LOW-G FLUID
BEHAVIOR TECHNOLOGY SUMMARIES

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GENERAL DYNAMICS
Convair Division
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.
FOREWORD

This report was prepared by the Convair Aerospace Division of General Dynamics Corporation in partial fulfillment of Contract NAS3-17514. 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.


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.


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. Monthly, Quarterly, 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 150°. 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.
Figure 1. Conical Tanks

<table>
<thead>
<tr>
<th>Frustum height, X, cm</th>
<th>Diameter, d, cm</th>
<th>Tank cone angle, α, deg</th>
<th>Volume, cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.96</td>
<td>4.15</td>
<td>26.6</td>
<td>91.8</td>
</tr>
<tr>
<td>6.62</td>
<td>5.34</td>
<td>30.8</td>
<td>92.2</td>
</tr>
<tr>
<td>5.72</td>
<td>6.19</td>
<td>50.6</td>
<td>92.6</td>
</tr>
<tr>
<td>3.81</td>
<td>7.53</td>
<td>81.0</td>
<td>84.5</td>
</tr>
</tbody>
</table>

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

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 of 3, 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, $\theta = 0^\circ$

(a) Low percentages of liquid volume.

(b) Moderate to high percentages of liquid volume.

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

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

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 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, $\theta = 0^\circ$. (Seebold, 1966)

Figure 2. Annular interface shape parameters
LOW-GRAVITY LIQUID-VAPOR INTERFACE CONFIGURATIONS
IN SPHERICAL CONTAINERS

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 \( 3.1 \times 10^{-2} \text{g} \). 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

<table>
<thead>
<tr>
<th>Tank eccentricity</th>
<th>Bond number ( n )</th>
<th>Fill level, percent ( a )</th>
<th>Tank bottom -</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0 ( \leq ) 1</td>
<td>( 25 ) ( \leq 25 )</td>
<td>Uncovered ( \leq 12.5 ) Covered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( a = 12.5 )</td>
<td></td>
</tr>
<tr>
<td>0.68</td>
<td>0 ( \leq ) 1</td>
<td>( 37.5 ) ( \leq 37.5 )</td>
<td>Uncovered ( a = 12.5 ) Covered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( a = 12.5 )</td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>0 ( \leq 1 )</td>
<td>( 62.5 ) ( \leq 62.5 )</td>
<td>Uncovered ( a = 12.5 ) Covered</td>
</tr>
<tr>
<td></td>
<td>1 ( \leq 2 )</td>
<td>( 12.5 ) ( \leq 12.5 )</td>
<td>Uncovered ( a = 12.5 ) Covered</td>
</tr>
<tr>
<td></td>
<td>( \geq 5 )</td>
<td>( a = 12.5 )</td>
<td></td>
</tr>
</tbody>
</table>

*Lowest volume tested.

Figure 1. Interface Curvature as Function of Fill Level or Bond Number. Eccentricity, 0.30.

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

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, \( \tilde{t}_p \), 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, \( \tilde{t}_d \), 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

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

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

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 limita-
tions on the Bond number or the contact angle. The solutions are applicable to cylin-
ders, 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 dimension-
   less 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 num-
   bers 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

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° - φ. 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.

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Figure 1. $f(1/2 \pi - \theta)$, 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 $\theta = 0$ deg.
THE EQUILIBRIUM FREE SURFACE OF A CONTAINED LIQUID UNDER LOW GRAVITY AND CENTRIFUGAL FORCES

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 $\omega^2 R^3 / 2\sigma$), 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 out 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. Sebold 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.
Liquid fuel under the influence of a constant thrust in the negative z-direction and a constant rate of rotation about the Y-y axis.

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.

Figure 2. Variation of the \( n \)-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, \( 1 \).

Figure 4. Variations in free surface due to changes in centrifugal number. Bond number, \( 3 \); contact angle, \( 90^\circ \); vapor area ratio, \( 1 \); total tank area, \( 4 \).
TIME FOR A TOTALLY WETTING LIQUID TO DEFORM FROM A GRAVITY-DOMINATED TO A NULLLED-GRAVITY EQUILIBRIUM STATE

OBJECTIVE. - Analytically determine the time required for a liquid to deform from a gravity dominated condition to that of a nullled 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, \( \beta \) is the ratio of surface tension to density, \( \tau \) is the deformation time and \( \tau_p \) is the dimensionless deformation time.

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

where \( R_c \) is one cm (constant).

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

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.

2-20
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

2-21
EFFECT OF SURFACE ENERGY ON THE LIQUID-VAPOR INTERFACE CONFIGURATION DURING WEIGHTLESSNESS

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 590 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.

\[
\frac{\dot{Z}}{Z} = \frac{\frac{\rho}{\sigma} \cos \theta \left( \frac{1}{r} - \frac{1}{R - r} \right) - \frac{1}{2} K Z^2 - \frac{8 \nu (t + Z)}{r^2}}{\left( 1 - \frac{A^2_c}{A^2_a} \right) Z + \frac{A^2_t}{A^2_a} + \frac{1}{A^2_c} + \frac{1}{A^2_t}}
\]

\( A_a \) cross-sectional area of annulus, \( \text{cm}^2 \)
\( A_c \) cross-sectional area connecting passage, \( \text{cm}^2 \)
\( A_t \) cross-sectional area of tube, \( \text{cm}^2 \)
\( K \) entrance-loss coefficient
\( \dot{Z}_a \) initial liquid height in annulus, cm
\( \dot{Z}_t \) effective length in connecting passage, cm
\( \dot{Z}_c \) initial liquid length in tube, cm
\( R \) radius of tank, cm
\( r \) radius of tube, cm
\( Z \) height, cm
\( \rho \) density, g/cm³
\( \sigma \) 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. Petrasch's work is useful in its treatment of the dynamics of the motion.
Figure 1. Sketch of spherical and cylindrical tanks with capillary surface-tension baffles.

(a) 100-milliliter sphere with standpipe.
(b) 400-milliliter cylinder with standpipe.

Figure 2. Sketch of capillary system under consideration showing system parameters:
(a) Capillary-force parameters.
(b) Surface-energy parameters.
(c) Liquid-motion parameters.

Figure 3. Variation of liquid rise in capillary tube as function of time in zero gravity:
(a) Tube diameter, 2.30 centimeters.

Figure 4. Variation of liquid rise in annular space as function of time in zero gravity:
(b) Tube diameter, 0.40 centimeters.
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 interaction and gas flow effects on liquid surfaces.
GAS-JET IMPINGEMENT NORMAL TO A LIQUID SURFACE


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:

$$\frac{W_{em}}{h/d} = 0.57 + 0.5 \beta_{om}$$

when $$H/d \leq 3$$, where $$W_{em} = \rho_{g} \frac{V}{d} \frac{2}{d/\sigma}$$ and $$\beta_{om} = \rho g A \frac{d^2}{\sigma}$$.

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. $$\frac{W_{em}}{h/d}$$, from experiments at $$H/d = 3$$, showed a greater slope ($$\frac{W_{em}}{h/d} = 0.57 + 0.9 \beta_{om}$$) 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:

$$\frac{W_{em}}{h/d} = K_1 + K_2 \beta_{om}$$

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:

$$h = \frac{1}{K_{g}} \frac{\rho g}{\rho_{l} \frac{F_{rM}}{\sigma}} \frac{V^2}{d}$$

where $$F_{rM} = V^2 / \sigma$$. 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

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 N2 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, \( \text{We}_{\text{Mcr}} = \frac{\rho g \bar{V}_j^2 d_0 / \sigma}{\rho g} \), where \( \bar{V}_j \) is the average jet velocity and \( d_0 \) is the nozzle diameter. This critical modified Weber number was experimentally shown to be a function of the Reynolds number and was empirically determined from the data (Figure 2) to be \( \text{We}_{\text{Mcr}} = (\text{Re}^{0.8})/89 \), where \( \text{Re} = \rho g \bar{V}_j d_0 / \mu g \).

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-Helmholtz Instability
SURFACE DISINTEGRATION OF LIQUID IN LONGITUDINALLY EXCITED CONTAINERS

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 \( \rho gd^2/\sigma \) were 1000 to 8000 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 \( \omega \) 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

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/sec² 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 \( V_o \) is given as
   \[ V_o = 0.48 \frac{(aR)^{1/2}}{1 - (0.84/Bo)} \frac{Bo^{4.7}}{R} \] for \( Bo > 1 \)

   The leading edge of the interface accelerates \( a_L = 3.8 V_o^2 / R \)
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 2. Interface Stability Delineated by Lateral Bond Number

Figure 3. Interface Velocity Parameters as Function of 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

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 Δh/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 $cV_m^2R/\sigma$ where $V_m$ is mean velocity in tank and the ratio $\Delta h/R$ where $\Delta h$ 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.

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

Figure 3. Geyser and No-Geyser Domains as Function of Weber Number and Kinematic Viscosity for Relative Interface Displacements of Less Than 5
CRYOGENIC LIQUID EXPERIMENTS IN ORBIT VOLUME 1: LIQUID SETTLING AND INTERFACE DYNAMICS

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 $B_o R$ equal to $\rho a R^2 \cos \alpha / \sigma$ where $\alpha$ is the acceleration angle to the axis and $\sigma_0$ is the initial acceleration angle prior to step change.

3. Figures 3 and 4 indicate the analytical predictions for liquid motion with $B_o R = 250$ and $B_o R = -60$ 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 $We < 10 \text{Bo}^{0.35}$ for $.1 \leq \text{Bo} < 100$. For Bond numbers $> 100$, the jump height at the wall is $\ell$ where $\ell = 0.5R (Fr)$ where $Fr = \frac{U_0^2}{gR}$. 

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

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Flow Rate (gpm)</th>
<th>Chlorinated Jet Velocity (cm/sec)</th>
<th>Acceleration Level</th>
<th>Base Number</th>
<th>Weber Number</th>
<th>Freon Number</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>9.6</td>
<td>12.7</td>
<td>1</td>
<td>7350</td>
<td>115</td>
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<td>1</td>
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<td>300</td>
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<td>56.5</td>
<td>1</td>
<td>7350</td>
<td>2200</td>
</tr>
</tbody>
</table>

Weber Number = $\frac{u^2 \rho}{\gamma}$

Freon Number = $\frac{u^2 \rho}{\gamma}$

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

Figure 2. Normalized Radial Velocity Distributions

Figure 3. Limiting Weber Number Correlations
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 existence 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 \( \Omega_0^2 \) curves, a stable interface exists. Below the dotted line but above the \( \Omega_0^2 \) 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 1961

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 \( B_{\text{crit}} = f \left( \frac{c}{r_w} \sin \theta, \phi \right) \). Maximum critical Bond numbers occur for flat interface \( (\phi = 90^\circ) \). 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 \( \frac{R_i}{R_o} = 1 \), \( B_{\text{crit}} = 1 \times 0.84/3.39 = 0.25 \).

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

3-20
Figure 1. Neutral Stability Curve for Axisymmetric Meniscus-Liquid Above

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

Figure 3. Stability of a Flat Annular Meniscus
HYDROSTATIC STABILITY OF THE LIQUID-VAPOR INTERFACE IN A LOW-ACCELERATION FIELD,

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 $Boc_{crit} = 0.84$ established there, tube diameters were selected for this study. The overall 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

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.

3-24
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 $0^\circ$, $\delta = 0.718$ 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

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 amplitudes 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 < 0.5; 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: Effect of Velocity Parameter on Baffle Pressure Parameter for a Range of Baffle Depths

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

Figure 3: Effect of Baffle Spacings and Depths on Liquid Damping

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 fluorinated ethylene propylene film), D (a polychlorotrifluoroethylene film), E (a polytetrafluoroethylene 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 $\zeta_0$, 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 gauges is now available to be used as flexible baffles.
Table 1. Properties of Candidate Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_{0.0}$ (kg/m$^3$)</th>
<th>$\sigma_{\min}$ (MPa)</th>
<th>$\rho_{\text{yield}}$ (kg/m$^3$)</th>
<th>$\sigma_{\text{ultimate}}$ (MPa)</th>
<th>$f_{\text{max}}$ (Hz)</th>
<th>$\sigma_{\text{min}}$ (MPa)</th>
<th>$\rho_{\text{max}}$ (kg/m$^3$)</th>
<th>$f_{\text{max}}$ (Hz)</th>
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<td>Plastic A</td>
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<td>2 x 10$^{-5}$</td>
<td>0.2 x 10$^4$</td>
<td>1.1 x 10$^4$</td>
<td>4.3 x 10$^3$</td>
<td>1.5 x 10$^1$</td>
<td>8.8 x 10$^3$</td>
<td>7.4 x 10$^3$</td>
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<tr>
<td>Plastic B</td>
<td>1.42 x 10$^3$</td>
<td>2 x 10$^{-3}$</td>
<td>4.2 x 10$^3$</td>
<td>1.0 x 10$^3$</td>
<td>3.1 x 10$^3$</td>
<td>1.9 x 10$^3$</td>
<td>5.3 x 10$^3$</td>
<td>3.8 x 10$^3$</td>
</tr>
<tr>
<td>Plastic C</td>
<td>2.15 x 10$^3$</td>
<td>8 x 10$^{-5}$</td>
<td>3.3 x 10$^3$</td>
<td>0.7 x 10$^3$</td>
<td>2.0 x 10$^3$</td>
<td>1.2 x 10$^3$</td>
<td>2.4 x 10$^3$</td>
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<td>Plastic D</td>
<td>2.30 x 10$^3$</td>
<td>5 x 10$^{-3}$</td>
<td>3.5 x 10$^3$</td>
<td>1.2 x 10$^3$</td>
<td>1.6 x 10$^3$</td>
<td>4.0 x 10$^3$</td>
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<tr>
<td>Plastic E</td>
<td>2.10 x 10$^3$</td>
<td>5 x 10$^{-3}$</td>
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<td>1.1 x 10$^3$</td>
<td>4.0 x 10$^3$</td>
<td>1.6 x 10$^3$</td>
<td>1.5 x 10$^3$</td>
<td>1.6 x 10$^3$</td>
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<tr>
<td>Plastic F</td>
<td>1.45 x 10$^3$</td>
<td>0</td>
<td>2.0 x 10$^{-3}$</td>
<td>4.0 x 10$^3$</td>
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<td>19.0 x 10$^3$</td>
<td>4.5 x 10$^3$</td>
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<tr>
<td>1100614 Alum.</td>
<td>2.70 x 10$^3$</td>
<td>2 x 10$^{-3}$</td>
<td>14.5 x 10$^3$</td>
<td>3.5 x 10$^3$</td>
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<td>1.4 x 10$^3$</td>
<td>6.3 x 10$^3$</td>
<td>1.2 x 10$^3$</td>
</tr>
</tbody>
</table>

NOTE: $6.9 \times 10^4$ newton/m$^2$ = 1 kN/m$^2$.

