left(\frac{1}{C_1}\right)^{1/2}$

$C_1 = 14.46 \times 10^2\ W/m^2\ {}^\circ K^2$. As used in Figure 1, however for Refrigerant 113 a best fit of the data would result in $C_1 = 5.86 \times 10^2$.

$$\bar{h}_c = 0.676 \frac{k}{D} \left(\frac{u_\infty D}{\upsilon}\right)^{0.466} \left(\frac{\mu C_p}{k}\right)^{0.31}$$

$$q_{PB} = \frac{0.94}{(Bo)^{1/8}} q_z \qquad \text{(Equ. 3)}$$

$$q_z = \left(\frac{\pi}{24}\right)(\rho_g)^{1/2} h_{fg} \left[6^* a(\rho_\ell - \rho_g)\right]^{1/4}, \quad Bo = R^2\ a\ \frac{(\rho_\ell - \rho_g)}{\sigma}$$

* A check of the basic reference shows this to be σ rather than 6.

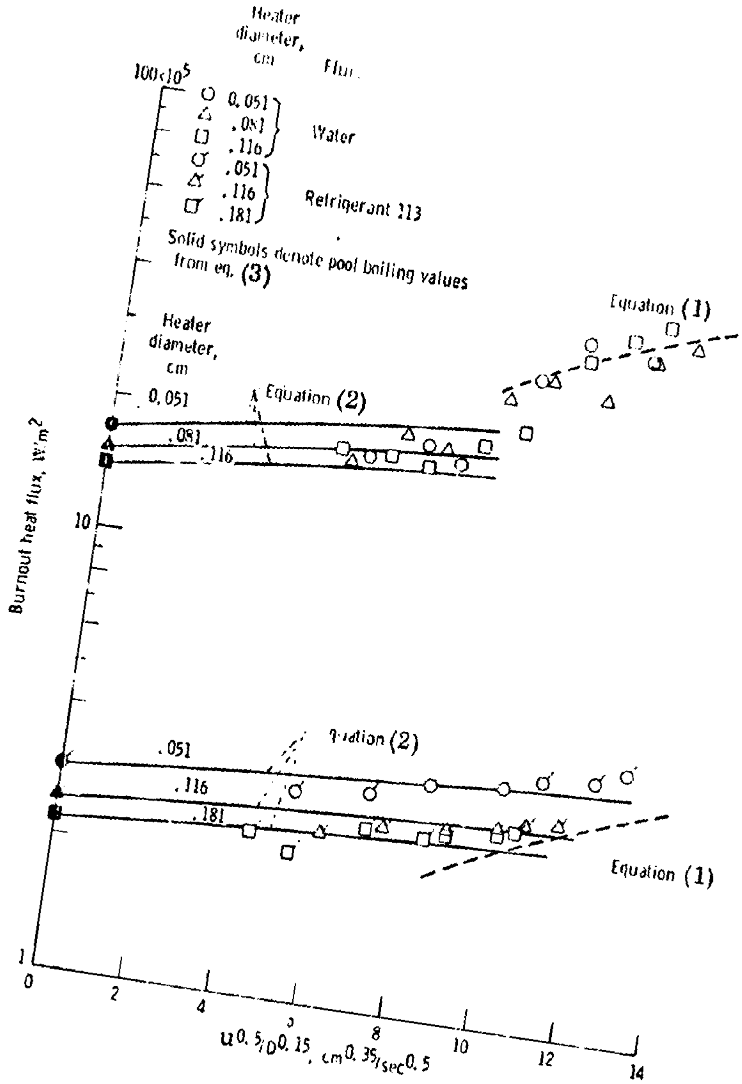


Figure 1. Correlation of Burnout Heat Flux Data

TRANSIENT BOILING HEAT TRANSFER IN SATURATED LIQUID NITROGEN AND F-113 AT STANDARD AND ZERO GRAVITY - FINAL REPORT

Oker, E., Merte, H. Jr., Univ. of Mich. 074610-52-F, NAS8-20228, Oct. 1973

OBJECTIVE. - To investigate the effects of gravity and heater surface orientation on transient and steady state nucleate boiling.

PERTINENT WORK PERFORMED. - A significant amount of testing was accomplished at $a/g = 1$ and $a/g = 0.004$ for horizontal up, vertical, and horizontal down heater surface orientations with LN_2 and F-113 at saturation or near saturation (1 - atm.). Heat flux was varied from 300 to 30,000 Btu/hr-ft^2. This report, along with one by Merte, H., Jr., 1970, describes the work accomplished under NAS8-20228. Drop test time was about 1.34 sec. Measurements were made of test surface, bulk liquid and saturation temperatures, heat flux, and bubble active site, population density, frequency and size and the following transient periods; time delay between start of power input and onset of natural convection, inception of first boiling site, maximum surface temperature and completion of nucleate boiling spread. A high speed camera was used to determine bubble data. The boiling surface was 1 in. by 7/8 in, open ended, and coated with 300-400Å of gold.

MAJOR RESULTS. -

1. Use of a thin gold film as both heater and resistance thermometer was demonstrated.
2. Time of conduction and convection dominated regimes, prior to boiling following a step increase in power, decreases as heat flux increases, as gravity is reduced and as orientation is changed from horizontal up to horizontal down. Fluid properties are also a factor, with delay time for boiling being shorter for LN_2 than F113.
3. The spread velocity for nucleate boiling increases with increasing heat flux and with reduction in gravity (Figure 1).
4. Surface superheat at the inception of boiling is relatively independent of heat flux and orientation, however, it is a function of gravity; being smaller at $a/g \simeq 0$ than at $a/g = 1$ (Figures 2 and 3).
5. Reduction of gravity appears to reduce or eliminate natural convection and orientation effects (Figure 4).
6. The maximum bubble size (D_{max}) and frequency of bubble departure ($\bar{f}$) are correlated by the relation, $(D_{max})^{1/2}\,\bar{f} = \text{constant}$.
7. The latent heat transport model ($\dot{q}$ TOT. BUB. $= \rho_v\, h_{fg}\, V_B$) predicts lower $\dot{q}$ than test, indicating other mechanisms acting, such as pumping and momentum effects of bubble growth and departure. The liquid exchange model $\left[\dot{q}_{TB} = V_B\, \rho_\ell\, C_{p\ell}\, (T_w - T_\ell)\right]$ predicts higher $\dot{q}$ than test.

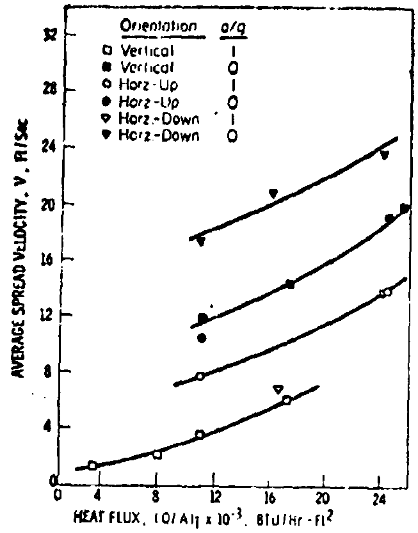


Figure 1. Average boiling spread velocity, LN_2, all orientations a/g = 1 and 0.

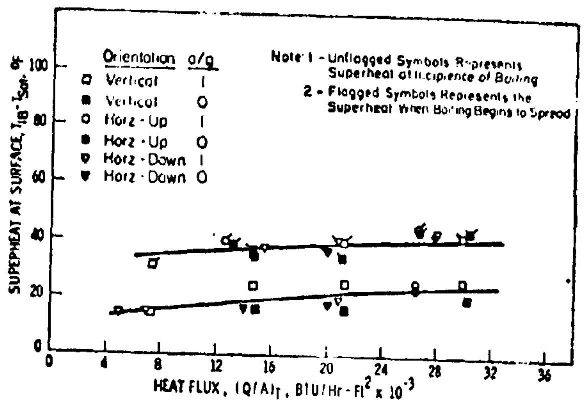


Figure 2 Surface superheat for incipient boiling, LN_2, all orientations, a/g = 1 and 0

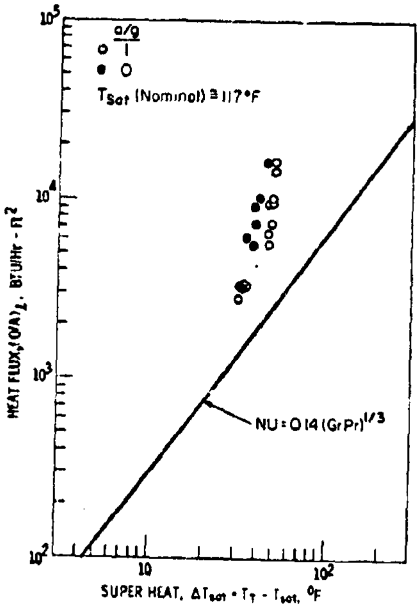


Figure 3 Saturated nucleate boiling heat transfer, F113, horizontal-up, a/g = 1 and 0.

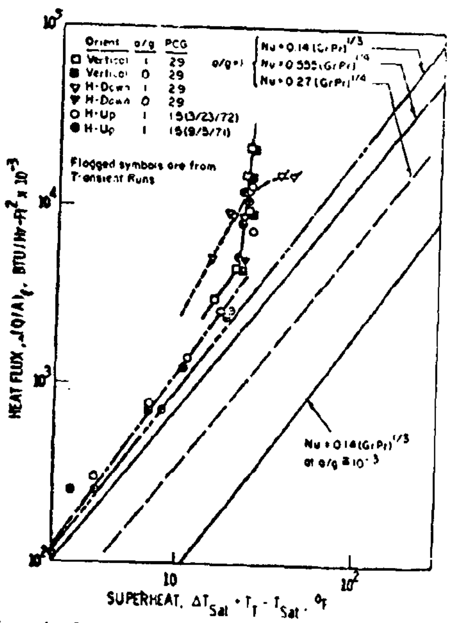


Figure 4. Saturated nucleate boiling heat transfer, LN_2, all orientations, a/g = 1 and 0.

EXTENDED HYDRODYNAMIC THEORY OF THE PEAK AND MINIMUM POOL BOILING HEAT FLUXES

Lienhard, J.H., Dhir, V.K., Univ. of Kentucky, NASA CR-2270, July 1973

OBJECTIVE. - To study the interacting effects of gravity and geometry on the peak and minimum pool boiling heat fluxes. This report describes the last three years of a five-year NASA supported study (NGL 18-001-035).

PERTINENT WORK PERFORMED. - The approach taken was to seek an understanding of the hydrodynamic mechanisms which dictate peak and minimum pool boiling heat fluxes. All theoretical results incorporate gravity explicitly and all experimental correlations incorporate gravity in the nondimensionalizations. Specific work accomplished included; (1) An extension of the hydrodynamic theory for inviscid liquids of the peak heat flux as originally formulated by Zuber in 1958, for flat plates of both finite and infinite size. Test data was obtained from 1-g up to 100 g's using acetone. benzene, isopropanol (corrected for viscosity), methanol, and distilled water. This data plus existing data including carbontetrachloride, n-pentane and ethanol were used in the overall correlations, (2) Development of a general theory of the peak heat flux on finite bodies of various configurations and applied to cylinders, spheres and ribbons. Some new data plus a considerable amount of existing data were used, (3) Formulation of viscous theories of Taylor and Helmholtz stability applied to film boiling and peak heat flux. New experimental data were generated to verify the theories, and (4) An examination of the deterioration of the conventional boiling curve, that takes place when size or gravity are reduced to the point at which inertia ceases to be important. Some new data using very small wires plus existing data were used. New test data at low-g was not obtained.

MAJOR RESULTS. -

1. Development of predictions of peak pool boiling heat fluxes on a variety of heaters in low viscosity liquids involving few or no empirical constants (Table 1) as verified by 1-g tests.

2. Formulation of a theoretical expression for q_{max} in viscous liquids. The viscous prediction is only valid when it predicts higher q_{max} than the equivalent inviscid theory.

3. The minimum heat flux was shown to be sensitive to liquid viscosity; however, the nature of this influence is not presently known.

4. Local maxima and minima and thus nucleate boiling in the boiling curve vanish for all $R' \leq .01$ where R' = (radius of body) $(\sqrt{a(\rho_\ell - \rho_g)/\sigma})$. The region $0.01 < R' < .15$ represents a transition in which the hydrodynamic mechanisms re-establish themselves. Typical boiling curves are presented in Figures 1 and 2. Natural convection and film boiling on small wires (or on large cylinders at low-g) are predictable by conventional methods.

Table 1. Pertinent Equations

$q_{max} = 1.14\, q_{max_z}$	Infinite Flat Plate (Dimensions >> λ_d)
$q_{max} = [0.94/(R')^{1/4}]\, q_{max_z}$	Small Cylinders ($0.15 < R' < 1.0$)
$q_{max} = .904\, q_{max_z}$	Large Cylinders ($R' > 1.0$)
$q_{max} = (1.734\sqrt{R'})\, q_{max_z}$	Small Spheres ($R' < 4.0$)
$q_{max} = .84\, q_{max_z}$	Large Spheres $R' > 4.0$
$q_{max} = 0.9\, q_{max_z}$	Large Ribbons ($H' > 3.0$)

λ_d = "most susceptible" wavelength

$q_{max_z} = (\pi/24)\, \rho_g^{1/2}\, h_{fg}\, [\sigma\, a\, (\rho_f - \rho_g)]^{1/4}$

H' = (Ribbon Height) $\sqrt{a\,(\rho_f - \rho_g)/\sigma}$ (Dimensionless)

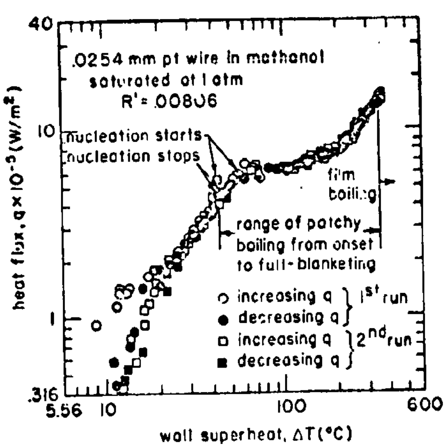


Figure 1. Boiling Curve for 0.0254 mm Platinum Wire in Methanol

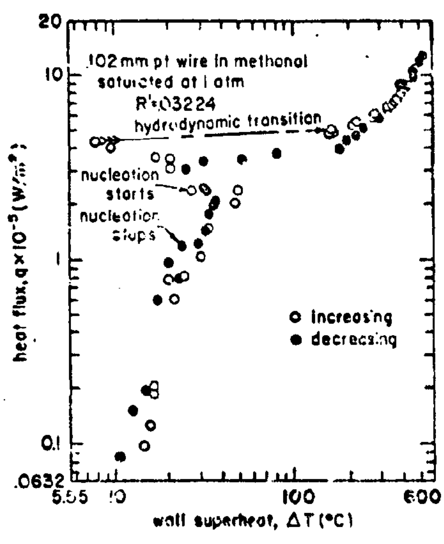


Figure 2. Boiling Curve for 0.102 mm Platinum Wire in Methanol

SURFACE-TENSION EFFECTS IN BOILING FROM A DOWNWARD-FACING SURFACE

Huplik, V., N.H.K.G. Research Institute, Raithby, G.D., University of Waterloo, ASME Paper No. 72-HT-42, August 1972.

OBJECTIVE. - To investigate the effect of surface-tension gradients in boiling heat transfer.

PERTINENT WORK PERFORMED. - Experiments and analyses were performed for flow around single air bubbles and for boiling vapor bubbles in de-ionized water on a downward-facing heater surface at 1-g. Test data was obtained at moderate heat fluxes and at heat fluxes near the burnout limit. Most of the experiments were conducted at liquid temperatures less than saturation. Streak photographs and shadowgraphs were used to measure flow patterns. Heater and bulk liquid temperatures and heat flux were also measured. Two different copper heaters (30 mm and 19 mm diameter) were tested in a 300 mm per side cubic glass tank. In the case of single air bubbles, injection on to the heater surface was by a hypodermic tube which also destroyed any previous free convective motion. The flow pattern and the temperatures were then recorded until a steady state was reached.

Definitions of Marangoni and Rayleigh numbers used in the correlations are; $M_a = L\,(T_o - T_c)(\partial\sigma/\partial T)/\bar{\mu}\,\alpha_B$ and $R_a = \beta g\,(T_c - T_B)\,R_o^3/\nu_c\,\alpha_B$ where L = length of bubble interface along which motion was observed, R_o = radius of bubble base, $\bar{\mu}$ = viscosity of liquid at $\left(\frac{T_o + T_c}{2}\right)$, and subscripts o, c and B refer respectively to conditions at heater surface, bubble crown and bulk liquid.

MAJOR RESULTS.

1. The cooling effect, particularly for low bulk temperatures, is considerable for the surface tension-driven flow. This is illustrated in Figures 1 and 2. In Figure 1, t/t_T is dimensionless time, where t_T is the time interval between the introduction of the bubble and transition.

2. For air and vapor bubbles at moderate heat flux (large number of discrete bubbles produced, $q \cong 3.5 \times 10^4\ W/m^2$) regimes of flow where surface-tension forces and buoyancy forces dominate were defined (Figure 3). From visual data, for boiling at heat fluxes near the burnout point, flow driven by surface-tension forces appears to play a large role in cooling the heated surface.

3. Addition of a surfactant to reduce surface tension had a significant effect on boiling heat transfer, resulting in a reduction at moderate heat transfer and an increase near burnout. The effect of the surfactant near burnout was to increase the number of small bubbles formed in relation to larger bubbles. At moderate heat flux the thermocapillary flow was simply reduced.

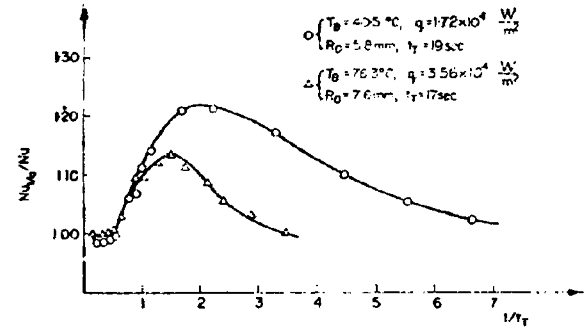


Fig. 1. Plot of ratio of Nusselt number with air bubble on surface to that without bubble, after removal of thermal boundary layer

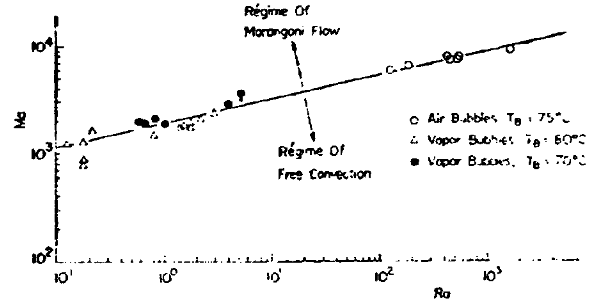


Fig. 3. Marangoni and Rayleigh numbers at transition for vapor bubbles (left-hand side) and air bubbles

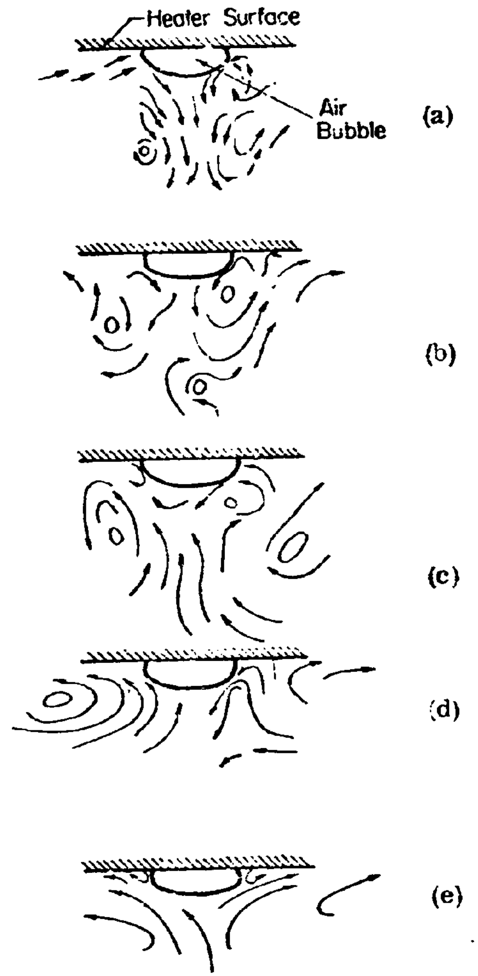


Fig. 2. Flow around an air bubble on heated surface showing surface-tension-dominated flow (a), increasingly important effect of buoyancy (b, c), transition (d), free-convection flow regime (e); T_R = 23 deg C, q = 2.2 × 10⁴ W/m², R_0 = 10 mm; interval between photos about 0.5 sec

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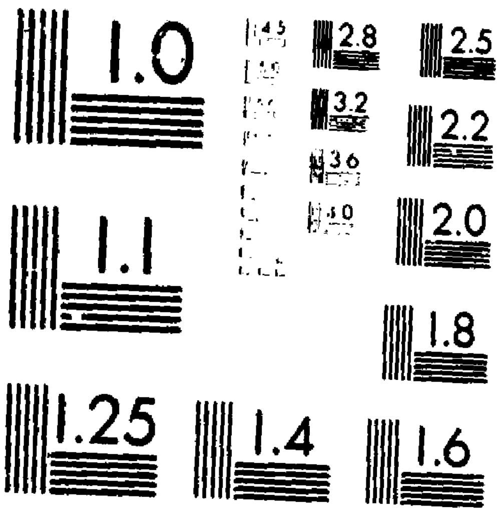

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

INCIPIENT AND STEADY BOILING OF LIQUID NITROGEN AND LIQUID HYDROGEN UNDER REDUCED GRAVITY
Merte, H., Jr., Univ. of Mich. Tech. Rep. No. 7, NASA CR-103047, NAS8-20228, November 1970.

OBJECTIVE. - To study incipient and steady boiling of cryogenic liquids under reduced gravity conditions with LN_2 and LH_2 as the test fluids. This report summarizes results of work under NAS8-20228 through Nov. 1970.

PERTINENT WORK ACCOMPLISHED. - Test results are presented for: (1) 1-in. dia. Cu. sphere in LH_2 at $a/g = 1$ and $a/g \cong 0$, which are similar in character to those obtained earlier (Lewis, 1967) with LN_2, (2) 2-1/4 in. dia. Cu. sphere in LN_2 and LH_2 at $a/g = 1$, (3) flat surfaces to determine the influence of orientation and geometry where a vertical 1-in. dia. Cu. cylinder was unsuccessfully used to simulate a vertical flat plate and a disc with 1-in. square Cu. measuring section was tested in LN_2 at $a/g = 1$ and $a/g \cong 0$ and in LH_2 at $a/g = 1$, (4) boiling on different surfaces, and (5) incipient boiling at $a/g = 1$ and $a/g \cong 0$ for both LN_2 and LH_2 under transient conditions with a step increase in power to a platinum wire. Low-g tests were conducted at $a/g = 0.008$ $+0.000/-0.008$ and $a/g = 0.23 \pm 0.03$ in a 1.34 sec. drop facility. Pressures ranged from 14.7 to 37 psia.

MAJOR RESULTS. -

1. At 14.7 psia LH_2 saturation, with spheres, a reduction in g level results in a significant decrease in boiling heat flux (Fig. 1). Also, it appears (Fig. 1) that the transition between film and nucleate boiling is independent of g-level. This effect, however, appears to decrease in the nucleate boiling region as pressure increases (Fig. 2). It is noted that q reductions with a/g in the nucleate boiling region were not observed with LN_2.

2. 1-g tests with a flat disc showed that nucleate boiling heat flux (for a given $\Delta T_{sat.}$), is greater for horizontal down, less for horizontal up, and in-between for the vertical (Fig. 3). Comparison with low-g data also indicated that prior acceleration history, as it influences liquid momentum, has an important bearing on what takes place during low-g boiling, thus illustrating the importance of long term low-g testing to adequately predict low-g steady-state boiling.

3. Incipient boiling tests with platinum wire indicated that, for both LN_2 and LH_2, the maximum heater transient and steady state super heat at nucleation was independent of g-level.

4. LH_2 film boiling data are compared with the 1/4 power correlation of Bromley, 1950, and the 1/3 power correlation from the LN_2 data (Fig. 4). $Ra' = 10^9$ was the lower limit for LN_2 data. LH_2 data appear to follow the shape of the 1/4 power curve and the effect of g-level appears to be negligible.

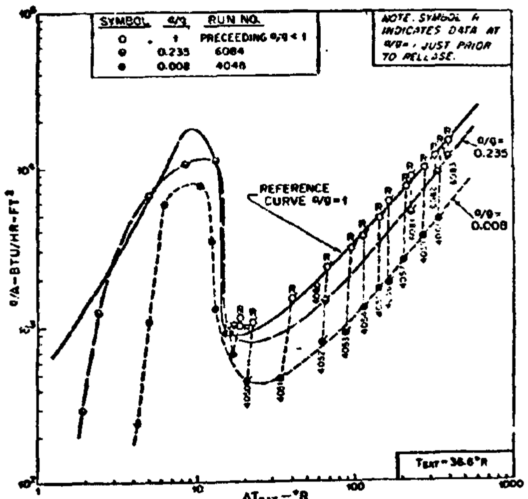

Figure 1. Effect of a/g at P = 14.7 psia. Saturated liquid hydrogen with 1 in. dia copper sphere.

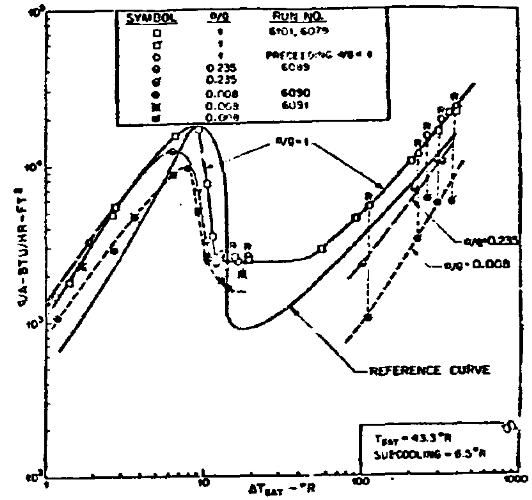

Figure 2. Effect of a/g with subcooling at P = 37 psia. Subcooled liquid hydrogen with 1 in. dia copper sphere.

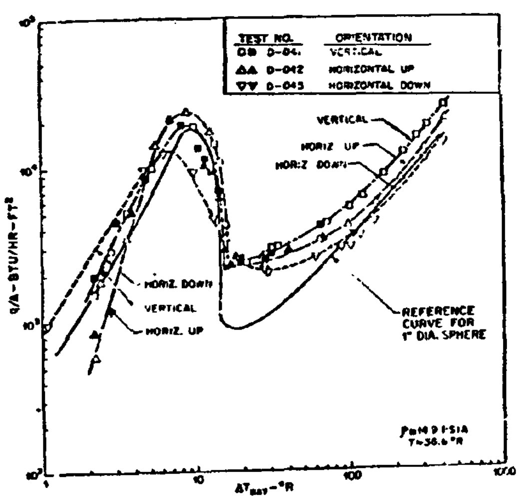

Figure 3. Disc in Saturated LH_2 - all orientations. a/g = 1.

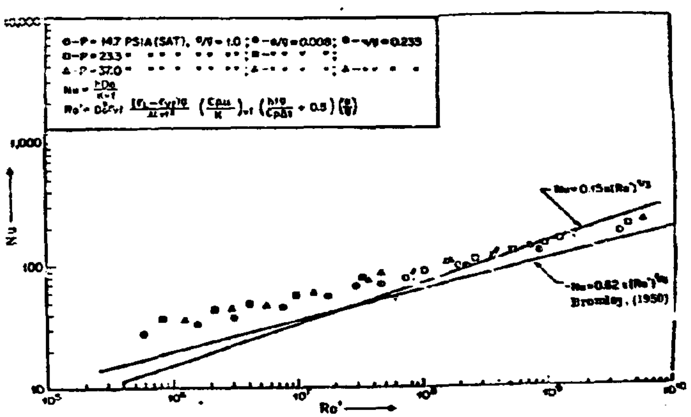

Figure 4. Correlation of film boiling from 1 in dia sphere in saturated liquid hydrogen

STUDIES OF LIQUID BOILING IN IMITATED REDUCED GRAVITY FIELDS

Kirichenko, Y. A., Charkin, A. I., USSR, 4th International Heat Transfer Conference, Versailles, France, Vol. 6, September 1970

OBJECTIVE. - To investigate liquid oxygen boiling at imitated reduced gravity.

PERTINENT WORK PERFORMED. - Tests were conducted on the boiling characteristics of LO_2 using a magnetic field to counteract Earth gravity. A platinum wire, 0.1 mm dia. was used as the heater, and also served as a resistance thermometer. Nucleate boiling and peak heat flux, bubble departure frequency and size and bubble growth rate data were obtained over the range $a/g_n = 0.01$ to 1.0. In each case a relatively large number of data points were obtained.

MAJOR RESULTS. -

1. Nucleate boiling heat flux was found to be essentially independent of gravity level.
2. The peak heat flux or burnout point was found to correlate almost exactly with $q = q_n \left(\frac{a}{g_n}\right)^{1/4}$ over the range of a/g_n from 0.01 to 1.0.
3. The average bubble departure frequency (f) for different gravity levels was found to agree well with the data of Siegel (1964). The current data resulted in the correlation, f, $\sec^{-1} = 106\ (a/g_n)^{0.85}$ over the range, $a/g_n = 0.02$ to 1.0.
4. The average bubble diameter at departure (D_o), taken as the average of horizontal and vertical diameters, was found to correlate with D_o, $m = 0.47 \times 10^{-3}\ (a/g_n)^{-0.35}$.
5. Bubble growth rate did not appear to be dependent on gravity level and the actual growth rates were close to that predicted by Siegel (1964).

INTERACTING EFFECTS OF GRAVITY AND SIZE UPON THE PEAK AND MINIMUM POOL BOILING HEAT FLUXES
Lienhard, J. H., University of Kentucky, NASA CR-1551, NGR 18-001-035, May 1970

OBJECTIVE. - To study the interacting effects of gravity and geometry on the peak and minimum pool boiling heat fluxes.

PERTINENT WORK PERFORMED. - Results are presented on the first two years of work under a five-year NASA supported study (NGL 18-001-035). Results of the final three years are reported in NASA CR-2270 (Lienhard and Dhir, 1973), which report is also summarized. New data using a centrifuge acting perpendicular to the heater surface, along with existing low-g and elevated gravity data, were used to correlate new peak and minimum heat transfer models developed under this program. A further discussion of the test data, along with the fluids used, is presented in the summary of the later work. In the present case, tests were accomplished with wires (horizontal cylinders) from 36 to 12 gage and with flat ribbons from 0.117 to 2.54 cm in width. Low-g sphere data, used for comparison, was taken from the LN_2 work of Merte and others at the University of Michigan. The major results of this current summary will concentrate on the q_{min} data, since this was not adequately covered in the later report.

MAJOR RESULTS. -

1. It was found that q_{max} and q_{min} could be correlated by: q_{max}/q_{max_F} and $q_{min}/q_{min_F} = f(L') = \phi$ under a wide variety of conditions. Pertinent nomenclature and definitions are presented in Table 1. Typical correlation results are presented in Figure 1 for a variety of configurations. For spheres and cylinders L = the radius (R), and for ribbons L = the width (W). It is noted that the induced convec-vection scale parameter (I) had an effect on the ribbon data but not on the cylinders.
2. The best estimate for q_{min} for wires over large ranges of a and R was found to be: $q_{min} = q_{min_F}\,[0.0217/R'^2\,(2R'^2 + 1)]$.
3. The correlations and calculation methods presented fail for cylinders when R' is less than 0.15 and for horizontal ribbons the correlation was becoming questionable at $W' \cong 0.70$.

Table 1. Nomenclature

$$q_{max_F} = (\pi/24)\,\rho_g^{1/2}\,h_{fg}\,[\sigma a\,(\rho_\ell - \rho_g)]^{1/4}$$

L = characteristic length

$$q_{min_F} = 0.09\,\rho_g\,h_{fg}\left[\frac{\sigma a\,(\rho_\ell - \rho_g)}{(\rho_\ell + \rho_g)^2}\right]^{1/4}$$

I = induced convection scale parameter, $[\rho_\ell L\sigma]^{1/2}/\mu$

$$L' = L\,[a\,(\rho_\ell - \rho_g)/\sigma]^{1/2}$$

I_c = I where L = width of test capsule

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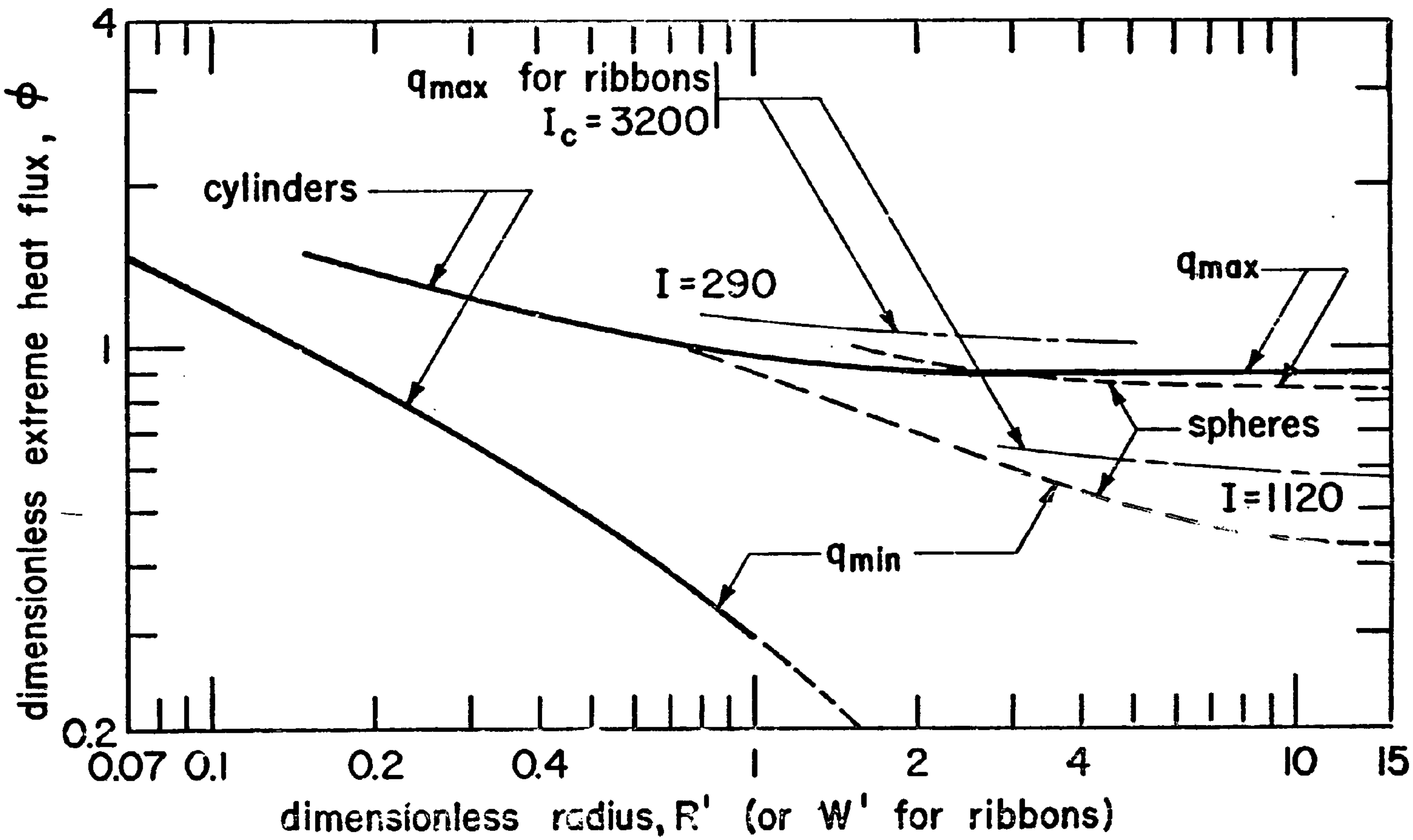


Figure 1. Collected Dimensionless Extreme Heat Flux Results

FORCED-CONVECTION BOILING NEAR INCEPTION IN ZERO GRAVITY

Cochran, T.H., NASA-LeRC, TN D-5612, January 1970

OBJECTIVE. - To study the behavior of forced convection boiling in zero gravity at low heat flux (near the inception point of boiling) and at low free-stream velocities.

PERTINENT WORK PERFORMED. - Zero-g ($a/g < 10^{-5}$) testing was accomplished in the NASA-LeRC 2.2 sec drop facility. Distilled water was the test fluid and boiling occurred on a thin chromel strip with an effective heating surface of 1.27 by 4.06 cm. This heater was located at the side of a brass tube with a plastic section employing a piston to force liquid flow over the heater section at a controlled free-stream velocity. Bulk fluid temperature and bubble size data were measured using a thermister and a 16-mm, 900 frames/sec camera. Test conditions are presented in Table 1. Free-stream velocities were of the same order of magnitude as free-convection velocities for the system in normal gravity. A typical plot of bubble diameter versus test time is presented in Figure 1.

MAJOR RESULTS. -

1. At low heat fluxes, typical of that anticipated at propellant tank walls in space, bubbles remained on the heated surface to form a bubble boundary layer.

2. The equilibrium size D_e of bubbles generated under the current test conditions was successfully correlated in terms of the evaporation layer thickness Y_{sat} (Figure 2). The correlating equation is $D_e = -0.06 + 4.6\, Y_{sat}$ where Y_{sat} can be determined for the transition regime (Figure 1) from $T - T_\infty = 0.625$ times $\left[\frac{Q_w \delta_T}{A k_\ell} \operatorname{ierfc}\left(1.6 \frac{Y_{sat}}{\delta_T}\right)\right]$ and $\delta_T = 3.2 \left(\frac{\nu_\ell t}{Pr_\ell}\right)^{1/2}$. For the convection regime

$$T - T_\infty = \frac{Q_w}{A k_\ell} \left(\frac{\delta_T}{2} - Y_{sat} + \frac{Y_{sat}^3}{\delta_T^2} - \frac{Y_{sat}^4}{2 \delta_T^3}\right) \text{ and } \delta_T = 2.2 \left[\frac{\delta_H\, \nu_\ell\, (\bar{x} - \bar{x}_o)}{u_\infty Pr_\ell}\right]^{1/3}$$

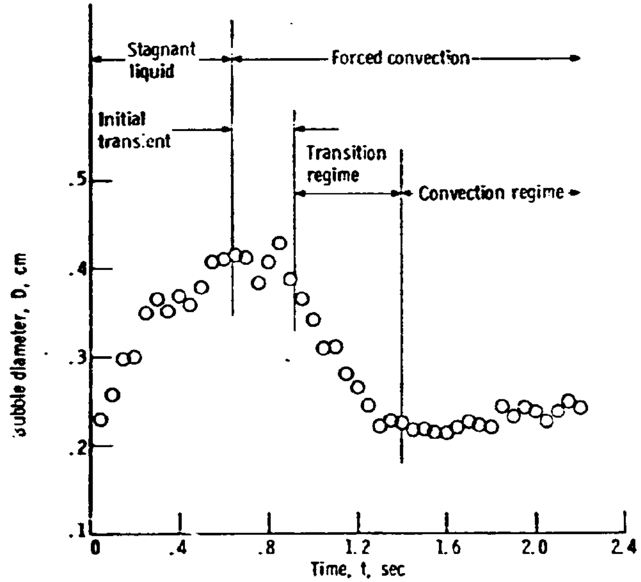
The end of the transition regime and start of the convection regime is defined by $\bar{x} - \bar{x}_o = \left(\frac{0.443}{Pr_\ell^{1/2}}\right) u_\infty t$. Nomenclature are:

A	=	heater surface area
Q_w	=	total heat flux at wall
δ_H	=	3.65 νt
$\bar{x}$	=	axial displacement along surface

subscript, ∞ = free stream conditions and o = thermal entrance region.

Table 1. Test Conditions

Test run	Bulk temper-ature, T, °C	Saturation tempera-ture, T_{sat}, °C	Heat flux, q, W/m^2	Free-stream velocity, U_∞, cm/sec
1	98.0	98.9	1223	4.2
2	98.3	99.2	1150	11.5
3	98.5	99.5	1254	7.2
4	98.5	99.5	1254	6.7
5	98.0	99.5	1226	6.9
6	98.8	99.5	1261	5.5
7	98.8	99.4	1072	6.0
8	98.8	99.2	1204	10.2
9	98.0	99.1	1239	9.9
10	98.1	99.1	1210	10.1
11	98.0	99.3	1128	7.4
12	98.5	99.3	1012	8.4
13	97.8	99.1	1305	7.8



Test run 8. Free-stream velocity, 10.2 centimeters per second.

Figure 1. Bubble Diameter as Function of Time for Various Freestream Velocities

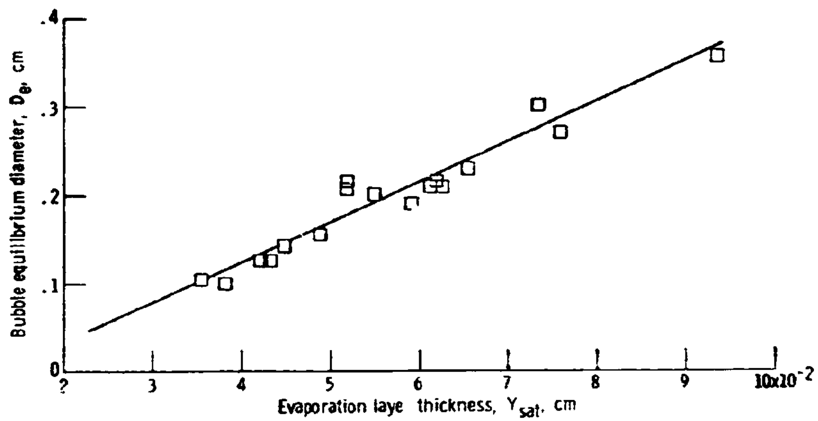


Figure 2. Bubble Diameter as Function of Evaporation Layer Thickness

NUCLEATE POOL BOILING OF SATURATED FREON 113 IN A REDUCED GRAVITY ENVIRONMENT.
Littles, J. W., Ph.D. Dissertation, University of Texas, Aug. 1969.

OBJECTIVE. - To study the effects of surface orientation and reduced gravity on nucleate boiling of saturated Freon 113 at 1-atm. pressure.

PERTINENT WORK PERFORMED. - 1-g and reduced gravity ($a/g = 0.01$ and 0.02) tests were performed with two different copper test heaters (2-in. wide by 4 in. long and 2 by 2-in.) at heat fluxes from 5,500 to 21,500 Btu/hr-ft^2. Horizontal down, horizontal up and vertical orientations were tested. Isolated bubble growth rates and bubble departure diameters and bubble coalescence were studied using a 400 frames/sec. camera. The MSFC 294 ft, 4 sec. drop facility was used. Also, new boiling and bubble growth rate models were developed along with an analysis of the relative importance of the various bubble forces.

MAJOR RESULTS. -

1. Nucleate boiling in the isolated bubble region was found to be dependent on both acceleration and surface orientation. The boiling curve shifted up (higher $\dot{Q}$ at given ΔT_{W-S}) for reduced acceleration for the horizontal up orientation and down for the horizontal down and vertical orientations. This is illustrated in Fig. 1 where a lower temperature decay rate indicates a lower $\dot{Q}$. Due to the nature of the heaters, a residual energy source was present and absolute $\dot{Q}$ data could not be obtained at low-g. However, based on energy differences between 1-g and 0.01g tests, Fig. 2 was generated. Fig. 2 also illustrates 1-g nucleate boiling as a function of orientation with progressively lower $\dot{Q}$ for horizontal up, vertical and horizontal down. Qualitatively, results were the same for both size heaters.
2. Only the Han and Griffith (1965) enthalpy transport model and possibly the Snyder (1968) mass transport model predict the trends of the present data with reduction in acceleration.
3. Bubble growth rates were not predicted by existing theories. A new calculation procedure was outlined which allowed the bubbles to grow through the thermal layer rather than moving it uniformly from the wall. Comparison with test data and other models is presented in Fig. 3. Reasonable correlation was also made with the water data of Schwartz (1966).
4. Coalescence of bubbles sliding up a vertical surface at reduced gravity produced large vapor accumulations near the surface. This could account for reduced $\dot{Q}$ at low-g for this orientation. A large scatter was seen in bubble departure dia's at low-g (Fig. 4).

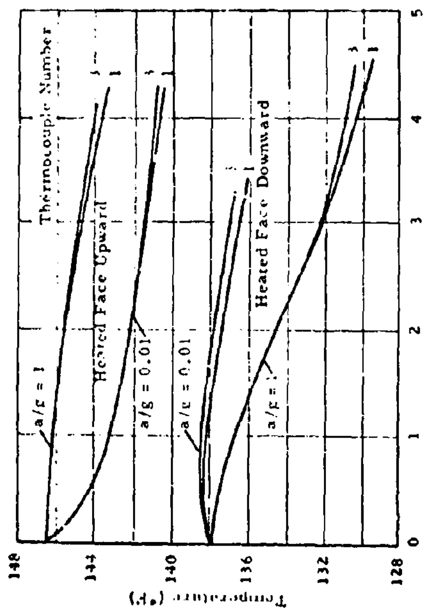


Figure 1. Comparison of Standard Gravity and Reduced Gravity for Horizontal Surface

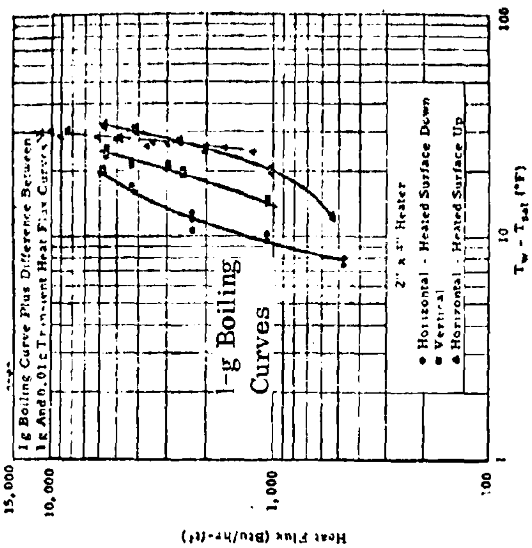


Figure 2. One g Boiling Versus Orientation and Enthalpy Change Effect for 0.01g

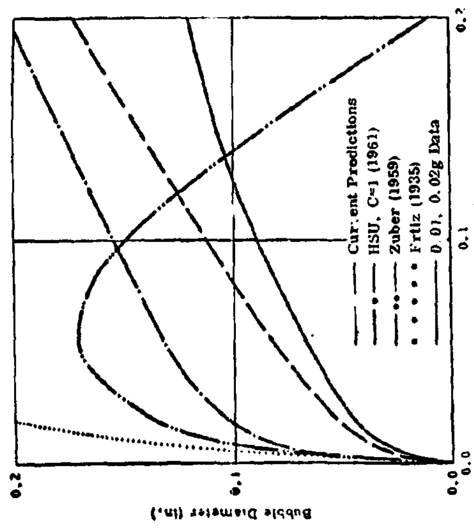


Figure 3. Reduced Gravity Data Compared

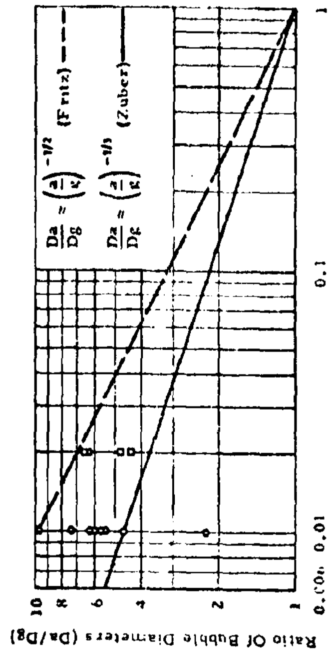


Figure 4. Comparison of Observed Bubble Departure Diameters with Theory

EXPERIMENTAL INVESTIGATION OF NUCLEATE BOILING BUBBLE DYNAMICS IN NORMAL AND ZERO GRAVITIES.
Cochran, T.H., et al, NASA-LeRC, TN D-4301
Feb. 1968.

OBJECTIVE. - To investigate effects of gravity on the dynamics of bubbles in the discrete bubble region over a range of subcooling, fluid properties, and heat transfer rates.

PERTINENT WORK PERFORMED. - Testing was accomplished at 1-g and $a/g < 10^{-5}$ in a 2.2 second drop tower. The test surface was a 0.25 inch wide chromel strip with an effective heating length of 0.5 inches tested in the horizontal up position. Data from previous work (Cochran, 1966 and 1967) are also summarized here. Including this previous work along with the current work, the following test conditions were covered: (1) Subcooling ($T_{sat} \simeq T_{bulk}$ = 5° to 40°F, 2.78° to 22.22°K), (2) heat transfer from 24,800 to 114,000 Btu/hr-ft^2; 7,820 to 35,900 w/m^2, and (3) water, 60% by weight sugar-water (high viscosity), and 10% by volume ethanol-water (low surface tension). A 6500 picture per second camera was used to measure bubble growth characteristics on a statistical and an individual basis.

MAJOR RESULTS. -

1. An increase in subcooling resulted in the dynamics of bubbles becoming gravity independent. This was shown both statistically (Fig. 1) and from force data on individual bubbles (Fig. 2); i.e. at 1-g, buoyancy had a relatively large role with low-subcooling and a small role with high-subcooling.

2. Bubble lifetime and maximum-radii statistical data indicated no effect of viscosity during growth, however, force data indicates that the sucrose (10 times viscosity of water) drag force had a value near separation comparable to other forces at zero-g and should thus be important in determining resultant bubble motion.

3. Reduction in surface tension to one-third that of water resulted in the 1-g and 0-g average bubble maximum - radii and lifetime becoming similar (Fig. 1). At higher subcooling, this similarity is explained by (1) above, however, at lower subcooling there should be an effect. Apparently, at low subcooling, geometric or dynamic changes took place in 0-g, in addition to the absence of buoyancy. One difference was that bubbles generated in the ethanol-water solution were more spherical than those in water. This reflects the relative importance of the pressure force as a removal agent as illustrated in Fig. 3 where $F_p/F_{sy} = 1$ for a spherical bubble.

4. A variation of heat flux within the discrete bubble region has no effect as a function of gravity on the average maximum radii and lifetime of bubbles generated in an ethanol-water solution. A significant effect was that, at the lower subcooling tested, the transition from the discrete bubble region occurred at a lower heat flux in zero gravity than in normal gravity.

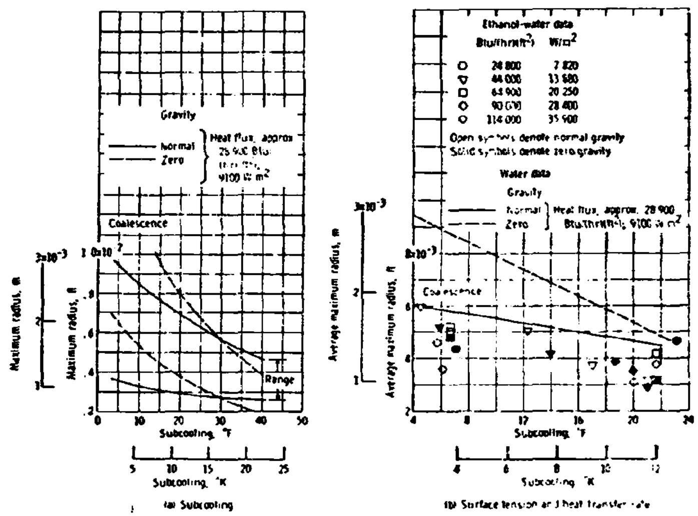


Figure 1. Effects of gravity on bubble maximum radius as function of subcooling, surface tension, and heat-transfer rate.

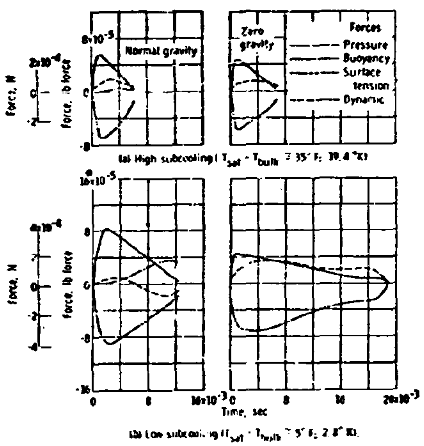


Figure 2. Dynamics of water bubbles at high and low subcoolings in normal and zero gravities

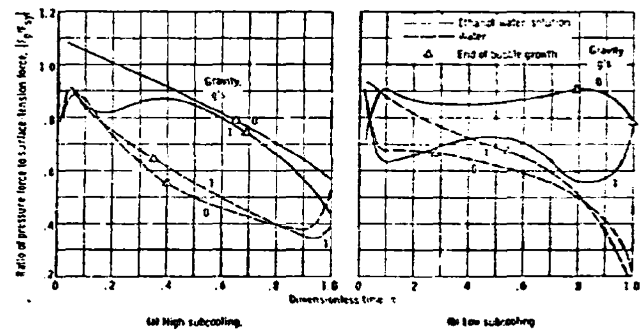


Figure 3. Distortion of bubbles from spherical at high and low subcoolings

EFFECTS OF REDUCED GRAVITY ON HEAT TRANSFER
Siegel, R., NASA-LeRC, Advances in Heat Transfer,
Vol. 4, 1967

OBJECTIVE. - To review and summarize low gravity heat transfer information up to about November 1966.

PERTINENT WORK PERFORMED. - Data and/or discussions are presented on free convection, pool and forced flow boiling, condensation in stationary vapor and in forced flow, and combustion. The major result of the study is the handy consolidation of data and the conclusions which resulted, highlights of which are presented below.

MAJOR RESULTS. -

1. In the area of free convection there is a lack of data. A difficulty is that such boundary layers have a relatively slow time response so that tests cannot be conducted with convenient facilities such as drop towers or airplane flights.
2. Both analysis and experiment indicate that nucleate pool boiling heat flux is insensitive to gravity, while the peak nucleate and minimum film boiling heat fluxes were found to vary reasonably well as $g^{1/4}$. In laminar film boiling the heat transfer coefficient depends on $g^{1/4}$, while for a turbulent film the exponent may be 2/5 to 1/2.
3. Photographic studies of reduced-g pool boiling for saturated conditions show that; (a) vapor tends to linger near the heater surface and collect new bubbles being formed, thus helping their removal, (b) bubble growth rate is insensitive to gravity, and (c) departure diameters of slowly growing single bubbles depend on $g^{-1/2}$ (buoyancy causes departure), while for rapidly growing bubbles departure size is relatively insensitive to gravity (inertia causes departure).
4. For reduced gravity forced-convection boiling, little experimental information is available, however, isothermal two-phase flow visualization tests with air-water mixtures indicate cross-sectional bubble distribution in a vertical tube at earth gravity is very similar to that in zero gravity.
5. For condensation without forced flow, no experimental results were found in the literature. For forced flow condensation in tubes, low gravity tests have been performed with nonwetting mercury, with the result that (a) pressure drop was insensitive to gravity for the conditions tested, (b) stability of the vapor-liquid interface was indicated from the Taylor type of instability theory, and (c) low gravity conditions aid in the trapping of noncondensable gas.
6. The experimental evidence to substantiate the above conclusions is mostly from tests of short duration. Additional experimental work is needed with longer testing times. This is especially true at very low gravities; for example, it has not been conclusively demonstrated that the critical heat flux does go to zero as exactly zero gravity is approached.

CRYOGENIC LIQUID EXPERIMENTS IN ORBIT- VOL. II.
McGrew, J.L., Larkin, B.K., MMC, NASA CR-562, NAS8-11328, December 1966

OBJECTIVE. - With respect to boiling heat transfer, to investigate bubble growth rate, size at departure and motion under the influence of surface tension and vapor pressure gradients.

PERTINENT WORK PERFORMED. - Data presented in this summary is concerned with boiling heat transfer and bubble mechanics. Other work in this report is concerned with venting (Vol. II) and propellant settling and interface dynamics (Vol. I) which are reviewed elsewhere. With respect to boiling heat transfer and bubble mechanics, the following work was accomplished: (1) analysis and experimentation (at 1-g using n-butyl alcohol) of Marangoni Flow (motion of liquid due to gradient in surface tension) at a flat liquid surface, (2) analysis and experimentation (at 1-g with n-butyl alcohol and methanol) of bubble thermophoresis or forces on a bubble due to temperature induced surface tension gradients around the bubble, (3) tests at 1-g with n-butyl alcohol and methanol, of liquid convection caused by Marangoni Flow around a bubble, and (4) analysis and test (at 1-g and a/g = 0 with LH_2) of bubble shape and boiling phenomenon. Low-g testing was accomplished in a 0.8 sec. drop tower with a flat CRES disk 11/16-in dia. as the boiling surface. Bubbles were formed at an imperfection in the center.

MAJOR RESULTS. -

1. Marangoni Flow on a flat surface and around bubbles was visually demonstrated.

2. Theoretical predictions of the thermophoretic force on a bubble showed good agreement with test in a low vapor pressure liquid (n-butyl alcohol). However, agreement using a relatively high vapor pressure liquid (methanol) was not nearly as good.

3. Formation of relatively large bubbles in zero gravity (Figure 1) appears to qualitatively verify the predictions of growth based on capillary theory developed in this work. However, quantitatively there is poor agreement, because the observed shapes do not resemble those predicted from the theory. In Figure 1 the probe is 1/32-in. diameter and located 1/4 in. from the wall. It is noted that even though there is one large bubble there are also smaller bubbles being generated. Results were essentially the same whether boiling was started before or after capsule release. Results suggest that it would not be possible to predict boiling heat transfer rates from free fall test data since many bubbles would need to be formed to insure steady state and here, after 0.8 sec., one bubble is still attached to the heating surface.

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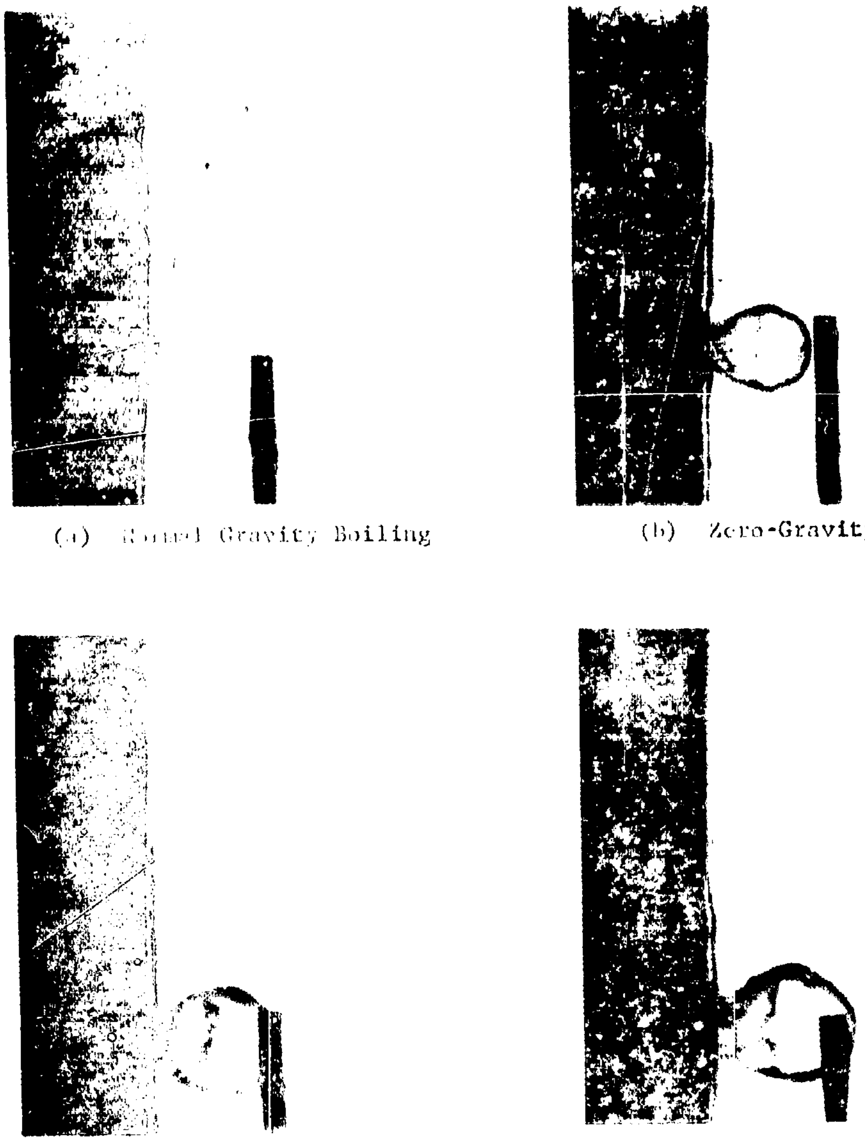


(a) Normal Gravity Boiling

(b) Zero-Gravity Boiling

(c) Zero-Gravity Boiling

(d) Zero-Gravity Boiling

Fig. 1. Boiling Experiment, Bubble Formation in Normal and Zero Gravity
(Test Liquid, Liquid Hydrogen)

BUOYANCY EFFECTS ON CRITICAL HEAT FLUX OF FORCED CONVECTIVE BOILING IN VERTICAL FLOW
Papell, S. S., et al, NASA-LeRC, TN D-3672, October 1966

OBJECTIVE. - To determine the conditions under which buoyancy influences the critical heat flux level of a vertically-flowing, two-phase heat transfer system.

PERTINENT WORK PERFORMED. - Tests were performed in which LN_2 was flowed vertically through a resistance-heated, 0.505-in. inside diameter, 12-in. long steel tube. At a constant inlet pressure, power input to the heaters was gradually increased until the condition of criticality was established. Inlet pressures ranged from 50 to 240 psia, inlet velocities from 0.5 to 11.0 feet per second, and fluid subcooling from 12 to 51 Fahrenheit degrees. Each set of conditions was run both in the upward and downward directions to determine the effect of buoyancy on critical heat flux. Test data were plotted in the form of critical heat flux versus inlet velocity for upward and downward flow at a given inlet pressure (Figure 1). Below a certain velocity, approximately 7 ft/sec in Figure 1b, buoyancy affected the level of the critical heat flux. Above this point, the flow direction apparently had no effect. It was postulated that below the critical velocity, in the "buoyancy-dependent" zone (Figure 2) the flow may have been annular-dispersed, characterized by liquid droplets in a gaseous core surrounded by a liquid annulus on the tube wall. Above the critical velocity in the "buoyancy-independent" zone, the flow was said to change to bubbly or slug flow. No data are presented to support this flow regime identification.

MAJOR RESULTS. -

1. Under certain conditions, the critical heat flux level for upward flow is significantly higher than that for downward flow.
2. Buoyancy effects on critical heat flux increased with decreasing inlet pressure and subcooling, but decreased with increasing inlet velocity. Above certain velocities buoyancy effects were erased by fluid momentum.
3. For upward flow, with pressure above 150 psia, above an inlet velocity of 5 ft/sec, an increase of pressure increases the critical heat flux, while below 5 ft/sec there is a decrease in the critical heat flux with increased pressure.

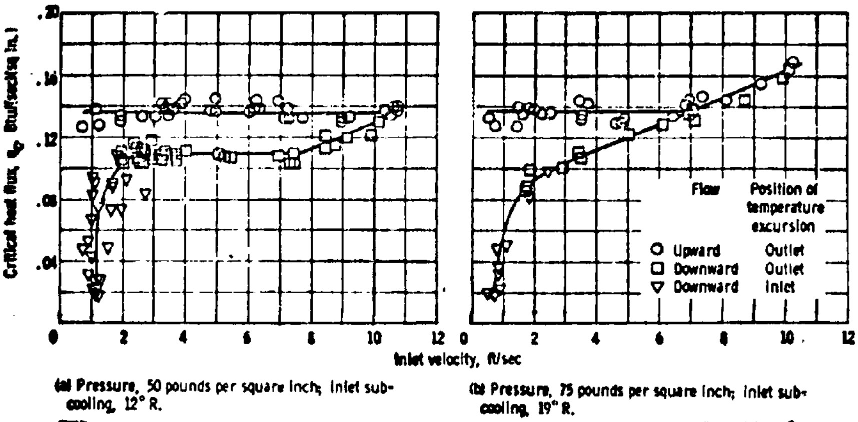


Figure 1. Critical heat flux as function of inlet velocity for upward and downward flow of liquid nitrogen.

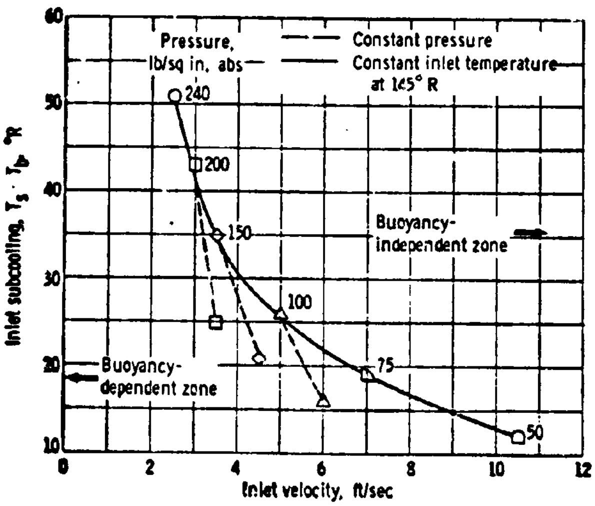


Figure 2. Susceptibility of liquid nitrogen flow system to buoyant effects on critical heat flux.

SATURATED POOL BOILING OF WATER IN A REDUCED GRAVITY ENVIRONMENT.

Schwartz, S. H., Univ. of Southern California, PhD Dissertation, June 1966

OBJECTIVE. - To study the effect of reduced gravity on nucleate pool boiling heat transfer.

PERTINENT WORK PERFORMED. - The test fluid was distilled saturated water at 1 atm. pressure. Tests were at 1-g and at low-g ($a/g = 0.02$ to 0.25) in an Aero Commander (8 to 10 sec. of low-g) with $\dot{Q} = 2,000$ to $65,000$ Btu/hr-ft^2 using a horizontal ribbon heater 2.75-in. long by 0.25 in. wide. A 400 frames/sec camera was also employed. Four low-g flights were made from which useful data were obtained, along with one-g data before and after each flight; nucleate pool boiling heat flux, isolated bubble growth rate and breakoff size, bubble population density, non-isolated unattached bubble size and frequency, unattached bubble size distribution, and surface bubble interactions. Also, existing boiling models were reviewed and a new model postulated.

MAJOR RESULTS. -

1. Temperature traces indicated steady state boiling was achieved within 2 to 3 sec. after start, which was well within the 8 to 10 sec. available. (The boiling curves show little change in the range from $a/g = 0.02$ to 1.0 (Fig. 1).

2. It did not appear that gravity had an effect on bubble growth rate, although statistical scatter may have masked any effect (Fig. 2).

3. Isolated bubble diameters at departure were found to agree with the prediction of Fritz (1935) where $D_0 \approx g^{-1/2}$ (Fig. 3). Bubbles remaining on the heated surface longer and growing to larger size in low-g seem to explain the results of this study that the fraction of total heat flux resulting in vapor formation increased with decreasing gravity.

4. A boiling model based on enthalpy transport similar to that of Han and Griffith (1962), was developed to explain the current test results. Models of Tien (1962) and Zuber (1963) did not explain the current low-g data since they showed a definite gravity dependence.

COMMENTS. - The boiling model developed appears to show which mechanisms are important, but is not presented in a manner which allows ready engineering use.

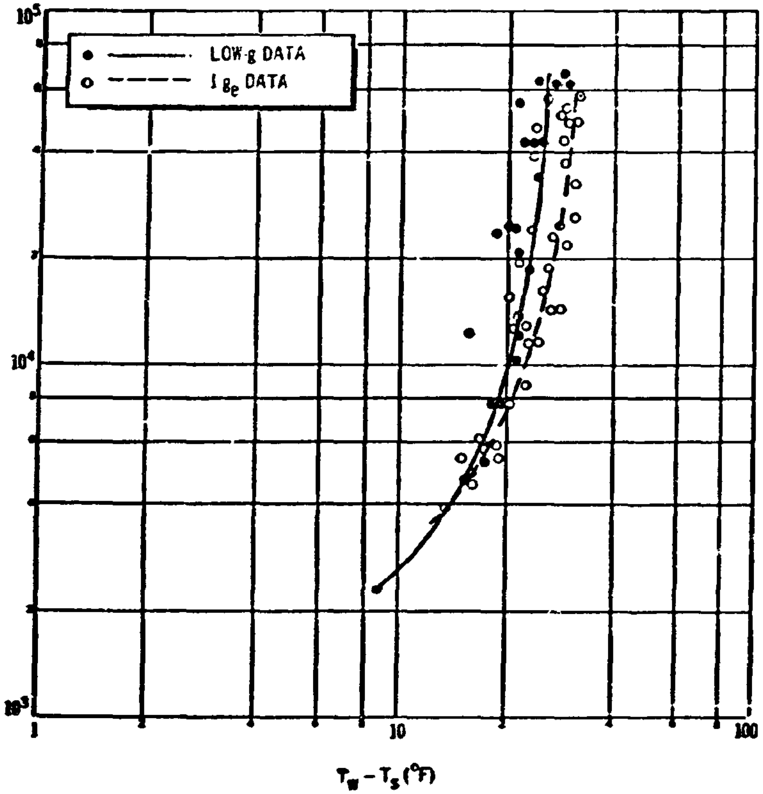


Figure 1. Combined $1G_e$ and Low Gravity Data

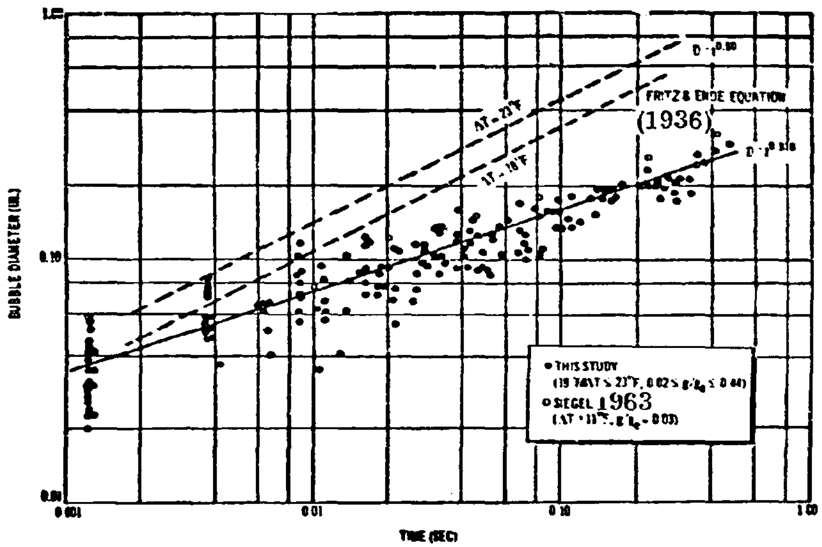


Figure 2. Bubble Diameter as a Function of Time

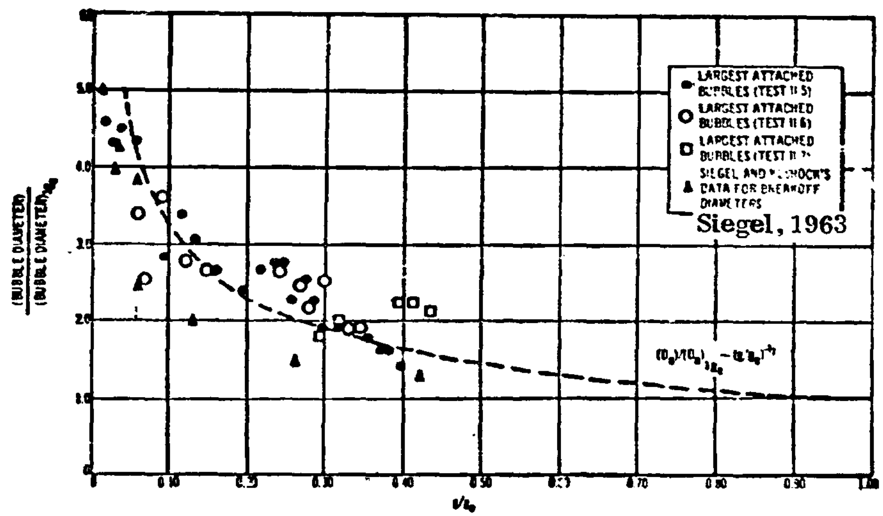


Figure 3. Largest Attached Isolated Bubble Diameter

ZERO- AND REDUCED-GRAVITY SIMULATION ON A MAGNETIC-COLLOID POOL-BOILING SYSTEM
Papell, S. S., Faber, O. C., NASA-LeRC, NASA TN D-3288, February 1966.

OBJECTIVE. - To study gravitational effects on the heat transfer characteristics of a pool boiling system using magnetic body forces to counteract the Earth's gravity.

PERTINENT WORK PERFORMED. - The test fluid was produced by suspending (68.3% by weight) ferromagnetic submicron particles (Fe_3O_4) as a colloidal dispersion in normal heptane. Proper control of the magnetic flux in a vertically mounted solenoid type magnet permitted the fluid to be subjected to effective gravity forces from nearly zero to one. The magnetic gradient was quite uniform and the addition of the ferromagnetic particles did not significantly change the fluid boiling point or its viscosity. The dispersion of the particles was also not effected by Earth gravity or the applied magnetic field. The heat transfer surface was a 1/16-in.-wide (0.159 cm) by 1-in.-long (2.54 cm) Chromel ribbon oriented perpendicular to Earth gravity. The fluid was saturated at the start of testing. The test set-up is shown in Figure 1.

It is noted that the present data, although unique because of their steady state nature, could still be subject to some of the shortcomings of the drop tower, such as apparatus geometry. In addition, the nature of the magnetic body force itself could influence the heat transfer data.

MAJOR RESULTS. -

1. Measurable changes in the boiling curves were observed in the critical-heat-flux region and the boiling incipience region (Figure 2). The incipient point, taken as the intersection of straight line extensions of the boiling and convective portions of the curve, shifted to lower temperatures as the net gravity field was reduced. It is believed that this is due to an increase in the thermal layer at low-g providing a medium more favorable for bubble ebullition.

2. Critical-heat-flux comparisons were made with data that included the present and reference data (Figure 3). At nearly zero gravity (0.01 to 0.04g) a spread in the data of 68% was observed. The differences could, in part, be attributed to possible transient, geometry control, and subcooling effects.

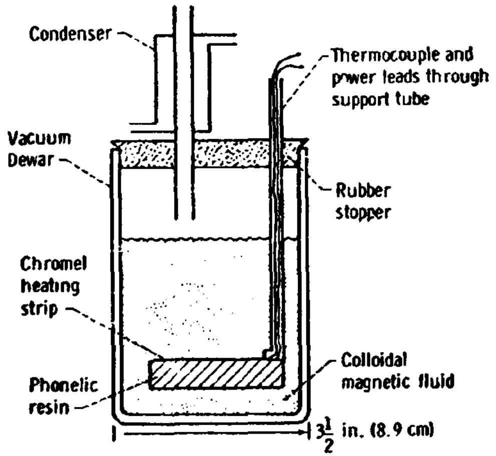


Figure 1.- Pool-boiling heat-transfer apparatus.

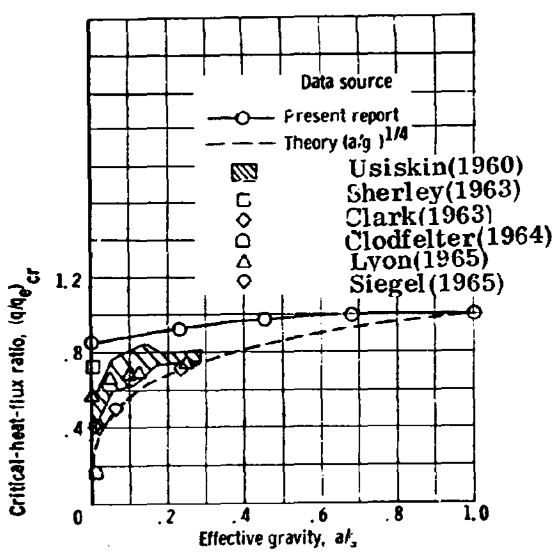


Figure 3. Gravitational effects on critical heat flux during pool boiling of magnetic iron oxide - normal heptane colloid.