Figure 1. Simplified Baffle Support System

- a. Stainless steel rigid baffle
- b. Plastic C Flexible baffle

Figure 2. Relative Damping as a Function of Flexibility and Period Parameters (Stephens 1997)

Figure 3. Damping Factors for Flexible Baffles

4-5
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, 0.65, 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 $\Omega$ is defined $\omega (\beta/x^3 + a/x)^{1/2}$ where $a$ is the acceleration, $x$ is the semimajor axis (Figure 1), $\beta$ is surface tension, and $\omega$ 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 $60 < Bo < 100$. 

4-6
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:
   \( \gamma_s = 0.83 N_{GA}^{-0.5} (1 + 8.20 N_{Bo}^{-0.6}) \) 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

\[ x_0 \text{ excitation amplitude} \]

\[ \gamma_0 \text{ damping coefficient} \]

Figure 3. Typical Force Response for Spherical Tanks

Figure 4. Variation of Natural Frequency with Bond Number for Spherical Tanks
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 $\zeta$ 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 $A/W$. 

EFFECTS OF VORTEX SHEDDING ON FUEL SLOSH DAMPING PREDICTIONS
### Table 1. Experimental Data

[Wave decay method]

<table>
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<th>Tank</th>
<th>Zs (in.)</th>
<th>w/s</th>
<th>d/a</th>
<th>Ys +</th>
<th>A/w</th>
<th>t_{meas}</th>
<th>t_o</th>
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<td>0.0667</td>
</tr>
</tbody>
</table>

*Unpublished Ames tests by James Delaurier.

*Estimated from reference (Stephene, 1962)

---

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

(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.
NATURAL FREQUENCY OF LIQUIDS IN ANNULAR CYLINDERS UNDER LOW GRAVITATIONAL CONDITIONS

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:

\[
\Omega^2 = \frac{\omega^2 R^3}{\beta} = f_2 (r/R) + f_1 (r/R) Bo
\]

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, \( \Omega^2 = \frac{\omega^2 R^3}{\beta} \), 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 \( \Omega_A \) 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 \( \Omega^2_A \), 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 Slish 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, $\zeta_{wd}$, is a function of the Galileo number, $Ga^{3/2}g^{1/2}/\nu$, where $g$ is the longitudinal acceleration; $\zeta_{wd} = \text{const.} \cdot Ga^{-1/2}$ for a non-baffled tank. A correction factor is multiplicative for low Bond numbers, i.e., $\zeta_{wd} = \text{const.} \cdot Ga^{-1/2} (1 + \text{const.} \cdot Bo^{-2/5})$. 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 superposition 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
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, 0.6, 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 $B_\alpha$ and $V$ for Tanks of Eccentricity 0, 0.5, 0.68, and 0.8 (Two Circle Eigenvalues are Circled)

$\omega$ = frequency
$H$ = $H/a$ = normal coordinate of free surface
$Z$ = $Z/a$ = axial coordinate
$R$ = $R/a$ = radial coordinate

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

Figure 3. Liquid Response to Square-Wave Lateral Perturbing Acceleration for $B_\eta = 1$, $V = 3/8$, and $e = 0.8$, for $B_\eta/B_1 = 0.7$
LATERAL SLOSHING IN CYLINDERS UNDER LOW GRAVITY CONDITIONS

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, \( \omega \), for deeper liquids \( h/R > 2 \) was correlated by

\[
\omega^2 = (2.6 + 1.84 \text{Bo}) \frac{\sigma}{\rho} R^3
\]

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 \( \delta = K_d \frac{\sigma}{\rho} R^2 \) 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 \( \text{Bo} < 1 \) 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 \( \nu \) is kinematic viscosity and \( \omega \) the natural damping frequency.

5. A damping coefficient \( \gamma = \delta \omega / 2 \pi \) is normalized by \( \sigma \) 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. Effect of Bond Number on Damping Data

Figure 4. Damping Coefficient as Function of Bond Number
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. Travelling 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 acceleration 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 $a_T = 4.0$ for $0 \leq t \leq 0.05$, $a_T = 0$ for $t > 0.005$, $a_z = -2.0$, $Bo = 25$, Contact Angle $= 90^\circ$.

Figure 2. Asymmetric Surface Motion with $a_T = 2.0$, $Bo = 20$, $\Delta T = 0.05$ and Contact Angle $= 45^\circ$.

Figure 3. Asymmetric Surface Motion with $a_T = -2.0$, $Bo = 0$, Contact Angle $= 45^\circ$.
AN EXPERIMENTAL STUDY OF THE BEHAVIOR OF A SLOSHING LIQUID SUBJECTED TO A SUDDEN REDUCTION IN ACCELERATION

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 = 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 thrusters 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

\[
\frac{\Delta \zeta}{R} = 0.99 \text{ Fr}^{0.018} \ln (\text{Fr}) + 0.177
\]

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 \(\Delta \zeta\) variable correlated in Equation (1) with the Froude number may not provide a convenient design equation unless good data is available on amplitude and Froude number.

4-22
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

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 cylinder 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.

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

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, $\omega^2$, is shown in Figure 2 as a function of Bond number, $B_\alpha$, and liquid depth, $h_o$. Note $\omega^2$ is an increasing function with $h_o$ for all $B_\alpha$; however, above a liquid depth $h_o/r > 1.5$, $\omega^2$ decreases as $B_\alpha$ increases independent of $h_o$.
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 existence 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 $B_\alpha \sin \omega_o t$, the maximum excursion at the wall occurs at $t = \pi/2 \omega_o$. 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 $h_0 = 3$, $B_\alpha = 0$

Figure 4. First Five Eigenmodes $B_\alpha = 0$, $\theta = 5$ Degrees, $h_0 = 0.25$

4-27
MINIMIZATION OF SLOSH AMPLIFICATION AT ORBITAL INJECTION OF THE S-IVB/SATURN V BY AN OPTIMUM THRUST TERMINATION SEQUENCE

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 offered 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 amplification 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.
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
NAS3-10772, 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 unbaflled 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 LH2 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 cases #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.
<table>
<thead>
<tr>
<th>Case</th>
<th>Radius cm</th>
<th>Fluid</th>
<th>Baffles</th>
<th>Liq. %</th>
<th>Bond No.</th>
<th>Acceleration cm/sec²</th>
<th>v cm²/sec</th>
<th>σ cm³/sec²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>7.0</td>
<td>FC-78²</td>
<td>No</td>
<td>20</td>
<td>10</td>
<td>-70.0</td>
<td>0.00477</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>5.5</td>
<td>Ethanol</td>
<td>No</td>
<td>65</td>
<td>15</td>
<td>-73.5¹</td>
<td>0.01520</td>
<td>0</td>
</tr>
<tr>
<td>Case 3</td>
<td>7.0</td>
<td>FC-78²</td>
<td>Yes</td>
<td>20</td>
<td>15</td>
<td>-69.6</td>
<td>0.00477</td>
<td>0</td>
</tr>
<tr>
<td>Case 4</td>
<td>152.4</td>
<td>LH₂</td>
<td>Yes</td>
<td>20</td>
<td>0</td>
<td>-0.643</td>
<td>0.00192</td>
<td>0</td>
</tr>
<tr>
<td>Case 5</td>
<td>152.4</td>
<td>LH₂</td>
<td>Yes</td>
<td>70</td>
<td>10</td>
<td>-0.377</td>
<td>0.00192</td>
<td>0</td>
</tr>
</tbody>
</table>

Note 1: Acceleration set to 0.001 cm/sec² 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
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 LH₂ 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 Pi 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 LcRc 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/sec²

\( a_L \)  acceleration of liquid leading-edge, cm/sec²

\( B_o \)  Bond number, \( B_o = \frac{\rho g R^2}{\sigma} \)

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

\( R_e_0 \)  Reynolds number, \( R_e_0 = \frac{V_L D_o}{\eta} \)

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

\( V_e \)  geyser tip velocity (fig. 5), cm/sec

\( V_o \)  ullage velocity (fig. 5), cm/sec

\( V_a \)  volume of ullage encompassed by liquid-vapor interface (fig. 5), cm³

\( V_d \)  volume of liquid film thickness \( \delta \), cm³

\( V_L \)  instantaneous leading-edge velocity at tank bottom, cm/sec

\( W_e_R \)  Weber number, \( W_e_R = \frac{(V_L)^2}{\eta} \)

\( W_o_R \)  Weber number, \( W_o_R = \frac{(V_o)^2}{\eta} \)

\( X_c \)  collected liquid height (fig. 5), cm

\( X_L \)  geyser tip displacement (fig. 5), cm

\( X_{L_0} \)  distance from interface edge to tank bottom (fig. 5), cm

\( X_{O_0} \)  distance from interface centerline to tank top (fig. 5), cm

\( \sigma \)  specific surface tension, \( \sigma / \rho \), cm³/sec²

\( \rho \)  liquid layer thickness, cm

\( \eta \)  viscosity, cP

\( \rho \)  liquid density, kg/cm³

\( \alpha \)  surface tension, dynes/cm

\( \omega \)  liquid flow rate, cm³/sec

---

**Table 1. SUMMARY OF REORIENTATION EVENT TIMES**

[All times are defined from initiation of threat.]

<table>
<thead>
<tr>
<th>Reorientation event time</th>
<th>Symbol</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of liquid impact at tank bottom</td>
<td>( t_1 )</td>
<td>( \frac{\sqrt{2} X_{I}}{a} )</td>
</tr>
<tr>
<td>Time of geyser initiation</td>
<td>( t_2 )</td>
<td>( 0.60 \cdot \frac{0.12}{\left( \frac{X_{L}}{X_{L_0}} \right)^{1/2}} \cdot \left( \frac{X_{O_0}}{X_{L_0}} \right)^{1/2} \cdot t_1 )</td>
</tr>
<tr>
<td>Time of geyser impact on liquid-vapor interface</td>
<td>( t_3 )</td>
<td>( 0.40 \cdot \frac{a_{L}}{X_{L_0}} \cdot \left( X_{L} - X_{L_0} \right) \cdot t_2 )</td>
</tr>
<tr>
<td>Time of geyser impact on tank top: 70-Percent fill</td>
<td>( t_4 )</td>
<td>( \frac{1.95 X_{L_0}}{1.2} \cdot t_3 )</td>
</tr>
<tr>
<td>20-Percent fill</td>
<td>( t_5 )</td>
<td>( \frac{2.95 X_{L_0}}{1.2} \cdot t_3 )</td>
</tr>
<tr>
<td>Time when tank top is clear of liquid</td>
<td>( t_5 )</td>
<td>( \frac{1.95 X_{L_0}}{1.2} \cdot (10.7 X_{L} - 2a_X)^{1/2} )</td>
</tr>
</tbody>
</table>

---

Figure 1. Geometry of liquid container
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 occurrence 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. Many of the analytical expressions were solved using 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. Transition amplitude between turbulent and laminar motion was assumed to be 0.5. 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., \( \gamma_T, \gamma_L, \eta_t/\eta_l \). If possible, methods for evaluating these variables as a function of known conditions should be determined.
Figure 1. Plexiglas Inverted Tank Dome Model