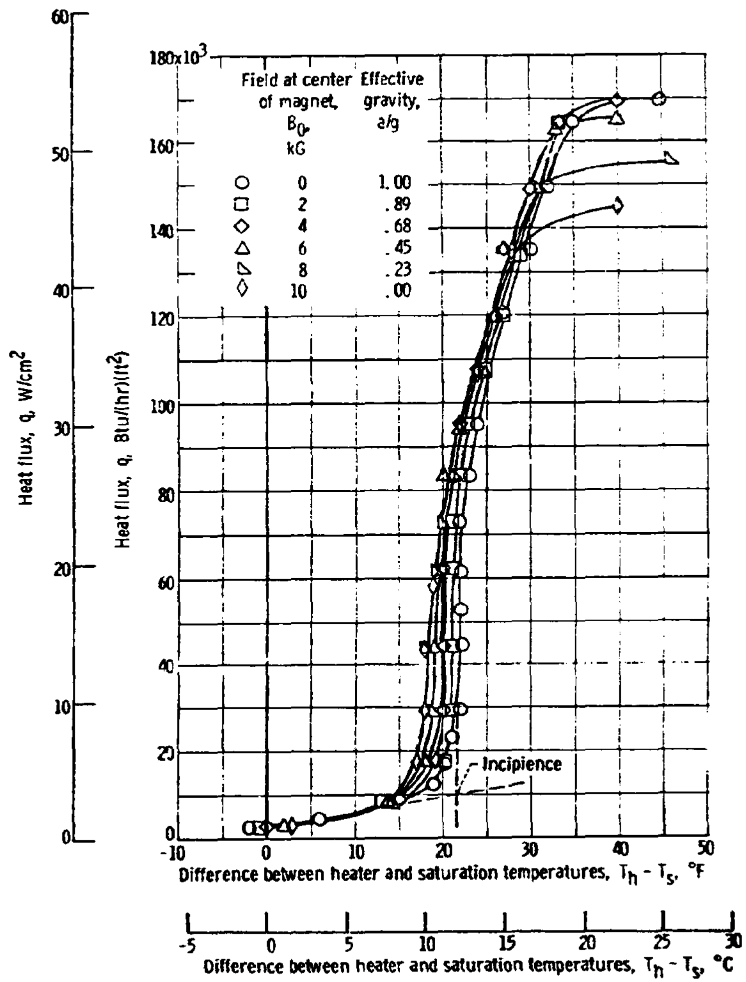


Figure 2.- Gravitational effects on pool-boiling heat transfer in magnetic iron oxide - normal heptane colloid. Saturation temperature, 205° F (96° C).

CRITICAL HEAT FLUX FOR SATURATED POOL BOILING FROM HORIZONTAL AND VERTICAL WIRES IN REDUCED GRAVITY
Siegel, R., Howell, J. R., NASA-LeRC TND-3123, Dec. 1965.

OBJECTIVE. - To provide critical heat flux data in reduced gravity, and specifically to examine the influence of test section orientation.

PERTINENT WORK PERFORMED. - Critical heat fluxes were obtained at a/g = 0.015 to 1.0 for water and ethyl alcohol boiling at saturation conditions from horizontal and vertical platinum wires (0.020 in. dia. by 1.5-in and 3-in long) and for 60% by weight water-sucrose solution from a vertical wire (1.5-in.). Drop time was approximately 1 sec. In addition to the test data obtained here, an interesting survey was made of data obtained previously (Fig. 1).

MAJOR RESULTS. -

1. In the range a/g = 0.015 to 1.0 it appears that the 1/4 power gravity dependence of the peak nucleate boiling heat flux can be used as a rough engineering guide (Fig. 2). However, definite deviations from this rule occur for some of the data; i.e. vertical wire in ethyl alcohol.

2. At a fixed gravity field, a vertical wire provided lower critical heat flux than a horizontal wire (Fig. 3). The fact that more bubble interference would be expected for a vertical surface because of the rising of bubbles along the surface may account for the lower critical fluxes. Wire length had no apparent effect, indicating that critical heat flux must be a local effect governed by accumulation of bubbles in the immediate vicinity of the wire.

3. The critical heat fluxes drop off more rapidly with gravity than those obtained during steady state experiments using a magnetic field (Papell, 1966).

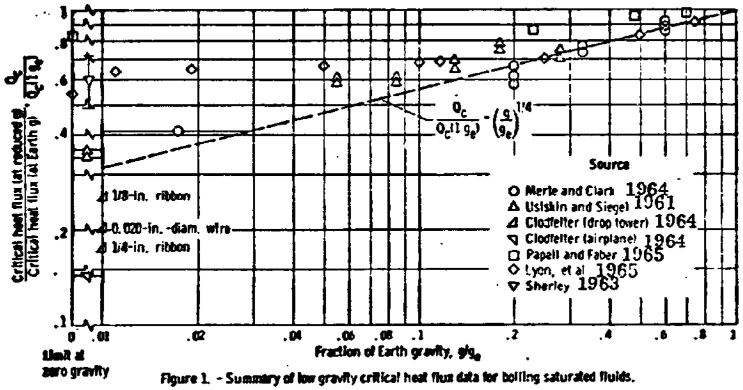
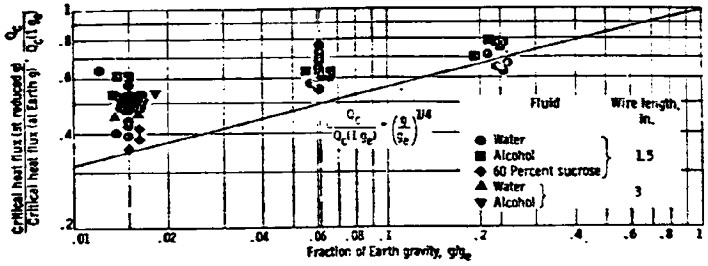
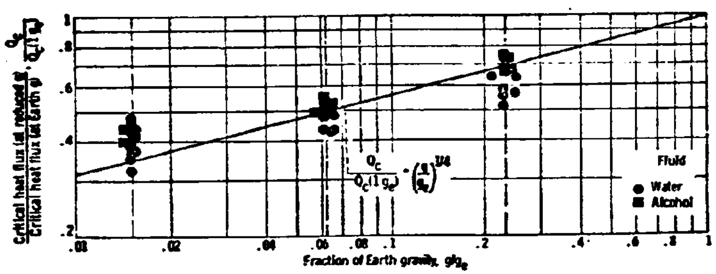


Figure 1. - Summary of low gravity critical heat flux data for boiling saturated fluids.



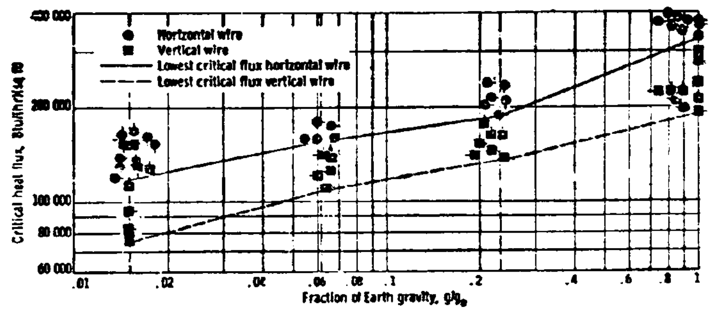
(a) Vertical wires. Wire lengths, 1.5 and 3 inches.

Figure 2. - Ratio of critical heat flux in reduced gravity to that in Earth gravity for heated vertical and horizontal wires in saturated water and ethyl alcohol and for vertical wire in sucrose solution. (Horizontal spread of data at each g/g_e does not represent a gravity variation but is for convenience in plotting the points. Only points where burnout occurred are shown.)



(b) Horizontal wires. Wire length, 1.5 inches.

Figure 2. - Concluded.



(a) Water.

Figure 3. - Comparison of critical heat flux values for horizontal and vertical orientations. Wire length, 1.5 inches. (Horizontal spread of data at each g/g_e does not represent a gravity variation but is for convenience in plotting the points. Only points where burnout occurred are shown.)

FORCES ACTING ON BUBBLES IN NUCLEATE BOILING UNDER NORMAL AND REDUCED GRAVITY CONDITIONS
Keshock, E. G., Siegel, R., NASA-LeRC, NASA TN D-2299, August 1964

OBJECTIVE. - To study the effects of reduced gravity on bubble growth, departure, and rise during saturated nucleate boiling.

PERTINENT WORK PERFORMED. - Tests were accomplished with aqueous-sucrose solutions ranging from 20- to 60-percent sucrose by weight in seven different gravity fields from 1.4 to 100% of Earth gravity. Results are compared with similar data from a previous study (Siegel and Keshock, 1963) using distilled water. In both cases a counterweighted 12.5 ft drop tower was used. The boiling surface was a highly polished 0.0005-in. nickel plating at the upper end of a 7/8-in. dia. Cu. rod. The study deals with bubbles originating from single nucleation sites spaced far enough apart so that the bubble columns do not interfere. A 16 mm, 3500 frames/sec camera was used. Equations for the various forces (inertia, buoyancy, surface tension and drag) acting on the bubbles were developed. Calculations were made of the magnitudes of these forces, throughout the growth period, from bubble dimensions determined from test.

MAJOR RESULTS. -

1. Viscous drag played only a minor role in bubble departure for all fluids tested.
2. A significant difference was noted in the way gravity affected the bubble departure diameters of water and aqueous-sucrose solutions (Fig. 1). This was explained by bubble force calculations which indicated that in the aqueous-sucrose case the initial bubble growth rate was large and the inertial force overcame the surface-tension force before buoyancy became significant. In the water case, slowly growing bubbles were generated and the surface tension force became large early in the growth, exceeding the inertia force before inertia could exert an effect. Inertia then decreased as the bubble growth continued, with only buoyancy remaining to lift the bubble from the surface. It must not be inferred that all bubbles growing in water would be of the gravity-dependent type observed here. If a particular nucleation site emitted rapidly growing bubbles, these would most likely be gravity independent.
3. After departure, the rise of a single bubble in 60% sucrose solution can be predicted reasonably well at low-g (Figure 2) with $C_D = 45/Re$.

NOMENCLATURE

$$X = X_o + \left(\frac{U_o - A}{B}\right)\left(1-e^{-Bt}\right) + At \quad \text{(Equ. 9)}$$

X = distance from surface to bubble center

U = velocity

$A = 4/3\, g\left(\frac{\rho_l - \rho_v}{a\,\mu_l}\right) D_r^2$

$B = \frac{12}{11}\ \frac{a}{\rho_l}\ \frac{\mu_l}{D_r^2}$

a = 45 and D_r = bubble dia. during rise

t = time from departure

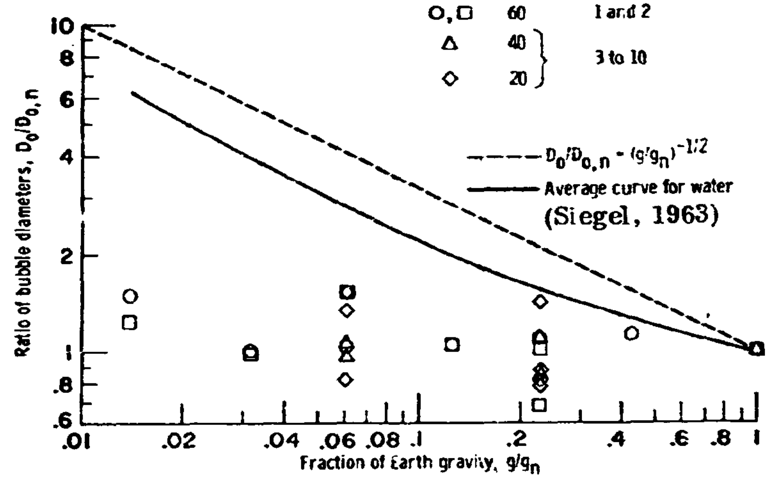
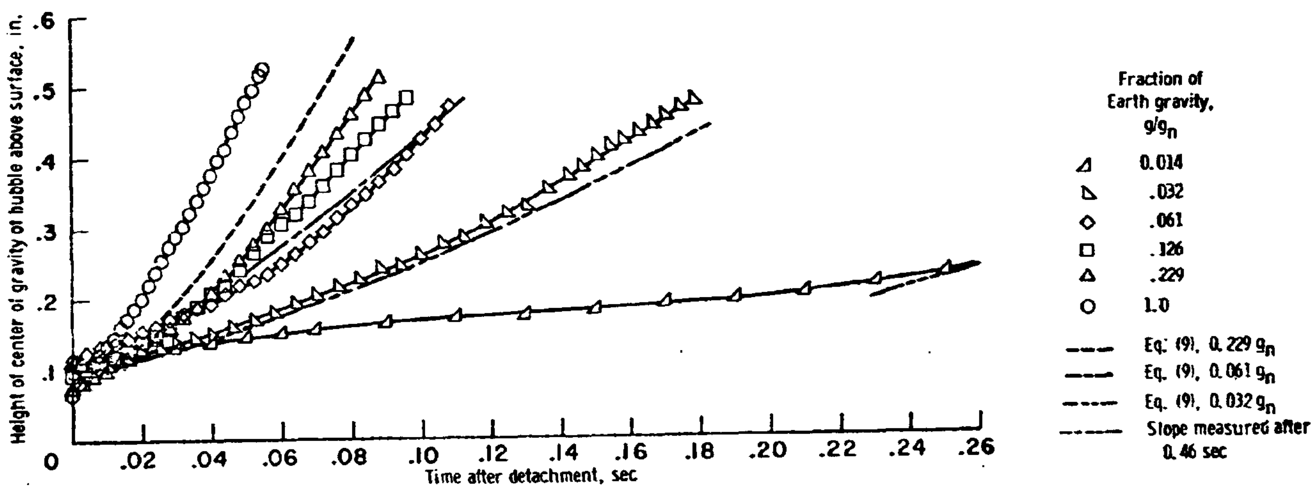


Figure 1.- Effect of reduced gravity on diameters of single undisturbed bubbles at instant of detachment from surface.



(b) Rise of center of gravity of bubbles for six gravity fields.

Figure 2. Motion of vapor bubbles after detachment at site 2 in 60-percent aqueous sucrose solution.

AN EXPERIMENTAL ASSESSMENT OF THE HEAT TRANSFER PROPERTIES OF PROPANE IN A NEAR-ZERO GRAVITY ENVIRONMENT
Rex, J., Knight, B.A.; R.A.F. TN No. Space 69, Aug. 1964.

OBJECTIVE. - To determine the heat transfer properties of propane in a near-zero gravity environment.

PERTINENT WORK PERFORMED. - An experiment was carried in a Skylark Rocket Head in a ballistic trajectory with $a/g < 4.5 \times 10^{-5}$ for 3 min. 40 sec. Rotation of the head was maintained at a minimum during the test by an air jet control set. Heat transfer was assessed by heating the tank wall and measuring wall temperature and pressure and temperature of the contents. The test tank was steel, spherical, 25.4 cm internal dia. (8600 cu.cm.) with a 2.7 mm wall. A heater covered the tank wall and was designed to supply a heat flux to the liquid of 0.14 cal/sec/sq. cm. The tank contained 1.36 kg of propane or 70% liquid at a saturation pressure of 110 psig. Pressure was allowed to rise during the test (Figure 1). Transducer No. 2 is considered to be correct, based on vapour pressure readings prior to heater actuation.

MAJOR RESULTS. -

1. Temperatures reached by the tank wall and the propane indicated that the wall was entirely covered with liquid at the test conditions.
2. Heat transfer rates at low-g were significantly lower than at 1-g (Figures 2 and 3). Low-g values ranged from 1/6 to 1/2 of the 1-g data at the same values of ΔT_{w-s} with a nominal value of 1/3 in the ΔT_{w-s} range of 2 to 2.5 °C. The magnitude of the temperature difference at low-g indicates that the heat transfer was in the nucleate boiling region.

COMMENTS. - Since the tank pressure increased with time and the Figure 3 boiling data was from the literature and was not the same exact surface as the orbital test, there is some question as to the value of a quantitative comparison between the low-g and 1-g data. however, the work presented here is significant in that a definite trend to reduced heat transfer at low-g seemed to exist.

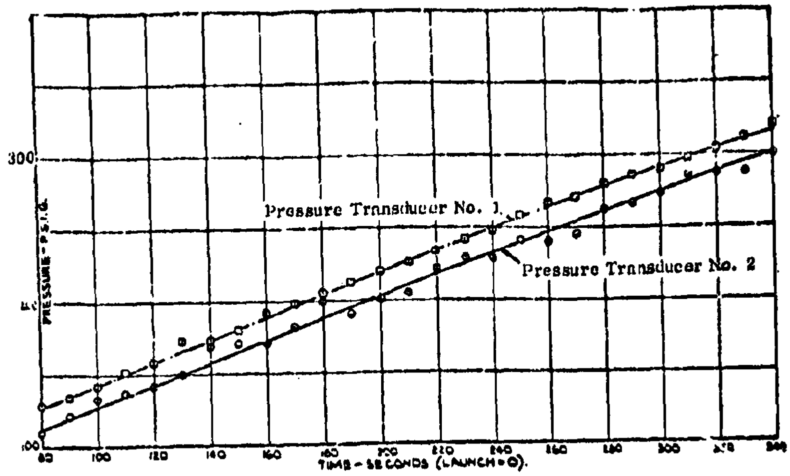


Figure 1. Pressure Insidr Tank

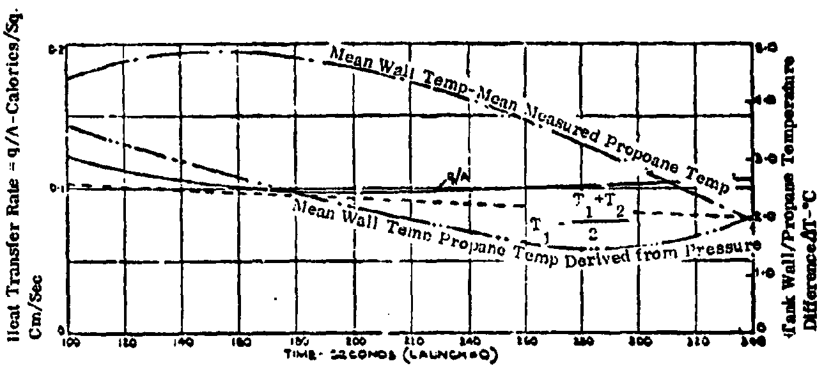


Figure 2. Heat Transfer Rate & Tank Wall/Propane Temperature Difference

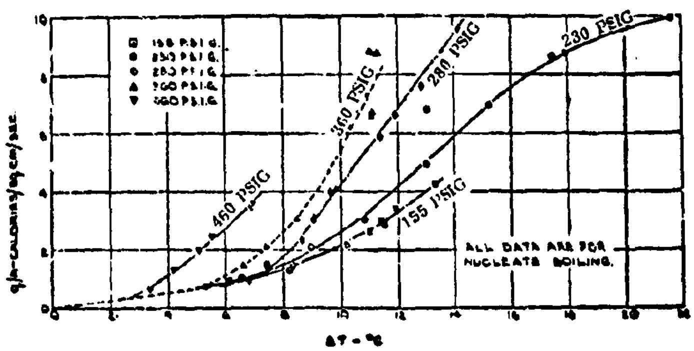


Figure 3. Boiling Heat Transfer to 99% Pure Liquid Propane at 1g.

LOW-GRAVITY POOL-BOILING HEAT TRANSFER
Clodfelter, R. G., APL-TDR-64-19, March 1964

OBJECTIVE. - To determine the magnitude of changes in nucleate boiling with a reduction in gravity, with particular attention to the threshold of nucleate boiling and the critical heat flux.

PERTINENT WORK PERFORMED. - Low-g (a/g = 0.01 to 0.04), testing was accomplished in a 1.8 sec. drop tower with saturated water at 1 atm. using a 0.020-in. diameter horizontal platinum wire and 1/8-in. and 1/4-in. horizontal platinum ribbons. In addition to heat flux and temperature measurements a 16 mm, 200 frames/sec camera was used. The specimen absolute temperature was accurate to only ±10°F, however, changes in temperature were much more accurate and were used to measure the effects of gravity on boiling phenomenon. Some data from KC-135 tests (a/g < 0.01) with water and a 0.02-in platinum wire are also presented.

MAJOR RESULTS. -

1. At reduced "g", the average bubble diameter at detachment was increased over that at 1-g (Figure 1).
2. No change in the threshold of nucleate boiling could be observed at low-g due to the slow-response time of the experiment.
3. In the nucleate boiling region the wall temperature decreased slightly at low-g, indicating slightly better heat transfer than at 1-g. A bubble force balance made, agrees with the nucleate boiling insensitivity to gravity since dynamic forces were calculated to be prominent in both cases (Table 1, where N = a/g).
4. Variation of peak heat flux with acceleration to the 1/4 power appears to be the minimum change (Table 2) and it is postulated that the time at reduced "g" has an effect on the peak heat flux, i.e. increased time will lower the peak heat flux. The KC-135 tests (Table 3) gives some support to this statement.

TABLE 1

COMPARISON OF BUBBLE FORCES AT ONE GRAVITY AND LOW GRAVITY

Test Conditions	N_{FR} $\frac{\text{dynamic}}{\text{buoyant}}$	N_{BO} $\frac{\text{buoyant}}{\text{capillary}}$	$N_{FR} \times N_{BO}$ $\frac{\text{dynamic}}{\text{capillary}}$
N = 1 (R = 0.05 in.)	34.9	562	19,600
N = 0.01 (R = 0.1 in.)	437	22.5	9,840

TABLE 2

ONE GRAVITY AND LOW GRAVITY PEAK HEAT FLUX

	$(q/A)_{max.}$ N = 1 BTU/HR-FT²	$(q/A)_{max.}$ N = 0.01 BTU/HR-FT²		$\frac{(q/A)_{max.}\ (N = 0.01)}{(q/A)_{max.}\ (N = 1)}$
Rohsenow	4.32×10^5	1.36×10^5		0.316
Zuber	4.79×10^5	1.52×10^5		0.316
		(1)	(2)	
0.020" PT Wire	3.0×10^5	6.09×10^4	6.88×10^4	0.203 and 0.229
1/8" PT Ribbon	4.8×10^5	1.22×10^5	9.92×10^4	0.254 and 0.207
1/4" PT Ribbon	3.0×10^5	5.27×10^4	1.46×10^5	0.176 and 0.487

(1) Lowest heat flux at which burnout occurred
(2) Highest heat flux at which burnout did not occur

TABLE 3
PEAK HEAT FLUX FOR KC 135 TESTS

q/A (BTU/HR-FT²)	TIME TO BURNOUT (Sec.)	TOTAL FLOAT TIME (Sec.)
5.2×10^4	2.5	3.5
4.9×10^4	2.0	7.0
4.4×10^4	3.0	5.0

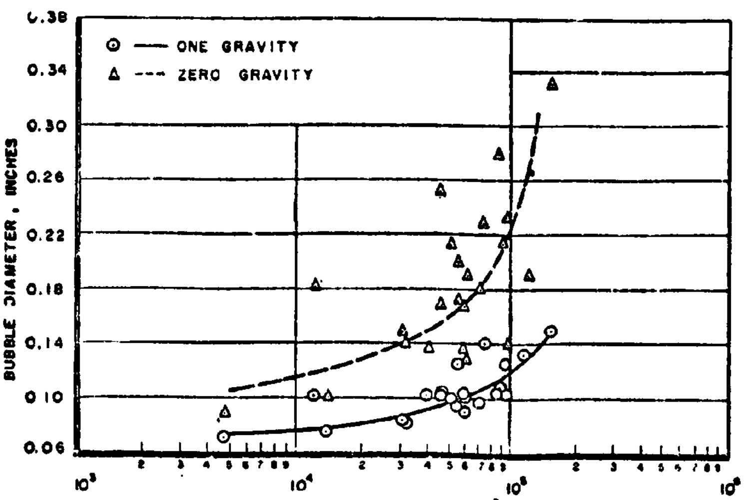


Figure 1. Influence of Acceleration and Heat Flux on Bubble Diameter (0.020-Inch Platinum Wire)

PERFORMANCE OF BOILING AND CONDENSING EQUIPMENT UNDER SIMULATED OUTER SPACE CONDITIONS
Feldmanis, C.J., WPAFB, ASD-TDR-63-862, Nov. 1963

OBJECTIVE. - To evaluate performance of boiling and condensing equipment, including radiators, under simulated outer space conditions.

PERTINENT WORK PERFORMED. - Various transparent evaporators and condensers were tested in a 1-g and 0-g (KC-135) environment and motion pictures taken on vortex and straight tube evaporators, and vortex and tapered tube condensers. Performance of the straight tube condenser was observed in a one gravity field only. The test fluid was water and all test results are based on visual observations using a high speed movie camera. No attempt was made to experimentally determine heat transfer coefficients. Analyses were, however, performed to estimate heat transfer coefficients, pressure drop and vortexing forces to be expected. The vortex evaporator consisted of 9 mm O.D. Pyrex tubing equipped with a 0.010 in. stainless steel twisted tape. The tape twist ratio, defined as internal diameters per 180-degree twist, was 8. The Pyrex tube test section was about 3 ft long. The electric heater, consisting of a bare nichrome resistance wire was wrapped around the tube. Heat input in the test section was controlled by a variac. The water, before it entered the test section, was preheated to a desired value and actual boiling performed in the test section. It was possible to evaporate at the rate of approximately 2 lbs of water per hour. The vortex condenser consisted of a 5/8 in. I.D. Pyrex tubing with 3/8 in. O.D. copper tubing mounted inside. In the space between the two tubes a coiled aluminum wire was installed. The mean twist ratio was 2 and is defined here as the number of mean diameters $(D_o + D_i)/2$ per 180-degree twist.

MAJOR RESULTS. -

1. According to movie films taken at high speed, the boiling and condensing processes in the vortex evaporator and condenser were essentially the same in zero gravity as they were under normal gravity.

2. These experiments also showed that boiling is possible in a small straight tube under zero gravity environment. There is probably a critical tube diameter at which liquid slugs completely fill the tube. This still has to be investigated.

3. It can be concluded that centrifugal, pressure, viscous, adhesive, and cohesive forces can be utilized for phase separation in a zero gravity environment. It also can be concluded that, in forced convection where the pressure and shear forces are an order of magnitude higher than gravity forces, the heat transfer equations derived for a normal gravity field should be applicable to the zero gravity environment.

COMMENTS. - The data obtained was only sufficient to indicate qualitative conclusions and thus those presented above by the author should only be taken as such.

NUCLEATE BOILING HEAT-TRANSFER DATA FOR LIQUID HYDROGEN AT STANDARD AND ZERO GRAVITY, Sherley, J. E., GD/C, Advances in Cryogenic Engineering, Vol. 8, p. 495, August 1962

OBJECTIVE. - To obtain basic heat transfer data on nucleate boiling of LH_2 in a zero-g environment.

PERTINENT WORK PERFORMED. - Heat flux as a function of ΔT was obtained at 1-g and "zero-g" in a 1-sec drop tower and KC-135 aircraft (15 sec. max.). The test specimen was a horizontal up 3 × 1 × 0.04-in. glass slide coated with a lead film having an effective heat transfer area of 2 in^2. Temperature differences of 0.1°K could be detected and recorded. The test container was a 4-liter glass dewar, and a 400 frames/sec camera was included.

MAJOR RESULTS. -

1. Visual observation of boiling for 250 to 7,000 Btu/hr-ft^2 showed that bubbles formed at the heated surface coalesced and, in every case, surface tension forces were sufficient to rewet the surface behind the bubble.
2. Recorded data indicated that zero-g nucleate boiling heat transfer is approximately the same as one-g (Figs. 1, 2, 3). Figure 2 contains data points from both the 1-sec. drop tower and the KC-135 flights.

COMMENTS. - Actual g-levels or disturbances at which the "zero-g" data were obtained are missing from the literature, which detracts somewhat from the quantitative value of this work.

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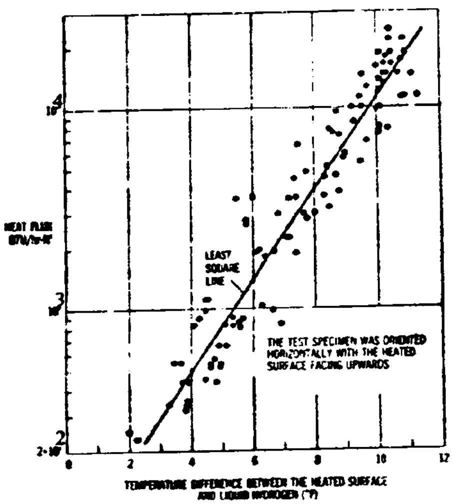

Fig. 1. Heat flux *vs.* temperature difference between a heated surface and liquid hydrogen at one-*g* in the nucleate boiling region.

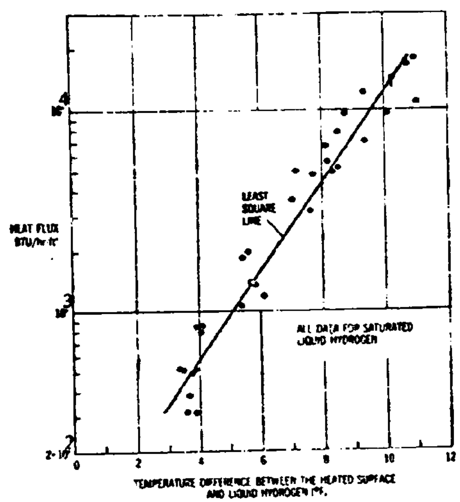

Fig. 2. Heat flux *vs.* temperature difference between a heated surface and liquid hydrogen at zero-*g* in the nucleate boiling region.

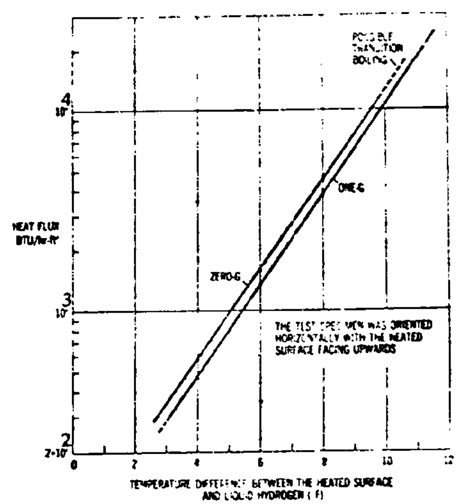

Fig. 3. Comparison of heat flux *vs.* temperature difference between a heated surface and liquid hydrogen at zero-*g* and one-*g* in the nucleate boiling region.

11.0 CONDENSATION HEAT TRANSFER

Covering dropwise and film condensation at liquid and solid surfaces.

PHOTOGRAPHIC STUDY OF CONDENSING MERCURY FLOW IN 0- AND 1-G ENVIRONMENTS

Namkoong, D., et al, NASA-LeRC, TN D-4023, June 1967.

OBJECTIVE. - To determine the effect of weightlessness on the flow phenomenon of nonwetting (dropwise) condensing mercury flow.

PERTINENT WORK PERFORMED. High-speed (4,700 to 8,000 frames/sec) motion pictures were taken of mercury vapor condensing in constant diameter glass tubes (0.27, 0.40, and 0.49-in. diameter) at 1-g and low-g ($a/g < 0.1$). Condensing lengths were fixed at 60 and 68-in. The tubes were horizontally oriented. An AJ-2 Navy bomber with 12 to 14 sec. of low-g time was used. For most tests the vapor inlet quality was 90 ±5% and the receiver pressure 14 to 15 psia. Flow rates were 0.03 to 0.05 lb/sec with inlet vapor velocities of 115 to 378 ft/sec.

MAJOR RESULTS. -

1. Flow distribution in the 0.27-in. diameter tube at low-g was similar to that at 1-g, however, in the 0.40 and 0.49-in. diameter tubes, flow at 1-g was characterized by a concentration of drops along the tube bottom and a nearly horizontal interface, while at low-g the drops on the wall were distributed uniformly and the interface was essentially vertical (Figure 1).

2. The interface in a horizontally oriented tube is more stable at low-g than at 1-g.

3. In general, gravity level had negligible effect on the velocity of the drops on the wall (including those on the tube bottom).

4. The ratio of the observed average vapor-borne drop velocity to the local vapor velocity varied from 0.3 at the inlet to 1.0 at approximately 3/4 of the condensing length.

5. Vapor pockets were observed within the liquid leg at both 1-g and low-g and the time interval between pocket formation and collapse was about 0.05 sec at 1-g and 0.04 sec. at low-g.

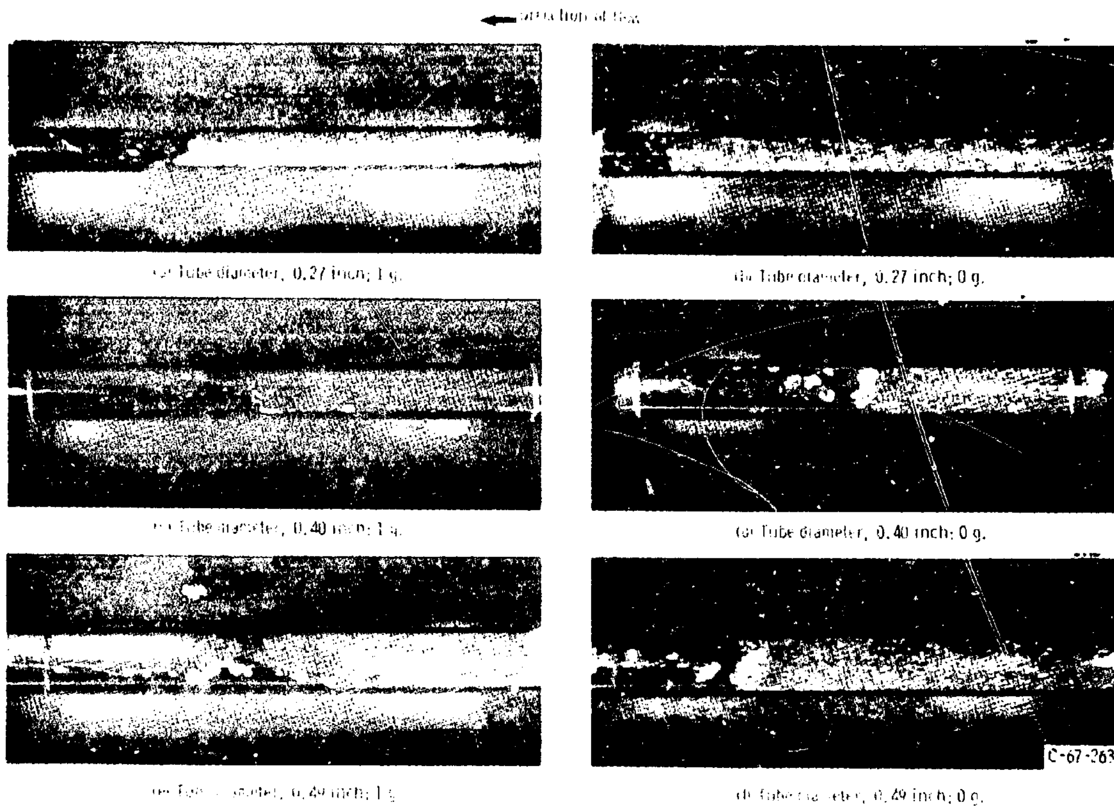

Figure 1. Condensing Mercury Vapor Flow at Interface. Flow Rate, 0.052 Pound Per Second

EFFECTS OF REDUCED GRAVITY ON HEAT TRANSFER
Siegel, R., NASA-LeRC, Advances in Heat Transfer, Vol. 4, 1967

OBJECTIVE. - To review and summarize low gravity heat transfer information up to about November 1966.

PERTINENT WORK PERFORMED. - Data and/or discussions are presented on free convection, pool and forced flow boiling, condensation in stationary vapor and in forced flow, and combustion. The major result of the study is the handy consolidation of data and the conclusions which resulted, highlights of which are presented below.

MAJOR RESULTS. -

1. In the area of free convection there is a lack of data. A difficulty is that such boundary layers have a relatively slow time response so that tests cannot be conducted with convenient facilities such as drop towers or airplane flights.

2. Both analysis and experiment indicate that nucleate pool boiling heat flux is insensitive to gravity, while the peak nucleate and minimum film boiling heat fluxes were found to vary reasonably well as $g^{1/4}$. In laminar film boiling the heat transfer coefficient depends on $g^{1/4}$, while for a turbulent film the exponent may be 2/5 to 1/2.

3. Photographic studies of reduced-g pool boiling for saturated conditions show that; (a) vapor tends to linger near the heater surface and collect new bubbles being formed, thus helping their removal, (b) bubble growth rate is insensitive to gravity, and (c) departure diameters of slowly growing single bubbles depend on $g^{-1/2}$ (buoyancy causes departure), while for rapidly growing bubbles departure size is relatively insensitive to gravity (inertia causes departure).

4. For reduced gravity forced-convection boiling, little experimental information is available, however, isothermal two-phase flow visualization tests with air-water mixtures indicate that cross-sectional bubble distribution in a vertical tube at earth gravity is very similar to that in zero gravity.

5. For condensation without forced flow, no experimental results were found in the literature. For forced flow condensation in tubes, low gravity tests have been performed with nonwetting mercury, with the result that (a) pressure drop was insensitive to gravity for the conditions tested, (b) stability of the vapor-liquid interface was indicated from the Taylor type of instability theory, and (c) low gravity conditions aid in the trapping of noncondensable gas.

6. The experimental evidence to substantiate the above conclusions is mostly from tests of short duration. Additional experimental work is needed with longer testing times. This is especially true at very low gravities; for example, it has not been conclusively demonstrated that the critical heat flux does go to zero as exactly zero gravity is approached.

CONDENSATION PRESSURE DROP OF NONWETTING MERCURY IN A UNIFORMLY TAPERED TUBE IN 1-g AND ZERO-GRAVITY ENVIRONMENTS
Albers, J.A., et al, NASA-LeRC, TN D-3185, January 1966

OBJECTIVE. - To determine the effect of weightlessness on the pressure loss of nonwetting (dropwise) condensing flow of mercury in a tapered tube.

PERTINENT WORK PERFORMED. Local and overall pressure drop data were obtained for a uniformly tapered (0.4-in. I.D. inlet, 0.15-in, I.D. outlet by 84-in long) stainless-steel horizontal tube for various flow rates (0.025 to 0.05 lb/sec), pressures (13 to 20 psia), and condensing lengths (37 to 71-in.). The inlet vapor temperature corresponded to approximately 300°F superheat. Testing was accomplished at 1-g and low-g ($a/g < 0.1$) using a Navy bomber (AJ-2) providing 12 to 14 sec of low-g time. The overall static pressure difference from inlet to the liquid interface varied from a pressure rise of 0.9 psi to a pressure drop of 0.1 psi.