- $a_i$: initial acceleration of vehicle
- $a_f$: final acceleration of vehicle
- $a_L$: leading edge acceleration
- $B_0$: Bond number, $\sigma g R^2 / c$
- $B':_0$: modified or dynamic Bond no., $\sigma g h_0 V_L / \gamma R$
- $C_D$: drag coefficient, $g (B/u)$
- $b_m$: distance between CG of liquid in initial and final states
- $h_m$: distance between CG of ullage in initial and final states
- $k$: wave number
- $m$: fraction of impact kinetic energy transformed to bubble surface free energy
- $M$: $\mu g R^2 / c^2$, dimensionless parameter
- $\alpha$: ratio of bubble volume to ullage volume
- $\alpha'$: ratio of bubble volume to liquid volume
- $\gamma_L$: liquid volume
- $V_U$: liquid volume
- $V_G$: ullage gas velocity
- $V_T$: total tank volume
- $W_w$: Weber no., $(2 \rho w^2 u_0) / \sigma$
- $\gamma_L$: laminar damping ratio
- $\gamma_T$: turbulent damping ratio
- $\eta$: wave amplitude
- $\omega$: slosh wave frequency
- $\text{INITIAL SETTLING TIME LIQUID FALLING}$
  $t_{\text{liq}} = \sqrt[4]{\frac{L}{0.662 \sqrt{g} \left[ 1 - 0.84 / R \left( B_0 / 4.7 \right) \right]}}$
- $t_{\text{ULLAGE GAS RISING}}$
  $t_{\text{ullage}} = \sqrt{\frac{h_{\text{MV}}}{2 \gamma_T \left( k \text{tr} / (B_k) \right) / 2}}$
- $\text{TURBULENT DISSIPATION TIME}$
  $t_{\text{turb}} = \frac{1}{2 \gamma_T \left( k \text{tr} / (B_k) \right) / 2} \log \left[ \frac{4}{\gamma_L} \left( \frac{h_{\text{MV}} V_L}{1 / R} \right) \right]$
- $\text{LAMINAR DISSIPATION TIME}$
  $t_{\text{lam}} = \frac{1}{2 \gamma_L}$
- $\gamma_L = \gamma_{\text{wall}} + \gamma_{\text{baffle}}$

Figure 2. Flow Regimes

I. STOKES REGIME

$C_D = 24 / Re_1$

$u_1 = \frac{2 r g}{9 \mu}$

$Re_1 < 3.7$

II. TRANSITION REGIME

$C_D = 18.5 / Re_2^{4/5}$

$u_2 = 0.317 r^{2/5} g^{5/6} \left( \rho / \mu \right)^{1/3}$

$3.7 < Re_2 < 8.8 \times 10^{12}$

III. HARMATHY REGIME

$C_D = 0.37 M^{1/4} Re_3$

$u_3 = 1.5 \left( \rho g / \mu \right)^{1/4}$

$8.8 \times 10^{12} < Re_3 < 7 M^{1/4}$

IV. SPHERICAL CAP REGIME

$C_D = 2.6$

$u_4 = \sqrt{\frac{g r}{2 \rho g}}$

$7 M^{1/4} < Re_4$

$C_{D_1} = \frac{g r}{2 \rho g}$

$Re_4 = \frac{u_4 \mu}{\rho g}$

$i = 1, 2, 3, 4$

Figure 3. Nomenclature

Figure 4. Representative Bubble-Velocity Equations

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 0.017\( r \) and a circular screen disk of 70% porosity were used. Two tanks had single baffles installed at 1.57\( R \) and 3.34\( R \) from the bottom of the tank and a third tank a screen at 3.34\( R \). 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<We<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

Table 1.

<table>
<thead>
<tr>
<th>Tower Height</th>
<th>186 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop Test Height</td>
<td>20 ft</td>
</tr>
<tr>
<td>Zero-g Test Time</td>
<td>2.9 sec</td>
</tr>
<tr>
<td>Drag Shield Length (overall)</td>
<td>19 ft  1 in</td>
</tr>
<tr>
<td>Drag Shield Diameter</td>
<td>5 in</td>
</tr>
<tr>
<td>Drag Shield Mass</td>
<td>1300 lb</td>
</tr>
<tr>
<td>Test Module Dimensions</td>
<td>36 in by 12 in by 1 L</td>
</tr>
<tr>
<td>Test Module Mass</td>
<td>300 lb</td>
</tr>
<tr>
<td>Acceleration Range (in both directions parallel to the drop axis)</td>
<td>0.3 $g_0$ to $10^{-2} g_0$</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>High speed motion pictures 1000 frames/sec</td>
</tr>
<tr>
<td>Power</td>
<td>On board batteries and umbilical cable prior to release</td>
</tr>
<tr>
<td>Release Mechanism</td>
<td>Jaw and latch - pneumatically operated</td>
</tr>
</tbody>
</table>
EXPERIMENTAL INVESTIGATION OF LIQUID-PROPELLANT REORIENTATION

Salzman, J. A., Masica, W. J.

OBJECTIVE. - To experimentally determine the criteria for predicting liquid re-orientation 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 number regimes. Ullage velocity, \( V_0 = 0.48 (aR)^{1/2} [1 - (0.84/Bo)^{1/4}] \), see Nomenclature. For \( We < 4 \), geysering will not occur, collection velocity, \( V_c = V_0 \), and reorientation time can be obtained directly if the amount of liquid in the tank is known. For \( We > 30 \), the data showed that \( V_c = V_0 [1 - 2.76K(X_L/R)^{1/2}] \) 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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>system acceleration, cm/sec^2</td>
</tr>
<tr>
<td>p_L</td>
<td>interface leading-edge acceleration, cm/sec^2</td>
</tr>
<tr>
<td>Bo</td>
<td>Bond number, Bo = 4R^2/3</td>
</tr>
<tr>
<td>D</td>
<td>tank diameter, cm</td>
</tr>
<tr>
<td>X, X'</td>
<td>nondimensional constants</td>
</tr>
<tr>
<td>L</td>
<td>tank length, cm</td>
</tr>
<tr>
<td>R</td>
<td>tank radius, cm</td>
</tr>
<tr>
<td>r</td>
<td>geyser radius, cm</td>
</tr>
<tr>
<td>t</td>
<td>time, sec</td>
</tr>
<tr>
<td>V_c</td>
<td>collected liquid velocity (fig. 2(a)), cm/sec</td>
</tr>
<tr>
<td>V_G</td>
<td>geyser tip velocity or growth rate (fig. 2(b)), cm/sec</td>
</tr>
<tr>
<td>V_L</td>
<td>instantaneous leading-edge velocity at impingement or convergence at tank bottom (fig. 2(a)), cm/sec</td>
</tr>
<tr>
<td>V_L^*</td>
<td>instantaneous leading-edge velocity in convex-bottomed models measured at end of cylindrical portion of tank (fig. 2(a)), cm/sec</td>
</tr>
<tr>
<td>V_0</td>
<td>ullage velocity, cm/sec</td>
</tr>
<tr>
<td>We</td>
<td>Weber number, We = (V_L L)^2/3</td>
</tr>
<tr>
<td>X_c</td>
<td>collected liquid depth (fig 2(b)), cm</td>
</tr>
<tr>
<td>X_g</td>
<td>geyser tip displacement (fig. 2(b)), cm</td>
</tr>
<tr>
<td>X_L</td>
<td>interface leading-edge displacement from initial 0-g configuration to convergence or impingement, cm</td>
</tr>
<tr>
<td>( \beta )</td>
<td>specific surface tension, ( \alpha/\rho ), cm^3/sec^2</td>
</tr>
<tr>
<td>( \rho )</td>
<td>liquid density, g/cm^3</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>surface tension, dyn/cm</td>
</tr>
</tbody>
</table>

**Figure 2**  Geyser formation delineated by Weber number criterion

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

**Figure 1**  Basic reorientation profiles
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1943 A
EXPERIMENTAL INVESTIGATION OF LIQUID IMPACT IN A MODEL PROPELLANT TANK.
Stephens, D.C., NAS' -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 thrusters 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 un baffled 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 un baffled 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).
Figure 1. Schematic representation of impact simulator.

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

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 Trichlorotrifluoroethane 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

\[
a_L = \frac{3V^2}{R} \text{ for Bo > 1.75 and } a_L = 0.87a \text{ for Bo > 12}
\]

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. Helmholtz 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 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.

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 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. 1. Summary of Test Results: General Classification of the Observed Flows

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

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 $\dot{g}$ tending to settle the liquid to the opposite end of the container and (2) acceleration of $\dot{g}$ 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.
<table>
<thead>
<tr>
<th>Figure no.</th>
<th>$\alpha(t)$</th>
<th>$\beta$</th>
<th>Initial shape</th>
<th>$H$</th>
<th>$\theta_o$</th>
<th>$\Delta t/r_0^{1/2}$</th>
<th>$t_{max}/r_0^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$+1.0$</td>
<td>0</td>
<td>Hemispherical</td>
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<td>8</td>
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<td>9</td>
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<td>Hemispherical</td>
<td>2.0</td>
<td>$15^\circ$</td>
<td>0.0266</td>
<td>0.48</td>
</tr>
</tbody>
</table>

**Table 1. Summary of the cases studied**

- $\alpha(t) =$ acceleration
- $\beta =$ surface tension
- $H =$ initial liquid height assuming a flat interface
- $\theta_o =$ initial contact angle
- $\Delta t =$ 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 $H = 2.0$, $\alpha(t) = +1$, $\beta = 0$, $\theta_o = 45^\circ$ and $\Delta t = 0.0177 r_o^{1/2}$ sec.**

**Figure 3. Hemispherical initial shape with $H = 2.0$, $\alpha(t) = 1^+$, $\beta = 0.005$, $\theta_o = 45^\circ$ and $\Delta t = 0.0177 r_o^{1/2}$ 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

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 \((0.03 \leq \alpha/g \leq 0.05)\) 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; \(r_{eq} = 0.4 (\rho/\alpha)^{1/2}\), 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

Hagyard, J. B., Maslca, W. J.,
NASA-LcRC, TN D-5462, October 1969

OBJECTIVE. - Examine single, noncondensible 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 \( R_e = \frac{v}{\nu} \) 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.) \( \geq 10 \), such that wall effects were negligible.

A theory proposed by Moore was used to correlate the data. This theory uses the M number \( \left( \frac{\mu^4}{\rho g} \right)^{1/2} \) 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 \( x = r_h/r_v \), 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
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: 

\[ R = 2\beta (\epsilon t)^{1/2}, \]

where the growth constant, \( \beta \), is given by 

\[ f(\epsilon, \beta) = \beta = \frac{J \alpha}{\rho L C_P \Delta T_{\text{superheat}}/\rho_v h_{fg}}, \]

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, \( \epsilon \) may be taken as 1 and \( f(\epsilon, \beta) = \beta = \beta \).

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 childdown.
EFFECT OF BAFFLES ON INFLOW PATTERNS IN SPHERICAL CONTAINERS DURING WEIGHTLESSNESS

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

<table>
<thead>
<tr>
<th>Type of inlet baffle</th>
<th>Liquid</th>
<th>Liquid surface tension, μ</th>
<th>Volumetric flow rate, Q</th>
<th>Inlet radius, R1</th>
<th>Weber number, We = Q² ( \rho ) / ( \nu² )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un baffled</td>
<td>Anhydrous ethanol</td>
<td>28.3</td>
<td>39</td>
<td>0.20</td>
<td>680</td>
</tr>
<tr>
<td>Un baffled; vents extended internally</td>
<td>Trichlorotrifluoroethane</td>
<td>11.6</td>
<td>52</td>
<td>0.20</td>
<td>2 000</td>
</tr>
<tr>
<td>Un baffled; vents extended internally</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>84</td>
<td>0.20</td>
<td>11 600</td>
</tr>
<tr>
<td>Solid hemisphere</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>46</td>
</tr>
<tr>
<td>Hemispherical screen (200 × 200 mesh)</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>710</td>
</tr>
<tr>
<td>Hemispherical screen (120 × 120 mesh)</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>710</td>
</tr>
<tr>
<td>Hemispherical screen (80 × 80 mesh)</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>710</td>
</tr>
<tr>
<td>Perforated hemisphere</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>710</td>
</tr>
<tr>
<td>Perforated hemisphere</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>710</td>
</tr>
<tr>
<td>Perforated hemisphere; vents extended internally</td>
<td>Anhydrous ethanol</td>
<td>7.7</td>
<td>92</td>
<td>0.50</td>
<td>710</td>
</tr>
</tbody>
</table>

* At 30°C.

a. Minnesota Mining and Manufacturing Co. registered trademark for fluorocarbon solvent.

![Figure 1. Test Container](image)

![Figure 2. Schematic of Baffles. (All Dimensions in cm Unless Indicated Otherwise)](image)
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/cm³, viscosity 0.012 and 0.007 g/cm·sec, and specific surface tension 28.3 and 11.8 cm³/sec². Acceleration levels of 0.003 to 0.015 g resulted in a Bond number (ar₁²/β) range of 0.059 to 2.80. Data was taken primarily by movie evaluation. Various inflow rates were used to vary Reynolds number (V₁/ν) 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/(h₁r₁) = V₁²/hβ (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

<table>
<thead>
<tr>
<th>Tank radius, ( r_t ) cm</th>
<th>Inlet radius, ( r_1 ) cm</th>
<th>Test liquid</th>
<th>Bond number, ( B_0 )</th>
<th>Weber number, ( \frac{W_0}{r_1^2} )</th>
<th>Ratio of maximum jet height to inlet radius, ( h/r_1 )</th>
<th>Flow regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>0.79</td>
<td>Ethanol</td>
<td>0.058</td>
<td>0.51</td>
<td>29.6</td>
<td>Laminar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TCTFE³</td>
<td>0.160</td>
<td>3.44</td>
<td>7.12</td>
<td>Transition</td>
</tr>
<tr>
<td>15</td>
<td>0.79</td>
<td>Ethanol</td>
<td>0.058</td>
<td>9.21</td>
<td>25.1</td>
<td>Laminar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TCTFE³</td>
<td>0.140</td>
<td>3.68</td>
<td>9.09</td>
<td>Transition</td>
</tr>
<tr>
<td>15</td>
<td>1.5</td>
<td>Ethanol</td>
<td>0.058</td>
<td>7.96</td>
<td>9.15</td>
<td>Transition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TCTFE³</td>
<td>0.541</td>
<td>4.49</td>
<td>3.77</td>
<td>Turbulent</td>
</tr>
</tbody>
</table>

*Trichlorotrifluoroethane.*

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**Figure 1. Experiment Tanks**

**Figure 2. Dependence of Jet Height on System Parameters with Liquid Flow in the Laminar and Transition Regimes**

**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 un baffled 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 un baffled 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 un baffled 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 un baffled 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

<table>
<thead>
<tr>
<th>Baffle</th>
<th>Inflow velocity, cm/sec</th>
<th>Interface stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>35.0</td>
<td>Stable. Liquid phase remains conical.</td>
</tr>
<tr>
<td></td>
<td>30.4</td>
<td>Unstable. Gas phase moves more rapidly.</td>
</tr>
<tr>
<td></td>
<td>25.0</td>
<td>Unstable. Gas phase moves more rapidly.</td>
</tr>
<tr>
<td></td>
<td>22.4</td>
<td>Unstable. Sheet flow up wall.</td>
</tr>
<tr>
<td>Ribbed sheet disk</td>
<td>22 Stable. Hemisphere fills at same rate.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42 Stable. Hemisphere fills more rapidly.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61 Marginal. Flow up cylinder before filling.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70 Unstable. Low flow up cylinder.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>118 Unstable. Sheet flow up wall.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>143 Unstable. Sheet flow up wall.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>174 Unstable. Sheet flow up wall.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 Unstable. Very rapid flow up cylinder.</td>
<td></td>
</tr>
<tr>
<td>Fluorocarbon cone visor</td>
<td>50 Stable. Hemisphere fills.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 Unstable. Gas phase moves at same rate.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61 Marginal. Flow up cylinder before filling.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>65 Marginal. Flow up cylinder before filling.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70 Stable. Hemisphere fills before sheet flow.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td>Disk and ring</td>
<td>60 Stable. Sheet flow up.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 Stable. Liquid phase moves at same rate.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80 Unstable. Sheet flow up wall.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>110 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<tr>
<td></td>
<td>120 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td>135°</td>
<td>70 Stable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>79 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>89 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>99 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td>135°</td>
<td>64 Stable. Hemisphere falls towards baffle.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70 Marginal. Flow up cylinder before sheet flow.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80 Unstable. Sheet flow up wall.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<tr>
<td></td>
<td>100 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<tr>
<td>Perforated plate</td>
<td>70 Stable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>79 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<tr>
<td></td>
<td>89 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<tr>
<td></td>
<td>99 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>100 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>110 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>120 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td></td>
<td>130 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<td></td>
<td>140 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>150 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>160 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td></td>
<td>170 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<td>180 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>190 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<td>200 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
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<tr>
<td></td>
<td>210 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
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<tr>
<td></td>
<td>220 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>230 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>240 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250 Unstable. Sheet flow up wall and sheet breaks off from disk.</td>
<td></td>
</tr>
</tbody>
</table>

a From Symons, 1971

Figure 1. Inflow Baffle Cross Sections

- [Diagram of inflow baffle cross sections]

Figure 2. Comparison of Inflow Baffle Effectiveness

- [Graph showing comparison of inflow baffle effectiveness for different materials and angles]
EXPERIMENTAL INVESTIGATION OF AN AXISYMMETRIC FREE JET WITH AN INITIALLY UNIFORM VELOCITY PROFILE


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 $U_{\text{max}} D_j/u$ 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/m² (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 $U_{\text{CL}}/U_{\text{max}} > .95$) 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 $M_0$ is the outlet momentum based on $U_{\text{max}}$, the $M/M_0$ 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 complement similar work on the full-developed laminar profile free jet by Symons (1971) NASA (TN D-6304).

7-8
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

Extrapolated data from fig. 3 using "95 percent" definition
Best-fit extrapolated data from (Hrycak 1970)
(using forced slope of -1 criterion)

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

Figure 4. Dependence of Entrained Mass Flux on Jet Reynolds Number
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 trichlorotrifluorethane 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 $2 V_i^2 \tan \theta / \rho R_i$, whereas the uniform jet is $V_i^2 \tan \theta / \rho R_j$ where $V_i$ 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.

$$R_j = R_i + H_i \tan \theta = R_i + 0.12 H_i$$
$$H_i < 12.4 R_i$$
$$R_j = R_i \left[ 1 + 12.4 \left( \tan \theta - \tan 11^\circ \right) \right] + H_i \tan 11^\circ$$
$$R_i > 12.4 R_i$$

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 $h_i/D_i$.  

7-10
Figure 1. Experiment Tank

Figure 2. Effect of Initial Liquid Height on Critical Inflow Velocity
From TM X-1931 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

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 $U_x/U_{max} = (U_c/U_{max}) \exp(-r^2/2c^2)$ where $r$ is the r value at which $U_x = 0.605 U_c$. 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 $= (0.95 U_{max})$. 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.
INTERFACE STABILITY DURING LIQUID INFLOW TO INITIALLY EMPTY HEMISPHERICAL ENDED CYLINDERS IN WEIGHTLESSNESS

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 D4028 (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 to 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.

$$\text{We}_{\text{crit}} = \frac{F_{\text{inf}}}{F_{\text{st}}} = \frac{V_{1, \text{avg}}^2 R_i^2 \rho}{\frac{V_{1, \text{avg}}^2 R_i}{2 \beta}}$$

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 $R_t$ 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°]

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Surface tension at 20°C, α, dynes/cm</th>
<th>Density at 20°C, ρ, gm/cm³</th>
<th>Viscosity at 20°C, μ, gm/cm-sec</th>
<th>Specific surface tension, β, cm²/sec²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrous ethanol</td>
<td>22.3</td>
<td>0.789</td>
<td>1.2×10⁻²</td>
<td>28.3</td>
</tr>
<tr>
<td>Trichlorotrifluoroethane</td>
<td>18.6</td>
<td>1.579</td>
<td>0.7×10⁻²</td>
<td>11.8</td>
</tr>
<tr>
<td>Butanol</td>
<td>24.6</td>
<td>0.809</td>
<td>2.9×10⁻²</td>
<td>30.4</td>
</tr>
</tbody>
</table>

![Figure 1. Stability of Liquid-Vapor Interface Delineated by Weber Number](image1)

![Figure 2. Experiment Tanks](image2)

![Figure 3. Delineation of Interface Behavior by Weber Number Criterion](image3)
OBSERVATIONS OF INTERFACE BEHAVIOR DURING INFLOW TO AN ELLIPTICAL ENDED CYLINDER IN WEIGHTLESSNESS

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

<table>
<thead>
<tr>
<th>Tank Diameter, D (cm)</th>
<th>Tank Length, L (cm)</th>
<th>Inlet Line Diameter, d (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

![Test Tank Diagram](image)

**Figure 1. Test Tank Details**
AN EXPERIMENTAL STUDY OF LIQUID FLOW INTO A BAFFLED SPHERICAL TANK DURING WEIGHTLESSNESS
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 \( \sim 70^\circ \) 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 un baffled 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 un baffled 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,

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 $\pm 0.15$ psi on pressure and $\pm 5\%$ 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.
RAPID, LOW-LOSS LIQUID HELIUM TRANSFERS

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

<table>
<thead>
<tr>
<th>Type of dewar received</th>
<th>Liq. He received, liters</th>
<th>Transfers into Supaireco N₂, shielded dewars, liters</th>
<th>Total transferred, liters</th>
<th>Loss, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryenco gas-shielded</td>
<td>97</td>
<td>47, 45.5</td>
<td>92.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Cryenco gas-shielded</td>
<td>95</td>
<td>43.5, 44.6</td>
<td>93.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Cryenco gas-shielded</td>
<td>89</td>
<td>21, 48.5, 18.5</td>
<td>88</td>
<td>1.1</td>
</tr>
<tr>
<td>Linde gas-shielded</td>
<td>103.25</td>
<td>46.5, 48.5, 5.5</td>
<td>100.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Cryenco gas-shielded</td>
<td>95</td>
<td>43, 48.5, 2.5</td>
<td>94</td>
<td>1.0</td>
</tr>
<tr>
<td>Cryenco gas-shielded</td>
<td>88</td>
<td>48, 38</td>
<td>86</td>
<td>2.3</td>
</tr>
<tr>
<td>Cryenco gas-shielded</td>
<td>95</td>
<td>17.5, 29, 27, 21</td>
<td>94.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Hofman nitrogen-shielded</td>
<td>93</td>
<td>43, 23.5, 23.5</td>
<td>90</td>
<td>3.2</td>
</tr>
</tbody>
</table>

![Distance Along Length of Liquid He Column, cm](image)

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

\[ \Delta T = \Delta T_0 \left[1 - 2; x^1 \int_0^{\sqrt{x/(2\mathcal{X}t)}} e^{-s^2} dx\right] \]

- \( \mathcal{X} \) = temperature diffusivity
- \( t \) = time
- \( x \) = distance from origin in column
- \( \xi = x/(2\mathcal{X}t)^{1/2} \)
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 

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.
VAPO R INGESTION IN A CYLINDRICAL TANK WITH A CONCAVE ELLIPTICAL BOTTOM
Klavin, A., LMSC, LMSC/D386845, NAS3-17798.
February 1974

OBJECTIVE: - Analytically estimate the propellant residual in the Centaur LH2 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 \( (B_0 \rightarrow \infty) \).

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

Propellants: liquid hydrogen; \( \rho / \rho_0 = 26.6 \text{ cm}^3/\text{sec}^2 \)
Initial vehicle weight \( W_0 = 14,000 \text{ lb} \)
Initial propellant loading \( = 27.45 \times 10^6 \text{ ft}^3 \)

Acceleration levels, based on \( W_0 \):

<table>
<thead>
<tr>
<th>Time</th>
<th>( \frac{t}{t_0} )</th>
<th>( t = 0 )</th>
<th>( t = 25 \text{ lb} )</th>
<th>( t = 50 \text{ lb} )</th>
<th>( t = 100 \text{ lb} )</th>
<th>( t = 30,000 \text{ lb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.274</td>
<td>1.96 \times 10^{-2}</td>
<td>2.09 \times 10^{-3}</td>
<td>6.16 \times 10^{-5}</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20</td>
<td>0.927</td>
<td>7.43 \times 10^{-1}</td>
<td>6.37 \times 10^{-4}</td>
<td>1.21 \times 10^{-4}</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30</td>
<td>2.773</td>
<td>9.25</td>
<td>6.31 \times 10^{-3}</td>
<td>1.51 \times 10^{-3}</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30.38</td>
<td>2.075</td>
<td>6.64</td>
<td>4.97 \times 10^{-3}</td>
<td>1.08 \times 10^{-3}</td>
<td>3.25 \times 10^{-4}</td>
<td>—</td>
</tr>
</tbody>
</table>

Flow region:

<table>
<thead>
<tr>
<th>Time</th>
<th>( \frac{t}{t_0} )</th>
<th>( t = 0 )</th>
<th>( t = 25 \text{ lb} )</th>
<th>( t = 50 \text{ lb} )</th>
<th>( t = 100 \text{ lb} )</th>
<th>( t = 30,000 \text{ lb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.274</td>
<td>1.96 \times 10^{-2}</td>
<td>2.09 \times 10^{-3}</td>
<td>6.16 \times 10^{-5}</td>
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<td>—</td>
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<td>20</td>
<td>0.927</td>
<td>7.43 \times 10^{-1}</td>
<td>6.37 \times 10^{-4}</td>
<td>1.21 \times 10^{-4}</td>
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<td>—</td>
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<tr>
<td>30</td>
<td>2.773</td>
<td>9.25</td>
<td>6.31 \times 10^{-3}</td>
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</tr>
<tr>
<td>30.38</td>
<td>2.075</td>
<td>6.64</td>
<td>4.97 \times 10^{-3}</td>
<td>1.08 \times 10^{-3}</td>
<td>3.25 \times 10^{-4}</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 1. Low-g Tank Draining Definition of Terms

Moreover, we can see:

\[
\frac{\partial}{\partial t} \left( \rho \frac{v}{v_0} \right) = \frac{\partial}{\partial x} \left( \rho v \right) - \frac{1}{v_0} \frac{\partial h}{\partial x}
\]

Table 2. Computation Sequence

(i) Pick Bond number and choose of A and l, where f is the curvature function and A is the control area
(ii) Pick \( W_0 \) and \( h_{bc} \)
(iii) Evaluate \( \text{flux}_{bc} \) and \( \text{flux}_{bc} \)
(iv) Evaluate the derivatives

\[
\frac{\partial h}{\partial h} = \frac{\partial h}{\partial h} \left( \frac{h_{bc} + 0.2 - h_{bc}}{f} \right)
\]

(v) Substitute the results of (iii) and (iv) into \( h_{bc} = h_{bc} \)

\[
\frac{\partial h}{\partial h} = \frac{\partial h}{\partial h} \left( \frac{h_{bc} + 0.2 - h_{bc}}{f} \right)
\]

(vi) Substitute the results of (iii) and (iv) into \( \frac{h}{h_{bc}} \)

\[
\frac{\partial h}{\partial h} = \frac{\partial h}{\partial h} \left( \frac{h_{bc} + 0.2 - h_{bc}}{f} \right)
\]

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


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.
Figure 1. Experiment Tank and Outlet Baffles

Figure 2. Comparison of Performance of Baffles

* Berenyi and Abdalla, 1969
UNSTEADY AXISYMMETRIC FLOWS OF A LIQUID DRAINING FROM A CIRCULAR TANK

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. \( H_c \), 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, \( F_{cr} = Q_c/(gh_c)^{5/2} \) = 0.51\( \pi \) where \( F_{cr} \) 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 than 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.