MAJOR RESULTS. -

1. The gravity effect was negligible for all flow rates investigated. This is illustrated in Figures 1 and 2.
2. Better agreement of the pressure drop data was found with the fog-flow theory of Koestel (1964, NASA TN D-2514) than with the Lockhart-Martinelli 1949 correlation.

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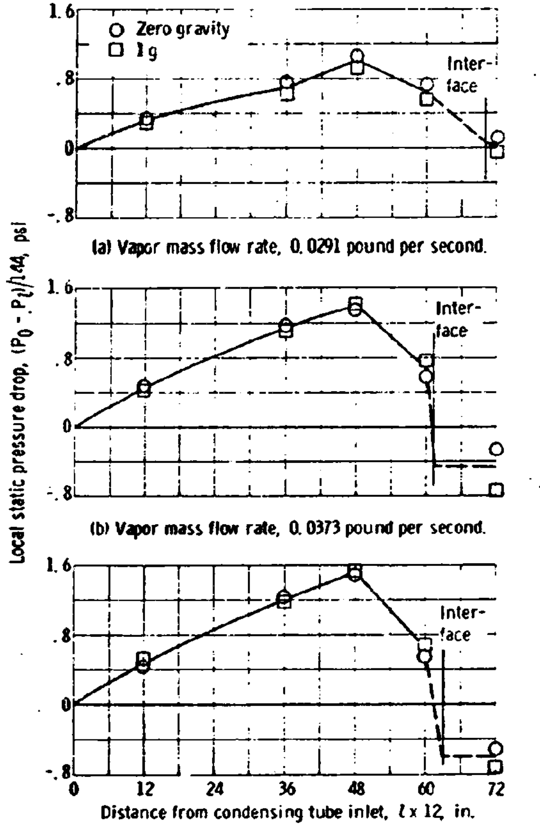
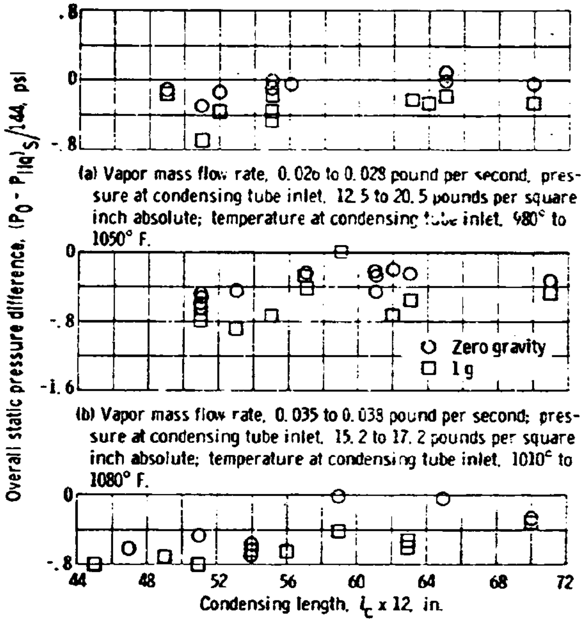


(a) Vapor mass flow rate, 0.0291 pound per second.

(b) Vapor mass flow rate, 0.0373 pound per second.

(c) Vapor mass flow rate, 0.0488 pound per second.

Figure 1. Typical Distributions of Local Static Pressure Drop for 1-g and Zero-Gravity Environments



(a) Vapor mass flow rate, 0.026 to 0.028 pound per second, pressure at condensing tube inlet, 12.5 to 20.5 pounds per square inch absolute; temperature at condensing tube inlet, 980° to 1050° F.

(b) Vapor mass flow rate, 0.035 to 0.038 pound per second; pressure at condensing tube inlet, 15.2 to 17.2 pounds per square inch absolute; temperature at condensing tube inlet, 1010° to 1080° F.

(c) Vapor mass flow rate 0.044 to 0.048 pound per second; pressure at condensing tube inlet, 14.5 to 18.5 pounds per square inch absolute, temperature at condensing tube inlet, 1000° to 1100° F.

Figure 2. Effect of Gravity on Overall Static Pressure Difference

EXPERIMENTAL PRESSURE-DROP INVESTIGATION OF NONWETTING, CONDENSING FLOW OF MERCURY VAPOR IN A CONSTANT-DIAMETER TUBE IN 1-G AND ZERO-GRAVITY ENVIRONMENTS

Albers, J. A., Macosko, R. P., NASA-LeRC, TN D-2838, June 1965.

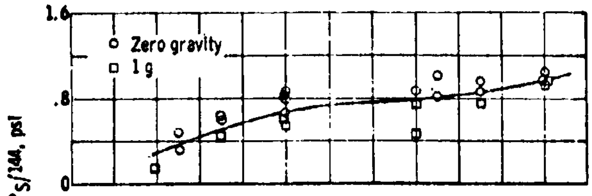
OBJECTIVE. - To determine the effect of weightlessness on the pressure loss of nonwetting (dropwise) condensing flow of mercury.

PERTINENT WORK PERFORMED. - Local and overall pressure-drop data were obtained for a horizontal, constant diameter (0.311 in. I.D.), stainless-steel (type 304) tube 87-in long. Flow rates were 0.027 to 0.047 lb/sec and the condenser outlet pressure was varied from approximately 15 to 20 psia for inlet vapor temperatures corresponding to approximately 300°F of superheat. The vapor inlet quality was always greater than 90%. A uniform and constant cooling rate was provided by GN_2. A Navy bomber (AJ-2) was used, resulting in 12 to 14 sec. of low-g ($a/g < 0.1$). About 4 to 5 sec. of the low-g time was required to damp out pressure oscillations induced by the aircraft pullup maneuver.

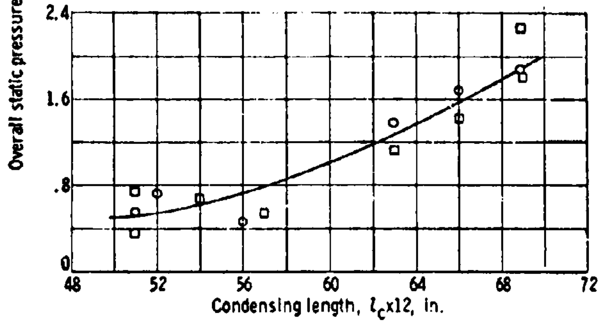
MAJOR RESULTS. -

1. The measured overall static and total pressure drop at flow rates of 0.028 and 0.046 lb/sec (where sufficiently comparable data were obtained) indicated little difference between 1-g and low-g pressure losses . This is illustrated in Figures 1 and 2.

2. The Lockhart-Martinelli, 1949, correlation predicts two-phase pressure drop only within ±70% for the high-velocity high quality region. Generally, the data trend correlates with the fog-flow theory of Koestel (1964, NASA TN D-2514). As expected, the data spread is least in the high-velocity (high-Weber-number) region of the tube that approaches the fog-flow regime.

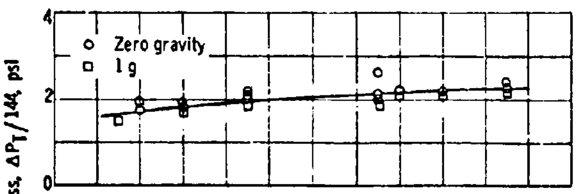


(a) Vapor mass flow rate, 0.027 to 0.029 pound per second; pressure at condensing tube inlet, 17 to 19 pounds per square inch absolute; temperature at condensing tube inlet, 1000° to 1050° F.

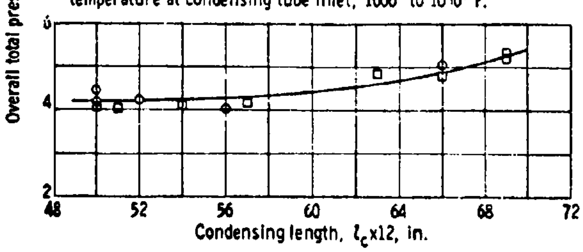


(b) Vapor mass flow rate, 0.045 to 0.047 pound per second; pressure at condensing tube inlet, 18.4 to 21.4 pounds per square inch absolute; temperature at condensing tube inlet, 980° to 1100° F.

Figure 1.- Effect of gravity on overall static pressure drop.



(a) Vapor mass flow rate, 0.027 to 0.029 pound per second; pressure at condensing tube inlet, 17 to 19 pounds per square inch absolute; temperature at condensing tube inlet, 1000° to 1050° F.



(b) Vapor mass flow rate, 0.045 to 0.047 pound per second; pressure at condensing tube inlet, 18.4 to 21.4 pounds per square inch absolute; temperature at condensing tube inlet, 980° to 1100° F.

Figure 2. Effect of gravity on overall total pressure drop.

PERFORMANCE OF BOILING AND CONDENSING EQUIPMENT UNDER SIMULATED OUTER SPACE CONDITIONS
Feldmanis, C.J., WPAFB, ASD-TDR-63-862, Nov. 1963

OBJECTIVE. - To evaluate performance of boiling and condensing equipment, including radiators, under simulated outer space conditions.

PERTINENT WORK PERFORMED. - Various transparent evaporators and condensers were tested in a 1-g and 0-g (KC-135) environment and motion pictures taken on vortex and straight tube evaporators, and vortex and tapered tube condensers. Performance of the straight tube condenser was observed in a one gravity field only. The test fluid was water and all test results are based on visual observations using a high speed movie camera. No attempt was made to experimentally determine heat transfer coefficients. Analyses were, however, performed to estimate heat transfer coefficients, pressure drop and vortexing forces to be expected. The vortex evaporator consisted of 9 mm O.D. Pyrex tubing equipped with a 0.010 in. stainless steel twisted tape. The tape twist ratio, defined as internal diameters per 180-degree twist, was 8. The Pyrex tube test section was about 3 ft long. The electric heater, consisting of a bare nichrome resistance wire was wrapped around the tube. Heat input in the test section was controlled by a variac. The water, before it entered the test section, was preheated to a desired value and actual boiling performed in the test section. It was possible to evaporate at the rate of approximately 2 lbs of water per hour. The vortex condenser consisted of 5/8' in. I.D. Pyrex tubing with 3/8 in. O.D. copper tubing mounted inside. In the space between the two tubes a coiled aluminum wire was installed. The mean twist ratio was 2 and is defined here as the number of mean diameters $(D_o + D_i)/2$ per 180-degree twist.

MAJOR RESULTS. -

1. According to movie films taken at high speed, the boiling and condensing processes in the vortex evaporator and condenser were essentially the same in zero gravity as they were under normal gravity.

2. These experiments also showed that boiling is possible in a small straight tube under zero gravity environment. There is probably a critical tube diameter at which liquid slugs completely fill the tube. This still has to be investigated.

3. It can be concluded that centrifugal, pressure, viscous, adhesive, and cohesive forces can be utilized for phase separation in a zero gravity environment. It also can be concluded that, in forced convection where the pressure and shear forces are an order of magnitude higher than gravity forces, the heat transfer equations derived for a normal gravity field should be applicable to the zero gravity environment.

COMMENTS. - The data obtained was only sufficient to indicate qualitative conclusions and thus those presented above by the author should only be taken as such.

12.0 VENTING EFFECTS

Covering bulk and surface vapor generation affecting liquid rise and vent liquid loss and fluid freezing and vehicle dynamics caused by tank venting or leakage.

ZERO-GRAVITY VENTING OF THREE REFRIGERANTS
Labus, T. L., et al, NASA-LeRC, TN D-7480,
January 1974

OBJECTIVE. - To predict the pressure response of saturated liquid-vapor systems undergoing a venting or depressurization process in zero gravity at low vent rates.

PERTINENT WORK PERFORMED. - Testing was accomplished with Refrigerants 11 (CCl_3F), C318 (C_4F_8), and 600 (C_4H_{10}, n-butane) using the NASA/LeRC 5-sec drop facility. The test containers were acrylic plastic cylindrical, having flat ends (0.06 m dia × 0.10 m long). The fluids were initially saturated. During the first 1.9 sec of drop no venting occurred and the liquid was allowed to achieve a hemispherical zero-g ($a/g < 10^{-5}$) interface configuration. The fluids used had essentially 0° static contact angle. Following this, for approximately 3 sec, venting from the top of the tank was accomplished.

The test data were compared to two different analytical models. The first was a simple adiabatic decompression model assuming an ideal gas ullage with fixed volume and no mass transfer between the liquid and vapor. The second model, developed as part of the current program, accounts for interfacial mass transfer, based on an infinitely planar (flat surface) conduction analysis from Yang, et al (1965), and Thomas and Morse (1962). Other assumptions were: (1) only vapor vented, (2) hemispherical interface area, (3) vapor and liquid are two separate and fixed control volumes, (4) no bulk boiling, (5) no external heating, (6) constant liquid temperature, (7) interface and ullage temperatures at saturation corresponding to ullage pressure, and (8) vent flow is choked.

Test parameters and results, for all tests where bulk boiling did not occur, are presented in Table 1.

MAJOR RESULTS. -

1. As shown in Table 1 the adiabatic decompression model predicted pressure reductions on the order of two times those from test. Use of the interfacial mass transfer model resulted in approximately a 30% improvement in prediction over that of the simple adiabatic model.

2. It is the authors' belief that the container walls act as a heat source and cause additional liquid evaporation, which is not accounted for in the models, which reduces the experimental pressure decay.

3. Where bulk boiling occurs, the current analysis would not apply. In the present series of tests with RC318 at a vent rate of 1.0 ullage volumes per sec, extensive bulk boiling occurred and the liquid-vapor interface was pushed toward the vent due to the growth of two rather large vapor bubbles.

TABLE I. - SUMMARY OF PARAMETERS

Refrigerant	Test	Initial filling, percent liquid	Initial vapor volume, m^3	Nozzle diameter, m	Discharge coefficient, C_D	Reduced flow rate, Q/V_{v_1}, ullage/sec	Initial ullage pressure, P_1, N/m^2	Initial ullage temperature, T_1, K	Final experimental ullage pressure, N/m^2	Final analytical ullage pressure, N/m^2	Final adiabatic ullage pressure, N/m^2	Dimensionless experimental pressure drop, $\Delta P_{exp}/P_1$	Dimensionless analytical pressure drop, ΔP_{anal} P_1	Dimensionless adiabatic pressure drop, ΔP_{adia} P_1
11	1	32	1.93×10^{-4}	0.406×10^{-3}	0.64	0.035	8.96×10^{4}	294.3	8.62×10^{4}	8.16×10^{4}	7.97×10^{4}	0.04	0.09	0.11
	2	29	2.01	.889	.69	.17	8.79	294.7	7.03	5.63	4.94	.20	.36	.44
	3	33	1.90	1.07	.86	.33	9.10	293.7	6.07	4.07	3.01	.33	.55	.67
	4	32	1.93	1.32	.875	.51	9.72	296.5	5.38	2.94	1.63	.45	.70	.83
	5	32	1.93	1.93	.77	1.12	10.1	295.4	4.14	1.31	.15	.59	.88	.99
C318	6	33	1.90×10^{-4}	0.406×10^{-3}	0.64	0.030	27.9×10^{4}	295.9	26.9×10^{4}	25.5×10^{4}	25.25×10^{4}	0.04	0.09	0.10
	7	34	1.87	.889	.69	.16	30.3	298.7	22.1	19.1	17.8	.27	.37	.41
	8	36	1.81	.889	.69	.165	29.0	297.3	21.0	18.0	16.7	.28	.38	.42
	9	34	1.87	1.07	.86	.29	30.0	297.3	17.2	13.1	11.4	.43	.56	.62
	10	35	1.84	1.32	.875	.455	29.0	296.3	13.0	8.10	6.35	.55	.72	.78
600	11	32	1.93×10^{-4}	0.330×10^{-3}	0.77	0.041	23.3×10^{4}	297.0	21.7×10^{4}	20.8×10^{4}	20.3×10^{4}	0.07	0.11	0.13
	12	35	1.84	.711	.81	.21	22.8	294.7	16.5	12.8	11.3	.28	.44	.50
	13	34	1.87	.889	.69	.27	21.0	293.7	14.8	10.0	8.50	.30	.52	.60
	14	35	1.84	.889	.69	.28	24.0	296.7	16.4	11.2	9.45	.32	.53	.61
	15	34	1.87	1.07	.86	.49	22.8	296.8	10.7	6.30	4.50	.53	.72	.80
	16	34	1.87	1.93	.77	1.31	23.6	297.0	5.65	1.52	.63	.76	.94	.97

LOW-GRAVITY VENTING OF REFRIGERANT 11
Labus, T. L., et al, NASA-LeRC TM X-2479,
February 1972

OBJECTIVE. - To experimentally examine the resulting behavior when an initially saturated liquid is vented under reduced gravity conditions.

PERTINENT WORK PERFORMED. - Low-g testing was accomplished using Refrigerant 11 in an acrylic plastic cylindrical container with a flat bottom and a hemispherical top (15 cm dia. by 30.1 cm overall length). The LeRC 5-sec. drop facility was used with Bond numbers of 0, 9, and 63, where; Bo = a $R^2 \rho_l / \sigma$. The liquid exhibited a near zero-degree contact angle on the container surface and was initially saturated at the start of the test. One second was allowed for the formation of a low-g interface, following which, venting from the top was allowed to occur for approximately 3 seconds. Liquid-vapor interface and bulk liquid temperatures, tank pressures and vent rates were recorded during the drop,along with high-speed motion pictures.

The basic test parameters and the estimated quantities of bulk vapor generation are presented in Table 1.

MAJOR RESULTS. -

1. During venting, significant vaporization occurred both in the liquid bulk and at the liquid-vapor interface and the temperature of the liquid near the interface decreased while the bulk liquid temperature remained constant.

2. Bulk boiling did not start until some time after vent initiation. When bulk boiling did occur, the generated vapor tended to remain below the surface, thereby moving the interface towards the vent.

3. As shown in Table 1, increased vent rate, reduced ullage volumes and increased Bond number resulted in the bulk boiling occurring sooner with increased generation of bulk vapor. Increased vapor generation with increased vent rate and lower ullage volumes can be explained by increased rates of pressure decay, while the Bond number effect appears to be more complex; i.e., an increasing Bond number reduces the exposed area for surface evaporation, thus increasing the chance of bulk boiling, while convection heat transfer is increased with the potential for an opposite effect (increased surface heat transfer and reduced bulk boiling).

TABLE I. - SUMMARY OF TEST PARAMETERS

Test number	Percentage vapor by volume	System acceleration, cm/sec^2	Bond number	Initial mass vapor, g	Average mass flow rate, g/sec	Percentage ullage volume per second	Total mass vented, g	Estimated bulk vapor generation	
								Volume, cc	Mass, g (a)
1	30	1.96	9	7.7	0.53	6.9	1.58	16	0.077
2	↓	0	0	7.7	.53	6.9	1.60	0	0
3	↓	1.96	9	7.2	.20	2.5	.60	1	.005
4	↓	1.96	9	7.2	.04	.6	.13	3	.014
5	↓	13.7	63	7.1	.47	6.6	1.40	11	.048
6	70	1.96	9	16.8	.52	3.9	1.56	3	.012
7	30	1.96	9	6.7	.77	11.5	2.31	47	.188

[a]Based on average density during venting.

VAPOR VOLUME ENTRAINED IN THE BOUNDARY LAYER DUE TO BOILING ON A VERTICAL PLATE IN A LOW GRAVITY FIELD

Navickas, J., Melton, H.R., MACDAC, ASME Paper No. 70-HT-SpT-17, NAS7-101, June 1970

OBJECTIVE. - To develop a method of predicting the volume of vapor entrained in the bulk of a liquid as a result of boundary layer boiling in a low-g field.

PERTINENT WORK PERFORMED. - A basic analytical model was developed assuming boundary layer boiling, as illustrated in Figure 1. Also shown in Figure 1 are significant elements of the Saturn V/S-IVB-501 and -502 vehicles which provided some orbital test data for comparison with the analytical model. The model presented here assumes zero liquid velocity and no convective heat transfer. Also, although the vapor exists in the form of discrete bubbles, this analysis treats it as an effective thickness, h_x, from the wall with the gravity vector acting parallel to the wall. The basic equation obtained from a mass balance on the two-phase boundary layer is: $q/h_{fg} - \rho_v u_v \frac{\partial h_x}{\partial x} - \rho_v \frac{\partial u_v}{\partial x} h_x = \rho_v \frac{\partial h_x}{\partial t}$ where x is the length along the boundary layer. Basically, three different solutions to this equation were obtained: (1) constant velocity with $\partial u_v/\partial x = 0$, (2) steady flow with $\partial h_x/\partial t = 0$, and (3) both steady flow and constant velocity. For the latter case a simple solution for the total entrained vapor volume is obtained as: $V_v = CH^2 q/2\, h_{fg}\, \rho_v\, u_v$ where C is the tank circumference, H the total boundary layer length and u_v the bubble velocity taken from Harmathy (1960) to be equal to $1.53 \left(\frac{g\sigma}{\rho_\ell}\right)^{1/4}$. In the steady flow case, equations for the vapor thickness h_x were obtained as a function of a bubble coalescence factor (K) and the bubble flow regimes. The final solutions for different Weber numbers, based on bubble diameter, are presented in Table 1.

MAJOR RESULTS. - Vapor entrainment was calculated for the Saturn V/S-IVB-502 orbital coast conditions; (1) between 8,000 and 10,000 sec of flight using the steady flow constant velocity model, and (2) at 9,000 sec using the equations from Table 1 integrated over the total boundary layer length for values of K = 1 and K = 2. Results are compared with the flight data in Figure 2, showing that both the equation and point calculation with K = 2 give reasonable approximations.

COMMENTS. - It is not completely clear in the text as to what equations are used for which calculations.

Table 1. Effective Vapor Film Thickness

Range	Fluid Thickness
We < 3.85	$h_x = \left(\frac{9}{2}\ \frac{q\mu}{h_{fg}\rho_v\rho_\ell}\right)^{1/3}\left(\frac{\pi}{3K^2}\right)^{2/3} x^{1/3}$
We = 3.85	$h_x = \left(\frac{q}{h_{fg}\rho_v}\right)^{2}\left(\frac{6\rho_\ell K^2}{3.85 g\sigma\pi}\right) x^{2}$
We>3.85 (C_D = 2.6)	$h_x = \left(\frac{0.98 q}{h_{fg}\rho_v}\right)^{2/3}\left(\frac{\pi}{3gK^2}\right)^{1/3} x^{2/3}$

C_D = bubble drag coefficient

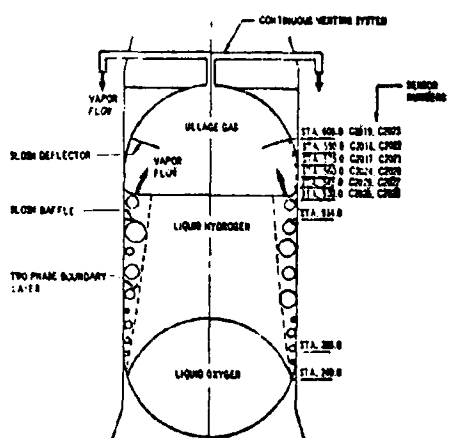


Fig. 1. Schematic diagram of the Saturn S-IVB stage continuous venting system and sidewall instrumentation

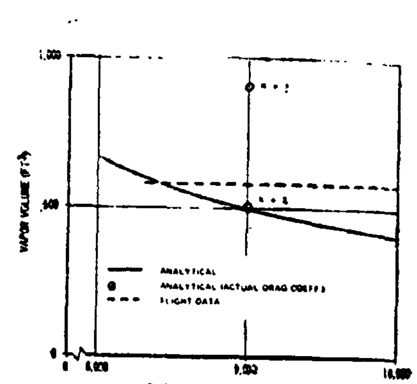


Fig. 2. Volume of entrained vapor in the boundary layer, Saturn V/S-IVB-502 orbital coast

EVALUATION AND APPLICATION OF DATA FROM
LOW-GRAVITY ORBITAL EXPERIMENT
Bradshaw, R.D., et al, GDC-DDB-70-003, NAS8-21291, April 1970

OBJECTIVE. - To analyze the S-IVB-AS-203 flight data and other available data to determine the applicability and adequacy of analytical models in several areas of thermodynamics and fluid mechanics.

PERTINENT WORK PERFORMED. - Work was accomplished in the areas of repressurization, closed tank pressure rise, liquid level phenomena during venting (venting effects) and propellant sloshing. Only the venting effects work will be discussed here. AS-203 data which could be used to verify analytical models was minimal. Three rapid depressurization tests were performed. The first was conducted through the continuous vent system and no significant level rise occurred. This was to be expected since in this test the liquid was significantly subcooled. The second and third tests were conducted through the non-propulsive vent and the LH_2 was initially saturated. During the second and third tests the TV camera at the top of the tank recorded a white fog above the liquid and the liquid level could not be observed. Also the temperature sensors were ineffective since both the liquid and vapor were saturated. The one liquid-vapor sensor which was operating suggested that most of any liquid level rise was due to sloshing rather than venting. During the 2nd blowdown of the third series of testing nearly spherical liquid globules ranging in size from one to six inches were observed flowing toward the vent with velocities of about 1.5 ft/sec. During the 3rd blowdown of this series, irregular globules several times larger than the spherical ones were observed. In any case the observed globules were considerably greater than could be entrained by drag of the vented vapor and could possibly have been caused by rapid surface boiling or break-up of a slosh wave. The vent quality meter did not perform satisfactorily, however, the vent appeared to be superheated and liquid loss minimal and not due to liquid level rise. In summary the AS-203 data did not indicate significant liquid level rise due to venting.

MAJOR RESULTS. - Three analytical models were developed and parametric data generated which agreed with the general results of the AS-203, that liquid level rise from venting was small. In order of increasing sophistication the first model portrays gross bulk boiling, a second develops boundary layer boiling and the third examines liquid level rise resulting from a solution to overall bubble dynamics in a settled liquid. Further characteristics are described in Table 1 and predictive results using the most sophisticated (Bubble Dynamics Model) are presented in Figure 2.

Table 1. Liquid Level Rise Model Characteristics

Bulk Liquid Model -
• All heat input is absorbed in vapor generation
• The fraction of generated vapor which remains in the liquid must be specified.
Boundary Layer Model (Figure 1) -
• Bubbles are spaced as a specified function of bubble diameter.
• A steady state boundary layer solution is used with the constraint of a mass balance on the boundary layer.
Bubble Dynamics Model
• Vaporization can be by nucleate boiling at the wall or evaporation at existing bubbles and at the liquid-vapor interface according to surface area.
• Considers bubble generation with time and spatial dependent radii and frequencies, kinematics and energetics in three dimensions, time and spatial dependent temperature and acceleration, effect of wakes on following bubbles, bubble agglomeration, and slip or no slip interaction with tank walls.

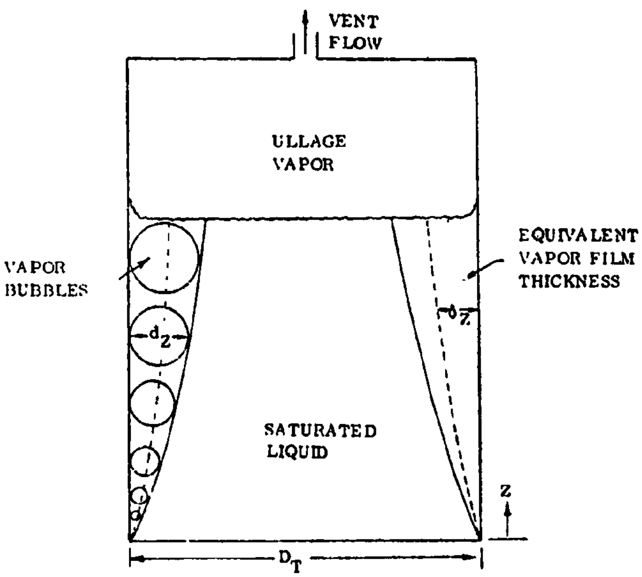


Figure 1. Bubble Boundary Layer Model

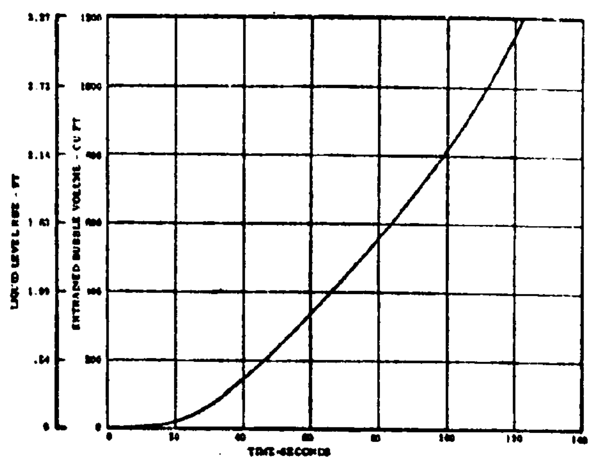


Figure 2. Liquid Level Rise and Entrained Volume for S-IVB Simulation

CRYOGENIC LIQUID EXPERIMENTS IN ORBIT, VOL. II
McGrew, J. L. , Larkin, B.K., MMC
NASA CR-652, NAS8-11328, December 1966

OBJECTIVE. - To experimentally study the problem of intermittent venting at low-g and to develop an analysis that would allow design of such venting systems.

PERTINENT WORK PERFORMED. - Only the venting work is discussed here. Other information in this report is summarized elsewhere. A series of free-fall venting experiments were performed, following a series of normal gravity tests, using Freon TF and LH_2. The Freon TF drop tests were accomplished in a 75-ft tower, while the LH_2 tests used a 16-ft tower. Freon test containers were 15.2 and 29.2 cm (inside diameter) plexiglass cylinders and LH_2 testing was accomplished in both 10.2- and 20.3-cm diameter glass dewars. In all cases the fluids were initially saturated. During the Freon tests, only qualitative data (motion pictures) were obtained, while for LH_2 the data presented in Table 1 was obtained in addition to movies. Venting was accomplished essentially throughout the entire drop, except for one hydrogen test, not listed in Table 1, where no venting occurred.

MAJOR RESULTS. -

1. Sudden venting at 1-g caused violent bubble evolution with vapor rising to the surface and tending to carry liquid into the vent at high vent rates.
2. At zero-g, the bubbles formed remained essentially at their nucleation sites below the liquid surface and vent rate did not appear to effect the potential for liquid being vented; the only limitation being that the vented volume of vapor must be less than the initial ullage volume. LH_2 tests showed that venting of vapor volumes much less than the ullage volume produces no more interface disturbance than dropping a non-vented vessel. By assuming that all the vapor formed from venting causes the liquid to expand, replacing the original ullage volume, a simple thermodynamic calculation of allowable pressure decrease was made.

COMMENT. - The postulated theory on allowable pressure decrease, as presented above, was not verified or compared to the test data.

Table 1 Liquid Hydrogen Venting Data

Run No.	Nominal Dewar Size (in.)	Volume (cc)		Vented Mass (gm)	Vented Volume* (cc)	Ullage Pressure (psia)		Liquid Temperature (°R)		Vent Time (sec)	g Level
		Ullage	Liquid			Initial	Final†	Initial	Final		
17	4	1280	1270	1.26	1730	20.1	16.2	38.8	37.1	0.76	1
19	4	1280	1270	1.24	1660	20.1	16.7	38.8	37.3	0.76	1
20	4	1280	1270	0.97	1300	20.1	16.7	38.7	37.3	0.82	1
21	4	1280	1270	0.68	900	20.1	17.0	38.8	37.4	0.80	1
24	4	1050	1500	1.27	1750	19.9	16.2	28.7	37.1	0.74	0
26	4	1100	1450	1.21	1710	20.1	15.7	38.8	36.9	0.71	0
27	4	1100	1450	0.76	1210	19.9	13.7	38.5	36.1	0.74	0
28	4	1100	1450	0.53	840	19.8	13.7	38.8	36.1	0.74	0
31	8	2960	5340	1.19	1570	19.8	17.0	38.6	37.4	0.68	1
32	8	3360	4940	1.08	1670	19.8	14.2	38.5	36.3	0.68	1
33	8	2960	5340	0.77	1090	19.6	15.7	33.5	36.9	0.70	1
34	8	3360	4940	0.61	980	19.6	13.5	38.5	36.0	0.69	1
35	8	3550	4750	0.44	630	19.6	14.2	38.5	36.3	0.70	1
36	8	3160	5140	0.83	1630	19.8	10.6	38.5	34.6	0.70	0
38	8	3160	5140	0.74	1380	21.1	11.6	38.8	35.1	0.69	0
39	8	2960	5340	0.57	1030	19.8	11.4	38.2	35.0	0.72	0
46	8	2370	5960	1.37	2210	19.6	13.5	37.5	36.0	0.75	1
47	8	2370	5960	1.06	2580	19.6	8.5	37.1	33.4	0.77	0

*Based on final temperature and pressure.

†Assumed as saturation pressure at final temperature.

13.0 FLUID PROPERTIES

Covering fluid properties which may be influenced by a reduction in gravity.

EFFECT OF FLOW RATE ON THE DYNAMIC CONTACT ANGLE FOR WETTING LIQUIDS

Coney, T.A., Masica, W.J., NASA-LeRC, TN D-5115, March 1969

OBJECTIVE - Determine the effect of interface velocity and liquid properties on the dynamic contact angle over a previously wetted liquid surface at low-g.

PERTINENT WORK PERFORMED. Weightless ($a/g < 10^{-5}$) experiments were conducted in the LeRC 2.2 sec. drop facility using rectangular glass tubing (1.0 × 0.25 cm in cross section) 20 cm in length. Interface velocities ranged from 1.4 to 28 cm/sec. The test liquids used were Ethanol, FC-43, Methanol and 1-Butanol, resulting in surface tensions from 16.6 to 24.4 dynes/cm and viscosities from 0.56 to 6.7 centipoise. All the liquids used exhibited zero degree static contact angle. Reynolds number, based on an average layer thickness of 0.1 cm, ranged from about 4 to 400. Data were recorded with a high-speed (400 fps), 16-mm camera. Contact angles were determined within a mean deviation of ±4°.

Test data were compared to a theoretical analysis by Friz (1965). The problem analyzed is illustrated in Figure 1. In the figure a liquid slug is moving through a pipe at constant interface velocity u_o. The inside of the pipe was assumed ideally smooth and previously wetted with a layer of liquid of constant thickness ℓ_∞. The coordinate axes was chosen to move with the liquid. The region of interest, enclosed in the dashed rectangle, included the dynamic contact angle θ and the standing wave formed in the liquid layer preceding the advancing interface. Curvature at the center of the interface was not considered. The analysis was limited to steady, two-dimensional flow with negligible body forces. The final equation resulting from a numerical solution and application of appropriate boundary conditions is $\tan\theta = 3.4\,(u_o\,\mu_\ell/\sigma)^{1/3}$ and is rigorously applicable only for $Re \ll 1$.

MAJOR RESULTS. -

1. The dynamic contact angle formed at a surface by an advancing liquid-vapor interface as the interface moves relative to that surface changes significantly as a function of interface velocity.

2. The test data showed that the theoretical relation derived by Friz is adequate (Figure 2) and that the implication that layer thickness has no effect on the contact angle appears to be correct.

3. The predicted waveform preceding the advancing interface agrees qualitatively with the waveform obtained experimentally.

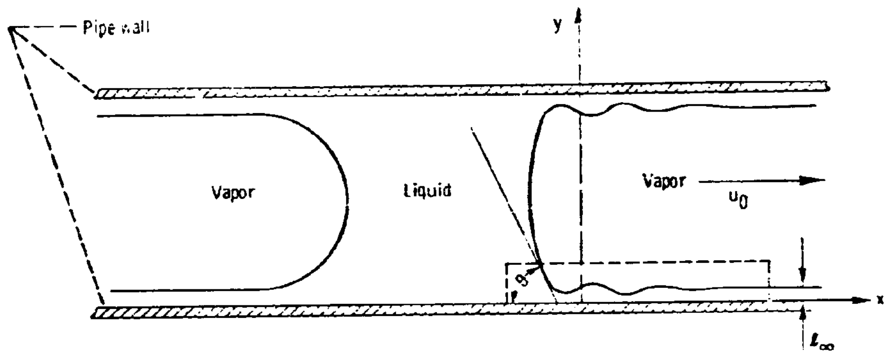


Figure 1. Interface Shape of a Liquid Slug Advancing Through a Pipe

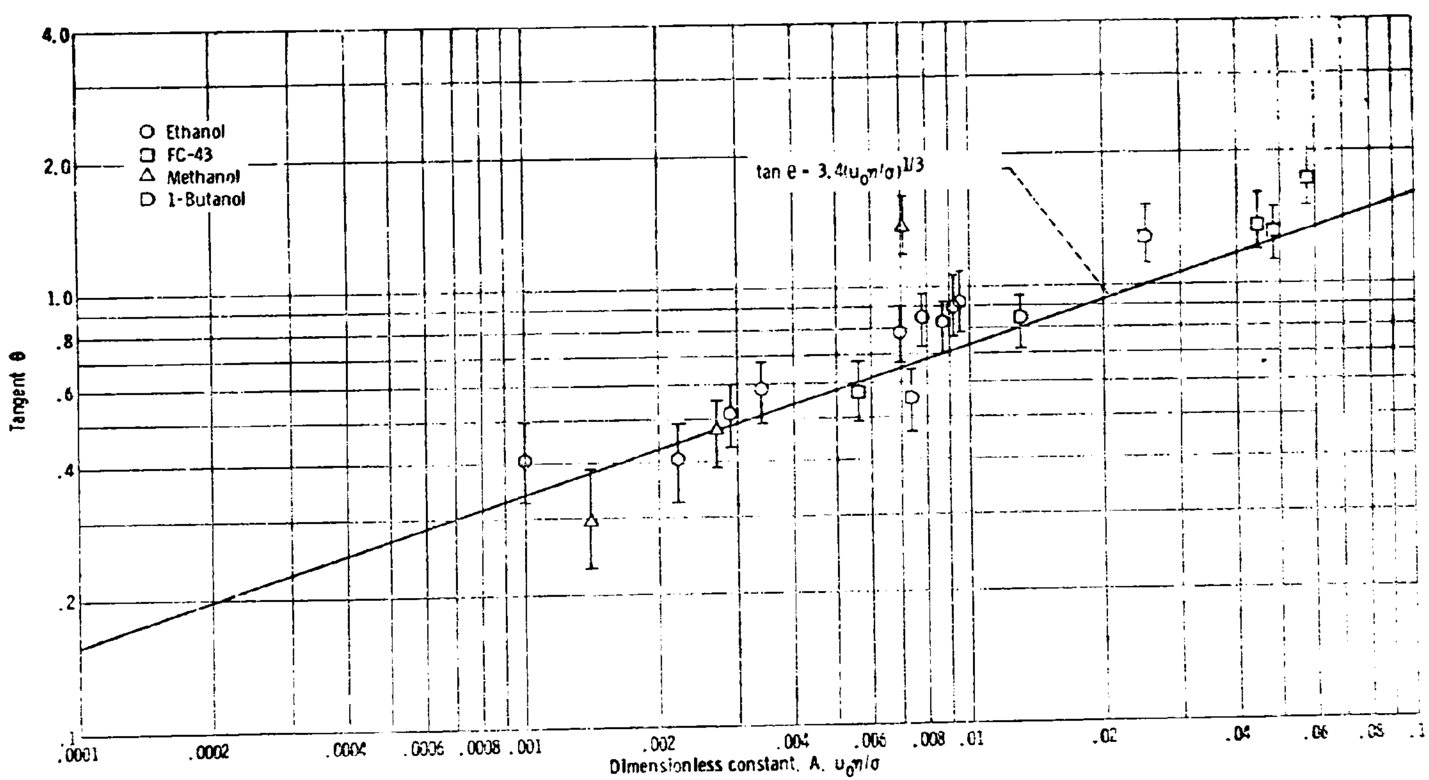


Figure 2. Dynamic Contact Angle as Function of Interface Velocity and Liquid Properties for Wetting Liquids

APPENDIX A

AUTHOR INDEX OF SUMMARIZED REPORTS

Anon., "Convection in the Tanks of a Rotating Spacecraft," June 1972, p. 9-4.