8-8
Nomenclature

\( A^e \) = coefficients
\( a \) = radius of the drain
\( \bar{a} \) = drain radius ratio \( a/r_a \)
\( B \) = Bond number \( \rho g (2a)^2/T \)
\( C \) = coefficients
\( C^e \) = a constant
\( J''(\xi) \) = functions of \( \xi \)
\( F \) = Froude number \( U^2 \) (\( \rho \) = \( \rho_k \))
\( F_r \) = critical Froude number \( Q_r (g h)^{1/2} \)
\( F_r^e \) = Froude number \( \nu (2a)^2 \)
\( g \) = gravitational acceleration
\( \rho \) = effective gravitational acceleration \( g(\rho - \rho_k) \)
\( h(t, \xi) \) = shape of the free surface
\( h_i \) = central height of the liquid at critical flow
\( h_c \) = initial height of the liquid in the tank
\( h_m \) = height of the free surface on the wall
\( h_i(t) \) = terms of expansion of \( h_i(t, \xi) \) on \( \xi \)
\( H_i \) = initial height ratio \( h_i/r_a \)
\( H(0, \xi) \) = center height ratio \( h_0(0, \xi)/r_a \)
\( h_0 \) = critical height ratio \( h_i/r_a \)
\( H_m \) = dimensionless height of the free surface on the wall
\( p \) = dimensionless height \( h_i/r_a \)
\( J_0(k) \) = Bessel function of the zero order
\( J_1(k) \) = Bessel function of the first order
\( k \) = constant
\( k_m \) = positive root of \( J_1(k) = 0 \)
\( \dot{Q} \) = constant rate of discharge through the drain
\( \dot{Q}_m \) = critical rate of discharge
\( r_c, Z \) = cylindrical coordinates
\( r_a \) = radius of the tank
\( t \) = critical time
\( t_l \) = time parameter \( t(\rho r_c^4/T)^{1/2} \)
\( \tau \) = surface tension
\( u_0(\xi) \) = ortho-normalized functions of \( \xi \)
\( u_l(\xi) \) = constant discharge velocity through the drain
\( v(\xi) \) = functions of \( \xi \)
\( V_c \) = average velocity of the liquid in the tank \( \dot{Q} / A \)
\( W_r \) = Weber number \( r_c \rho v^2 \)
\( W_t \) = Weber number \( 2 \rho r_c^2 \nu^2 T \)
\( \xi, \eta \) = dimensionless cylindrical coordinates \( \xi = \xi r_c \)
\( \xi, \eta \) = \( \eta = \xi r_c \)
\( \Phi \) = velocity potential
\( \Phi = \varphi(\xi, \eta, t) \) = dimensionless velocity potential \( \Phi_0 = Ur_c \)
\( \Phi^m \) = dimensionless velocity potentials
\( \phi(\xi, \eta, t) \) = dimensionless velocity potential
\( \phi_m(\xi, \eta, t) \) = dimensionless velocity potential
\( \tau \) = dimensionless time \( t(\dot{Q} A) \)

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
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 Bercuti 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

Nomenclature

\[ v = \text{outlet line velocity} \]
\[ a = \text{acceleration} \]
\[ d = \text{outlet line diameter} \]

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-LaRC, 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 cm³/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

<table>
<thead>
<tr>
<th>Pressure Profiles</th>
<th>Pressurant Inlet Configuration</th>
<th>Residual Fraction*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Peak</td>
<td>1.25-cm-diam pipe</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>30° Cone</td>
<td>1.81</td>
</tr>
<tr>
<td>Wall Peak</td>
<td>Flat Plate</td>
<td>1.09</td>
</tr>
<tr>
<td>Uniform</td>
<td>Porous Plate</td>
<td>0.96</td>
</tr>
</tbody>
</table>

*Residual fraction = (Residual volume)/(reference volume or (2/3) π R³).
Figure 1. Inlet Configurations Tested

Figure 2. Dynamic Pressure Distributions in Normal Gravity
LOW GRAVITY DRAINING FROM HEMISPHERICALLY BOTTOMED CYLINDRICAL TANKS

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: $B=0$, $W=36.06$, $h_0=2.670u$, $r=1/10$; experimental data furnished by NASA-Lewis Research Center.
EFFECT OF OUTLET BAFFLING ON LIQUID RESIDUALS FOR OUTFLOW FROM CYLINDERS IN WEIGHTLESSNESS

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

VAPOG 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. Cri-
tical 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,

MAJOR RESULTS.

1. Vapor ingestion height in normal gravity may be scaled by the Froude number (Fig-
ure 2). Nomenclature are presented in Table 1. Vapor ingestion heights were approxi-
mately 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 num-
ber (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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>acceleration, cm/sec²</td>
</tr>
<tr>
<td>h₀</td>
<td>acceleration due to gravity, 980 cm/sec²</td>
</tr>
<tr>
<td>hₙ</td>
<td>critical height, cm</td>
</tr>
<tr>
<td>h₀r₀</td>
<td>initial liquid height, cm</td>
</tr>
<tr>
<td>hₙr₀</td>
<td>vapor ingestion height, cm</td>
</tr>
<tr>
<td>Q₀</td>
<td>outflow rate, cm³/sec</td>
</tr>
<tr>
<td>R</td>
<td>tank radius, cm</td>
</tr>
<tr>
<td>R/R₀</td>
<td>radius ratio</td>
</tr>
<tr>
<td>r₀</td>
<td>outlet radius, cm</td>
</tr>
<tr>
<td>t</td>
<td>time, sec</td>
</tr>
<tr>
<td>V₀</td>
<td>average outflow velocity (velocity in outlet line), cm/sec</td>
</tr>
<tr>
<td>Vₚ</td>
<td>average liquid velocity in tank, cm/sec</td>
</tr>
<tr>
<td>We</td>
<td>Weber number, V₀²r₀/ß or Q₀²/R₀³</td>
</tr>
<tr>
<td>ß</td>
<td>specific surface tension, e/p, cm³/sec²</td>
</tr>
<tr>
<td>μ</td>
<td>absolute viscosity, g/(cm-sec)</td>
</tr>
<tr>
<td>ρ</td>
<td>density, g/cm³</td>
</tr>
<tr>
<td>σ</td>
<td>surface tension, dynes/cm (or 10⁻⁵ N/cm)</td>
</tr>
</tbody>
</table>

Figure 1. Vapor Ingestion Phenomenon

Figure 2. Vapor Ingestion Heights in Normal Gravity With Froude 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, $We = \rho V^2_m R / 4 \sigma$
- $\beta$: specific surface tension, cm$^3$/sec$^2$
- $\mu$: viscosity, g/cm-sec
- $\rho$: liquid density, g/cm$^3$
- $\sigma$: 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*
VAPOUR INGESTION PHENOMENON IN WEIGHTLESSNESS


OBJECTIVE. - To computationally 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 from 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 $Q_o^2/\beta R^3 = 4000 (h_{cr}/R)^8$, where $Q_o$ was the outflow rate, $\beta$ 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.

8-24
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


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, 0.38% 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 initially 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.
Common outflow line; o.d., 2 in. (5.08 cm); i.d., 1.875 in. (4.76 cm)

Stainless-steel outflow line; o.d., 1 in. (2.54 cm); i.d., 0.875 in. (2.22 cm)

Cylindrical sump

Figure 1. Four Tanks With Equal-Length Outflow Lines

Tank
Antivortex baffle

Sump
Crossflow line
Outflow line

Typical sump region

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 \( h_c/D = f \left( \frac{V^2}{g d}, \frac{D}{d}, \frac{h_0}{d} \right) \) 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 \( h_0 \gg h_c \)) 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
\( (c) \)  critical value
\( (o) \)  initial value

Table 1. Nomenclature

![Figure 1. Types of Tanks](image)

Figure 1. Types of Tanks

![Figure 2. Dimensionless Critical Height as a Function of Froude Number - Cylindrical Tank with Axisymmetric Outlet](image)

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](image)

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

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

PERTINENT WORK PERFORMED. - 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.

MAJOR RESULTS. -

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 \( Fr = \frac{V^2}{aD} \). (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.

COMMENTS. - The method of analysis is useful for the regime where gravitational and inertial forces predominate over the viscous and surface tension forces.
Table 1. Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>a</td>
<td>fluid acceleration, m/sec²</td>
</tr>
<tr>
<td>D</td>
<td>diameter of tank outlet, m</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity, m/sec²</td>
</tr>
<tr>
<td>h</td>
<td>liquid height at tank wall, m</td>
</tr>
<tr>
<td>h₀</td>
<td>liquid height at tank wall at which vapor ingestion occurs, m</td>
</tr>
<tr>
<td>h₀c</td>
<td>liquid height at Centaur tank wall at which vapor ingestion occurs, m</td>
</tr>
<tr>
<td>h₀b</td>
<td>liquid height above tank outlet perimeter at which vapor ingestion occurs, m</td>
</tr>
<tr>
<td>Pₚ</td>
<td>pressure at liquid surface at tank wall, kg/m²</td>
</tr>
<tr>
<td>Pₖ</td>
<td>pressure at liquid surface above tank outlet perimeter, kg/m²</td>
</tr>
<tr>
<td>Q</td>
<td>volumetric tank outflow rate, m³/sec</td>
</tr>
<tr>
<td>r₀</td>
<td>radius of tank outlet, m</td>
</tr>
<tr>
<td>t</td>
<td>time, sec</td>
</tr>
<tr>
<td>u₀</td>
<td>stream velocity normal to hemispherical surface constructed over tank outlet, m/sec</td>
</tr>
<tr>
<td>V</td>
<td>tank outflow velocity, m/sec</td>
</tr>
<tr>
<td>p</td>
<td>fluid density, kg/m³</td>
</tr>
</tbody>
</table>

Subscripts

1. fluid 1
2. fluid 2

Figure 1. Centaur Liquid Hydrogen Tank

Figure 2. Centaur Liquid Hydrogen Tank Critical Liquid Height Ratio at Pump Zero Discharge Flow Rate (2.5×10⁻² m³/sec)

Figure 3. Centaur Liquid Hydrogen Tank Critical Liquid Height Ratio at Main Engine Firing Flow Rate (7.6×10⁻² m²/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 (Sand 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
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 \( h_c \gg r \), \((h_c/r_0)^5 = 1.5 \left( \frac{V_d^2}{r_0 g} \right) \) (Equation 1) at high g and \((h_c/r_0)^5 = \left( \frac{(0.76 \rho V_d^2 r_0)}{\sigma} \right) \left( \frac{R}{r_0} \right)^2 \) for zero g, where \( V_d \) is the drain velocity, \( R \) the tank radius, and \( \rho \) the gravitational acceleration, \( r_0 \) the drain radius, \( \sigma \) is the surface tension and \( h_c \) is the liquid free surface height at pullthrough.

2. For \( h_c \ll r \), \((h_c^3/r_0) = 1.9 \left( \frac{V_d^2}{r_0 g} \right) \) (Equation 2) at high g and \((h_c/r)^3 = 0.95 \left( \frac{(\rho V_d^2 r_0)}{\sigma} \right) \left( \frac{R}{r_0} \right)^2 \) for zero-g.