Abdalla, K.L., Berenyi, S.G., "Vapor Ingestion Phenomenon in Weightlessness," May 1969, p. 8-24.

Abramson, H.N., "The Dynamic Behavior of Liquids in Moving Containers," 1966, p. 4-30.

Abramson, H.N., "Slosh Suppression," May 1969, p. 4-14.

Albers, J.A., et al, "Condensation Pressure Drop of Nonwetting Mercury in a Uniformly Tapered Tube in 1-g and Zero Gravity Environments," January 1966, p. 11-6.

Albers, J.A., Macosko, R.P., "Experimental Pressure-Drop Investigation of Non-wetting, Condensing Flow of Mercury Vapor in a Constant-Diameter Tube in 1-g and Zero-Gravity Environments," June 1965, p. 11-8

Andracchio, C.R., Abdalla, K.L., "An Experimental Study of Liquid Flow Into a Baffled Spherical Tank During Weightlessness," April 1968, p. 7-18.

Barton, J.E., et al, "Apollo Oxygen Tank Stratification Analysis, January 1972, p. 9-6.

Berenyi, S.G., "Effect of Pressurant Inlet Configuration on Liquid Outflow in Weightlessness, October 1970, p. 8-14.

Berenyi, S.G., "Effect of Outlet Baffling on Liquid Residuals for Outflow From Cylinders in Weightlessness, May 1970, p. 8-18.

Berenyi, S.G., Abdalla, K.L., "Vapor Ingestion Phenomenon in Hemispherically Bottomed Tanks in Normal Gravity and in Weightlessness," April 1970, p. 8-20.

Berenyi, S.G., Abdalla, K.L., "The Liquid-Vapor Interface During Outflow in Weightlessness," June 1969, p. 8-22.

Bizzell, G.D., "Low Gravity Draining from Hemispherically Bottomed Cylindrical Tanks, June 1970, p. 8-16.

Blackmon, J.B., "Pressurization Gas Flow Effects on Liquid Interface Stability," May 1969, p. 3-6.

Blackmon, J.B., et al, "Propellant Settling," May 1968, p. 5-8.

Blackshear, W.T., Eide, D.G., "The Equilibrium Free Surface of a Contained Liquid Under Low Gravity and Centrifugal Forces, October 1964, p. 2-18.

Bowman, T.E., "Liquid Settling in Large Tanks," June 1965, p. 5-18.

Bowman, T.E., "Cryogenic Liquid Experiments in Orbit Volume 1: Liquid Settling and Interface Dynamics," December 1966, p. 3-14.

Bradshaw, R.D., et al, "Evaluation and Application of Data from Low-Gravity Orbital Experiment," April 1970, p. 12-8.

Bradshaw, R.D., Kramer, J.L., "An Analytical Study of Reduced Gravity Propellant Settling," February 1974, p. 5-2.

Chow, C.Y., Lai, W.M., "Unsteady Axisymmetric Flows of a Liquid Draining from a Circular Tank," August 1972, p. 8-8.

Clodfelter, R.G., "Low-Gravity Pool-Boiling Heat Transfer," March 1964, p. 10-40.

Cochran, T.H., et al. "Experimental Investigation of Nucleate Boiling Bubble Dynamics in Normal and Zero Gravities," February 1968, p. 10-22.

Cochran, T.H., "Forced-Convection Boiling Near Inception in Zero Gravity," January 1970, p. 10-18.

Cochran, T.H., et al, "Forced Convection Peak Heat Flux on Cylindrical Heaters in Water and Refrigerant 113," February 1974, p. 10-4.

Cole, Jr., H.A., "Effects of Vortex Shedding on Fuel Slosh Damping Predictions," March 1970, p. 4-10.

Concus, P., et al, "Small Amplitude Lateral Sloshing in a Cylindrical Tank with Hemispherical Bottom Under Low Gravitational Conditions," January 1967, p. 4-26.

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Concus, P., et al, "Small Amplitude Lateral Sloshing in Spheroidal Containers Under Low Gravitational Conditions," February 1969, p. 2-12.

Concus, P., "Capillary Stability in an Inverted Rectangular Tank," 1963, p. 3-24.

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Coney, T.A., Salzman, J.A., "Lateral Sloshing in Oblate Spheroidal Tanks Under Reduced and Normal-Gravity Conditions," March 1971, p. 4-6.

Curtis, H.S., "Minimization of Slosh Amplification at Orbital Injection of the S-IVB/ Saturn V by an Optimum Thrust Termination Sequence," December 1966, p. 4-28.

Derdul. J.D., et al, "Experimental Investigation of Liquid Outflow from Cylindrical Tanks during Weightlessness," December 1966, p. 8-38.

Dodge, F.T., "Studies of Propellant Sloshing Under Low Gravity Conditions, Final Report," October 1970, p. 4-8.

Dodge, F.T., "Engineering Study of Flexible Baffles for Slosh Suppression," September 1971, p. 4-4.

Easton, C.R., Catton, I., "Nonlinear Free Surface Effects in Tank Draining at Low Gravity," December 1970, p. 8-12.

Edeskuty, F.J., "Pool Boiling Heat Transfer to Liquid Helium and Liquid Nitrogen in a Nearly Zero Gravity Environment," May 1974, p. 10-2.

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Florschuetz, L.W., et al, "Growth Rates of Free Vapor Bubbles in Liquids at Uniform Superheats Under Normal and Zero Gravity Conditions," April 1969, p. 6-6.

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Gluck, D.F., et al, "Distortion of a Free Surface During Tank Discharge," November 1966, p. 8-40.

Grodzka, P.G., Bannister, T.C., "Natural Convection in Low-G Environments," February 1974, p. 9-2.

Grubb, L.S., Petrash, D.A., "Experimental Investigation of Interfacial Behavior Following Termination of Outflow in Weightlessness," April 1967, p. 3-12.

Haggard, J.B., "Unstable Bubble Motion Under Low-Gravitational Conditions," May 1970, p. 6-2.

Haggard, J.B., Masica, W.J., "Motion of Single Bubbles Under Low Gravitational Conditions," October 1969, p. 6-4.

Hastings, L.J., Rutherford III, R., "Low Gravity Liquid-Vapor Interface Shapes in Axisymmetric Containers and a Computer Solution," October 1968, p. 2-14.

Hastings, L.J., "Experimental Study of the Response of a Static Liquid-Vapor Interface After a Sudden Reduction in Acceleration," June 1969, p. 2-10.

Hollister, M.P., et al, "Liquid Propellant Behavior During Periods of Varying Accelerations,"June 1967, p. 5-10.

Hollister, M.P., et al, "Liquid Propellant Behavior During Periods of Varying Accelerations," June 1967, p. 4-24.

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Hurd, S.E., et al, "Analytical and Experimental Study of Liquid-Ullage Coupling and Low Gravity Interface Stability," August 1966, p. 3-16.

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Keshock, E.G., Siegel, R., "Forces Acting on Bubbles in Nucleate Boiling Under Normal and Reduced Gravity Conditions," August 1964, p. 10-36.

Kirichenko, Y.A., Charkin, A.I., "Studies of Liquid Boiling in Imitated Reduced Gravity Fields," September 1970, p. 10-14.

Klavins, A., "Vapor Ingestion in a Cylindrical Tank with a Concave Elliptical Bottom," February 1974, p. 8-4.

Koval, L.R., Bhuta, P.G., "An Analytical Study of Liquid Outflow from Cylindrical Tanks During Weightlessness," June 1966, 8-42.

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Labus, T.L., et al, Effect of Baffles on Inflow Patterns in Spherical Containers during Weightlessness," November 1972, p. 7-2.

Labus, T.L., et al, "Low-Gravity Venting of Refrigerant 11,"February 1972, p. 12-4.

Labus, T.L., Masica, W.J., "Liquid Reorientation in Spheres by Means of Low-G Accelerations," October 1968, p. 5-6.

Labus, T.L., Symons, E.P., "Experimental Investigation of an Axisymmetric Free Jet with an Initially Uniform Velocity Profile," May 1972, p. 7-8.

Labus, T.L., Aydelott, J.C., "Gas Jet Impingement Normal to a Liquid Surface," May 1971, p. 3-2.

Labus, T.L., "Cavity Stability During Gas Jet Impingement on Liquid Surfaces in Weightlessness," September 1970, p. 3-4.

Labus, T.L., "Liquid-Vapor Interface Configuration in Annular Cylinders," March 1970, p. 2-6.

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Lacovic, R.F., Stofan, A.J., "Experimental Investigation of Vapor Ingestion in the Centaur Liquid Hydrogen Tank," March 1968, p. 8-30.

Lienhard, J.H., "Interacting Effects of Gravity and Size Upon the Peak and Minimum Pool Boiling Heat Fluxes," May 1970, p. 10-16.

Lienhard, J.H., Dhir, V.K., "Extended Hydrodynamic Theory of the Peak and Minimum Pool Boiling Heat Fluxes," July 1973, p. 10-8.

Littles, J.W., "Nucleate Pool Boiling of Saturated Freon 113 in a Reduced Gravity Environment," August 1969, p. 10-20.

Lubin, B.T., Springer, G.S., "The Formation of a Dip on the Surface of a Liquid Draining from a Tank," 1967, p. 8-36.

Marshall, F.L., "Surface Deformations in a Draining Cylindrical Tank," December 1967, 1. 8-32.

Masica, W.J., et al, "Hydrostatic Stability of the Liquid-Vapor Interface in a Low-Acceleration Field," August 1964, p. 3-22.

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Masica, W.J., Petrash, D.A., "Motion of Liquid-Vapor Interface in Response to Imposed Acceleration," September 1965, p. 5-16.

McGrew, J.L., Larkin, B.K., "Cryogenic Liquid Experiments in Orbit, Vol. II," December 1966, p. 12-10.

McGrew, J.L., Larkin, B.K., "Cryogenic Liquid Experiments in Orbit - Vol. II," December 1966, p. 10-26.

Merte, H., Jr., "Incipient and Steady Boiling of Liquid Nitrogen and Liquid Hydrogen Under Reduced Gravity," November 1970, p. 10-12.

Moore, R.E., Perko, L.M., "Inviscid Fluid Flow in an Accelerating Cylindrical Container," 1965, p. 5-20.

Namkoong, D., et al, "Photographic Study of Condensing Mercury Flow in 0- and 1-G Environments," June 1967. p. 11-2.

Navickas, J., Melton, H.R., "Vapor Volume Entrained in the Boundary Layer Due to Boiling on a Vertical Plate in Low Gravity Field," June 1970., p. 12-6.

Oker, E., Merte, H., Jr., "Transient Boiling Heat Transfer in Saturated Liquid Nitrogen and F-113 at Standard and Zero Gravity-Final Report," October 1973, p. 10-6.

Papell, S.S., et al, "Buoyancy Effects on Critical Heat Flux of Forced Convective Boiling in Vertical Flow," October 1966, p. 10-28.

Papell, S.S., Faber, O.C., "Zero-and Reduced Gravity Simulation on a Magnetic Colloid Pool-Boiling System," February 1966, p. 10-32.

Paynter, H.L., "Time for a Totally Wetting Liquid to Deform from a Gravity-Dominated to a Nulled-Gravity Equilibrium State," September, 1964, p. 2-20.

Perko, L.M., "Large Amplitude Motions of a Liquid-Vapor Interface in an Accelerating Container," 1969, p. 4-20.

Petrash, D.A., et al, "Effect of Surface Energy on the Liquid-Vapor Interface Configuration During Weightlessness, January 1963, p. 2-22.

Rex, J., Knight, B.A., "An Experimental Assessment of the Heat Transfer Properties of Propane in a Near-Zero Gravity Environment," August 1964, p. 10-38.

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Reynolds, W.C., "Configuration and Stability of a Rotating Axisymmetric Meniscus at Low-G," March 1965, p. 3-18.

Saad, M.A., "Free Surface Behavior During Propellant Withdrawal," May 1968, p. 8-28.

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Salzman, J.A., Masica, W.J., "Experimental Investigation of Liquid-Propellant Reorientation," January, 1967, p. 5-13.

Salzman, J.A., et al, "Low-Gravity Reorientation in a Scale Model Centaur Liquid Hydrogen Tank," February 1973, p. 5-4.

Salzman, J.A., Masica, W.J., "Lateral Sloshing in Cylinders Under Low Gravity Conditions," February 1969, p. 4-18.

Satterlee, H.M., Hollister, M.P., " Low-G Liquid Propellant Behavior, Engineers Handbook," May 1967, p. 8-34.

Scholl, H.F., et al, "Ring Baffle Pressure Distribution and Slosh Damping in Large Cylindrical Tanks," December 1972, p. 4-2.

Schwartz, S.H., "Saturated Pool Boiling of Water in a Reduced Gravity Environment," June 1966, p. 10-30.

Sexton, R.E., et al, "In-Space Propellant Logistics,", June 1972, p. 8-10.

Sherley, J.E., "Nucleate Boiling Heat-Transfer Data for Liquid Hydrogen at Standard and Zero Gravity," August 1962, p.10-44.

Siegel, R., "Effects of Reduced Gravity on Heat Transfer," 1967, p. 9-9, 10-24, 11-4.

Siegel, R., Howell, J.R., "Critical Heat Flux for Saturated Pool Boiling from Horizontal and Vertical Wires in Reduced Gravity," December 1965, p. 10-34.

Spuckler, C.M., "Liquid Inflow to Initially Empty Cylindrical Tanks in Low Gravity," August 1974, p. 7-4.

Spuckler, C.M., Abdalla, K.L., "Zero-Gravity Liquid-Vapor Interface Configuration in Conical Tanks,", September 1971, p. 2-2.

Staskus, J.V., "Liquid Inflow to a Baffled Cylindrical Tank During Weightlessness," August 1972, p. 7-6.

Stephens, D.G., "Experimental Investigation of Liquid Impact in a Model Propellant Tank," October 1965, p. 5-14.

Symons, E.P., "Zero-Gravity Equilibrium Configuration of Liquid-Vapor Interface in Toroidal Tanks," November 1970, p. 2-4.

Symons, E.P., "Outlet Baffles - Effect of Liquid Residuals from Zero-Gravity Draining of Hemispherically Ended Cylinders," September 1972, p. 8-6.

Symons, E.P., "Effect of Throttling on Interface Behavior and Liquid Residuals in Weightlessness," May 1974, p. 8-2.

Symons E.P., "Interface Stability During Liquid Inflow to Initially Empty Hemispherical Ended Cylinders in Weightlessness,", April 1970, p. 7-14.

Symons, E.P., Labus, T.L., "Experimental Investigations of an Axisymmetric Fully Developed Laminar Free Jet," April 1971, p. 7-12.

Symons, E.P., Nussle, R.C., "Observations of Interface Behavior During Inflow to an Elliptical Ended Cylinder in Weightlessness," January 1969, p. 7-16.

Symons, E.P., Staskus, J.V, "Interface Stability During Liquid Inflow to Partially Full, Hemispherical Ended Cylinders During Weightlessness,"August 1971, p. 7-10.

Szara, R.J., "Rapid, Low-Loss Liquid Helium Transfers," 1967, p. 7-22.

Toole, L.E., Hastings, L.J., "An Experimental Study of the Behavior of a Sloshing Liquid Subjected to a Sudden Reduction in Acceleration," August 1968, p. 4-22.

Vernon, R.M., Brogan, J.J., "A Study of Cryogenic Container Thermodynamics During Propellant Transfer," November 1967, p. 7-20.

APPENDIX B

REPORTS REVIEWED AND NOT SUMMARIZED

This section contains a listing of reports which were reviewed, but not summarized, including reasons for not summarizing. The listing is by category and author. The categories are the same as described for the detailed summaries, except that several general categories have been added to include reports covering more than one aspect of low-g fluid behavior and/or heat transfer or which do not fit into the basic categories. This page location of each category is presented below.

LOW-G FLUID BEHAVIOR GENERAL

Anon., "Evaluation of AS-203 Low Gravity Orbital Experiment," Chrysler Corp., Technical Report HSM-R421-67, BB-3.4.3-5-101, January 1967.

> The pertinent work reported here is adequately covered and extended in a later report by Bradshaw (1970), which is summarized.

Anon., "Preparative Electrophoresis Experiment Design," Beckman Instrument Inc., NASA CR 123972, October 1972.

> This work is only applicable to biochemistry, biomedical research and applied medicine.

Alekseeva, L. M., "Rotational Self-Excitation in a Liquid," Scientific Research Institute of Nuclear Physics, Soviet Physics-Doklady, Vol. 16, No. 10, March 1971.

> Detailed mathematical treatment of one narrow aspect of hydrodynamics as applied to a hydromagnetic dynamo and does not deal with low-g.

Ballinger, J. C., Wood, G. B., "Low-Gravity Capabilities of Life Support System Components and Processes, GD/C, SAE Paper No. 680742, October 1968.

> This work is reported in greater detail in contract reports: eg. Burnett, et al, 1970, which is reviewed elsewhere.

Ballinger, J. C., et al, "Final Technical Report Study of Zero Gravity Capabilities of Life Support System Components and Processes," GD/C, NASA CR 66534, GDC-DBD67-004, Contract No. NAS1-6939.

> The pertinent low-g test phase of this work is reported in GDC report CASD-NAS74-054 (King, et al, 1974), yet to be published.

Biev, M., Snyder, R. S., "Electrophoresis in Space at Zero Gravity," AIAA Paper No. 74-210, February 1974.

> Deals with biology.

Boiteux, H. L., "Weightlessness Research at ONERA," ONERA Laboratory, France, NASA TT F-11,515, 1965.

> Only a general discussion of low-g fluid behavior without specific data of interest.

Boiteux, H. L., "The ONERA Laboratory for Research on Weightlessness," ONERA Laboratory, France, A65-22522, April 1965, (In French).

> Discusses the free fall facility at the ONERA Laboratory and is not worthy of translation.

Bowman, T. E., Paynter, H. L., "Weightless Liquids," MMC, Science Journal, pp 44-49, September 1966.

General discussion of the behavior of liquids at low-g, with pertinent information contained in other work in more detail.

Brown, E. L., "Human and Systems Performance During Zero G," SAE-AFOSR Preprint 2301, October 1960.

No specific data is given which adds to the state-of-the-art of low-g fluid behavior.

Burge, G. W., et al, "Analytical Approaches for the Design of Orbital Refueling Systems," MACDAC, AIAA Paper 69-567, June 1969.

In fluid behavior more advanced modeling with marker-and-cell is reported elsewhere (Bradshaw, 1974). Work on fluid reorientation was discussed in more detail in Blackmon, et al, 1968. The sloshing and dissipation work is qualitative. The interface stability data is developed in more detail elsewhere (Blackmon, 1969).

Burnett, J., et al, "Final Report Gravity-Sensitivity Assessment Criteria Study," GD/C, NASA CR-66945, GDC-DBD70-003, Contract No. NAS1-8494," June 1970.

The pertinent low-g test phase of this work is reported in GD/C report CASD-NAS74-054 (King, et al, 1974), yet to be published.

Chin, J. H., et al, "Analytical and Experimental Study of Liquid Orientation and Stratification in Standard and Reduced Gravity Fields," LMSC, 2-05-64-1, Contract No. NAS8-11525, July 1964.

Key results of heat transfer work culminated in a computer model described in LMSC-A794909-A, Vol. IV (Anon., 1968), which report is summarized in the fluid management volume. The interface configuration work is covered by Reynolds and Satterlee in NASA SP-106 (Abramson, 1966) which is summarized.

Clayton, D. A., "Passive Control of a Liquid in a Zero Gravity Environment," Royal Aircraft Est., Technical Report 67207, 1967

The report describes dimensionless parameters applicable to low gravity fluid behavior, capillary pumping for liquid acquisition and zero gravity heat transfer. Some aircraft testing was conducted for capillary pumping and boiling. No quantitative data is presented.

Cline, F. B., "Saturn I-B Liquid Hydrogen Orbital Experiment Definition," NASA-MSFC, TM X-53158, November 1964.

Later work, reviewed elsewhere, presents results of the experiment, along with pertinent experiment descriptions.

Clodfelter, R. G., Lewis, R. C., "Fluid Studies in a Zero Gravity Environment," WPAFB, ASD TN 61-84, June 1961.

A series of tests investigating low-g fluid behavior was conducted in C-131 and KC-135A aircraft affording nearly 30 seconds low-g of which the observed results have been quantitatively developed in more recent literature.

Cochran, T. H., Masica, W. J., "An Investigation of Gravity Effects on Laminar Gas Jet Diffusion Flames," NASA-LeRC, 13th International Symposium on Combustion, August 1970.

Work on low-g combustion is not considered pertinent to the current program and is therefore not covered.

Congelliere, J. T., et al, "The Zero-G Flow Loop: Steady-Flow, Zero-Gravity Simulation for Investigation of Two-Phase Phenomena," Rocketdyne, 1963.

Only a theoretical discussion is presented and the state-of-the-art of low g fluid behavior is not advanced.

Cummings, J. W., "Dynamic Techniques for Extending Zero G Duration," Proceedings of American Astronautical Society, Physical and Biological Phenomena Under Zero-Gravity Conditions, 2nd Symposium, January 1963.

This report does not add anything to the knowledge of low-g fluid behavior.

Dean, W. G., et al, "Results of a Preliminary Design and Symposium Integration Study of Flying Several Cryogenic and Fluid Mechanics Experiments on an Unmanned Saturn IB for Long-Term, Low-G Investigations," LMSC, LMSC/HREC A791322, Contract No. SVD-3-67-002, March 1968.

No new technology data are presented.

Doughty, J. O., Henry, H. R., "Two Phase Flow and Heat Transfer in Porous Beds Under Variable Body Forces, Part 1," Alabama Univ., NASA CR-108137, Univ. of Alabama No. 22-6560, Contract No. NAS8-21143, November 1969.

Report contains information on using porous materials for low gravity applications with experiments and analysis performed for predicting two phase flow and heat transfer in reduced gravity. No experimental data was obtained for reduced gravity. Packed beds and porous media are of limited use for fluid transfer.

Fineblum, S. S., "The Behavior of Liquids Under Conditions of Zero and Near-Zero Gravity," NAR, AETN62-1, June 1962.

An analytical development of the basic equations of hydrostatics and hydrodynamics is presented without comparison with experimental data which adds no pertinent information to the current state-of-the-art.

Gershman, R. (MACDAC), Chu, C. (Univ. of California), "Effect of Wall Heating on Low-G Liquid-Vapor Interface Configuration," ASME Paper 67-WA/HT-33, November 1967.

An analytic treatment of the subject with little offered in the way of solution or a contribution to design.

Heppner, D. B. (GD/C), Jackson, P. M. (NASA-Langley), "Influence of the 'Weightless' Environment on Fluid Management Systems," AIAA Paper No. 71-864, August 1971.

This work is reported in greater detail in contract reports; eg, Burnett, et al (1970) which is reviewed elsewhere.

Hurd, S. E., et al, "Analytical and Experimental Study of Liquid-Ullage Coupling and Low Gravity Interface Stability," LMSC, NASA CR-61620, LMSC 2-05-66-1, Contract No. NAS8-11525, August 1966.

Not summarized with respect to heat transfer. The key results of this heat transfer work culminated in a computer model described in LMSC-A794909-A, Vol. IV, Anon. (1968), which is summarized in the fluid management volume. It is summarized for interface stability (pg. 3-16).

Jensen, D. H., et al, "Saturn S-IVB-203 Stage Flight Evaluation Report," Vol. I and II, MACDAC, SM-46988, March 1967.

The data presented in this report are not evaluated to the extent necessary to add significantly to the state-of-the-art of low-g fluid behavior. Later work has performed more extensive evaluations of the data (Chrysler, 1967 and Bradshaw, 1970).

Kallis, S. A., Jr., "Problems of Liquid Behavior in Weightless Environments," Chrysler Corp., Technical Report HEC-R108, April 1965.

A basic simplified discussion of weightlessness and possible fluid configurations is presented, however no applicable data is presented or discussed in this simplified discussion.

Keller, J. B., Geer, J., "Flows of Thin Streams With Free Boundaries," New York Univ., Courant Inst. of Math., J. Fluid Mechanics, Vol. 59, Part 3, January 1973.

This report is concerned with thin steady two-dimensional potential flow with free and/or rigid boundaries in the presence of gravity and not with low-g or the effects of variations in gravity.

Ketchum, W. J., "Orbit-to-Orbit Shuttle Toroidal Tank Outflow and Slosh Characteristics," GD/C, AIAA Paper 70-1225, 1970.

Insufficient new data is presented and application to low-gravity conditions is not discussed. No correlations or data are presented that can be extrapolated to low-gravity.

Kidder, J. H., "Hydrodynamics of Superfluid Helium With Quantized Vorticity and Phase," Dartmouth College, AD 689 293, Contract No. AF49(638)-1717, June 1969.

In this case gravitational flow simply means the flow resulting from an induced level difference between two reservoirs where the driving force is gravity.

Kosmahl, H. G., "Optimum Design of Magnetic Braking Coils With Special Application to Lewis Drop Tower Experiments," NASA-LeRC, NASA TN D-3132, December 1965.

Applies only to drop tower facility design and does not add to the state-of-the-art of low-g fluid behavior.

Lacovic, R. F., et al, "Management of Cryogenic Propellants in a Full-Scale Orbiting Space Vehicle," NASA-LeRC, NASA TN D-4571, May 1968.

Data analysis on sloshing and pressure rise are presented, however, generalized correlations are not presented. The sloshing data verified vehicle changes correcting propellant control problems, however model verification is not discussed. Also, the stratification/pressurization data is not developed to generalized correlations.

Lacy, L. L. (NASA-MSFC), Guenther, H. O. (Univ. of Alabama), "The Behavior of Immiscible Liquids in Space," July 1974.

Applicable to space manufacturing type processes and not the current in-orbit fluid transfer program.

Lepper, R., "Northrop Space Laboratories Zero Gravity Simulation Facilities, Northrop Space Labs., Proceedings of Annual Technical Meeting, Institute of Environmental Sciences, 1963.

Does not add to the state-of-the-art of low-g fluid behavior.

Li, T., "Liquid Behavior in a Zero-G Field," GD/C, IAS Paper 61-20, AE-60-0682, Contract No. AF18(600)-1775), September 1960.

Heat transfer data is only speculation based on the work of others and low-g fluid behavior is covered in greater detail in recent literature.

Long, R. R., Moore, M. J., " Experimental Investigations of Stratified Shearing Flow," John Hopkins Univ., Grant No. E22-36-70(G), 1970.

Gravitational effects as used here refer to the earth's gravity as it affects fluid flow in the oceans and atmosphere.

Majoros, J. J., et al, "Present State-of-the-Art in Designing for Storage of Cryogenic Propellants in Space, MACDAC, Cryogenic Technology, Nov/Dec 1966.

The pertinent data presented is taken from other work which is reviewed elsewhere.

McCarthy, J. R., Jr., et al, "Zero-G Propulsion Problems," NAR, Jet, Rocket, Nuclear, Ion and Electric Propulsion: Theory and Design, New York, Springer Verlay, 1968.

Discussions are only brief reviews not amenable to summarization.

Nayfeh, A. H., Meirovitch, L., "The Stability of Motion of Satellites With Cavities Partially Filled With Liquid," Virginia Polytechnic Inst., AIAA Paper 74-168, January 1974.

This paper is concerned with the stability of a satellite and is not directly applicable to low-g transfer.

Neimer, J. J., "Effect of Zero Gravity on Fluid Behavior and System Design," WADC, TN-59-149, ASTIA No. AD 228810, April 1959.

Pertinent aspects of this work are reviewed elsewhere, Trusela, 1960 under General Heat Transfer.

Nein, M. E., Arnett, C. D., "Program Plan for Earth-Orbital Low-G Heat Transfer and Fluid Mechanics Experiments," NASA-MSFC, NASA TM X-53395, February 1966.

The technology data presented is only in terms of brief reviews of existing work.

O'Neal, A. P., et al, "Saturn V/S-IVB Stage Modifications for Propellant Control During Orbital Venting," MACDAC, SM-47177, Contract No. NAS7-101, April 1965.

The technology aspects of the vent work reported here are covered in more detail in other reports reviewed elsewhere; eg, Mitchell, et al (1966) under vent systems in the fluid management volume. Slosh data is presented but not extended to generalized correlations; similar data is discussed in the Curtis, 1966 summary.

Otto, E. W., "Static and Dynamic Behavior of the Liquid-Vapor Interface During Weightlessness," NASA-LeRC, Chemical Engineering Progress Symposium Series No. 61, 168-177, NASA TM X-52016 (April 1964), A66-39886, also NATO AGARD A67-14987, 1966.

A survey paper which confirms basic principles, but the pertinent work is summarized from the original source documents.

Paynter, H. L., "The Martin Company's Low-G Experimental Facility," LMSC, USAF-LMSC Symposium on Fluid Mechanics and Heat Transfer Under Low-G Conditions, June 1965.

Does not provide data on low-g fluid behavior.

Porter, J., Clayton, D. A., "An Introduction to Zero-G Research at the Royal Aircraft Establishment," Royal Aircraft Establishment, Technical Report 65016, February 1965.

Mostly a generalized discussion of future work with no new data presented.

Povitskii, A. S., Lyubin, L. Y., "Certain Features of the Motion of a Fluid Under Weightlessness Conditions," USSR, N70, N6727521, NASA TT F-10, 868, 1967.

Oriented to problems of concern to doctors and biologists with only general discussions and no specific data given to advance the state-of-the-art.

Pradhan, G. K., et al, "On the Equilibrium of Circular Flows Under Gravity," Indian Institute of Technology, Journal of Mathematical Analysis and Applications, Vol. 42, pp 138-147, 1973.

"Gravity effects," as used in this work is concerned with 1-g and does not add to the state-of-the-art of low-g fluid behavior.

Reynolds, W. C., "Hydrodynamic Considerations for the Design of Systems for Very Low Gravity Environments," Stanford Univ., LG-1, September 1961.

Does not advance the state-of-the-art since it is basically a general survey of existing data with respect to heat transfer and only fundamental definitions are given.

Rumiantsev, B. N., "The Motion of a Body Containing a Viscous Fluid," USSR, Fluid Dynamics Transactions, Vol. 5, Part II, pp. 219-227, September 1969.

An analytical discussion with the results not presented in a useful form for design.

Satterlee, N. M., "Propellant Orientation, Venting, and Temperature," LMSC, Spacecraft Thermodynamics Symposium, March 1962.

No new data of significance was presented.

Satterlee, H. M., "Propellant Control at Zero-G," LMSC, Space/Aeronautics, Vol. 38, No. 1, July 1962.

The work presented is very general and no specific data is given which advances the state-of-the-art of low-g fluid behavior.

Satterlee, H. M., Reynolds, W. C., "The Dynamics of the Free Liquid Surface in Cylindrical Containers Under Strong Capillary and Weak Gravity Conditions," Stanford Univ., LG-2, May 1964.

Low-g interface stability state-of-the-art has been advanced by Masica (1964, 1967) and Hines (1966). Sloshing work in this early report is not current with the state-of-the-art reported elsewhere.

Schweikle, J. D., et al, "Orbital Experimentation for Advancing Cryogenic Technology," MACDAC, Journal of Spacraft, Vol. 6, No. 3, March 1969.

This work is reviewed in more detail under the project THERMO contract reports, Schweikle, 1967.

Schweikle, J. D., et al, "Project Thermo - Phase B Prime," MACDAC, DAC- 60799, Contract No. NAS8-21129, September 1967.

This study explores the possibility of individual experimentation utilizing smaller carrier vehicles. No new low-g fluid behavior technology data are presented.

Selyakov, V., "Pecularities of Dynamic Weightlessness," USSR, AD602571, June 1963.

A qualitative discussion of low-g in relation to early USSR programs is given, however, no significant fluids data is present.

Sherley, J. E., Merino, F., "The Final Report for the General Dynamics/Astronautics Zero G Program Covering the Period From May 1960 Through March 1962," GD/C, Contract Nos. AF18(600)-1775 and NAS8-2664, August 1962.

Results are specifically oriented to the Centaur application and are not significant for general use. See Sherley, 1962 for summarized boiling heat transfer data.

Steinle, H. F., "Review of Zero-G Studies Performed at General Dynamics/Astronautics," GD/C, American Astronautical Society, Physical and Biological Phenomena Under Zero Gravity Conditions, 2nd Symposium, January 1963.

Covers essentially the same material presented in AY62-0031 by Sherley and Merino (1962).

Swalley, F. E., et al, "Saturn V Low-Gravity Fluid Mechanics Problems and Their Investigation by Full-Scale Orbital Experiment," NASA-MSFC, Proceedings Fluid Mechanics and Heat Transfer Under Low Gravity Symposium, June 1965.

Describes the anticipated low-gravity fluid mechanics problems of the Saturn V/S-IVB stage and the planned SIVB (AS-203) orbital experiment with only limited data presented which is only speculation based on existing technology.

Symons, E. P., "Zero Gravity Propellant Transfer," NASA-LeRC, Space Transportation System Propulsion Technology Conference, Vol. IV, April 1971.

Reviews the results of drop tower work at LeRC on liquid inflow and outflow which covered in NASA reports reviewed elsewhere.

Turnbull, R. J., Melcher, J. R., "Electrohydrodynamic Rayleigh-Taylor Bulk Instability," Physics Fluids, Vol. 12, 1969.

This work is an investigation of stability criterion for an initially static and stratified liquid subjected to an electrical stress and is not concerned with low-g fluid behavior.

Unterburg, W., Congelliere, J., "Zero Gravity Problems in Space Power Plants: A Status Survey," ARJ Journal, Vol. 32, No. 6, A-113, June 1962.

Basically a survey and general discussion of other work and does not add to the state-of-the-art of low-g fluid behavior.

Welch, J. E., et al, "The MAC Method - A Computing Technique for Solving Viscous, Incompressible, Transient Fluid-Flow Problems Involving Free Surfaces," Los Alamos Sci. Lab., LA-3425, March 1966.

Improved codes have been developed; a review of these developments are summarized by Bradshaw, 1974.

Wolczek, O., "On the Technical Realization of Subgravity and Weightlessness," Polish Astronautical Society and Institute for Nuclear Research - Polish Academy of Science, 10th Intl Astro Congress Proceedings, Vol. 1, 1959.

Methods are discussed for the realization of rapid transitions from multi-g field to states of subgravity and weightlessness and vice versa, which does not add to the state-of-the-art of low-g fluid behavior.

Worley, H. E., et al, "An Orbital Facility for Low Gravity Fluid Mechanics Experiments." NASA, TM X-53561, December 1966.

The data contained in this report does not add to the state-of-the-art of low-g fluid behavior.

Zenkevich, V. B., "On the Behavior of a Liquid Under Conditions of Weightlessness," Scientific Research Institute of High Temperatures, High Temperature, Vol. 2, Translated from Telplotizika Vysokikh

Information is not directly applicable to low-g fluid transfer and basic theory has been incorporated into other more recent documents.

INTERFACE CONFIGURATION

Andes, G. M., McNutt, J. E., "Capillary Phenomena in Free Fall," E.I. duPont de Nemours & Co., Journal Aerospace Science, Vol. 29, pp 103-104, January 1962.

Interesting qualitative data, but not pertinent to system design.

Benedikt, E. T., "General Behavior of a Liquid in a Zero or Near Zero Gravity Environment," Norair Division of Northrop, Weightlessness - Physical Phenomena and Biological Effects, Plenum Press, New York, 1961.

This fundamental investigation into surface tension has been covered in more recent thorough works by Reynolds, et al, in the LG series 1961, 1964.

Benedikt, E. T., "Scale of Separation Phenomena in Liquids Under Conditions of Nearly Free Fall," MACDAC, ARS Journal, February 1959.

Sketchy basic information is presented which is not significant in view of current literature.

Berenson, P. J., "Fundamentals of Low Gravity Phenomena Relevant to Fluid System Design," AiResearch Mfg. Co., Proceedings of American Astronautical Society, Physical and Biological Phenomena Under Zero Gravity Conditions, 2nd Symposium, January 1963.

More complete information with design data are presented, ie, Reynolds and Satterlee in SP 106 in Abramson, 1966, and no significant data on interface configuration on other low-g areas appear.

Brazinsky, I., Weiss, S., "A Photograph Study of Liquid Hydrogen Under Simulated Gravity Conditions," NASA-LeRC, TM X -479, February 1962.

Early drop tower work at LeRC with qualitative phenomena only.

Callaghan, E. E., "Weightlessness," NASA-LeRC, Machine Design, Vol. 34, No. 24, October 1962.

A non-technical presentation of fluid behavior in weightlessness is given in which work from NASA TN's reviewed elsewhere are presented at a simplified level.

Chernous'ko, F. L., "Self-Similar Motion of Fluid Under the Action of Surface Tension," USSR, Moscow PMM Vol. 29, No. 1, pp 54-61, 1965.

The relaxation of the interface as the g-level changes is predicted by two equations developed from theory but more workable methods are contained elsewhere.

Clodfelter, R. G., "Fluid Mechanics and Tankage Design for Low Gravity Environments," WPAFB, ASD-TDR-63-506, September 1963.

More extensive information which has been validated is contained in later publications.

DiMaggio, O. D., "Equilibrium Configuration of the Liquid-Vapor Interface in a Rotating Container Under Zero Gravity Conditions," NAR, Proceedings, American Astronautical Society, Physical and Biological Phenomena Under Zero Gravity Conditions, January 1963.

Similar paper to Blackshear, TN D2471, 1964, which is summarized.

Geiger, F. W., "Hydrostatics of a Fluid Between Parallel Plates at Low Bond Numbers," Brown Engineering Co., NASA CR-68658, Brown Technical Note R-159, October 1965.

The discrepancy with results by Reynolds, LG1, 1961 was not resolved elsewhere in the literature. Improved techniques for interface displacement exist: Hastings, 1968, Concus, 1967.

Geiger, F. W., "Hydrostatics of a Fluid in a Cylindrical Tank at Low Bond Numbers," Brown Engineering Co., TNR-207, July 1966.

Other work treats this subject in a sufficient, more usable manner.

Habip, L. M., "On The Mechanics of Liquids in Subgravity," Univ. of Florida, Astronautica Acta, Vol. 11, No. 6, pp 401-409, 1965.

Significant data in this report have been updated in more recent literature.

Jahsman, W. E., "The Equilibrium Shape of the Surface of a Fluid in a Cylindrical Tank," LMSC, Development in Mechanics, Vol. 1, pp. 603-612, Plenum Press, New York, AF04(647)-347, 1961.

Later work contains solutions for interface shape without restrictions on contact angle or Bond number.

Lacovic, R. F., Berns, J. A., "Capillary Rise in the Annular Region of Concentric Cylinders During Coast Periods of Atlas-Centaur Flights," NASA-LeRC, TM X-1558, May 1968.

This is a special case, not of sufficient general applicability to summarize.

Larkin, B. K., "Numerical Solution of the Equation of Capillary," MMC, Journal of Colloid and Interface Science, 23, pp 305-312, 1967.

The equations do not suggest a design tool. See CLEO report (Bowman, 1966), for further analysis.

Li, T., "Cryogenic Liquids in the Absence of Gravity," GD/C, Advances in Cryogenic Engineering, Vol. 7, pp. 16, August 1961.

Analytical development of reduced gravity/surface tension fluid behavior is presented. Same material as Li's article in Journal Chemical Physics, 1962.

Li, T., "Hydrostatics in Various Gravitational Fields," GD/C, Journal Chemical Physics, Vol. 36, No. 9, p. 2369, May 1962.

The highly mathematical treatment here is not readily usable; no design data is presented and the development is criticized by Neu (AIAA J., 1, p. 814, 1963) as not rigorous.

Masica, W. J., "Zero-Gravity Effects," NASA-LeRC, TM X-52395, 1968.

General discussion of the effects of zero-g on liquid configuration which does not add to the state-of-the-art.

Maulard, J., Jourdin, A., "Experimenting on Liquid Behavior at the Weightlessness Laboratory," (Test in French), France, La Recherche Aerospatiale, No. 110, 1966.

This paper presents no pertinent data which has not been covered in reports of LeRC drop tower work.

Moiseev, N. N., et al, "On the Problems of Hydrodynamics in Cosmonautics," Moscow, Kharkov, International Astronautical Federation, 15th International Astronautical Congress, Warsaw, Poland, September 1964.

The status of those problem areas identified have been advanced by technology studies since that time and significant progress has been achieved in reported U.S. studies.

Neu, J. T., Good, R. J., "Equilibrium Behavior of Fluids in Containers at Zero Gravity," GD/C, AIAA Journal, Vol. 1, No. 4, p. 814, April 1963.

Better data is contained in LMSC Handbook (Satterlee, 1967) and in the Stanford LG series (Reynolds, 1964), both summarized in this volume.

Petrash, D. A., Otto, E. W., "Controlling the Liquid-Vapor Interface Under Weightlessness," NASA-LeRC, Journal of Astronautics and Aeronautics, p. 56-61, March 1964.

This paper is only a qualitative treatment of these authors' TN D-1582 (January 1963), summarized in this volume, which contains both theory and experimental results.

Petrash, D. A., et al, "Effect of Contact Angle and Tank Geometry on the Configurations of the Liquid-Vapor Interface During Weightlessness," NASA-LeRC, TN D-2075, October 1963.

More recent quantitative data now available.

Petrash, et al, "Experimental Study of the Effects of Weightlessness on the Configuration of Mercury and Alcohol in Spherical Tanks," NASA-LeRC, TN D-1197, April 1962.

Only qualitative behavior presented.

Petrash, D. A., Otto, E. W., "Studies of the Liquid-Vapor Interface Configuration in Weightlessness," NASA-LeRC, American Rocket Society, Paper 2514-62, September 1962.

Similar material by the same author's is contained elsewhere in more detail (Petrash, TN D-1582, 1963, summarized in this volume and Otto CEP Synopsis, 1966) reviewed in low-g general section.

Petrov, V. M., Chernous'ko, F. L., "Determination of the Equilibrium Shape of a Fluid Under the Effect of Gravity Forces and Surface Tension," (In Russian), USSR, Izv. AN SSSR, Mekhanika Zhidkosti i Gaza, Vol. 1, No. 5., 1966.

Data covered elsewhere (Hastings, TM X-53790, 1968).

Raco, R. J., et al, "Use of an Electric Field to Attain A Zero-Gravity Liquid-Vapor Interface Configuration Under One-Gravity," NASA-LeRC, TM X-52486, 1968.

Use of an electric field to attain a low-g configuration in one-g prior to drop tower test experiments was investigated and found infeasible for greater than a 2.5 cm diameter cylinder. This was also investigated by Dodge, 1970. This is not a significant contribution to the state-of-the-art.

Reynolds, W. C., "Behavior of Liquids in Free Fall," Stanford Univ., Journal Aeronautics/Space Science, Vol. 26, No. 12, December 1959.

Only basic ideas presented; much better data has been developed.

Roennau, L., "Liquid-Gas Interface in Zero-G," Space Tech. Labs, 6101-6374-RU-000, Contract No. AF04(694)-1, December 1961.

No data is reported;only the experimental configuration.

Satterlee, H. M., Chin, J. H., "Meniscus Shape Under Reduced-Gravity Conditions," LMSC, USAF-OSR and LMSC Symposium on Fluid Mechanics and Heat Transfer Under Low Gravitational Conditions, Palo Alto, CA, June 1965.

Data for interface configurations in right circular cylinders has been extensively covered in later work by Hastings (1968) and Concus (1968).

Seebold, J. G., et al, "Capillary Hydrostatics in Annular Tanks," LMSC, AIAA Paper No. 66-425, Journal Spacecraft and Rockets 4, pp. 101-105, January 1967.

Although the paper gives more extensive data than NASA TM X-1973, Labus, 1970, the work by Labus provides experimental verification with notable exception and is summarized.

Seebold, J. G., Reynolds, W. C., "Shape and Stability of the Liquid-Gas Interface in a Rotating Cylindrical Tank at Low G," SRI, USAF-OSR and LMSC Symposium on Fluid Mechanics and Heat Transfer Under Low Gravitational Conditions, Palo Alto, CA, June 1965.

This article is a condensation of LG-4, Seebold and Reynolds (1965) from SRI by the same authors, which report is summarized under Interface Stability.

Shashin, V. M., "Some Problems of the Dynamics of a Space Vehicle With Tanks Partially Filled With Liquid," USSR, International Conference on Space Engineering, 2nd, Venice Italy, May 1969.

A qualitative presentation of some interface shapes in various geometry containers in low-gravity is presented; however it is not sufficient for a design application.

Shashin, V. M., et al, "Equilibrium Shapes of the Free Surface of a Fluid in Gravitational and Magnetic Fields With Surface Tension Forces Taken into Consideration," USSR, NASA-TT-F-13462, May 1970.

A considerably more in depth presentation on magnetic fluid simulation is presented by Dodge, 1970.

Shuleikin, V. V., "Shape of the Surface of a Liquid in Process of Losing its Weightlessness," USSR, NASA-TTF-8373, Doklady, A. N. SSSR, Tom 147, No. 1, 92-95, Moscow, November 1962.

Nothing significant for design purposes is given.

Siegel, R., "Transient Capillary Rise in Reduced and Zero-Gravity Fields," NASA-LeRC, Transaction, ASME, Journal Applied Mechanics, Vol. 28, pp. 165-170, June 1961.

Data is basic in nature and contained in later low-g handbooks.

Siegert, E., et al, "Time Response of Liquid-Vapor Interface After Entering Weightlessness," NASA-LeRC, TN D-2458, August 1964.

This approach requires an experimental appraisal of an empirical constant K and is not as convenient to use as the more recent work in Hastings TM X-53841, 1969.

Siegert, C. E., et al, "Behavior of Liquid-Vapor Interface of Cryogenic Liquids During Weightlessness," NASA-LeRC, TN D-2658, February 1965.

Nothing new over Paynter's 1964 article except for additional data points.

Slobozhanin, L. A., "Hydrostatics in Weak Force Fields - Equilibrium Shapes of the Surface of a Rotating Fluid in Zero Gravity Conditions," (In Russian, Translation Available), USSR, Izv AN SSSR, Mekhanika Zhidkoski i Gasa, Vol. 1, No. 5, pp. 157-160, 1966.

Highly specialized application; insufficient data presented to be useful.

Srubshchik, L. S., Yudovich, V. I., "On the Asymptotic Integration of the Equilibrium Equations of a Fluid With a Surface Tension in a Gravity Field," Rostov on Don, USSR, Zh, vychisl, Mat. mat. Fiz. 6, 6, 1127-1133, 1966.

Highly mathematical treatment not supported by experiment.

Sterling, K. R., "Behavior of Liquid Hydrogen in a Space Environment," NASA-Hqtrs, British Interplanetary Society, Journal, Vol. 18, p. 245, December 1961.

Does not contain data relative to transfer and the material presented does not contribute to a data bank for fluid transfer.

Symons, E. P., Abdalla, K. L., "Liquid-Vapor Interface Configurations in Toroidal Tanks During Weightlessness," NASA-LeRC, TN D-4819, October 1968.

Pertinent results are included elsewhere (Symons, TN D-6076, 1970).

Welch, P. W., Ujihara, B. H., "Zero-G Mercury Dynamics Analysis," NAR, AIAA Paper No. 73-1121, October 1973.

A mathematical solution is presented for a constrained mercury bladder system in low-g. The assessment of the interface is made to aid in the structural design computations for the system which are achieved with the finite element methods. This paper does not contribute significant data useful for low-g fluid behavior.

Wood, B., "A Zero Gravity Liquid Behavior Problem," GD/C, Proceedings of American Astronautical Society - 2nd Symposium on Physical and Biological Phenomena Under Zero-G Conditions, Los Angeles, p. 72-84, January 1963.

More extensive data in this subject has been published (Petrash, TN D-1582, 1963).

INTERFACE STABILITY

Anliker, M., Pi, W. S., "Effects of Geometry and Unidirectional Body Force ... ie Stability of Liquid Layers," Stanford University, SUDAER No. 150, NONR-22... March, 1963.

Although the intent of the study was to specify surfaces and thicknesses of layers which are stable according to Bond number criteria, the results remain highly theoretical and not readily adaptable to design application.

Banks, R. B. (SEATO Graduate School of Engineering), Chandrasekhara, D. V., (Northwestern univ.), Journal Fluid Mechanics, Vol. 15, Part 1, pp. 13-34, January 1963.

For more pertinent work see Labus and Aydelott, 1971, which is summarized.

Beam, R. M., "On the Stability of a Liquid Layer of Uniform Thickness Spread Over a Rigid Circular Cylinder Subjected to Lateral Accelerations," NASA-Ames, TN D-2450, August 1964.

The Application is minimal, it does not present immediate application to geometry common to the low-g transfer problem.

Beam, J., Anliker, M., "On the Stability of Liquid Layers Spread Over Simple Curved Bodies," Stanford Univ., SUDAER Report No. 104, NONR 225(30), June 1961.

The highly mathematical examination of interface stability on the outer surfaces of spheres and cylinders and the brief examination of interior surfaces provides no design data with reasonable applicability to low-g fluid transfer.

Bellman, R., Pennington, R. H., "Effects of Surface Tension and Viscosity on Taylor Instability," Rand Corp., Quarterly Applied Mathematics, Vol. 12, pp. 151-162, July 1954.

More recent literature is available on techniques for assessing the occurrence of Taylor instabilities (Hurd, 1966, Bowman, 1966, Reynolds, 1964).

Bowman, T. E., "Response of the Free Surface of a Cylindrically Contained Liquid to Off-Axis Accelerations," MMC, Proceedings Heat Transfer and Fluid Mechanics Institute, Stanford Univ. Press, June 1966.

The results of this work are summarized in the final report, NASA CR-651, Bowman, 1966.

Bretherton, F. P., "The Motion of Long Bubbles in Tubes," Trinity College, Cambridge, England, Journal Fluid Mechanics, Vol. 10, pp. 166-188, September 1961.

This rather theoretical effort does not have visible application to low-g fluid transfer.

Burshtein, E. L., Solov'ev, L. S., "Stability of a Rotating Liquid," Academy of Sciences, USSR, Moscow, Soviet Physics - Doklady, Vol. 17, p. 441, November 1972.

The application to low gravity has not been established and no test data is presented.

Concus, P., "Capillary Stability in an Inverted Rectangular Channel for Free Surfaces With Curvature of Changing Sign," Univ. of California at Berkeley, AIAA Journal, Vol. 2, No. 12, December 1964.

The conclusions are not significantly different from Concus, 1963, and the rectangular configuration is not particularly applicable to low-g fluid transfer.

Daly, B. J., "A Technique for Including Surface Effects in Hydrodynamic Calculations," Los Alamos, Journal Computational Physics, Vol. 4, pp. 97-117, January 1969.

This is a companion article to a numerical applications article (Daly, 1969) on the same subject. The importance of surface tension in MAC techniques is discussed (Bradshaw, 1974).

Daly, B. J., "Numerical Study of the Effect of Surface Tension on Interface Stability," Los Alamos, The Physics of Fluids, Vol. 12, p. 1340, July 1969.

This paper does not discuss gravity effects which are available in the SMAC code discussions (Bradshaw, 1974).

Daly, B. J., "Numerical Study of Two Fluid Rayleigh-Taylor Instability," Los Alamos, Physics of Fluids, Vol. 10, p. 297, February 1967.

Primarily qualitative data are presented and a computer model introduced, however, the data presented are not applicable to design and do not address the transfer problem specifically.

Daly, B. J., Pracht, W. E., "Numerical Study of Density-Current Surges," Los Alamos, The Physics of Fluids, Vol. 11, p. 15, January 1968.

Not relatable to low-g fluid transfer.

Emmons, H., et al, "Taylor Instability of Finite Surface Waves," Harvard Univ., Journal Fluid Mechanics, Vol. 7, Part 2, pp. 177-193, 1960.

This work is excellent for a description of Taylor instabilities but does not contain valid data for low-g fluid transfer application. For an applicable treatment of instabilities, see Bowman, 1966.

Fontenot, L. L., Bernstein, E. L., "Stability of Nonlinear Vehicle Systems," GD/C, GDC-DDF66-009, Contract No. NAS8-20270, December 1966.

The highly mathematical treatment with extensive derivations does not develop any data or usable models applicable to the liquid during low-g transfer.

Fung, F. C. W., "Dynamic Response of Liquids in Partially-Filled Containers Suddenly Experiencing Weightlessness," Cornell Aero Lab., Proceedings of Symposium - Fluid Mechanics and Heat Transfer Under Low Gravity, Palo Alto, Ca., P. 7-1 to 7-32. June 1965.

A highly theoretical and mathematical solution is presented which has as one assumption, the slope of the free surface is everywhere small, i.e., tan θ is large in comparison to unity (θ = contact angle). This assumption is seldom valid. No experimental data is shown and little graphical data is given.

Gerlach, C. R., "Surface Instability and Disintegration of Liquid in a Longitudinally Excited Container, SwRI, Technical Report 9, SwRI Project No. 02-1391, Contract No. NAS8-11045, March 1967.

This same information is presented in a Journal Spacecraft article (Gerlach, 1967) which is summarized. The information is valid and necessary since it indicates response to vehicle disturbances attributable to engine transients.

Greenspan, H. P., Howard, L. N., "On a Time-Dependent Motion of a Rotating Fluid," MIT, Journal Fluid Mechanics, Vol. 17, No. 385, May 1963.

The basic technology presented is not low-g; however, application to rotational type liquid orientation is summarized in a report by Morgan, 1968.

Habip, L. M., "Capillary Stability of Rotating Dielectric Liquid Cylinder in an Electric Field," Univ. of Florida, Proceedings of the SE Symposium on Missiles and Aerospace Vehicle Science, Paper No. 51, NASA-NSG-542, December 1966.

This work superimposes the electrical field on the rotating cylinder stability analysis, however, inadequate data and verification exist to merit its use.

Hirt, C. W., "Heuristic Stability Theory for Finite-Difference Equations," Los Alamos, Journal of Computational Physics, Vol. 2, p. 339, 1968.

The stability of fluids is calculated using the marker-and-cell technique; applications of the MAC technique are summarized by Bradshaw (1974).

Hirt, C. W., Harlow, F. H., "A General Corrective Procedure for the Numerical Solution of Initial-Value Problems," Los Alamos, Journal of Computational Physics, Vol. 2, p. 114, 1967.

Not applicable to low-g transfer of fluids.

Hirt, C. W., Shannon, J. P., "Free-Surface Stress Conditions for Incompressible-Flow Calculations," Los Alamos, Journal Computational Physics, Vol. 2, p. 403, 1968.

This method is adequately described in a summarized report by Bradshaw, 1974.

Jetter, R. I., "Orientation of Fluid Surfaces in Zero Gravity Through Surface Tension Effects," ADL, Physical and Biology Phenomena in a Weightless State - Advances in Astronautical Sciences, Vol. 14, p. 60, January 1963.

The qualitative data is not generalized to a correlation suitable for design. This represented one-g tests.

Kholin, B. G., "Effect of the Form of Regular Perturbations of the Surface of a Liquid Stream on its Disintegration Into Drops," Soviet, Lenin Khar'kov Poly. Inst., Soviet Physics - Doklady, Vol. 15, No. 9, p. 849, March 1971.

Does not consider the aspects of gravity sensitivity or low-g fluid behavior.

Kirko, I. M., et al, "Phenomenon of the Capillary 'Ball Game' Under the Condition of Weightlessness," Academy of Sciences of the Latvian SSR, Soviet Physics - Doklady, Vol. 15, No. 4, 71A-11925, November 1970.

The data presented are the fundamental laws and the energy analysis is for mercury droplets rebounding from hydrochloric acid solution.

Labus, T. L., "Gas Jet Impingement on Liquid Surfaces During Weightlessness," NASA-LeRC, TN D-5720, March 1970.

An extension of this work is presented by Labus and Aydelott, 1971, which is summarized.

Lepper, R., "Experimental Studies of the Hydrodynamic Behavior of Liquids in a Zero Gravity Environment," Norair Div. of Northrop Corp., ASG-TM-61-13-Z5, November 1961.

Better, more complete data is presented elsewhere in more recent literature.

Lewis, D. J., Taylor, G., "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes," Univ. of Cambridge, Proceedings of Royal Society A, Vol. 201, pp 192-196, January 1950.

Later work has been done to apply this initial work to the low-gravity application, (Bowman, 1966).

Lynn, Y. M., "Free Oscillation of a Liquid During Spin Up," Ballistic Research Lab., AD-769 710, August 1973.

This is an analytical study of liquid in a fully-filled cylinder applicable to liquid-filled projectiles.

Masica, W. J., et al, "Hydrostatic Stability of the Liquid-Vapor Interface in a Gravitational Field," NASA-LeRC, TN D-2267, May 1964.

The results of a series of one-g tests are extended to low-g drop tower tests in a follow-up work (Masica, 1964, D-2444) and are presented and discussed in the summary of that report.

Masica, W. J., Salzman, J. A., "An Experimental Investigation of the Dynamic Behavior of the Liquid-Vapor Interface Under Adverse Low-Gravitational Conditions," NASA-LeRC, Proceedings of Symposium - Fluid Mechanics and Heat Transfer Under Low Gravity, Palo Alto, Ca., pp 2-1 to 2-18, June 1965.

This paper covers the work of NASA TN's 2444 (Masica, 1964) and 4066 (Masica, 1967), each of which have been summarized to provide adequate details of work.

Melcher, J. R. (MIT), Hurwitz, M. (Dynatech), "Gradient Stabilization of Electrohydrodynamically Oriented Liquids," Journal Spacecraft, Vol. 4, p. 864, July 1967.

Techniques for use of electric fields to stabilize liquids are discussed in a report by Blutt, 1968.

Melcher, J. R., Smith, C. V., Jr., "Electrohydrodynamic Charge Relaxation and Interfacial Perpendicular Field Instability," MIT, The Physics of Fluids, Vol. 12, p. 778, April 1969.

This subject is adequately covered under dielectrophoresis summarization (Blutt, 1968).

Melcher, J. R., Schwartz, W. J., Jr., "Interfacial Relaxation Overstability in a Tangential Electric Field," MIT, The Physics of Fluids, Vol. 11, p. 2604, December 1968.

The concepts of dielectrophoretic control are covered elsewhere (Blutt, 1968).

Melcher, J. R., Warren, E. P., "Continuum Feedback Control of a Rayleigh-Taylor Instability," MIT, Physics Fluids, Vol. 9, p. 2085, November 1966.

The aspects of low gravity fields and fluid transfer are not discussed. The work of Blutt (1968) is summarized and addresses application of electrical fields.

Merkin, J. H., "The Flow of a Viscous Liquid Down a Variable Incline," School of Mathematics, Univ. of Leeds, United Kingdom, Journal of Engineering Mathematics, Vol. 7, No. 4, p. 319, October 1973.

Not applicable to low-gravity transfer.

Nayfeh, A. H., Saric, W. S., "Non-linear Kelvin-Helmholtz Instability," Aerotherm Corp. and Sandia Lab., Journal Fluid Mechanics, Vol. 46, Part 2, pp. 209-231, 1970.

This highly mathematical approach to the non-linear Kelvin-Helmholtz instability does not address gravity effects on propellant transfer.

Petrash, D. A., et al, "Effect of the Acceleration Disturbances Encountered in the MA-7 Spacecraft on the Liquid-Vapor Interface in a Baffled Tank During Weightlessness," NASA-LeRC, TN D-1577, January 1963.

This small amount of data (one point) affords no generalization of interface stability which is of a design nature. No attempt is made to use the data to verify a stability model or criteria.

Petrash, D.A., Otto, E. W., "Controlling the Liquid-Vapor Interface Under Weightlessness," NASA-LeRC, Journal Astronautics and Aeronautics, pp. 56-61, March 1964.

Information was useful when presented but is now contained in other sources (such as Mariner 75 reports) that are summarized.

Rabinovich, B. I., et al, "Plotting of the Dynamic Stability Domains for Longitudinal Vibrations of Liquid Propellant Space Vehicles," USSR, Kosmicheskie Issledovaniya, Vol. 11, p. 651, September 1973.

This paper is not directed towards low-gravity or the transfer process; further it does not specifically address interface stability.

Rajappa, N. R., "A Non-Linear Theory of Taylor Instability of Superposed Fluids," Stanford Univ., PhD Dissertation, 1967.

No data is developed applicable to low-g transfer; the study is highly theoretical without direct application to fluid transfer.

Rajappa, N. R., Change, I. D., "Surface Tension Effects on the Motion of a Bubble and Spike Generated by Taylor Instability," Stanford Univ., SURAAD 286, 1966.

This report is exactly the same data presented in Rajappa, 1967, PhD thesis; it is a mathematical treatment with no design data or tools presented.

Randolph, B. W., "Linear Approaches to the Dynamics of Fluids Subjected to Time Varying Body Forces," Northrop Corp., NSL 63-21, Contract No. NASr-23, April 1963.

This work has been extended and improved by investigators (Bowman, 1966, Hurd, 1966), and experimentalists at LeRC (Masica, 1966).

Rose, R. G., "Dynamic Analysis of Longitudinal Instability in Liquid Rockets," GD/C, AIAA 66-472, Contract No. AF04(611)-9956, June 1966.

A mathematical model is developed which addresses overall vehicle stability, however the emphasis is primarily on the structure and does not address interface stability. Further, the model is not readily related to low-g transfer.

Ross, D. K., "The Stability of a Rotating Liquid Mass Held Together by Surface Tension," Univ. of Melbourne, Australian Journal of Physics, Vol. 21, p. 837, 1968.

The configuration has little applicability and does not consider influences of a non-rotating g-field.

Rumianstev, V. V., "On the Stability of Motion of a Rigid Body Containing a Fluid Possessing Surface Tension," USSR, PPM Vol. 28, No. 4, May 1964.

A purely mathematical treatise to investigate the complexity of the numerical solution for a fluid surface when surface tension is considered with no workable model offered and no data presented.

Scriven, L. E., "Dynamics of a Fluid Interface," Shell Development Co., Chemical Engineering Science, Vol. 12, pp. 98-108, 1960.

This is a highly theoretical paper which derives the basic equations for the shear effect at a static interface and in two-phase flow. No data is presented and the low-g aspects are not considered.

Serebryakov, V. N., "Control of the Dynamics of a Two-Phase Liquid-Gas Weightless Medium With the Aid of Surface Effects," USSR, NASA TT F-469, Kosmichaeskiye Issledovaniya, Vol. 4, No. 5, May 1967.

Nothing on interface configuration. Work relative to capillary acquisition in using screens is covered more recently by Burnett, 1970.

Shuleykin, V. V., "More on a Liquid in Process of Losing Its Weightness, USSR, NASA TT F-8374, Doklady, A. N. SSSR, Tom 147, No. 5, 1075-8, January 1963.

Only a basic discussion is presented; later literature is more complete.

Shuleykin, V. V., "Second Series of Ground Tests With Weightless Liquids," Joint Publications Research Service, JPRS 23259, Doklady Adkedemii Nauk SSR, Vol. 153, No. 6, December 1963.

No significant data is included.

Smith, R. D., "Interfacial Stability of Liquid Layers on Elastic Surfaces," LMSC, Proceedings of Symposium - Fluid Mechanics and Heat Transfer Under Low Gravity, Palo Alto, Ca., pp. 9-1 to 9-35, June 1965.

This theoretical paper considers two-dimensional stability of elastic tanks and lacks direct applicability to low-g transfer. No useful data.

Taylor, G., Lewis, D. J., "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes II," Univ. of Cambridge, Proceedings of Royal Society A, Vol. 202, pp. 81-96, January 1950.

Work has been done to apply this early work to low-g application, (Bowman, 1966).

NATURAL FREQUENCY AND DAMPING

Anon., "Numerical Analysis of Low-g Propellant Flow Problems," MACDAC, Journal Spacecraft, Vol. 7, No. 1, pp. 89-91, AIAA Paper 69-567, Contract No. NAS7-101, January 1970.

The Marker and Cell technique is covered in summary by Bradshaw, 1973.

Abbott, A. S., Gille, J. P., "A Model to Approximate the Effects of Propellant Slosh on Vehicle Dynamics Under Zero Gravity Conditions," NAR, Proceedings of the Southeastern Symposium on Missiles and Aerospace Vehicles Sciences, Paper 99, December 1966.

This mathematical model does not significantly advance the state-of-the-art.

Abramson, H. N., et al, "Propellant Dynamics Problems in Space Shuttle Vehicles," SwRI, Space Transportation System Technology Symposium, Vol. II, p. 59, NASA TMX-52876, July 1970.

This is only a general discussion of potential slosh-settling problems.

Admire, J. R., "Nonlinear Fluid Oscillations in a Partially Filled Axisymmetric Container of General Shape," NASA-MSFC, TN D-5808, June 1970.

This mathematical dissertation does not address low-g problems.

Bauer, H. F., Siekmann, J., "Note on Linear Hydroelastic Sloshing," Georgia Inst. of Technology, ZAMM 49, Helt 10, Seit 577-589, October 1969.

This is a classical mathematical approach to the problem which does not yield any additional new design data for low-g transfer.

Buchanan, H. J., Bugg, F. M., "Orbital Investigation of Propellant Dynamics in a Large Rocket Booster," NASA-MSFC, TN D-3968, May 1967.

This is only one point of data at a point design and does not provide a generalization of the problem. The authors pointed out the need for data on sloshing in the range $0.1 < Bo < 100$.

Buchanan, H. J. (NASA-MSFC), Shih, C. C. (Univ. of Alabama), "An Expression for Ring-Baffle-Slosh-Damping Under Reduced Gravity Conditions," Journal Spacecraft, Vol. 8, No. 3, pp. 294-295, March 1971.

Damping factors for low-g ring baffles includes this correction factor and are reported elsewhere in the literature TN D-6870 (Scholl, 1972) and TN D-5058 (Salzman, 1969).

Bugg, F. M., "Effect of Wall Roughness on the Damping of Liquid Oscillations in Rectangular Tanks," NASA-MSFC, TN D-5687, March 1970.

The concept of induced wall roughness to dampen sloshing does not appear to be a viable candidate in low-g transfer applications.

Chandler, T. S., Fontenot, L. L., "Digital Analysis of Liquid Sloshing in Rotationally Symmetric Tanks Under Weak Gravitational Fields, Vol. 2, UNIDE V, Huntsville, NASA CR-111729, Contract NAS8-21272, March 1970.

Computer program documentation for NAS8-21272 is presented, the theory appears in NASA CR-113117 (Fontenot, 1970). No parametric data is developed.

Chandler, T. S., Lomen, D. O., "Analysis of Fluid Sloshing in Arbitrary Tanks Having Rotational Symmetry: A Correction for Low Gravity Conditions," Vol. 2: Computation Application," UNIDEV, Huntsville, NASA CR-102732, Contract No. NAS8-21272, March 1970.

A computer program is presented for axially symmetric tanks with small perturbations in axial acceleration for Bond numbers ten to infinity. The theory is given in NASA CR-113117, Fontenot, 1970. No numerical design information is developed.

Chin, J. H., Gallagher, L. W., "Effect of Fluid Motion on Free Surface Shape Under Reduced Gravity," LMSC, AIAA Journal, Vol. 2, pp. 2215-2217, Contract No. NAS8-11525, December 1964.

Data in this paper is updated, expanded and presented elsewhere in LMSC work, Hollister, 1967.

Chu, W. H., "Fuel Sloshing in a Spherical Tank Filled to an Arbitrary Depth," SwRI, AIAA Journal, Vol. 2, pp. 1972-1979, November 1964.

Low-g sloshing in spherical tanks has been investigated more recently by Concus, 1969, and experimentally by Coney, 1971.

Chu, W. H., "Low Gravity Liquid Sloshing in an Arbitrary Axisymmetric Tank Performing Translational Oscillations," SwRI, NASA CR-84404, Technical Report 4, Contract No. NAS8-20290, March 1967.

These results are assessed in respect to the overall program results in the summarized final report by Dodge, 1970.

Chu, W., "Sloshing of an Arbitrary Two-Dimensional Tank With Flat Mean Free Surface," SwRI, CASI Transations, Vol. 4, pp. 58-60., March 1971.

The study is analytical and is not compared with experimental results. This work does not significantly add to the work of Dodge, 1970.

Chu, W. H., "Low Gravity Fuel Sloshing in an Arbitrary Axisymmetric Rigid Tank," SwRI, Transactions ASME, Journal Applied Mech., Vol. 37, pp. 828-837, September 1970.

Although the method is general, it is probably more complex than required for earlier published analyses. The verifications are not as extensive as provided with earlier documented work, which is summarized by Dodge, 1970.

Chu, W. H., "Low-Gravity Fuel Sloshing in an Arbitrary Axisymmetric Rigid Tank," SwRI, NASA CR-102361, April 1969.

This work has been expanded on and corrections made to numerical examples and published by Dodge, 1970, and by Chu Transactions ASME, Journal Applied Mechanics, September 1970.

Clark, L. V., Stephens, D. G., "Simulation and Scaling of Low-Gravity Slosh Frequencies and Damping," NASA-LRC, TMX-60484, September 1967.

This has been superseded by more recent work, Salzman (1969) and Dodge (1970).

Concus, P., et al, "Low Gravity Lateral Sloshing in a Hemispherically Bottomed Cylindrical Tank," LMSC, Heat Transfer and Fluid Mechanics Institute Proceedings, pp. 80-97, Contract No. NAS3-7119, 1968.

This journal article is essentially identical to NASA CR-54700 (Concus, 1967), which is summarized.

Cooper, R. M., O'Neill, J. P., "Damping Ratios for Sloshing Liquids in a Cylindrical Tank Having a Hemispherically Domed Bottom and Roof; Applications to the Able-Star Propellant Tanks," STL, STL/TR-59-0000-09780, Contract No. AF04(647)-309, October 1959.

More recent data in slosh damping in low-g is now available as well as handbooks with verified correlations.

Dodge, F. T., "Further Studies of Propellant Sloshing Under Low Gravity Conditions," SwRI, NASA CR-119892, Contract No. NAS8-24022, March 1971.

The work here is not a significant departure from results and correlations presented in the summarized report by Dodge, 1970.

Dodge, F. T., "A Discussion of Laboratory Methods of Simulating Low-Gravity Fluid Mechanics," SwRI, NASA CR-83856, Technical Report 3, Contract No. NAS8-20290, February 1967.

This is a report on one task under a broad contract to investigate aspects of sloshing (Dodge, 1970). No significant data is developed here.

Dodge, F. T., et al, "Magnetic Fluid Simulation of Liquid Sloshing in Low Gravity," SwRI, NASA CR-102869, Technical Report 9, Contract No. NAS8-20290, August 1970.

These results are discussed in respect to the overall program results in the summarized final report by Dodge, 1970.

Dodge, F. T., et al, "Simulated Low-Gravity Sloshing in Spherical Tanks and Cylindrical Tanks With Inverted Ellipsoidal Bottoms," SwRI, NASA CR-61583, Technical Report 6, Contract No. NAS8-20290, February 1968.

These results are assessed in respect to overall program results in the summarized final report by Dodge, 1970.

Dodge, F. T., et al, "Slosh Force, Natural Frequency, and Damping of Low-Gravity Sloshing in Oblate Ellipsoidal Tanks," SwRI, NASA CR-98443, Technical Report 7, Contract No. NAS8-20290, February 1969.

These results are assessed in respect to overall program results in the summarized final report by Dodge, 1970.

Dodge, F. T., Garza, L. R., "Simulated Low-Gravity Sloshing in Cylindrical Tanks Including Effects of Damping and Small Liquid Depth," SwRI, Proceedings of the 1968 Heat Transfer and Fluid Mechanics Institute, Stanford Univ. Press, pp. 67-79, 1968.

This paper is contained in total in the Final Report of NAS8-20290 (Dodge, 1970) which is summarized.

Dodge, F. T., Garza, L. R., "Simulated Low-Gravity Sloshing in Spherical, Ellipsoidal, and Cylindrical Tanks," SwRI, Journal of Spacecraft, Vol. 7, No. 2, pp. 204-206, Contract No. NAS8-20290, February 1970.

This work is covered in the summarized report by Dodge, 1970.

Dodge, F. T., Garza, L. R., "Simulated Low-Gravity Sloshing in Spherical, Ellipsoidal, and Cylindrical Tanks," SwRI, AIAA Journal Spacecraft and Rockets, Vol. 7, pp. 204-206, February 1970.

This paper is contained in total in the Final Report of NAS8-20290 (Dodge, 1970) which is summarized.

Dodge, F. T., Garza, L. R., "Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low Gravity," SwRI, Transactions ASME, Journal Applied Mechanics, Vol. 34, pp. 555-561, September 1967.

This paper is contained in total in the Final Report of NAS8-20290 (Dodge, 1970) which is summarized.

Dodge, F. T., Garza, L. R., "Free-Surface Vibrations of a Magnetic Liquid," SwRI, ASME Paper No. 71-Vibr-24, Contract No. NAS8-20290, September 1971.

This is a research paper to show how magnetic fluids can be used to simulate low-g fluid sloshing. Deviations occur for Bond number less than 1. No useful design data for low-g transfer is presented.

Dodge, F. T., Garza, L. R., "Simulated Low-Gravity Sloshing in Cylindrical Tanks Including Effects of Damping and Small Liquid Depth," SwRI, NASA CR-61469, Technical Report 5, Contract No. NAS8-20290, December 1967.

These results are assessed in respect to other overall results in the summarized final report by Dodge, 1970.

Feng, C. C., "Dynamic Loads Due to Moving Liquid," LMSC, AIAA Paper No. 73-409, March 1973.

This is a paper derived from the report LMSC-HREC D225632 by Feng, 1972. A more complete description of the method is given there. Application of this technique was summarized by Bradshaw, 1974.

Feng, G. C., Robertson, S. J., "Study on Propellant Dynamics During Docking," LMSC, HREC-5712-1, LMSC-HREC D225157, Contract No. NAS8-25712, June 1971.

This is an Interim Report on a study which is reviewed (Feng, 1972). The results are not significant in the marker-and-cell state-of-the-art.

Feng, G. C., Robertson, S. J., "Study on Propellant Dynamics During Docking," LMSC, HREC-5712-2, LMSC-HREC D225632, March 1972.

An addquate description of marker-and-cell technique is provided by Bradshaw (1974). In its present form, the three-dimensional model technique has many limitations to make it of questionable value.

Fontenot, L. L., "Dynamic Stability of Space Vehicles," GD/C, NASA CR-941, Contract No. NAS8-11486, March 1968.

This is a highly mathematical treatment of the sloshing problem. The pendulum model is used to develop a six-degree-of-freedom modeling, however, the results are not reduced to numerical form to produce design data. No model verification is presented.

Fontenot, L. L., "On the Motion of Liquids Enclosed in Aerospace Vehicle Tanks Under Weak Gravitational Fields," Vol. 1, UNIDEV, Huntsville, NASA CR-113117, Contract No. NAS8-21272, March 1970.

No numerical examples are presented and the program does not appear to possess the applicability of Concus, 1967, or Dodge, 1970. A related volume is NASA CR-102732, Chandler, 1970.

Fontenot, L. L., "Theoretical Studies of Propellant Behavior in the State of Weightlessness," GD/C, NASA CR-81711, GDC-DDF66-010, Contract No. NAS8-20364, December 1966.

A theoretical development is performed for fluid behavior in tanks with perturbations in acceleration with no solutions or experimental verification.

Fontenot, L. L., Clark, M. O., "Assessment of Slosh Coupling With Space Vehicle," GD/C, NASA CR-79541, GDC-DDF66-009, Contract No. NAS8-20302, 1966.