3. Present results are compared with the results of other investigators in Figure 2 for gravity dominated draining. \( h_c/r_0 = 0.86 \) tank \( [1.3 \left( \frac{V_m^2}{2g r_o} \right)^{0.29}] \) (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 \( h_c \ll r \), \((h_c/r_0)^3 = 0.83 \left( \frac{V_d^2}{g r_0} \right) \left( \frac{r_0^2}{r_b} \right) \) (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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8-34
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
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 quiescence 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

\[ H_c = 0.69 \left( \frac{Q^2}{(1 - \rho_2/\rho_1) g a^5} \right)^{1/5} \]

where \( H_c \) is the liquid free surface height at pull-through, \( a \) is outlet radius, \( \rho_1 \) is the density of the bottom fluid and \( \rho_2 \) 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
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 trichloroethane, 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

(a) Flat bottom.  (b) Hemispherical bottom.  (c) 55° Elliptical bottom.

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_o$</td>
<td>cross-sectional area of outlet, cm$^2$</td>
</tr>
<tr>
<td>$A_t$</td>
<td>cross-sectional area of tank, cm$^2$</td>
</tr>
<tr>
<td>$F_c$</td>
<td>capillary forces, dynes</td>
</tr>
<tr>
<td>$F_p$</td>
<td>pressure forces, dynes</td>
</tr>
<tr>
<td>$R$</td>
<td>cylinder radius, cm</td>
</tr>
<tr>
<td>$V$</td>
<td>liquid-vapor interface velocity at centerline of tank in weightlessness, cm/sec</td>
</tr>
<tr>
<td>$V_m$</td>
<td>mean liquid velocity in weightlessness, $A_oV_o/A_t$, cm/sec</td>
</tr>
<tr>
<td>$V_o$</td>
<td>outlet velocity in weightlessness, cm/sec</td>
</tr>
<tr>
<td>$W_e$</td>
<td>Weber no., $W_e = \rho V_m^2 R/4\sigma$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>liquid density, g/cm$^3$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>surface tension, dynes/cm</td>
</tr>
</tbody>
</table>
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
   \[ \frac{h}{D} = 0.43 \left( \frac{V}{a} \right)^{1/4} \left( \frac{g}{D} \right) \] where \( \frac{h}{D} \) = normalized liquid height and \( \frac{V}{a} \) = Froude number, \( \frac{g}{D} \) = 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. 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 \( D >> d \), gas ingestion height is independent of tank diameter and
   \[ \frac{h}{d} = 0.43 \left( \frac{V}{a} \right)^{1/4} \] 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.

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 non-linear, 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 oscillations.
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 \((a/g<3\times10^{-6})\) 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

Convection $g = 10^{-3}$
Constant
Convection "g-jitter" ($\pm 10^{-3}$)
$r = 0.635$ cm
Flight Data
Conduction Only

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 O₂ 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

OBJECTIVE. - Develop analytical methods suitable for prediction of Apollo super-critical 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 super-critical O₂ 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-LcRC, 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.

9-8
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.
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 LN₂, LH₂ and LO₂ which have been tested at low g. The LN₂ provided thermal shielding for the LHe as well as a comparison with previous LN₂ 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 despine. A constant 1 atm. pressure was maintained during flight. At launch both vessels were approximately 50% full. LHe temperature varied between 4.1°K and 4.25°K while the N₂ 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/cm² at a ΔT of 12°K, while under low-g it was 9 W/cm² (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/cm²), 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/cm² at a ΔT between 0.15 and 0.20°K. At 1-g the maximum flux was 1 W/cm² 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 11.3

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 Vllet 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.

\[
q_{\text{max}}^\prime \text{W/m}^2 = 30.8 \times 10^4 \left( \frac{u_{\infty}}{D_{c}, \text{cm}} \right)^{0.15} \quad \text{(Equ. 1 Water)}
\]

\[
q_{\text{max}} = 2.45 \times 10^4 \frac{u_{\infty}}{D_{c}, \text{cm}}^{1/2} \quad \text{(Equ. 1 Refr. 113)}
\]

\[
q_{\text{max}} = \frac{1}{2} \left( B^2 + 2q_{PB} + B \sqrt{B^2 + 4q_{PB}} \right) \quad \text{(Equ. 2)}
\]

where: \( B = \sqrt{\frac{1}{C_1}} \)

\[
C_1 = 14.46 \times 10^2 \text{ W/m}^2 \cdot \text{K}^2 \text{. As used in Figure 1, however for Refrigerant 113 a best fit of the data would result in } C_1 = 5.86 \times 10^2.
\]

\[
\bar{h}_c = 0.676 \frac{k}{D} \left( \frac{u_{\infty} D}{v} \right)^{0.466} \left( \frac{\mu C_p}{k} \right)^{0.31}
\]

\[
q_{PB} = \frac{0.94}{(Bo)^{1/8}} q_z \quad \text{(Equ. 3)}
\]

\[
q_z = \left( \frac{n}{24} \right) \left( \rho C_p g \right)^{1/2} h_{fg} \left[ 6a(\rho_f - \rho_g) \right]^{1/4}, \quad Bo = R^2 a \frac{(\rho_f - \rho_g)}{\sigma}
\]

* A check of the basic reference shows this to be \( \sigma \) 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

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 LN₂ and F-113 at saturation or near saturation (1 atm.). Heat flux was varied from 300 to 30,000 Btu/hr-ft². 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 LN₂ 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 < 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 (Dmax) and frequency of bubble departure (f) are correlated by the relation, (Dmax)²/f = constant.
7. The latent heat transport model (\( \dot{q}_{TOT, BUB.} = c_v h_{fg} V_B \)) 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 \( \left( \dot{q}_{TR} = V_B c_f (T_w-T_f) \right) \) predicts higher \( \dot{q} \) than test.

10-6
Figure 1: Average boiling spread velocity, $v_A$, all orientations, $g = 1$ and 0.

Figure 2: Surface superheat for incipient boiling, $T_{s}$, all orientations, $g = 1$ and 0.

Figure 3: Saturated nucleate boiling heat transfer, FIT, horizontal-up $g = 1$ and 0.

Figure 4: Saturated nucleate boiling heat transfer, $h_{g}$ all orientations, $g = 1$ 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 $q_{\text{max}}$ in viscous liquids. The viscous prediction is only valid when it predicts higher $q_{\text{max}}$ 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 $R' = (\text{radius of body}) \left( \sqrt{\frac{a}{(\rho \_L - \rho \_g)/\sigma}} \right)$. 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

\[ q_{\text{max}} = 1.14 q_{\text{max}_2} \]
\[ q_{\text{max}} = \frac{(0.94/\eta)^{1/4}}{q_{\text{max}_2}} \]
\[ q_{\text{max}} = 0.904 q_{\text{max}_2} \]
\[ q_{\text{max}} = (1.734/\eta) q_{\text{max}_2} \]
\[ q_{\text{max}} = 0.84 q_{\text{max}_2} \]
\[ q_{\text{max}} = 0.9 q_{\text{max}_2} \]

\( \lambda_d \) = "most susceptible" wavelength
\[ q_{\text{max}_2} = (\pi/24) \frac{1}{\eta_0} \frac{h}{g} \frac{1}{(\alpha - \alpha_g)^{1/4}} \]

\( R' = \text{(ribbon height)} / \sqrt{a/(\alpha - \alpha_g/\alpha)} \) (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


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: $M_b = \frac{L}{\beta} \frac{(T_o - T_c)}{(\alpha / \nu)} \frac{\sigma B}{\gamma}$ and $R_a = \frac{\beta g (T_c - T_B) \rho_o^2}{\nu c \gamma}$ where $L =$ length of bubble interface along which motion was observed, $R_o =$ radius of bubble base, $\mu =$ viscosity of liquid at $\frac{1}{2} (T_o + T_c)$, 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, $q = 3.5 \times 10^4$ 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.

10-10
Fig. 1. Plot of ratio of Nusselt number with air bubble on surface to that without bubble, after removal of thermal boundary layer.

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); $\theta_f = 23$ deg C, $q = 2.2 \times 10^4$ W/m$^2$, $R = 10$ mm; interval between photos about 0.5 sec.

Fig. 3. Marangoni and Rayleigh numbers at transition for vapor bubbles (left-hand side) and air bubbles.
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1968 A
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 = 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 = 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 = 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 ±0.008 to 0.23 ±0.03 in a 1.34 sec. drop facility. Pressures ranged from 14.7 psia 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). $Ra^{1/4} = 10^9$ 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.
STUDIES OF LIQUID BOILING IN IMITATED REDUCED GRAVITY FIELDS

OBJECTIVE. - To investigate liquid oxygen boiling at imitated reduced gravity.

PERTINENT WORK PERFORMED. - Tests were conducted on the boiling characteristics of LO₂ 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/gₙ = 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
   \[ q = q_n \left( \frac{a}{g_n} \right)^{0.85} \]
   over the range of a/gₙ 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/gₙ = 0.02 to 1.0.
4. The average bubble diameter at departure (D₀), taken as the average of horizontal and vertical diameters, was found to correlate with D₀, m = 0.47 \times 10^{-3} (a/gₙ)^{-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 LN2 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_{maxF} and q_{min}/q_{minF} = 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 convection 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:

$$q_{min} = q_{minF} \left[0.0217/R^{1/2} (2R^{1/2} + 1)\right].$$

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' \approx 0.70.

<table>
<thead>
<tr>
<th>Table 1. Nomenclature</th>
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<td>(q_{maxF} = (\pi/24) \rho_g^{1/2} h_{fg} \left[\sigma a (\rho_L - \rho_g)\right]^{1/4})</td>
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<td>(q_{minF} = 0.09 \rho_g h_{fg} \left[\sigma a (\rho_L - \rho_g) - 1/4\right])</td>
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<td>(L = \text{characteristic length})</td>
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<td>(I = \text{induced convection scale parameter, } [\rho_g \text{ L} \sigma]^{1/2}/\mu)</td>
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<td>(I_0 = \text{I where } L = \text{width of test capsule})</td>
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FORCED-CONVECTION BOILING NEAR INCEPTION IN ZERO GRAVITY

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 thermistor 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

$$\frac{Q_w}{A k} \left[ \text{erfc} \left( \frac{1.6 Y_{sat}}{\delta T} \right) \right]$$

and $\delta T = 3.2 \left( \frac{v}{Pr_L} \right)^{1/2}$. For the convection regime

$$T - T_\infty = \frac{Q_w}{A k} \left( \frac{\delta T}{2} - Y_{sat} \right) \frac{Y_{sat}^3}{\delta T^2} - \frac{Y_{sat}^4}{2 \delta T^3}$$

and $\delta T = 2.2 \left[ \frac{\delta H}{u_\infty \Pr_L} \left( \frac{\bar{x} - \bar{x}_o}{u_\infty} \right) \right]^{1/3}$

The end of the transition regime and start of the convection regime is defined by

$$\frac{\bar{x} - \bar{x}_o}{u_\infty} = \left( \frac{0.443}{Pr_L^{1/2}} \right) u_\infty t.$$ Nomenclature are:

- **A** = heater surface area
- **$Q_w$** = total heat flux at wall
- **$\delta_H$** = 3.65 $vt$
- **$\bar{x}$** = axial displacement along surface

subscript, $\infty$ = free stream conditions and $o$ = thermal entrance region.

10-18
Table 1. Test Conditions

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<th>Saturation temperature, $T_{sat}$, °C</th>
<th>Heat flux, $q$, W/m²</th>
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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.

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-ft². 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 Q at given ΔTw-g) 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 Q. Due to the nature of the heaters, a residual energy source was present and absolute 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 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 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,
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. In-
cluding this previous work along with the current work, the following test conditions
were covered: (1) Subcooling (T_{sat} - T_{bulk} = 5^\circ C to 40^\circ C, 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,
00% 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.
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.

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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10-26
Fig. 1. Boiling Experiment, Bubble Formation in Normal and Zero Gravity (Test Liquid, Liquid Hydrogen)
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 LN₂ 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 Q = 2,000 to 65,000 Btu/hr-ft² 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

$\tau - \tau_g(\eta)$

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

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$_3$O$_4$) 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 affected 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, 265°F (66°C).
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).
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 pol-
ished 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 bub-
ble 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, exceed-
ing 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 pre-
dicted reasonably well at low-g (Figure 2) with \( C_D = \frac{45}{Re} \).
NOMENCLATURE

\[ X = X_0 + \left( \frac{U - A}{B} \right) \left( 1 - e^{-Bt} \right) + At \] (Equ. 9)

\[ X = \text{distance from surface to bubble center} \]
\[ U = \text{velocity} \]
\[ A = \frac{4}{3} g \left( \frac{\rho_l - \rho_v}{\alpha \mu_l} \right) D_r^2 \]
\[ B = \frac{12}{11} \frac{a}{\rho_l} \frac{\mu_l}{D_r^2} \]
\[ a = 45 \text{ and } D_r = \text{bubble dia. during rise} \]
\[ t = \text{time from departure} \]

Figure 1: Effect of reduced gravity on diameters of single undisturbed bubbles at instant of detachment from surface.