This work does not address propellant motion in low-g; see NASA CR-113117, Fontenot, 1970.

Glaser, R. F., "Analysis of Axisymmetrical Vibration of a Partially Liquid-Filled Elastic Sphere by the Method of Green's Function," NASA-MSFC, TN D-7472, November 1973.

The purely mathematical discussion does not lend itself to analysis of the low-g transfer problem.

Gluck, D. F., Gille, J. P., "Fluid Mechanics of Zero G Propellant Transfer in Spacecraft Propulsion Systems," NAR, SAE/ASME Paper 862A, April 1964.

The total subject of liquid supply to the engines after coast is discussed. However, none of the material is developed in adequate detail to provide usable design information.

Gold, H., et al, "Slosh Dynamics Study in Near Zero Gravity," NASA-LeRC, TN D-3985, May 1967.

This was a commendable experimental achievement and most appropriate in 1967, however, the single configuration, single data point does not offer general data for design at this time.

Grosbeck, W. A., "Design of Coast-Phase Propellant Management System for Two-Burn Atlas-Centaur Flight AC-8," NASA-LeRC. TM X-1318, November 1966.

This report considers only a specific application and does not present generalized data applicable to low-g systems design.

Harlow, F. H., Welch, J. E., "Numerical Study of Large-Amplitude Free-Surface Motions," Los Alamos, Physics of Fluids, Vol. 9, p. 842, May 1966.

The use of the MAC technique to analyze sloshing and the resultant Taylor-instabilities are discussed. The use of a MAC technique for fluid studies is adequately discussed in the summarized report by Bradshaw, 1974.

Hirt, C. W., et al, "A Lagranian Method for Calculating the Dynamics of an Incompressible Fluid With Free Surfaces," Los Alamos, Journal Computational Physics, Vol. 5, pp. 103-124, January 1970.

Marker-and-cell techniques were acquately discussed (Bradshaw, 1974). The method described here is limited to minor fluid distortions.

Hung, F. C., "Propellant Behavior in Zero-Gravity," NAR, NASA CR-62508, SID64-1989, Contract No. NAS8-11097, November 1964.

This early work in the field has long been surpassed by the state-of-the-art.

Hurwitz, M., et al, "Dielectrophoretic Control of Propellant Slosh in Low Gravity," Dynatech Corp., NASA CR-98168, Contract No. NAS8-20553, March 1968.

The applications of dielectrophoretic control of propellants is adequately covered in the summarized report by Blutt, 1968.

Hwang, C., "Longitudinal Sloshing of a Liquid in a Flexible Hemispherical Tank," Univ. of Texas. Trans. of the ASME, Journal Applied Mechanics, Vol. 32, p. 665, also ASME Paper No. 65-APM-14, September 1965.

The analysis is for flexible hemispherical tanks supported along the edge. The analysis does not address the low-g sloshing problem. No significant design data is presented.

Khabbaz, G. R., "Dynamic Behavior of Liquids in Elastic Tanks," LMSC, AIAA Journal, Vol. 9, No. 10, pp. 198-1990, October 1971.

This computer program for slosh eignevalues in elastic tanks has potential application, however, experimental verification in 1-g and extension to low-g has not been accomplished.

Kopachevskii, N. D., Myshkis, A. D., "Hydrodynamics in Weal Fields of Force. The Small Oscillations of a Viscous Liquid in a Potential Field of Force," USSR (Translated), Zh. vychisl. Mat. mat. Fiz. 6, 6, 1954-1063, December 1963.

In this mathematical discussion of surface oscillations, no usable data for low-g transfer is developed.

Koval, L. R., "A Zero-g Slosh Problem," TRW, Journal Spacecraft, Vol. 5, pp. 865-868, Contract No. NAS7-100, July 1968.

The mathematical derivation for the free oscillations and the forced motion-effective mass evaluation is presented and closed-form solutions result with no verification of the data offered.

Koval, L. R., Bhuta, P. G., "A Direct Solution for Capillary-Gravity Waves in a Cylindrical Tank," TRW, 1965.

This analytical development is not extended to numerical results nor is data provided of utility to low-g transfer design studies.

Kuttler, J. R., Sigillito, V. G., "Lower Bounds for Sloshing Frequencies," John Hopkins Univ., Quarterly of Applied Mathematics, Vol. 27, p. 405, Contract No. AR-8-0001, October 1969.

This mathematical proof that a lower bound for sloshing frequency can be mathematically derived does not present any data or address the problem of low gravity transfer.

Lomen, D. O., "Digital Analysis of Liquid Propellant Sloshing in Mobile Tanks With Rotational Symmetry," GD/C, NASA CR-230, Contract No. NAS8-11193, May 1965.

This is a computer program documentation for Lomen's work under NASA CR-222, 1965. More recent work is available.

Lomen, D. O., "Liquid Propellant Sloshing in Mobile Tanks of Arbitrary Shape," GD/C, NASA CR-222, Contract No. NAS8-11193, April 1965.

The basic equations for a mechanical analogy of sloshing are developed; however, no verification is presented. More recent work with numerical examples are presented by Concus, 1967, 1969 and Perko 1969.

McNeill, W. A. (Univ. Southern Alabama), Lamb, J. P., (Univ. of Texas), "Fundamental Sloshing Frequency for an Inclined, Fluid-Filled Right Circular Cylinder," Journal Spacecraft, Vol. 7, pp. 1001-1002, August 1970.

The technical effort does not represent a significant contribution to the data in this field.

Miles, J. W., Troesch, B. A., "Surface Oscillations of Rotating Liquid in a Gravity-Free Field," TRW, STL/TR-60-0000-09137, June 1960.

Improved models have been developed since this early work in sloshing and the data are not readily adaptable to the low-g transfer application.

Moiseyev, N. N., Chernous'ko, F. L., "Problems of Oscillations of a Fluid Subjected to Surface Tension Forces," USSR, NASA TT F-10141, 1965.

The equations presented are primarily theoretical and do not lead to immediate applicable design data.

Pao, S. K. P., Siekmann, J., "Oscillations of a Vapor Cavity in a Rotating Cylindrical Tank," Univ. of Florida, Journal Fluid Mechanics, Vol. 31, pp. 249-271, 1968.

The treatment is highly mathematical and is not reduced to a practical state of application. The significance of interface disturbances in a rotating tank is not readily apparent in a transfer application.

Petrov, A. A., "Variational Statement of the Problem of Liquid Motion in a Container of Finite Dimensions," Moscow, PPM Vol. 28, No. 4, pp. 754-758, 1964.

The analytical theory is developed for non-linear oscillations in a gravity/surface tension field. The approach is not developed to the extent of providing any useful data.

Platt, G. K., "Space Vehicle Low Gravity Fluid Mechanics Problems and the Feasibility of Their Experimental Investigation," NASA-MSFC, TM X-53589, October 1967.

The discussion is related to the S-IV and the AS-203 flight. No new data is introduced in this report, moreover data is not presented on the AS203 flight (July 1966) to substantiate the conclusions.

Randolph, B. W., "Fluid Dynamics in a Cylindrical Container After Gravitational Body Force Vanishes Abruptly," IBM, ASME Paper 65-AV-43, March 1965.

A discussion of numerical techniques to solve the Euler equations of fluid motion are discussed with suggestions as to the solution for the Euler equation but no program model was prepared nor is data given.

Reiter, G. S., Lee, D. A., "Zero Gravity Stability Testing of a Liquid-Filled Space Vehicle," TRW, AIChE Symposium on Effects of Zero Gravity on Fluid Dynamics and Heat Transfer, Houston, Texas, Preprint 17C, A65-15255, February 1965.

An experimental, qualitative report with insufficient data which can be applied to design.

Roberts, J. R., et al, "Slosh Design Handbook I," Northrop, NASA CR-406, Contract No. NAS8-11111, May 1966.

The work does not address low-gravity sloshing, although some of the data can be extrapolated to low-g. Adequate data is available in this area; Dodge, 1970; Salzman, 1969.

Ryan, R. S., Buchanan, H., "An Evaluation of the Low G Propellant Behavior of a Space Vehicle During Waiting Orbit," NASA-MSFC, TM X-53476, June 1966.

Although this TM represents a literature survey of design tools thru 1965; it provides no new developments in sloshing correlations.

Salzman, J. A., et al, "Effects of Liquid Depth on Lateral Sloshing Under Weightless Conditions," NASA-LeRC, TN D-4458, May 1968.

Developments here are included in Summary of TN D-5058 (Salzman 1969). This work was in the 2.2 sec tower, and additional work was performed in the 5.1 sec tower for the later report.

Salzman, J. A., et al, "An Experimental Investigation of the Frequency and Viscous Damping of Liquids During Weightlessness," NASA-LeRC, TN D-4132, August 1967.

Results of this study in the 2.2 sec tower are essentially included in TN D-5058 (Salzman 1969) which is on this subject of lateral sloshing in cylinders and is summarized.

Sandorff, P. E., "Principles of Design of Dynamically Similar Models for Large Propellant Tanks," MIT, NASA TN D-99, January 1960.

This report is addressed to selection of models to determine structural similitude for large elastic-wall propellant tanks for coupling of slosh and vehicle stability with no useful data presented.

Schiffner, K., "Dynamic Behavior of Liquid Propellant in the Tanks of the 3rd Stage of the European Eldo-A-Rocket," Bolkow GmbH, Ottobrunn bei Munchen, Germany, IAF Paper P79, October 1968.

Although extensive 1-g full-scale test data is presented, it is not generalized to other tankage and to low gravity application.

Scholl, H. F., et al, "Investigation of Slosh Anomally in Apollo Lunar Module Propellant Gage," NASA-LRC, TM X-2362, October 1971.

The extensive test program resulted in a movie on sloshing, however, this is not a general investigation but is addressed at a specific piece of Apollo lunar module hardware for propellant gauging.

Shashin, V. M., "Dynamics of a Fluid in a Conical Tank During the Transition from Small to Appreciable Gravity" (In Russian), Akademiia Nauk SSSR, Izvestiia, Meckhanika Zhidkosti i Gaza, pp. 74-79, A69-17335, November 1968.

This paper is a discussion of the dynamic loads that can arise in fuel tanks when the engine is fired under weak gravity conditions, however, the method of data presentation makes the data not useful.

Sickmann, J., Chang, S. C., "On Liquid Sloshing in a Cylindrical Tank With a Flexible Bottom," Univ. of Florida, Proceedings of SE Symposium on Missiles & Aerospace Vehicle Science, Huntsville, Alabama, Paper 98, NsG-542, December 1966.

Only limited data is developed in this mathematically oriented paper. A more complete paper is available (Sickmann 1968).

Sickmann, J., Chang, S. C., "On the Dynamics of Liquids in a Cylindrical Tank with a Flexible Bottom," Univ. of Florida, Ingenieur-Archiv, Vol. 37, pp. 99-109, 1968.

This highly mathematical approach to sloshing with rigid sidewalls and flexible bottom tank does not consider the low Bond number range.

Stephens, D. G., et al, "Effectiveness of Flexible and Rigid Ring Baffles for Damping Oscillations in Large Scale Cylindrical Tanks," NASA-LRC, TN D-3878, March 1967.

Material in this report is updated in later work by Scholl, 1972 in TN D-6870 and by Dodge, 1971 in NASA-CR-1880.

Tong, P., "Liquid Sloshing in an Elastic Container," California Institute of Technology, AFOSR 66-0943, June 1966.

This is another mathematical development of sloshing; more recent developments are available which have been more extensively verified.

Tong, P., Fung, Y. C., "The Effect of Wall Elasticity and Surface Tension on the Forced Oscillations of a Liquid in a Cylindrical Container," California Institute of Technology, Symposium on Fluid Mechanics and Heat Transfer Under Low Gravitational Conditions, Palo Alto, June 1965.

This is another mathematical development of sloshing; more recent developments are available which have been more extensively verified.

Toole, L. E. (Chrysler Corp.), Hastings, L. J. (NASA-MSFC), "Behavior of a Sloshing Liquid Subjected to a Sudden Reduction in Axial Acceleration," AIAA/Aerospace Convcrence on Low Gravity Propellant Orientation and Expulsion, Los Angeles, May 1968.

This paper is a brief review of NASA TM-53755 by these authors. More detail is contained in the original document and it is summarized.

Yeh, G. C. K., "Free and Forced Oscillations of a Liquid in an Axisymmetric Tank at Low-Gravity Environments," TRW, Transcript ASME, Journal Applied Mechanics, Vol. 34, p. 23, March 1967.

This technique has been applied by other investigators more recently, i.e. Concus 1969, Dodge 1968, who presented data and typical results. This paper presented no numerical results.

Zeytounian, R. Kh., "On the Oscillations of a Liquid Mass in a Weightlessness State" (In French), Office National d'Etudes et de Recherches Aerospatiazes, France, ONERA-NT-153, N70-29452, 1969.

A mathematical presentation which is not developed in adequate detail for design application.

LIQUID REORIENTATION

Betts, W. S., Jr., "An Analytical Study of Reduced-Gravity Liquid Reorientation Using a Simplified Marker and Cell Technique," GD/C, NASA-CR-120944, GDCA-DDB72-003, Contract No. NAS3-14361, August 1972.

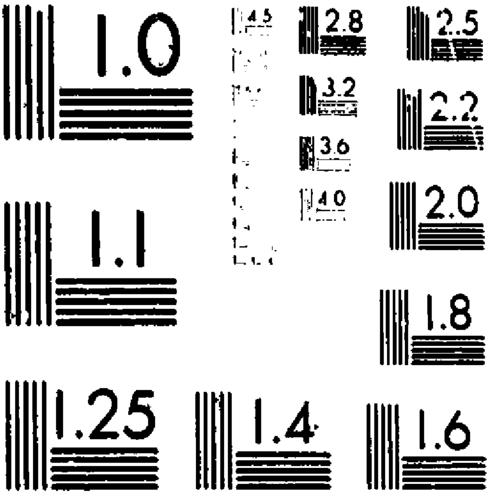
Recommendations and improvements have been implemented in Bradshaw and Kramer, "An Analytical Study of Reduced-Gravity Propellant Settling," 1974 that adequately covers the current state of the art in this area.

Blackmon, J. B., "Proceedings of Low-G Seminar, Chapter 17 Propellant Settling," MACDAC, N71-13101, DAC-63140, May 1969.

Lecture is a summarization of Blackmon, Castle and Heckman, May 1968 that is being summarized.

Bowman, T. E., "Dynamics of an Axi-Symmetric Liquid Free Surface Following a Stepwise Acceleration Change," MMC, Institute of Environmental Sciences 1966 Annual Technical Meeting, April 1966.

Settling from an initially flat interface is covered in Bowman, Liquid Settling in Large Tanks".



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

Concus, P., et al, "Inviscid Fluid Flow in an Accelerating Axisymmetric Container," LMSC, Symposium — Fluid Mechanics and Heat Transfer Under Low Gravity, June 1965.

Results are preliminary with no usable information given.

Gluck, D. F., Gille, J. P., "Fluid Mechanics of Zero G Propellant Transfer in Spacecraft Propulsion Systems," NAR, SAE 862A, April 1964.

Much more sophisticated tests were run by NASA-LeRC and semiempirical expressions were developed (see Salzman and Masica, 1967).

Hollister, M. P., Satterlee, H. M., "Low Gravity Liquid Reorientation," LMSC, Symposium Fluid Mechanics and Heat Transfer Under Low Gravity, June 1965.

The pertinent information in this work is reported in Hollister, et al, 1967, which is being summarized.

Krause, R. P., "Propellant Settling Time from a Zero-G Condition for I-Centaur with TIIID and TIIIB Boosters," GD/C, Memo 966-3/R69/03, March 1969.

Basically uses the information presented in "A Study of Liquid Propellant Behavior During Periods of Varying Acceleration," with no new technology information presented.

Madsen, R. A., et al, "Numerical Analysis of Low-G Propellant Flow Problems," MACDAC et al, AIAA 5th Propulsion Joint Specialist Conference, Paper 69-567, Journal of Spacecraft and Rockets, Vol. 7, #1, January 1970.

Advanced versions of this technique are discussed in Bradshaw and Kramer, "An Analytical Study of Reduced Gravity Propellant Settling", 1974.

Masica, W. J., and Salzman, J. A., "An Experimental Investigation of the Dynamic Behavior of the Liquid-Vapor Interface Under Adverse Low-Gravitational Conditions," LeRC, Symposium on Fluid Mechanics and Heat Transfer Under Low Gravity Conditions, LMSC, Palo Alto, June 1965.

Much of the quantitative information is contained in Salzman, et al, 1973 and Masica and Petrosh, 1965 that are being summarized.

Meadows, M. E., "Propulsion Requirements for Low Gravity Liquid Settling," Proceedings of the Southeastern Symposium on Missiles and Aerospace Vehicles Sciences, Huntsville, Alabama, Paper No. 90, December 1966.

Oversimplified approach to reorientation; does not take into account the overwhelming importance or geysering and recirculation at high reorientation Bond number.

O'Loughlin, J. R., "Liquid Film Drain from an Accelerating Tank Wall, " Boeing, AIAA Journal, Vol. 3, 1, 158, H 214, January 1965.

Analysis neglects inertia and surface forces, therefore, results are not applicable to low-g since surface forces must be large in the absence of inertia.

Perkins, C. K., "Liquid Response to an Orientation Maneuver, " GD/C, 55D 859-7, July 1962.

Trajectory simulated is very specific and results are not usable for other vehicle or operations.

Regetz, J. D., Jr., et al, "Weightlessness Experiments with Liquid Hydrogen in Aerobee Sounding Rockets; Nonuniform Radiant Heat Addition — Flight 4, " NASA-LeRC, TM X-873, 1964.

Results indicate that the effect of initial distribution of liquid and vapor on reorientation flow may be worthy of additional study, however, results are qualitative in nature and do not yield any useful details.

Welch, N. E., Funk, E., "Distribution of Noncondensible Gases in Liquids Under Low-g Conditions, " NASA-MSFC, LMSC Symposium — Fluid Mechanics and Heat Transfer Under Low Gravity, June 1965.

Results are obtained both analytically and experimentally for the distribution of vapor bubbles in a liquid subjected to sloshing motions that disperse to liquid and gas phases, however, the experiments do not represent realistic mission conditions and means for extending the empirical relations to cases not tested are not indicated.

BUBBLES & DROPLETS

Barcatta, F., "Zero-G Liquid Studies: Critical State and Drop Dynamics, " Electro-Optical Systems, Inc., 7170-Q-1, Contract No. NAS8-21012, April 1967.

Data is of an experimental design nature and not pertinent to system design.

Bauer, H. F., "Migration of a Large Gas-Bubble Under the Lack of Gravity in a Rotating Liquid, " Georgia Institute of Technology, AIAA Journal, Vol. 9, No. 7, July 1971.

This is strictly analytical with application to space manufacturing. The word "large" in the title means bubbles with volumes greater than 0.3-m^3.

Bauer, H. F., Siekmann, J., "Theoretical Investigation of Gas Management in Zero-Gravity Space Manufacturing, " Georgia Institute of Technology, N71-11721, October 1969.

A general discussion with no new data presented.

Chernous'ko, F. L., "Motion of a Solid Body With A Cavity Containing An Ideal Fluid and An Air Bubble," Moscow, PMM Vol. 28, pp. 735-745, January 1964.

Although the problem addresses the motion of a bubble when an acceleration is placed on the container, a very realistic problem, this highly mathematical treatment is very theoretical, little is presented to represent its solution.

Davies, R. M., Taylor, G., "The Mechanics of Large Bubbles Rising Through Extended Liquids and Through Liquids in Tubes," FRS, Proceedings Royal Society (London), Ser. A, Vol. 200, No. 1062, pp. 375-390, February 1950.

Basic information on bubble rise is presented which has been incorporated into more recent work.

Goldsmith, H. L., Mason, S. G., "The Movement of Single Large Bubbles in Closed Vertical Tubes," Journal Fluid Mechanics, Vol. 14, Pt. 1, pp. 42-58, September 1962.

Other studies have adequately handled reorientation of large ullage bubbles (Masica and Petrash, 1965).

Habip, L. M., et al, "On the Shape of a Rotating Liquid Drop in an Electric Field," Univ. of Florida, Acta Mechanica, Vol. 4, 1. 107, NASA Grant NsG-542, October 1966.

The application of this phenomena is too limited to be worthy of summarization.

Kana, D. D., Chu, W. H., "Bubble Dynamics In Vibrated Liquids Under Normal and Simulated Low Gravity Environments," SwRI, Technical Report No. 8, N67-30501, Contract NAS8-11045, February 1967.

The application of this work is very limited and requires a prediction of actual induced pressure distributions within a specific space vehicle tank, as well as bubble sizes, both formidable tasks.

Keshock, E. G., Bell, K. J., "Heat Transfer Coefficient Measurements of Liquid Nitrogen Drops Undergoing Film Boiling," Oklahoma State Univ., Advances in Cryogenic Engineering, Vol. 15, p. 271, Jun 1969.

A study consisting of the measurement of the instantaneous heat transfer coefficients between a solid heated surface and vaporizing drops of liquid nitrogen at atmospheric pressure and in a pure nitrogen atmosphere, which does not detail low-g sensitivity.

Knapp, K. K., et al, "Zero-G Liquid Studies: Critical State and Liquid Drop Dynamics," Electro Optical Systems, Inc., N68-15731, EOS 7170, Contract No. NAS8-21012, November 1967.

This is only proposed low-g work, without the actual low-g data and does not add to the state-of-the-art of low-g fluid behavior.

Madsen, R. A., Castle, J. N., "Low-G Bubble Behavi r," MACDAC, Proceedings of Low-G Seminar, Blackmon, et al, N71-13101-119, May 1969.

The work reported is all based on 1-g data with no real effort made to relate to low-g.

Ross, D. K., "The Shape and Energy of a Revolving Liquid Mass Held Together by Surface Tension," Univ. of Melbourne, Australian Journal Physics, Vol. 21, pp. 823-835, 1968.

Analytical treatment only, of a specialized subject not specifically applicable to in-orbit fluid transfer.

Sawi, M. EL., "Distorted Gas Bubbles at Large Reynolds Number," Imperial College, London, Journal Fluid Mechanics, Vol. 62, Part 1, pp. 163-183, 1974.

Gravity is factored into the equations for bubble shape but no discussion of the specific effects of low-g or any comparison with such data is made.

Sy, F. L., "Droplet Fluid Mechanics," Univ. of Wisconsin, Ph.D. Thesis No. 71-20, 695, 1971.

The detailed analysis and testing as accomplished on the flow behavior of single drops; such as terminal velocity, drop deformation, drag coefficients and unsteady state behavior was not at low-g.

FLUID INFLOW

Baumeister, K. J., Simon, F. F., "Leidenfrost Temperature — Its Correlation for Liquid Metals, Cryogens, Hydrocarbons, and Water," NASA-LeRC, Transactions of the ASME, Journal Heat Transfer, p. 166, May 1973.

Although the phenomena of liquid droplets evaporating off hot surfaces is important to tank chilldown in fluid inflow, this data does not address gravity-sensitivity which is very important.

Gauntner, J. W., et al, "Survey of Literature on Flow Characteristics of a Single Turbulent Jet Impinging on a Flat Plate," NASA-LeRC, TN D-5652, February 1970.

This survey paper is not addressing the subject of fluid transfer or low-g fluid behavior, the gravity sensitivity of jets is not discussed, and no new data is generated.

Hetsroni, G. (Israel Institute of Technology), Sokolov, M. (Brown Univ.), "Distribution of Mass, Velocity, and Intensity of Turbulence in a Two-Phase Turbulent Jet," Journal of Applied Mechanics, pp. 315-327, June 1971.

While descriptive equations and graphs are presented to work with mass flow and velocity profiles in analyzing inflow and chilldown to tanks, no data is presented addressing the low-gravity fluid transfer problem.

Heyt, J. W., Jain, S. C., "Evaporation and Liquid Film Dry-Out in Binary Spray Flow," Univ. of Texas, ASME Paper 72-HT-30 presented at AIChE-ASME Heat Transfer Conference, Denver, August 1972.

The solution is geometry sensitive and not applicable to fluid inflow, further no mention of the significance of gravity is made although the high air velocities may overshadow gravity effects.

Povitskii, A. S., Lyubin, L. Ya., "Emptying and Filling Vessels in Conditions of Weightlessness," USSR, Planet, Space Science, Vol. 11, pp. 1343-1358, 1963.

The work is complex mathematically with results presented in a form that is difficult to use and terminology that is confusing.

Shen, H. S., Rockwell, D. O., "Wall Jet Receiver Flow Field," Lehigh Univ., AD-768 882 (MF), THEMIS-LU-TR-18, Contract No. N00014-69-A-0417, August 1973.

Only applicable to fluid amplifier devices and therefore not useful in the current program.

Symons, E. P., "Liquid Inflow to Initially Empty, Hemispherical Ended Cylinders During Weightlessness," NASA-LeRC, TN D-4628, June 1968.

Results are reported in the summary of TM X-2003 (Symons 1970) where tests were extended to larger containers in the 5.1 sec tower.

Symons, E. P., "Liquid Inflow to Partially Full, Hemispherical-Ended Cylinders During Weightlessness," NASA-LeRC, TM X-1934, December 1969.

These results are also discussed in a summarized work by Symons 1971 in TM X-2348 where a more adequate correlation is developed.

Torii, K., "Some Flow Characteristics of a Curved Wall Jet," Univ. of Minnesota, Proceedings of Second International Symposium, Japan, Society of Mechanical Engineers, Tokyo, Vol. 3, pp. 111-119, Microfiche A73-29038, AIAA TIS3/12, September 1972.

No design data is presented and the geometry is not applicable to fluid transfer.

Woerner, R. C., "Study on Liquid Cylinder Filling Technques," ADP Division, Air Reduction Company, Advances in Cryogenic Engineering, Vol. 13, p. 237, August 1967.

Data presented are applicable to specific commercial type cylinders and are not applicable to in-orbit transfer.

Zhitomirskiy, I. S., Pestryakov, V. I., "Calculation of the Hydrodynamic and Heat Transfer Processes Occurring During Filling, Pressurizing, and Emptying of Cryogenic Vessels," USSR, NASA-TT-F-15535, N74-28015, 1973.

Mostly analytical and only applicable to 1-g conditions.

FLUID OUTFLOW

Abramson, H. N., et al, "Some Studies of Liquid Rotation and Vortexing in Rocket Propellant Tanks," SwRI, NASA TN D-1212, January 1962.

An experimental and analytical study of tank draining related to sloshing and vortexing was conducted which was not low-g oriented.

Bhuta, P. G., Koval, L. R., "Sloshing of a Draining or Filling Tank Under Variable G Conditions," TRW, Symposium on Fluid Mechanics and Heat Transfer Under Low Gravity, Palo Alto, June 1965.

Results are too specific to be of general use due to the numerical nature of the solution; also, no comparison is given between analyses and data.

Bizzell, G. D., et al, "An Analytic Study of Liquid Draining From Cylindrical Tanks Under Zero and Low Gravity Conditions," LMSC, A965647, Contract NAS3-11526, February 1970.

Interim Report, Final Report, Bizzell, June 1970 was summarized.

Dergarabedian, P., "The Behavior of Vortex Motion in an Emptying Container," TRW, Proceedings Heat, Transfer and Fluid Mechanics Institute, Stanford,Univ., pp. 47-61, June 1960.

While the results were presented in the form of several equations, the physical implications of the equations were not explained, nor was experimental verification given for the analysis.

Dodge, F. T., "Liquid Rotation and Vortexing During Draining," SwRI, NASA SP-106, The Dynamic Behavior of Liquids in Moving Containers, 1966.

No pertinent information is given except that slosh baffles can be used to control vortexing.

Gluck, D. F., et al, "Distortion of the Liquid Surface During Tank Discharge Under Low G Conditions," NAA, Chemical Engineering Progress Symposium Series, Aerospace Chemical Engineering, Vol. 62, No. 61, 1966.

Similar work covered in Gluck, Journal of Spacecraft and Rockets, 1966.

Hirt, C. W., et al, "A Lagrangian Method for Calculating the Dynamics of an Incompressible Fluid with a Free Surface," Los Alamos, Journal of Computational Physics, Vol. 5, No. 1, pp. 103-124, February 1970.

A Langrangian technique was employed in Bizzell, et al, 1970, which is summarized elsewhere.

Ingram, E., "Equation Governing the Two Dimensional Behavior of a Liquid Surface in a Reduced Gravity Field," Brown Engineering Co., Inc., TN R-165, October 1965.

Report is not readily available.

Ketchum, W. J., "Torus Propellant Tank Liquid Residual Prediction and Experimental Results," GD/C, GDC-BNZ67-063, August 1967.

An internal document that is not readily available, see Ketchum, AIAA 70-1325, 1970.

Lee, C. C., "A Study of Baffle Effects on Flow Behavior Under Low-G Conditions," Brown Engineering Co., Journal Spacecraft, Vol. 6, No. 4, April 1969.

Results are not presented in sufficient detail to be useful.

Madsen, R. A., et al, "Numerical Analysis of Low G Propellant Flow Problems," Journal of Spacecraft and Rockets, Vol. 7, No. 1, pp. 89-91, January 1970.

The marker and cell method was used to solve the Navier Stokes and thermal energy equations cast in finite difference form and solved explicitly as an initial value problem. Basic results are cited in Easton and Catton, 1970, which is summarized.

Miles, J. W., "Notes on the Damping of Free Surface Oscillations Due to Drainage," Aerospace Corporation, Journal Fluid Mechanics, Vol. 12, Part 3, pp. 438-440, 1962.

No pertinent data was presented.

Nussle, R., et al, "Photographic Study of Propellant Outflow from a Cylindrical Tank During Weightlessness," NASA-LeRC, TN D-2572, January 1965.

Early work of a qualitative nature has been superseded by more recent efforts.

Raco, R. J., et al, "Dielectrophoretic Baffling to Control Vapor Ingestion in Weightlessness," Newark College of Engineering, NASA TMX-2040, July 1970.

Not too practical unless dielectrophoresis is used for acquisition as well, which is highly unlikely.

Roberts, R. H., Burns, W. J., "A Liquid Hydrogen Inlet Distributor," NASA-KSC, KSC-10380, 1970.

Presents a brief discussion on use of a distributor to provide for the vaporization of liquid entering a header, in order to equalize the childown of the system, however, no data are presented and insufficient information is given to add quantitatively to the state of the art.

Saad, M. A., DeBrock, S. C., "Simulation of Fluid Flow Phenomena in Propellant Tanks at High and Low Accelerations," LMSC, Journal Spacecraft, Vol. 3, H-191, 1966.

Results are too specifically oriented to Agena to be of general use to other applications.

Schweikle, J. D., et al, "Thermo and Hydrodynamic Experiment Research Module in Orbit," MACDAC, DAC 60594, March 1967.

Two-fluid "low-g simulations" were run at relatively high Froude numbers; not enough details are presented to advance the state of the art.

Streetman, J. W., "Propellant Tank Dropout Residual Analysis and Test," GD/C, 100-32-050, April 1973.

Document not readily available (internal document).

Tallmade, J. A., "A Test of the Medium Speed Theory of Cylinder Withdrawal," Drexel Institute of Technology, I&EC Fundamentals, Vol. 8, No. 1, 70N-73670, February 1969.

Deals with the withdrawal of cylinders from liquid baths and is not applicable to the present program.

Vernon, R. M., "Analysis of Propellant Outflow Conditions During Nuclear Stage Operation," LMSC, AIAA Paper No. 70-677, June 1970.

The overall systems analysis procedure appears useful, however, details of the specific contents of the analyses are not presented.

White, D. A., Tallmadge, J. A., "A Gravity Corrected Theory for Cylinder Withdrawal," Yale University, AIChE Journal, Vol. 13, No. 4, 1967.

Deals with the withdrawing of cylinders from liquid baths and is not applicable to the current program.

Yeh, G. C., Bhuta, P. G., "Expulsion Efficiency of a Bladderless Spherical Tank," TRW, AIAA/Aerospace Conference, May 1968.

Conclusions do not seem logical and results are not in a useful form.

Yeh, G. C. K., Graham, D. J., "Draining of a Liquid from a Transversely Moving Cylindrical Tank," TRW, AIAA Fluid and Plasma Dynamics Conference, Paper No. 69-679, June 1969.

The inviscid linear analysis is extended to include the effect of small transverse motions on the draining of a cylindrical tank with a circular outlet pipe at the bottom, however, no test results or correlations are shown to verify the analyses.

INTERNAL HEAT & MASS TRANSFER, GENERAL

Adelberg, M., "Zero Gravity Heat Transfer," ADL, Proceedings of the Institute of Environmental Sciences, 1963 Annual Technical Meeting, April 1963.

Represents primarily a general survey of other work and is also discussed in other work by the same author, which is reviewed elsewhere.

Adelberg, M., Schwartz, S. H., "Heat Transfer Domains for Fluids in a Variable Gravity Field With Some Applications to Storage of Cryogens in Space," MACDAC, Advances in Cryogenic Engineering, Vol. II, 1965.

The information reported here is essentially the same as that reported by Schwartz and Adelberg in the 1965 Symposium on Fluid Mechanics and Heat Transfer Under Low Gravity Conditions, which report is reviewed elsewhere.

Adelberg, M., Schwartz, S. H., "Thermal Problems Peculiar to Cryogens in Space," MACDAC, 670588, 1967.

Essentially just a general discussion and rehash of other work.

Alts, T., Muller, Ingo, "Relativistic Thermodynamics of Simple Heat Conducting Fluids," Arch Rational Mechanical Analysis, Vol. 48, 1972.

The work is concerned with the difference between relativistic and non-relativistic thermodynamics of a fluid in a gravitational field but the effects of low-g are not addressed.

Eckert, E. R. G., "Goals and Trends in Heat Transfer Research," Univ. of Minnesota, Warme-und Stoffubertraguing 5 (1972) 3-8, 1972.

Does not contain data associated with low-g heat transfer problems.

Gerstein, M., Ellion, M. E., "Study of Forces on Propellants due to Heat Transfer Influencing Propellant Temperature in a Recovery Type Vehicle," Dynamic Science Corporation for LMSC, Report No. R-6 of P-72, January 1963.

Calculations of low-g heat transfer were by conventional means and applied specifically to the Agena; the state-of-the-art with respect to technical capability was not advanced.

Ginwala, A., "Engineering Study of Vapor Cycle Cooling Equipment for Zero-Gravity Environment," Northern Research & Engineering Corporation, WADD TR60-776, Contract No. AF33(616)-6783, January 1961.

Operation at low-g is only speculative, since no low-g data or comparisons with low-g data are presented, and actual low-g test of twisted tape evaporators and condensers is summarized in Feldmanis (1963).

Graham, R. W., et al, "A Survey of Heat Transfer to Low-Temperature Fluids," Space Institute, Univ. of Tennessee, January 1970.

A review of forced convection and natural convection in low temperature (cryogenic) fluids not specifically applicable to low-g; also this paper is not generally available.

Hammel, R. L., et al, "Environmental Research Satellites for Space Propulsion Systems Experiments," TRW, AFRPL-TR-66-290, Contract No. AF 04(611)-10747, October 1966.

An orbital flight experiment to obtain low-g heat transfer coefficients for natural convection, nucleate boiling, and film boiling of Freon 114 is described. Of the two flight experiment packages fabricated, one flew without obtaining useful information because of electronics failure and the second was never flown.

Hedgepeth, L. M., "Zero Gravity Boiling and Condensing," WPAFB, ARS Space Power Systems Conference, 1322-60, September 1960.

Results of tests are discussed, however, specific data are not given and no pertinent conclusions are reached.

Hung, F. C., et al, "Propellant Behavior in Zero Gravity," NAR, NASA CR-62508, M/F X65-14834, Contract No. NAS8-11097, November 1964.

Detailed equations for heat transfer were developed without the means for solution and test data is not presented or even referred to.

Schwartz, S. H., Adelberg, M., "Some Thermal Aspects of a Contained Fluid In a Reduced-Gravity Environment," MACDAC, Proceeding, Fluid Mechanics and Heat Transfer Under Low Gravity, Symposium, Palo Alto, June 1965.

Mainly general discussions with the only data presented being speculation based on existing technology.

Sexl, R., et al, "Study of Interfacial Conductivity," P.E.C. Research Associates, Inc., NASA CR-120989, Micro Folio No. 71-15601, Contract No. NAS8-30171, 1970.

Deals with the analysis and prediction of conduction heat transfer between metal surfaces in contact with each other and not applicable to the present work.

Trusela, R. A., Clodfelter, R. G., "Heat Transfer Problems of Space Shuttle Power Systems," WPAFV, SAE National Aeronautic Meeting, 154C, April 1960.

A general discussion of work done and potential work which should be done, without enough data presented to reach meaningful conclusions.

Zipkin, M. A., "Environmental Problems in the Design of Space Power Systems," Aerospace Engineering, Vol. 20, No. 8, 1961.

Gives some general discussion of design approaches for promoting boiling at low-g, such as using twisted tapes in exchanger tubes, however, no specific data given to advance the state-of-the-art of low-g fluid behavior.

CONVECTION HEAT TRANSFER

Babskiy, V. G., et al, "Thermocapillary Convection in Weightless Conditions," USSR, NASA-TT-F-15535, N74-28015, 1973.

For the most current work on low-g convection see Grodzka and Bannister, 1974, which is summarized.

Bain, R. L., et al, "The Effect of Gravity Inducted Free Convection Upon the Melting Phenomena of a Finite Paraffin Slab for Thermal Control," Colorado School of Mines, Micro Folio No. N73-13130, NASA CR-123954, January 1972.

Applicable to detailed material study and not the specific state-of-the-art of low-g fluid behavior or cryogenic thermal control.

Bannister, T. C., "Heat Flow and Convection Demonstration (Apollo 14)," NASA-MSFC, TMX-64735, MF N73-27797, March 1973.

This work is adequately covered in a summarized paper by Gordzka and Bannister (1974).

Bannister, T. C., et al, "Apollo 14 Heat Flow and Convection Experiments: Final Data Analyses Results," NASA-MSFC, RM-X-64772, MF N73-31840, July 1973.

This work is adequately covered in a summarized paper by Grodzka and Bannister (1974).

Bourgeois, S. V., Jr., "Convection in Skylab M512 Experiments, M551, M552, and M553, Phase B Report," LMSC, NASA CR-124329, Micro Folio No. 73-28852, July 1973.

Work consists of analyzing Skylab experiments M551 (Metals Melting), M552 (Exothermic Brazing), M553 (Sphere Forming), and M566 (Al-Cu Eutectic Growth which are only applicable to space manufacturing.

Bratukhin, Iu. K., Maurin, L. N., "Thermocapillary Convection in a Fluid Filling an Half-Space," USSR, PPM, Vol. 31, No. 3, 1967.

Without low-g test data this detailed analysis does not add significantly to the state-of-the-art of low-g heat transfer. Information, sufficient for the current program, on this subject is found in McGrew and Larkin (1966), which report is summarized.

Catton, I., et al, "Natural Convection Flow in Finite Rectangular Slot Arbitrarily Oriented With Respect to the Gravity Vector," Univ. of California, International Journal Heat Transfer, Vol. 17, pp. 173-184, MF A74-22762, 1974.

By itself, without low-g test data, this work just adds to the large amount of 1-g information available under a large variety of conditions, without advancing the state-of-the-art of low-g heat transfer.

Clark, A., et al, "Spin-up of a Strongly Stratified Fluid in a Sphere," Univ. of Rochester, Journal Fluid Mechanics, Vol. 45, Part 1, pp. 131-149, 1971.

Is primarily concerned with geophysical flows in a 1-g field and does not address the low-g problem.

Davis, S. H., et al, "Motion Driven by Surface Tension Gradients in a Tubing Lining," Johns Hopkins University, Journal of Fluid Mechanics (1974), Vol. 62, Part 4, pp. 737-751, December 1972.

Work applicable to the human respiratory system and not useful to the current study.

Debier, W. R., Wolf, L. W., "The Effects of Gravity and Surface Tension Gradients on Cellular Convection in Fluid Layers With Parabolic Temperature Profiles," Univ. of Micnigan, Journal of Heat Transfer, August 1970.

The work is purely analytical and as pointed out by Grodzka and Bannister, 1974, the actual value and correctness of such work cannot be determined until significant low-g test data is obtained.

Edwards, D. K., "Rotation-Induced, Free-Convection Heat Transfer in a Zero-Gravity Field," TRW, AIAA Journal, Technical Note, Vol. 5, No. 2, February 1967.

This subject does not have primary application to in-orbit fluid transfer problems and more recent and complete work covering fluid rotation in low-g is presented in NASA TR R-386 (Anon.).

Forester, C. K., "Nonequilibrium Storage and Expulsion of Single Phase Cryogens," Boeing, Second Joint AIChE-IIQPR Meeting, May 1968.

This work has been expanded and updated in later reports (Forester, et al, 1970 and Barton, et al, (1972).

Forester, C. K., et al, "Apollo Oxygen Tank Stratification Analysis," Boeing, D2-118357-1, Contract No. NAS9-10364, November 1970.

This work has been expanded and updated in a report by Barton, et al (1972).

Gebhart, B., "Random Convection Under Conditions of Weightlessness," Cornell Univ., AIAA Journal, Vol. 2, No. 2., February 1963.

Later works, reviewed elsewhere, have covered this subject more thoroughly and compared results with flight data, e.g., Martin, et al (1972), Barton, et al (1972), and Grodzka and Bannister (1974).

Gershuni, G. Z., et al, "On Convective Stability in the Presence of Periodically Varying Parameters," USSR, Journal of Applied Mathematics and Mechanics, (PMM) Vol. 34, No. 3, pp. 470-480, 1970.

Strictly analytical with no specific application to low-g heat transfer.

Gresho, P. M., Sani, R. L., "The Effects of Gravity Modulation on the Stability of a Heated Fluid Layer," Univ. of Illinois, Journal Fluid Mechanics (1970), Vol. 40, pp. 783-806, May 1969.

Vibration of a heated liquid layer at 1-g conditions are discussed here, which does not add significantly to the current state-of-the-art of low-g fluid behavior.

Grodzka, P. G., et al, "Types of Natural Convection in Space Manufacturing Processes: Summary Report," LMSC, MF X73-10208, Contract No. NAS8-25577, January 1973.

This subject is adequately covered in a summarized paper by Grodzka and Bannister (1974).

Grodzka, P. G. (LMSC), Bannister, T. C. (NASA-MSFC), "Heat Flow and Convection Demonstration Experiments Aboard Apollo 14," Science, Vol. 176, p. 506, Contract No. NAS8-25577, May 1974.

This work is adequately covered in a summarized paper by the authors in 1974.

Kirk, D. A., "The Effects of Gravity on Free Convection Heat Transfer the Feasibility of Using an Electromagnetic Body Force," WPAFB, WADD Technical Report 60-303, August 1960.

By itself, in the absence of any test data, this work does not add to the state-of-the-art of low-g heat transfer.

Krzywoblocki, M. Z. v., "Gravitational Effects on the Thermal Instability," Michigan State Univ., Journal of Heat Transfer, November 1967.

This is only brief work and purely analytical speculation as to the actual effects of variation in gravity.

Larkin, B. K., "Heat Flow to a Confined Fluid in Zero Gravity," MMC, AIAA No. 67-337, April 1970.

This work has been superseded by more recent work; e.g., Thuraisamy (1972), which uses a similar numerical technique.

Lester, J. M., et al, "Zero-Gravity Thermal Performance of the Apollo Cryogenic Gas Storage System," Beech Aircraft Corp., Advances in Cryogenic Engineering, Vol. 17, p. 156, June 1970.

Very brief summary of the Apollo supercritical storage systems and their basic operating principles, with no technology data presented which would be of interest to the current program.

Lienhard, J. H., et al, "Laminar Natural Convection Under Nonuniform Gravity," Univ. of Kentucky, Journal of Heat Transfer, Vol. 94, No. 1, pp. 80-86, 1972.

The only difference between this work and standard convection theory is that the gravity term is allowed to vary over the body and this does not add to the state-of-the-art of low-g heat transfer.

Markman, G. S., "Convective Instability of a Fluid Layer in a Modulated External Force Field," USSR, Journal of Applied Mathematics and Mechanics (PMM), Vol. 36, No. 1, 1972.

Strictly analytical with limited application.

Martin, E. D., et al, "Effects of Circular Geometry in Simulation of Convection in Rotating Spacecraft Tanks," NASA-ARC, TR R-392, October 1972.

This work is covered sufficiently in the summary prepared for NASA TR R-386, Anon. (1972).

McKinney, P. H., "An Investigation of the Thermodynamic Performance of a Discharging Spherical Pressure Vessel," Rice Univ., Ph.D. Thesis 73-21, 579, 1973.

The General Elliptic Method (GEM) was used to solve the equations and this work is similar to that of Barton, et al (1972), which is summarized.

Polyakov, A. F., "Transient Effects Due to Thermogravity in Turbulence and Heat Transfer," High Temperature Institute, USSR, Teplofizika Vysokikh Temperatur, Vol. 11, No. 1, UDC 536.7, MF A74-13937, February 1973.

As with most work on this subject, the effects of gravity variations are taken into account only by including a gravity term in the theoretical equations.

Potter, J. A. (AiResearch), Brill, F. Z. (USAF), "Zero-Gravity Performance of a Supercritical Oxygen Storage and Supply System for Spacecraft Life Support," Advanced in Cryogenic Engineering, Vol. 9, August 1963.

This work has been superseded by more recent and comprehensive data associated with the Apollo program.

Povitskii, A. S., Lyubin, L. Ya., "Influence of Oscillations On Transport Processes Under Conditions of Weightlessness," USSR, Cosmic Research, Vol. 5, No. 6, UDC 523.54, December 1967.

The work is analytical and is not any more applicable to low-g than other work done on the effects of vibration on convection heat transfer and by itself does not add to the state-of-the-art of low-g heat transfer.

Scriven, L. E. (Univ. of Minnesota), Sternling, C. V. (Shell Development Co.), "On Cellular Convection Driven by Surface Tension Gradients; Effects of Mean Surface Tension and Viscosity," Journal of Fluid Mechanics, Vol. 19, Part 3, 1964.

This work is only analytical with very limited application. Also, the correctness and application at low-g is only speculation without actual low-g test data.

Sollami, B. J., Abraham, W. H., "Heat-Transfer Characteristics of a Supercritical Cryogenic Storage System in Space," Iowa State Univ., Bendix Technical Journal, 1970.

As a result of the Apollo 13 fire, this subject has been covered quite thoroughly and there are a number of other reports, reviewed elsewhere, which are more comprehensive than this one.

Spradley, L. W., et al, "A Numerical Solution for Thermoacoustic Convection of Fluids in Low Gravity," LMSC, NASA CR-2269, Contract No. NAS8-27015, May 1973.

This work is generated for primary application to determining the role of low-gravity convection in space manufacturing processes, and would not have significant application to larger systems, as would be encountered in low-g fluid transfer.

Sternling, C. V., Scriven, L. E., "Interfacial Turbulence: Hydrodynamic Instability and the Marangoni Effect," Shell Oil, AIChE Journal, 1959.

Later work on this subject is reviewed elsewhere.

Tatom, J. W., et al, "Free Convection in Rocket Propellant Tanks," Lockheed Nuclear Products, ER-6216, M/F N65-11696, May 1963.

This is only a progress report.

Thuraisamy, V., "Thermodynamic Flow of Super-Critical Oxygen in Zero Gravity," Bellcomm, Inc., NASA CR-126387, Micro Folio X72-10253, March 1972.

Other work in this area is considered to be more advanced and representative of the state-of-the-art, e.g., Barton et al, (1972), which is summarized.

Vidal, A., Acrivos, A., "Effect of Nonlinear Temperature Profiles on the Onset of Convection Driven by Surface Tension Gradients," Stanford Univ., I&EC Fundamentals, Vol. 7, No. 1, February 1968.

This work has very limited application and is not in itself significant to low-g convection without low-g test data for verification. Reference Grodzka and Bannister, 1974 which report is summarized.

Zeldin, B. (JPL), Schmidt, F. W. (Pennsylvania State Univ.), "Developing Flow With Combined Forced-Free Convection in an Isothermal Vertical Tube," Journal of Heat Transfer, Paper No. 71-HT-6, May 1972.

The influence of gravity on developing forced, laminar flow in a vertical isothermal tube was investigated by means of a numerical analysis and an associated experiment, however, the only gravity effects tested for were those occurring at 1-g.

BOILING HEAT TRANSFER

Adelberg, M., "Boiling, Condensation and Convection in a Gravitational Field," American Institute of Chemical Engineers, Fifty-Fifth National Meeting, February 1965.

The information presented is only of a general discussionary nature and is not significant without more correlation with actual data.

Adelberg, M., "Effect of Gravity Upon Nucleate Boiling," ADL, January 1963.

This represents only initial work in the field to obtain an insight into the effects that gravity might have on boiling heat transfer; more pertinent quantitative data are contained in later reports.

Adelberg, M., Forster, K., "The Effect of Gravity Upon Nucleate Heat Transfer," STL, In Weightlessness — Physical Phenomena and Biological Effects, Plenum Press, 1961.

This work is quite general and is also discussed by the same author in later references which are reviewed elsewhere.

Adelberg, M., Schwartz, S. H., "Scaling of Fluids for Studying the Effect of Gravity Upon Nucleate Boiling," MACDAC, Institute of Environmental Sciences, 1966 Annual Meeting, 1966.

The information presented here, by itself, is not significant since, in general, dimensionless ratios for scaling require correlation with a significant number of data points before their value can be realized. For a more complete treatment of force considerations, see Keshock (1964) and Cochran (1968) which reports are summarized.

Bakhru, N. (IBM Corp), Lienhard, J. H., (Univ. of Kentucky), "Boiling from Small Cylinders," NASA Grant NGR/18-001-035, September 1971.

Covers the same work as reported in NASA CR-2270 by Lienhard and Dhir (1973).

Boulay, Jean-Louis, "Heat Transfer in Liquid Nitrogen in a Zero-Gravity Field," La Recherche Aerostatiale, No. 122, 1968.

Text in French. There is a significant amount of data on this subject from other sources and from the report summary, which is in English, and a review of the Figures it did not appear to warrant translation.

Boulay, J. L., "Heat Transfer In Liquid Nitrogen in a Zero-Gravity Field," O.N.E.R.A., Aerospace Research No. 122, February 1968.

This subject is adequately covered in other reports which have been summarized.

Brentari, E. G., et al, "Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen and Helium," NASA Scientific and Technical, Technical Note 317, September 1965.

The discussion is general and only refers to other work which is reviewed elsewhere.

Clark, J. A., "Gravic and Agravic Effects in Cryogenic Heat Transfer," Univ. of Michigan, Advances in Cryogenic Heat Transfer — Chemical Engineering Program Symposium Series, No. 87, Vol. 64, 1968.

Pertinent aspects are covered in other work and a more complete survey of this subject is presented by Siegel, 1967, which is summarized.

Clark, J. A., Merte, H., Jr., "Nucleate, Transition, and Film Boiling Heat Transfer at Zero Gravity," NASA-MSFC, Contract No. NAS8-825, January 1963.

This work is included in more detail in later reports by the same authors (e.g., Merte 1964), which are reviewed elsewhere.

Cochran, T. H., Aydelott, J. C., "Effects of Subcooling and Gravity Level on Boiling in the Discrete Bubble Region," NASA-LeRC, TN D-3449, September 1966.

This work is adequately summarized in NASA TN D-4301, dated February 1968, by Cochran, et al.

Cochran, T. H., et al, "An Experimental Investigation of Boiling in Normal and Zero Gravity," NASA-LeRC, Paper for presentation at 1967 Annual Meeting, Institute of Environmental Sciences, TMX-52264, April 1967.

This work is reported in NASA TN's, which are reviewed elsewhere.

Cochran, T. H., Aydelott, J. C., "Effects of Fluid Properties and Gravity Level on Boiling in the Discrete Bubble Region," NASA-LeRC, TN D-4070, August 1967.

This work is adequately summarized in NASA TN D-4301, dated February 1968, by Cochran, et al.

Graham, R. W., "Experimental Observations of Transient Boiling of Subcooled Water and Alcohol on a Horizontal Surface," NASA-LeRC, TN D-2507, January 1965.

Even though some speculation was presented as to the effects of gravity on boiling, no low-g data was obtained as back up, and also, the type of investigation has been covered in much more detail in a summarized report by Oker (1973).

Graham, R. W., Hendricks, R. C., "Assessment of Convection, Conduction, and Evaporation in Nucleate Boiling," NASA-LeRC, TN D-3943, May 1967.

Various heat-transfer mechanisms including convection, transient conduction, and evaporation are discussed and evaluated as to their contribution to the overall nucleate-boiling heat flux, however, this is not low-g and other work covering the low-g problem is summarized elsewhere.

Heath, C. A., et al, "The Effect of the Orientation and Magnitude of Gravity Fields Upon Film Boiling from a Flat Plate," Washington Univ., NSF Grant GP 530, March 1964.

Elevated gravity tests are not considered significant for low-g until compared with actual low-g data to cover a complete range of accelerations, which was not done here.

Hedgepeth, L., Zara, E. A., "Zero Gravity Pool Boiling," USAF, ASD TDR-63-706, September 1963.

This paper presents the results of nucleate pool boiling of water under low-g, as tested in a KC-135 aircraft, however, the nature of the tests are such that meaningful substantial conclusions could not be reached.

Hendricks, R. C., "Film Boiling From Spheres — A Comparison of Theory and Data at Standard and Reduced Gravity," NASA-LeRC, TM X-2344, August 1971.

No new test data was presented and the correlations made with existing data were not extensive enough to reach any final conclusions.

Kirichenko, Yu. A., "Heat Transfer With Nucleate Boiling of Liquids Under Weak Mass Force Field Conditions," USSR, NASA-TT-F-15535, N74-28015, 1973.

This subject is adequately covered in other reports summarized elsewhere.

Kirichenko, Y. A., Dolgoi, M. L., "Study of Boiling in Flat Inclined Containers, Modeling Weak Gravitational Fields," Academy of Sciences, Ukrainian, Teplofizika Vysokikh Temperatur, Vol. 8, No. 1, pp. 130-135, 1970.

A method is proposed for modeling weak gravitational fields, for boiling heat transfer, using a thin flat liquid container oriented at various angles with the horizontal, however, the value of the proposed method and the data obtained are only speculative since no real low-g data is used for comparison and there is no real basis for establishing similarity with boiling in a large volume.

Kirichenko, Y. A., et al, "Investigation of Heat Transfer During Boiling Employing Simulated Weak Gravitational Fields," USSR, NASA TT F-12, 940, M/F-N70-25610, August 1969.

This work is included in a 1970 report by the author which is summarized.

Kirichenko, I. A., Verkin, B. I., "Simulation of Weightlessness and Weak Gravitational Fields in Heat-Transfer Studies During Boiling (In Ukrainian)," Technical Information Service, American Institute of Aeronautics and Astronautics, Inc., A69-41235, 1968.

Does not appear to have verified the techniques and does not present much data. Looks like mostly theory.

Kotake, S., "Effects of Reduced Gravity on Nucleate Boiling," Univ. of Tokyo, Bulletin of JSME, Vol. 12, No. 54, 1961.

This work essentially confirms that of others and the report does not present enough data to add significantly to the current state-of-the-art.

Larkin, B. K., "Thermocapillary Flow Around Hemispherical Bubble," AIChE Journal, Vol. 16, No. 1, January 1970.

The analysis provides only unconfirmed conclusions and does not in itself add to the current state-of-the-art of low-g boiling.

Lewis, E. W., "Boiling of Liquid Nitrogen in Reduced Gravity Fields with Subcooling," Univ. of Michigan, Technical Report No. 2, NASA CR-98248, Contract No. NAS8-20228, May 1967.

Data and conclusions of primary interest are contained in a report by Merte (1970), NASA CR-103047.

Lienhard, J. H., "Gravity Boiling Studies," Kentucky Univ., NASA CR-118638, Micro Folio N71-25963, May 1971.

Narrative summary of work done under NASA Grant NGL 18-001-035 up through December 1970. Specific results and data are not presented and pertinent references presented are reviewed elsewhere.

Lyon, D. N., et al, "Peak Nucleate Boiling Fluxes for Liquid Oxygen on a Flat Horizontal Platinum Surface at Buoyancies Corresponding to Accelerations Between -0.03 and $1g_E$," Univ. of California, AIChE Journal, Vol. 11, No. 5, 1965.

The specific data presented is subject to some question until it or the test method employed is verified by long term low-g data. The use of magnetic fields in general to study boiling is covered in a report by Papell (1966) which is summarized. Also, later O_2 work was done by Kirichenko (1970), which report is summarized.

McGrew, J. L, Bamford, F. L., "Marangoni Flow: An Additional Mechanism in Boiling Heat Transfer," MMC, Science, Vol. 153, No. 3740, pp. 1106-1107, September 1966.

This work is reported in greater detail by McGrew (1966) in NASA CR-652 which report is summarized.

McGrew, J. L., et al, "Boiling Heat Transfer in a Zero Gravity Environment," MMC, SAE-862C, C-90, M-64-70, April 1964.

The data presented is insufficient to support any meaningful conclusions.

Merte, H., Jr., Clark, J. A., "Pool Boiling in an Accelerating System," Univ. of Michigan, Journal of Heat Transfer, Transactions of ASME, August 1961.

Elevated gravity tests are not considered significant for low-g until compared with actual low-g data to cover a complete range of accelerations, which was done in later works which are reviewed elsewhere.

Merte, H., Jr., Clark, J. A., "Boiling Heat Transfer With Cryogenic Fluids at Standard, Fractional and Near-Zero Gravity," Univ. of Michigan, Journal of Heat Transfer, ASME, August 1964.

In its essentials this work is covered by the authors in other reports; e.g. (Merte 1970) which is summarized.

Merte, H., et al, "Boiling Heat Transfer to LN_2 and LH_2: Influence of Surface Orientation and Reduced Body Forces," Univ. of Michigan, 1971 Congress International Institute of Refrigeration Commission 1, Preprint 1.62, 1971.

New data presented comes from Merte (1970), NASA CR-103047, which is summarized.

Prisnyakov, V. F., "Boiling Under Reduced-Gravity Conditions," USSR, Cosmic Research, Vol. 8, October 1971.

This work presents a simple correlation of some existing test data, but is not extensive or complete enough to reach significant conclusions beyond those previously reached on this subject.

Rehm, T. R., "Subcooled Boiling in a Negligible Gravity Field," Denver Research Institute, NASA Grant NsG-143-61, May 1965.

There has been a significant amount of work accomplished on this same general subject, which include low-g testing, which was not included in the current work (Ref. Cochran 1968 and Keshock 1964).

Rohsenow, W. M., "Boiling," MIT, Annual Review of Fluid Mechanics, Vol. 3, p. 211, 1971.

The effect of gravity on pool-boiling is only briefly discussed and then only in terms of other work which is reviewed elsewhere.

Shelef, G., "The Interplay of Surface Tension, Inertial, and Gravitational Forces in the Nucleate Boiling 'Burnout' Heat Flux," Univ. of California, Ph.D. Thesis No. 69-18, 1969.

More significant data related to the low-g problem are presented in other reports reviewed elsewhere.

Siegel, R., Keshock, E. G., "Effects of Reduced Gravity on Nucleate Boiling Bubble Dynamics in Saturated Water," NASA-LeRC, AIChE Journal, Vol. 10, No. 4, July 1964.

The major results obtained here are further evaluated along with additional data by Keshock and Siegel, (1964), which report is summarized.

Siegel, R., Keshock, E. G., "Nucleate and Film Boiling in Reduced Gravity from Horizontal and Vertical Wires," NASA-LeRC, TR R-216, February 1965.

The data here is covered by Siegel (1967), which report is summarized (ref. Lienhard 1970 and 1973).

Siegel, R., Usiskin, C., "A Photographic Study of Boiling in the Absence of Gravity," NASA-LeRC, ASME Av. Conference, Los Angeles, ASME Transcript, Paper No. 59-Av-37, 1959.

This work has been superseded by more complete data which includes quantitative as well as qualitative results.

Steinle, H. F., "An Experimental Study of the Transition from Nucleate to Film Boiling Under Zero-Gravity Conditions," GD/C, Advances in Cryogenic Engineering, 1960.

Only general type qualitative conclusions could be made from the small amount of data obtained and significantly more complete information on the subject is contained in later works.

Ul'yanov, A. F., Alad'ev, I. T., "Experimental Study of Heat Transfer During Boiling in Conduits During Weightlessness," USSR, Cosmic Research, Vol. 6, March 1968.

It was concluded that over the range of conditions tested, mass velocity 134-328 Kg/m^2-sec and q_w = 70-600 KW/m^2, the heat transfer rate to subcooled water does not change significantly under conditions of reduced gravity, however, the data presented is sketchy and the results are really only qualitative at best. For later data on the subject see TND-5612 by Cochran, 1970, which is summarized.

Usiskin, C. M., Siegel, R., "An Experimental Study of Boiling in Reduced and Zero Gravity Fields," NASA-LeRC, Journal of Heat Transfer, August 1961.

This work has been superseded by better data.

Williamson, K. E., Jr., et al, "A Rocket-Borne, Low Gravity Cryogenic Heat Transfer Experiment," Los Alamos Scientific Laboratory, AIAA/NASA/ASTM/IES 7th Space Simulation Conference, Los Angeles, 1973.

The data presented is only preliminary; a later discussion of this work is presented by Eduskuty, et al (1974), which report is summarized.

CONDENSATION HEAT TRANSFER

Bobe, L. S., Soloukhin, V. A., "Experimental Study of Heat and Mass Transfer in the Condensation of Vapor From Vapor-Gas Mixtures Under Conditions of Viscous and Viscous-Gravitational Flow," USSR, Teplofizika Vysokikh Temperature, Vol. 11, No. 1, A74-13939, February 1973.

As in most condensation work a gravitational acceleration term is included in the equations, however, no work is reported here to verify the applicability to low-g.

Cary, J. D., Mikic, B. B., "The Influence of Thermocapillary Flow on Heat Transfer in Film Condensation," MIT, ASME Paper No. 72-HT-H, M/F A-72-39654, 1972.

The work is analytical only; it does not address the low-g problem, and does not advance the state-of-the-art of low-g condensation heat transfer.

Dhir, V., Lienhard, J., "Laminar Film Condensation on Plane and Axisymmetric Bodies in Nonuniform Gravity," Univ. of Kentucky, Journal of Heat Transfer, February 1971.

As in most condensation work, a gravitational acceleration term is included in the equations; however, no work is reported here to verify the applicability to low-g.

Gellersen, E. W., et al, "Analysis, Criteria Development, and Design of an Orbital Condensing Heat Transfer Experiment, Final Report, Volumes I and II," AiResearch Report No's. 67-1797-1 and -2, Contract No. NAS8-21005, March 1967.

The work accomplished is based essentially on existing technology and, without orbital experimentation, does not add to the current state-of-the-art of low-g condensation heat transfer.

Kosky, P. G., "Thin Liquid Films Under Simultaneous Shear and Gravity Forces," GE, International Journal Heat Mass Transfer, Vol. 14, pp. 1220-1224, December 1970.

This work is concerned with the computation of the film thickness of a liquid with a parallel flow of vapor acting on it, and gravity as referred to in this is basically concerned with that at 1-g.

Lancet, R. T., et al, "The Fluid Mechanics of Condensing Mercury in a Low-Gravity Environment," NAR, LMSC Symposium, June 1965.

No low-g test data is presented or even referred to and thus, as applied to low-g, the data presented is only speculation.

Leppert, G., Nimmo, B., "Laminar Film Condensation on Surfaces Normal to Body or Inertial Forces," Stanford Univ., Journal of Heat Transfer, February 1968.

As in most condensation work a gravitational acceleration term is included in the equations, however, no work is reported here to verify the applicability to low-g.

Lienhard, J. H., Dhir, V. K., "A Simple Analysis of Laminar Film Condensation With Suction," Univ. of Kentucky, Journal of Heat Transfer, Vol. 94, No. 3, pp. 334-336, 1972.

Limberg, H., "Turbulent Flow of A Falling Liquid Film," Berlin, Germany, Archives of Mechanics, Vol. 24, No. 1, 1972.

As in most condensation work, a gravitational acceleration term is included in the equations, however, no work is reported here to verify the applicability to low-g.

Reitz, J. G., "Zero Gravity Mercury Condensing Research," TRW, Aerospace Engineering, September 1960.

The information presented is only qualitative and is covered more thoroughly in later work at NASA-LeRC, which reports are reviewed elsewhere.

Rohsenow, W. M., "Film Condensation," MIT, Applied Mechanics Review, Vol. 23, pp, 487-495, A70-32541, 1970.

This is a review of the various types of condensation and the corresponding equations, including flow in a tube and condensation at a liquid vapor interface, however, with respect to low-g, only simple theory is presented and no test data is included or referred to.

Sturas, J. I., "Mercury Droplet Size and Distribution in Glass Condenser Tube in 1-g and Zero-Gravity Environments," NASA-LeRC, TM X-1338, February 1967.

The work may furnish a starting point for a quantitative statistical description of droplet size distribution in a uniformly cooled condenser tube, however, by itself the data is too specific and is not sufficient for adding to the general knowledge of low-g condensation.

VENTING EFFECTS

Adelberg, M., "Level of a Boiling Liquid in a Low-Gravity Environment," MACDAC, Journal of Spacecraft, Vol. 5, No. 1, January 1968.

Later and more complete work on this subject is presented by Bradshaw, et al (1970) and Navickas and Melton (1970), which reports are reviewed elsewhere.

Aydelott, J. C., Spuckler, C. M., "Venting of Liquid Hydrogen Tankage," NASA-LeRC, TN D-5263, June 1969.

This work is strictly -1g; for more pertinent work, see Labus and Aydelott (1972 and 1974), which reports are reviewed elsewhere.

Larkin, B. K., Bowman, T. E., "The Venting of Saturated Liquids in Zero Gravity," MMC, Proceedings of the 13th Annual Technical Meeting of the Institute of Environmental Sciences, Vol. 2, 1967.

This is the same information as reported under Contract NAS8-11328, which work is reviewed elsewhere (McGrew and Larkin, 1966).

Navickas, J., Madsen, R. A., "Propellant Behavior During Venting In An Orbiting Saturn S-IVB Stage," MACDAC, Advances in Cryogenic Engineering, Vol. 13, pp. 188-198, August 1967.

This testing, along with analysis, was covered in more detail in later reports, such as Bradshaw, et al (1970.

Navickas, J., Melton, H. R., "Vapor Volume Entrained in the Bulk of the Liquid Due to Boundary Layer Boiling In A Low-Gravity Field," MACDAC, Proceedings of Low-G Seminar, Blackmon, et al, N71-13101-119, May 1969.

This is essentially the same work as reported by the same authors in 1970 (ASME Paper 70-HT-SpT-17), which report is reviewed elsewhere.

Simmons, J. A., et al, "Investigation of the Effects of Vacuum on Liquid Hydrogen and Other Cryogens Used on Launch Vehicles," Atlantic Research Corp., Contract No. NAS8-11044, December 1964.

The work is a very detailed analysis of primarily only one aspect of venting (liquid freezing upon exposure to vacuum) and does not address low-g problems or have significant application to in-orbit fluid transfer.

Smith, D. A., Majoros, J., "Control of Liquid Entrainment at Venting," MACDAC, Institute of Environmental Sciences Annual Technical Meeting Proceedings, 1965.

Similar and more complete work on this subject are presented by Bradshaw (1970), Navickas and Melton (1970), and McGrew and Larkin (1966), which reports are reviewed elsewhere.

Walburn, A. B., "An Analytical and Experimental Examination of the Effect of Cryogenic Propellant Venting on Orbital Vehicle Dynamic Behavior," GD/C, Southwestern Symposium in Missiles and Aerospace Vehicles Sciences, Huntsville, December 1966.

This work is covered in greater detail by Walburn, et al, 1968, which report is reviewed below.

Walburn, A. B., et al, "Emergency Propulsive Propellant Venting Systems Concepts," GD/C, October 1968.

The technology presented here has only limited application and consists of detailed analysis and 1-g testing associated with thermodynamics and thrust forces resulting from fluid (liquid and/or vapor and/or solid) flow from a propellant tank into a vacuum.

Youngberg, R. O., "A Technical Note on Propellant Venting for Discoverer, Midas, and Samos Satellites," LMSC, SS-T61-15, LMSD-448154, Contract No. AF04(647)-558, April 1961.

The problem of unbalanced forces being introduced on a vehicle due to venting can be fairly easily solved by proper design and is not by itself a significant technology problem at the present time. Also, the design and operation of such systems is peculiar to each specific vehicle and the work here is not of general use.

FLUID PROPERTIES

Corruccini, R. J., "Surface Tensions of Normal and Para Hydrogen, " NBS, Technical Note No. 322, August 1965.

The effects of gravity were not considered.

Ellison, A. H., Tejada, S. B., "Dynamic Liquid/Solid Contact Angles and Films on Contaminated Mercury, " Gillette Research Institute, NASA CR 72441, N69-12346, Contract NAS3-9705, July 1968.

Dynamic contact angle data were obtained for selected combinations of seven liquids and five solids, however, the effects or potential effects of low-g on the fluid property data were not considered.

Fritsch, K., Carome, E. F., "Behavior of Fluids in the Vicinity of the Critical Point, " John Carroll Univ., NASA CR-1670, NGR 36-006-002, September 1970.

Results of analyses and test of single component fluids CO_2 and SF_6 are presented, but gravitational effects were not explored to the extent necessary to arrive at meaningful conclusions relevant to the current program.

Krasnyi, Yu. P., Shimanskiu, Yu, I., "Thermodynamic Theory of the Gravitational Effect in Binary Mixtures, " USSR, NASA TT F-12,397, N69-34742, August 1969.

The gravitational effect as used here means the changes in the characteristics of matter with altitude, and, as such, is strictly theoretical but not directly applicable to the present program.

Lyerly, G. A., Peper, H., "Studies of Interfacial Surface Energies, " Harris Research Laboratory, NASA CR-54175, Contract No. NAS3-5744, December 1964.

Low-g effects were not considered.

Razouk, R., "Surface Tension Propellants, " JPL, JPL Quarterly Technical Review, Vol. 2, No. 1, April 1972.

Experiments were conducted with hydrazine and monomethylhydrazine at temperatures between 275.4 and 353.2K, however, low-gravity effects were not considered.

Saffren, M. M., et al, "Low Gravity Superfluid Helium Cooling Systems, " JPL, Proceedings of Cryogenic Workshop at NASA-MSFC, March 1972.

Orbital flight tests are planned for 1975, however, no low-g data have been obtained to date on this program.

Schwartz, A. M., et al, "Exploratory Studies of Contact Angle Hysteresis, Wetting of Solidified Rare Gases and Surface Properties of Mercury," Gillette Research Institute, NASA CR-72269, May 1967.

The effects of low-g were not considered.

Smith, R. V., "Review of Heat Transfer to Helium 1," National Bureau of Standards, Cryogenics Magazine, February 1969.

No specific low-g data.

APPENDIX C

NASA - LITERATURE SEARCH - KEY WORDS

A retrospective literature search was conducted using the Convair IBM 370 and CDC Cyber 70 computers and the NASA Data Base. The portion of the Data Base searched was 30 September 1974 back through 1969.

A complete listing of the key words employed in the search is presented below. All documents containing words A thru C were cited plus those matching words D through I with words J through YY.

A. Weightless Fluids
B. Settling
C. Expulsion Bladders
D. Gravitation
E. Gravitational Effects
F. Reduced Gravity
G. Weightlessness
H. Gravitational Fields
I. Propellant Transfer
J. Fluids
K. Liquids
L. Liquefied Gases
M. Heat Transfer
N. Thermodynamics
O. Liquid-Liquid Interfaces
P. Liquid-Vapor
Q. Interface Stability
R. Liquid Surfaces
S. Hydrodynamics
T. Capillary Flow
U. Inlet Flow
V. Fluid Dynamics
W. Liquid Rocket Propellants
X. Fluid Mechanics
Y. Propellant Properties
Z. Venting
AA. Exhausting
BB. Interfacial Tension
CC. Wetting
DD. Interfaces
EE. Instruments
FF. Cryogenics
GG. Liquid Flow
HH. Water Flow
II. Fluid Flow
JJ. Vents
KK. Exhaust Systems
LL. Cryogenic Fluids
MM. Liquid Sloshing
NN. Ullage
OO. Rotating Fluids
PP. Rotating Liquids
QQ. Liquid-Vapor Equilibrium
RR. Free Boundaries
SS. Liquid Oxygen
TT. Liquid Hydrogen
UU. Refueling
VV. Fuel Control

WW. Acquisition

XX. Expulsion

YY. Flow

APPENDIX D

ABBREVIATIONS, DEFINITIONS AND NOMENCLATURE

D.1 INDUSTRY AND GOVERNMENT AGENCY ABBREVIATIONS

ADL	Arthur D. Little
AFAPL	Air Force Applied Physics Laboratory
AFFDL	Air Force Flight Dynamics Laboratory
AFOSR	Air Force Office of Scientific Research
AFRPL	Air Force Rocket Propulsion Laboratory
AIAA	American Institute of Aeronautics and Astronautics
AMRL	Aerospace Medical Research Laboratory
ASME	American Society of Mechanical Engineers
CPIA	Chemical Propulsion Information Agency
GD/C	General Dynamics Convair
GD/FW	General Dynamics Fort Worth
GE	General Electric
JPL	Jet Propulsion Laboratory
LMSC	Lockheed Missiles and Space Company
LTV	Ling Temco Vought
MACDAC	McDonnell Douglas Aircraft Company
MIT	Massachusetts Institute of Technology
MMC	Martin Marietta
NAR	North American Rockwell
NASA-GSFC	Goddard Space Flight Center
NASA-JSC	Johnson Space Center (Formerly MSC)
NASA-KSC	Kennedy Space Center
NASA-LeRC	Lewis Research Center
NASA-LRC	Langley Research Center
NASA-MSFC	Marshall Space Flight Center
NBS	National Bureau of Standards
NRC	National Research Corporation
STL	Space Technology Laboratory
SRI	Stanford Research Institute

SwRI	Southwest Research Institute
TRW	Thompson Ramo Woolridge
WPAFB	Wright Patterson Air Force Base

D.2 GLOSSARY OF TERMS

ACS	Attitude Control System
Al Aly	Aluminum Alloy
AS-203	Apollo Saturn No. 203 Flight Vehicle
CRES	Corrosion Resistant Steel
F_2	Fluorine
FEP	Teflon Polymer-Hexafluoropropylene
GHe	Gaseous Helium
GH_2	Gaseous Hydrogen
GN_2	Gaseous Nitrogen
GO_2	Gaseous Oxygen
He	Helium
H_2	Hydrogen
LEM	Lunar Excursion Module
LHe	Liquid Helium
LH_2	Liquid Hydrogen
LM	Lunar Module
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
LOX	Liquid Oxygen
MMH	Monomethyl Hydrazine
MLI	Multilayer Insulation
N_2	Nitrogen
N_2O_4	Nitrogen Tetroxide
O_2	Oxygen
S-IIB	Saturn Two B Vehicle

S-IVC	Saturn Four C Vehicle
Superfloc	Trade Name of GD/C Tufted Insulation System
TFE	Teflon Polymer - Polytetrafluoroethylene
T/M	Telemetering
TPS	Thermal Protection System

D.3 NOMENCLATURE

A	area
a	acceleration
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D, d	diameter
F_{tu}	ultimate tensile stress
G	mass flow flux, $\dot{m}/A$
g	gravity or gravitational constant
g_o	gravitational constant
h	heat transfer coefficient or specific enthalpy
h_f	film heat transfer coefficient
h_{fg}	latent heat of vaporization
k	thermal conductivity
L	length
m	mass
$\dot{m}$	mass flow rate
N	speed, rpm
N_{Bo}, Bo	Bond number
N_{Fr}, Fr	Froude number
N_{Gr}, Gr	Grashof number
N_{Re}, Re	Reynolds number
N_{Pr}, Pr	Prandtl number
N_{We}, We	Weber number

OD	outside diameter
P, p	absolute pressure
q, $\dot{Q}$	heat transfer rate
Q	volume flow rate
R, r	radius
t	time
T	absolute temperature
u, U	velocity
v	specific volume
V	volume
W	weight
$\dot{w}$	weight flow rate
x	distance
X	fluid quality
z	vertical coordinate
Z	compressibility factor
α	thermal diffusivity
β	kinematic surface tension
γ_s	slosh damping coefficient
ΔH	head
ζ	damping ratio
θ	contact angle
μ	dynamic viscosity
ν	kinematic viscosity (μ/ρ)
ρ	density
σ	surface tension
ω	frequency or angular velocity

Subscripts

c	critical

g	gas
i	initial, inside
j	jet
ℓ, L	liquid
n	conditions at normal gravity (1-g)
o	stagnation, outside
p	propellant
s	saturation
T	tank
u	ullage
v	vapor
w	wall
∞	infinity