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 PROPAINE IN A NEAR-ZERO GRAVITY ENVIRONMENT

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 \(\Delta T_{w-g}\) with a nominal value of 1/3 in the \(\Delta T_{w-g}\) 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 Inside Tank

Figure 2. Heat Transfer Rate & Tank Wall/Propylene Temperature Difference

Figure 3. Boiling Heat Transfer to 99% Pure Liquid Propylene at 1 g.
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 \( (a/g = 0.01 \text{ to } 0.04) \), 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 \( \pm 10^\circ F \), 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

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>$N_{FR}$ dynamic</th>
<th>$N_{BO}$ buoyant</th>
<th>$N_{FR} \times N_{BO}$ dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N = 1$ (R = 0.05 in.)</td>
<td>34.9</td>
<td>562</td>
<td>19,600</td>
</tr>
<tr>
<td>$N = 0.01$ (R = 0.1 in.)</td>
<td>427</td>
<td>22.5</td>
<td>9,840</td>
</tr>
</tbody>
</table>

TABLE 2
ONE GRAVITY AND LOW GRAVITY PEAK HEAT FLUX

<table>
<thead>
<tr>
<th>Material</th>
<th>$(Q/A)_{max.}$ (N = 1) BTU/HR-FT²</th>
<th>$(Q/A)_{max.}$ (N = 0.01) BTU/HR-FT²</th>
<th>$(Q/A)_{max.}$ (N = 0.01)</th>
<th>$(Q/A)_{max.}$ (N = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rohsenow Zuber</td>
<td>$4.32 \times 10^4$</td>
<td>$1.36 \times 10^4$</td>
<td>$0.316$</td>
<td>$0.316$</td>
</tr>
<tr>
<td>0.020&quot; PT Wire</td>
<td>$6.09 \times 10^4$</td>
<td>$9.9 \times 10^4$</td>
<td>0.203 and 0.259</td>
<td></td>
</tr>
<tr>
<td>1/8&quot; PT Ribbon</td>
<td>$5.27 \times 10^4$</td>
<td>$1.46 \times 10^4$</td>
<td>0.176 and 0.487</td>
<td></td>
</tr>
</tbody>
</table>

(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

<table>
<thead>
<tr>
<th>$Q/A$ (BTU/HR-FT²)</th>
<th>Time to Burnout (Sec.)</th>
<th>Total Float Time (Sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5.2 \times 10^4$</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$4.9 \times 10^4$</td>
<td>2.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$4.4 \times 10^4$</td>
<td>3.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

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.

OBJECTIVE. - To obtain basic heat transfer data on nucleate boiling of LH2 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 in². 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-ft² 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.
Fig. 1. Heat flux vs. temperature difference between a heated surface and liquid hydrogen at one-g in the bubble boiling region.

Fig. 2. Heat flux vs. temperature difference between a heated surface and liquid hydrogen at zero-g in the bubble 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 bubble 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

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 charac-
   terized 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 noncondensible 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

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.
Figure 1. Typical Distributions of Local Static Pressure Drop for 1-g and Zero-Gravity Environments

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

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 GN₂.
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 °F 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 °F to 1100 °F.

Figure 1. Effect of gravity on overall static pressure drop.

(c) 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 °F 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 \((D_0 + D_1)/2\) 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 (CCl₃F), C₃₁₈ (C₄F₈), and 600 (C₄H₁₀, n-butane) using the NASA/LeRC 5-sec drop facility. The test containers were acrylic plastic cylindrical, having flat ends (0.06 m dia x 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.

12-2
### Table I - Summary of Parameters

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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; $Bo = \frac{R^2 \rho_l \gamma}{\sigma}$. 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

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<td>30</td>
<td>1.96</td>
<td>9</td>
<td>6.7</td>
<td>0.77</td>
<td>11.5</td>
<td>2.31</td>
<td>47</td>
</tr>
</tbody>
</table>

*Based on average density during venting.*
VAPOUR 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:

$$
\frac{q}{h_f g} - \rho_v \frac{\partial u_v}{\partial x} - \rho_v \frac{\partial U_v}{\partial x} h_x = \rho_v \frac{\partial h_x}{\partial t}
$$

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:

$$
V_v = C H^2 q/2 h_f g \rho_v u_v
$$

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 $1.53 (g \alpha)^{1/4}$. 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

<table>
<thead>
<tr>
<th>Range</th>
<th>Fluid Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$We &lt; 3.85$</td>
<td>$h_x = \left( \frac{9}{2} \frac{a \mu}{h_g \rho_v \rho_f} \right)^{1/3} \left( \frac{\pi}{3K^2} \right)^{2/3}$</td>
</tr>
<tr>
<td>$We = 3.85$</td>
<td>$h_x = \left( \frac{a}{h_g \rho_v} \right)^2 \left( \frac{6 \rho_f K^2}{3.85g\sigma \pi} \right)^x$</td>
</tr>
</tbody>
</table>
| $We > 3.85$   | $C_D = 2.6$  

$C_D = \text{bubble drag coefficient}$

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 pressurization, 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 LH₂ 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

<table>
<thead>
<tr>
<th>Bulk Liquid Model</th>
<th>Boundary Layer Model (Figure 1)</th>
<th>Bubble Dynamics Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>• All heat input is absorbed in vapor generation.</td>
<td>• Bubbles are spaced as a specified function of bubble diameter.</td>
<td>• Vaporization can be by nucleate boiling at the wall or evaporation at existing bubbles and at the liquid-vapor interface according to surface area.</td>
</tr>
<tr>
<td>• The fraction of generated vapor which remains in the liquid must be specified.</td>
<td>• A steady state boundary layer solution is used with the constraint of a mass balance on the boundary layer.</td>
<td>• 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.</td>
</tr>
</tbody>
</table>

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 LH₂. The Freon TF drop tests were accomplished in a 75-ft tower, while the LH₂ tests used a 16-ft tower. Freon test containers were 15.2 and 29.2 cm (inside diameter) plexiglass cylinders and LH₂ 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 LH₂ 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 affect the potential for liquid being vented; the only limitation being that the vented volume of vapor must be less than the initial ullage volume. LH₂ 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

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Nominal Dever Size (in.)</th>
<th>Volume (cc)</th>
<th>Vented Mass (gm)</th>
<th>Vented Volume*</th>
<th>Volume Pressure (psig)</th>
<th>Liquid Temperature (°R)</th>
<th>Vent Time (sec)</th>
<th>@ Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>4</td>
<td>1280</td>
<td>1270</td>
<td>1.26</td>
<td>1730</td>
<td>20.1</td>
<td>16.2</td>
<td>0.76</td>
</tr>
<tr>
<td>19</td>
<td>4</td>
<td>1280</td>
<td>1270</td>
<td>1.24</td>
<td>1680</td>
<td>20.1</td>
<td>16.7</td>
<td>0.76</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
<td>1280</td>
<td>1270</td>
<td>0.97</td>
<td>1300</td>
<td>20.1</td>
<td>16.7</td>
<td>0.82</td>
</tr>
<tr>
<td>21</td>
<td>4</td>
<td>1280</td>
<td>1270</td>
<td>0.68</td>
<td>900</td>
<td>20.1</td>
<td>17.0</td>
<td>0.80</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>1050</td>
<td>1500</td>
<td>1.27</td>
<td>1750</td>
<td>19.9</td>
<td>16.2</td>
<td>0.74</td>
</tr>
<tr>
<td>31</td>
<td>8</td>
<td>1050</td>
<td>1450</td>
<td>1.21</td>
<td>1710</td>
<td>20.1</td>
<td>15.7</td>
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</tr>
<tr>
<td>27</td>
<td>4</td>
<td>1100</td>
<td>1450</td>
<td>0.76</td>
<td>1210</td>
<td>19.9</td>
<td>13.7</td>
<td>0.74</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>1100</td>
<td>1450</td>
<td>0.53</td>
<td>840</td>
<td>19.8</td>
<td>13.7</td>
<td>0.74</td>
</tr>
<tr>
<td>34</td>
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<td>2960</td>
<td>5350</td>
<td>1.19</td>
<td>1570</td>
<td>19.8</td>
<td>17.0</td>
<td>0.68</td>
</tr>
<tr>
<td>33</td>
<td>8</td>
<td>2960</td>
<td>5350</td>
<td>0.77</td>
<td>1090</td>
<td>19.6</td>
<td>15.7</td>
<td>0.70</td>
</tr>
<tr>
<td>35</td>
<td>8</td>
<td>3360</td>
<td>4940</td>
<td>0.61</td>
<td>980</td>
<td>19.6</td>
<td>13.5</td>
<td>0.69</td>
</tr>
<tr>
<td>36</td>
<td>8</td>
<td>3360</td>
<td>4940</td>
<td>0.44</td>
<td>680</td>
<td>19.6</td>
<td>14.2</td>
<td>0.68</td>
</tr>
<tr>
<td>38</td>
<td>8</td>
<td>3160</td>
<td>5140</td>
<td>0.83</td>
<td>1680</td>
<td>19.8</td>
<td>10.6</td>
<td>0.66</td>
</tr>
<tr>
<td>39</td>
<td>8</td>
<td>3160</td>
<td>5140</td>
<td>0.74</td>
<td>1390</td>
<td>21.1</td>
<td>11.6</td>
<td>0.59</td>
</tr>
<tr>
<td>46</td>
<td>8</td>
<td>2370</td>
<td>5960</td>
<td>1.37</td>
<td>2210</td>
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<td>0.75</td>
</tr>
<tr>
<td>47</td>
<td>8</td>
<td>2370</td>
<td>5960</td>
<td>1.06</td>
<td>2580</td>
<td>19.6</td>
<td>8.5</td>
<td>0.77</td>
</tr>
</tbody>
</table>

*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

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 \( h_o \). The coordinate axes was chosen to move with the liquid. The region of interest, enclosed in the dashed rectangle, included the dynamic contact angle \( \theta \) 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 \( \tan \theta = 3.4 \left( \frac{u_o h_o}{\sigma} \right)^{1/3} \) and is rigorously applicable only for \( Re << 1 \).

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


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.

<table>
<thead>
<tr>
<th>Category</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-G Fluid Behavior General</td>
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</tr>
<tr>
<td>Interface Configuration</td>
<td>B-10</td>
</tr>
<tr>
<td>Interface Stability</td>
<td>B-16</td>
</tr>
<tr>
<td>Natural Frequency and Damping</td>
<td>B-23</td>
</tr>
<tr>
<td>Liquid Reorientation</td>
<td>B-34</td>
</tr>
<tr>
<td>Bubbles &amp; Droplets</td>
<td>B-36</td>
</tr>
<tr>
<td>Fluid Inflow</td>
<td>B-38</td>
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<tr>
<td>Fluid Outflow</td>
<td>B-40</td>
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<tr>
<td>Internal Heat &amp; Mass Transfer, General</td>
<td>B-43</td>
</tr>
<tr>
<td>Convection Heat Transfer</td>
<td>B-45</td>
</tr>
<tr>
<td>Boiling Heat Transfer</td>
<td>B-50</td>
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<tr>
<td>Condensation Heat Transfer</td>
<td>B-56</td>
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<tr>
<td>Venting Effects</td>
<td>B-58</td>
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<tr>
<td>Fluid Properties</td>
<td>B-60</td>
</tr>
<tr>
<td></td>
<td>B-1</td>
</tr>
</tbody>
</table>
LOW-G FLUID BEHAVIOR GENERAL


The pertinent work reported here is adequately covered and extended in a later report by Bradshaw (1970), which is summarized.


This work is only applicable to biochemistry, biomedical research and applied medicine.


Detailed mathematical treatment of one narrow aspect of hydrodynamics as applied to a hydromagnetic dynamo and does not deal with low-g.


This work is reported in greater detail in contract reports; eg. Burnett, et al, 1970, which is reviewed elsewhere.


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.


Deals with biology.


Only a general discussion of low-g fluid behavior without specific data of interest.


Discusses the free fall facility at the ONERA Laboratory and is not worthy of translation.

B-2

General discussion of the behavior of liquids at low-g, with pertinent information contained in other work in more detail.


No specific data is given which adds to the state-of-the-art of low-g fluid behavior.


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).


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.


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.


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.


Later work, reviewed elsewhere, presents results of the experiment, along with pertinent experiment descriptions.

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.


Work on low-g combustion is not considered pertinent to the current program and is therefore not covered.


Only a theoretical discussion is presented and the state-of-the-art of low-g fluid behavior is not advanced.


This report does not add anything to the knowledge of low-g fluid behavior.


No new technology data are presented.


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.


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.

An analytic treatment of the subject with little offered in the way of solution or a contribution to design.


This work is reported in greater detail in contract reports; eg, Burnett, et al (1970) which is reviewed elsewhere.


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).


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).


A basic simplified discussion of weightlessness and possible fluid configurations is presented, however no applicable data is presented or discussed in this simplified discussion.


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.


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.

In this case gravitational flow simply means the flow resulting from an induced level difference between two reservoirs where the driving force is gravity.


Applies only to drop tower facility design and does not add to the state-of-the-art of low-g fluid behavior.


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.


Applicable to space manufacturing type processes and not the current in-orbit fluid transfer program.


Does not add to the state-of-the-art of low-g fluid behavior.


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.


Gravitational effects as used here refer to the earth's gravity as it affects fluid flow in the oceans and atmosphere.


The pertinent data presented is taken from other work which is reviewed elsewhere.

Discussions are only brief reviews not amenable to summarization.


This paper is concerned with the stability of a satellite and is not directly applicable to low-g transfer.


Pertinent aspects of this work are reviewed elsewhere, Trusela, 1960 under General Heat Transfer.


The technology data presented is only in terms of brief reviews of existing work.


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.


A survey paper which confirms basic principles, but the pertinent work is summarized from the original source documents.


Does not provide data on low-g fluid behavior.


Mostly a generalized discussion of future work with no new data presented.

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.


"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.


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.


An analytical discussion with the results not presented in a useful form for design.


No new data of significance was presented.


The work presented is very general and no specific data is given which advances the state-of-the-art of low-g fluid behavior.


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.


This work is reviewed in more detail under the project THERMO contract reports, Schweikle, 1967.

This study explores the possibility of individual experimentation utilizing smaller carrier vehicles. No new low-g fluid behavior technology data are presented.


A qualitative discussion of low-g in relation to early USSR programs is given, however, no significant fluids data is present.


Results are specifically oriented to the Centaur application and are not significant for general use. See Sherley, 1962 for summarized boiling heat transfer data.


Covers essentially the same material presented in AY62-0031 by Sherley and Merino (1962).


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.


Reviews the results of drop tower work at LeRC on liquid inflow and outflow which covered in NASA reports reviewed elsewhere.


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.


Basically a survey and general discussion of other work and does not add to the state-of-the-art of low-g fluid behavior.

Improved codes have been developed; a review of these developments are summarized by Bradshaw, 1974.


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.


The data contained in this report does not add to the state-of-the-art of low-g fluid behavior.


Information is not directly applicable to low-g fluid transfer and basic theory has been incorporated into other more recent documents.

INTERFACE CONFIGURATION


Interesting qualitative data, but not pertinent to system design.


This fundamental investigation into surface tension has been covered in more recent thorough works by Reynolds, et al, in the LG series 1961, 1964.


Sketchy basic information is presented which is not significant in view of current literature.

More complete information with design data are presented, i.e., Reynolds and Satterlee in SP 106 in Abramson, 1966, and no significant data on interface configuration on other low-g areas appear.


Early drop tower work at LeRC with qualitative phenomena only.


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.


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.


More extensive information which has been validated is contained in later publications.


Similar paper to Blackshear, TN D2471, 1964, which is summarized.


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.

Other work treats this subject in a sufficient, more usable manner.


Significant data in this report have been updated in more recent literature.


Later work contains solutions for interface shape without restrictions on contact angle or Bond number.


This is a special case, not of sufficient general applicability to summarize.


The equations do not suggest a design tool. See CLEO report (Bowman, 1966), for further analysis.


Analytical development of reduced gravity/surface tension fluid behavior is presented. Same material as Li's article in Journal Chemical Physics, 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.


General discussion of the effects of zero-g on liquid configuration which does not add to the state-of-the-art.

This paper presents no pertinent data which has not been covered in reports of LeRC drop tower work.


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.


Better data is contained in LMSC Handbook (Satterlee, 1967) and in the Stanford LG series (Reynolds, 1964), both summarized in this volume.


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.


More recent quantitative data now available.


Only qualitative behavior presented.


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.

Data covered elsewhere (Hastings, TM X-53790, 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.


Only basic ideas presented; much better data has been developed.


No data is reported only the experimental configuration.


Data for interface configurations in right circular cylinders has been extensively covered in later work by Hastings (1968) and Concus (1968).


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.


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.

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.


A considerably more in depth presentation on magnetic fluid simulation is presented by Dodge, 1970.


Nothing significant for design purposes is given.


Data is basic in nature and contained in later low-g handbooks.


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.


Nothing new over Paynter's 1964 article except for additional data points.


Highly specialized application; insufficient data presented to be useful.

Highly mathematical treatment not supported by experiment.


Does not contain data relative to transfer and the material presented does not contribute to a data bank for fluid transfer.


Pertinent results are included elsewhere (Symons, TN D-6076, 1970).


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.


More extensive data in this subject has been published (Petrash, TN D-1582, 1963).

INTERFACE STABILITY


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.


For more pertinent work see Labus and Aydelott, 1971, which is summarized.


B-16
The Application is minimal, it does not present immediate application to geometry common to the low-g transfer problem.


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.


The results of this work are summarized in the final report, NASA CR-651, Bowman, 1966.


This rather theoretical effort does not have visible application to low-g fluid transfer.


The application to low gravity has not been established and no test data is presented.


The conclusions are not significantly different from Concus, 1963, and the rectangular configuration is not particularly applicable to low-g fluid transfer.


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).

This paper does not discuss gravity effects which are available in the SMAC code discussions (Bradshaw, 1974).


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.


Not relatable to low-g fluid transfer.


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.


The highly mathematical treatment with extensive derivations does not develop any data or usable models applicable to the liquid during low-g transfer.


A highly theoretical and mathematical solution is presented which has as one assumption, the slope of the free surface is everywhere small, i.e., $\tan \theta$ is large in comparison to unity ($\theta =$ contact angle). This assumption is seldom valid. No experimental data is shown and little graphical data is given.


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.

The basic technology presented is not low-g; however, application to rotational type liquid orientation is summarized in a report by Morgan, 1968.


This work superimposes the electrical field on the rotating cylinder stability analysis, however, inadequate data and verification exist to merit its use.


The stability of fluids is calculated using the marker-and-cell technique; applications of the MAC technique are summarized by Bradshaw (1974).


Not applicable to low-g transfer of fluids.


This method is adequately described in a summarized report by Bradshaw, 1974.


The qualitative data is not generalized to a correlation suitable for design. This represented one-g tests.


Does not consider the aspects of gravity sensitivity or low-g fluid behavior.


The data presented are the fundamental laws and the energy analysis is for mercury droplets rebounding from hydrochloric acid solution.

An extension of this work is presented by Labus and Aydclott, 1971, which is summarized.


Better, more complete data is presented elsewhere in more recent literature.


Later work has been done to apply this initial work to the low-gravity application, (Bowman, 1966).


This is an analytical study of liquid in a fully-filled cylinder applicable to liquid-filled projectiles.


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.


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.


Techniques for use of electric fields to stabilize liquids are discussed in a report by Blutt, 1968.

This subject is adequately covered under dielectrophoresis summarization (Blutt, 1968).


The concepts of dielectrophoretic control are covered elsewhere (Blutt, 1968).


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.


Not applicable to low-gravity transfer.


This highly mathematical approach to the non-linear Kelvin-Helmholtz instability does not address gravity effects on propellant transfer.


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.


Information was useful when presented but is now contained in other sources (such as Mariner 75 reports) that are summarized.


This paper is not directed towards low-gravity or the transfer process; further it does not specifically address interface stability.

B-21

No data is developed applicable to low-g transfer; the study is highly theoretical without direct application to fluid transfer.


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.


This work has been extended and improved by investigators (Bowman, 1966, Hurd, 1966), and experimentalists at LeRC (Masica, 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.


The configuration has little applicability and does not consider influences of a non-rotating g-field.


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.


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.


B-22
Nothing on interface configuration. Work relative to capillary acquisition in using screens is covered more recently by Burnett, 1970.


Only a basic discussion is presented; later literature is more complete.


No significant data is included.


This theoretical paper considers two-dimensional stability of elastic tanks and lacks direct applicability to low-g transfer. No useful data.


Work has been done to apply this early work to low-g application, (Bowman, 1966).

NATURAL FREQUENCY AND DAMPING


The Marker and Cell technique is covered in summary by Bradshaw, 1973.


This mathematical model does not significantly advance the state-of-the-art.


This is only a general discussion of potential slosh-settling problems.


This mathematical dissertation does not address low-g problems.

This is a classical mathematical approach to the problem which does not yield any additional new design data for low-g transfer.


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.


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-5658 (Salzman, 1969).


The concept of induced wall roughness to dampen sloshing does not appear to be a viable candidate in low-g transfer applications.


Computer program documentation for NAS8-21272 is presented, the theory appears in NASA CR-113117 (Fontenot, 1970). No parametric data is developed.


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.


B-24
Data in this paper is updated, expanded and presented elsewhere in LMSC work, Hollister, 1967.


Low-g sloshing in spherical tanks has been investigated more recently by Concus, 1969, and experimentally by Coney, 1971.


These results are assessed in respect to the overall program results in the summarized final report by Dodge, 1970.


The study is analytical and is not compared with experimental results. This work does not significantly add to the work of Dodge, 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.


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.


This has been superseded by more recent work, Salzman (1969) and Dodge (1970).


This journal article is essentially identical to NASA CR-54700 (Concus, 1967), which is summarized.

More recent data in slosh damping in low-g is now available as well as handbooks with verified correlations.


The work here is not a significant departure from results and correlations presented in the summarized report by Dodge, 1970.


This is a report on one task under a broad contract to investigate aspects of sloshing (Dodge, 1970). No significant data is developed here.


These results are discussed in respect to the overall program results in the summarized final report by Dodge, 1970.


These results are assessed in respect to overall program results in the summarized final report by Dodge, 1970.


These results are assessed in respect to overall program results in the summarized final report by Dodge, 1970.


This paper is contained in total in the Final Report of NAS8-20290 (Dodge, 1970) which is summarized.

This work is covered in the summarized report by Dodge, 1970.


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This paper is contained in total in the Final Report of NAS8-20290 (Dodge, 1970) which is summarized.


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.


These results are assessed in respect to other overall results in the summarized final report by Dodge, 1970.


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.


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.


B-27
An adequate 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.


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.


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.


A theoretical development is performed for fluid behavior in tanks with perturbations in acceleration with no solutions or experimental verification.


This work does not address propellant motion in low-g; see NASA CR-113117, Fontenot, 1970.


The purely mathematical discussion does not lend itself to analysis of the low-g transfer problem.


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.

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.


This report considers only a specific application and does not present generalized data applicable to low-g systems design.


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.


Marker-and-cell techniques were adequately discussed (Bradshaw, 1974). The method described here is limited to minor fluid distortions.


This early work in the field has long been surpassed by the state-of-the-art.


The applications of dielectrophoretic control of propellants is adequately covered in the summarized report by Blutt, 1968.


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.

This computer program for slosh eigenvalues in elastic tanks has potential application, however, experimental verification in 1-g and extension to low-g has not been accomplished.


In this mathematical discussion of surface oscillations, no usable data for low-g transfer is developed.


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.


This analytical development is not extended to numerical results nor is data provided of utility to low-g transfer design studies.


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.


This is a computer program documentation for Lomen's work under NASA CR-222, 1965. More recent work is available.


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.

The technical effort does not represent a significant contribution to the data in this field.


Improved models have been developed since this early work in sloshing and the data are not readily adaptable to the low-g transfer application.


The equations presented are primarily theoretical and do not lead to immediate applicable design data.


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.


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.


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.

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.


An experimental, qualitative report with insufficient data which can be applied to design.


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.


Although this TM represents a literature survey of design tools thru 1965; it provides no new developments in sloshing correlations.


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.


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.


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.


B-32
Although extensive 1-g full-scale test data is presented, it is not generalized to other tankage and to low gravity application.


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.


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.


Only limited data is developed in this mathematically oriented paper. A more complete paper is available (Sickmann 1968).


This highly mathematical approach to sloshing with rigid sidewalls and flexible bottom tank does not consider the low Bond number range.


This is another mathematical development of sloshing; more recent developments are available which have been more extensively verified.

This is another mathematical development of sloshing; more recent developments are available which have been more extensively verified.


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.


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.


A mathematical presentation which is not developed in adequate detail for design application.

LIQUID REORIENTATION


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.


Lecture is a summarization of Blackmon, Castle and Heckman, May 1968 that is being summarized.


Settling from an initially flat interface is covered in Bowman, Liquid Settling in Large Tanks".

B-34

Results are preliminary with no usable information given.


Much more sophisticated tests were run by NASA-LeRC and semiempirical expressions were developed (see Salzman and Masica, 1967).


The pertinent information in this work is reported in Hollister, et al, 1967, which is being summarized.


Basically uses the information presented in "A Study of Liquid Propellant Behavior During Periods of Varying Acceleration," with no new technology information presented.


Advanced versions of this technique are discussed in Bradshaw and Kramer, "An Analytical Study of Reduced Gravity Propellant Settling", 1974.


Much of the quantitative information is contained in Salzman, et al, 1973 and Masica and Petrosh, 1965 that are being summarized.


Oversimplified approach to reorientation does not take into account the overwhelming importance or geysering and recirculation at high reorientation Bond number.

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.


Trajectory simulated is very specific and results are not usable for other vehicle or operations.


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.


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


Data is of an experimental design nature and not pertinent to system design.


This is strictly analytical with application to space manufacturing. The word "large" in the title means bubbles with volumes greater than 0.3-\(m^3\).

A general discussion with no new data presented.


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.


Basic information on bubble rise is presented which has been incorporated into more recent work.


Other studies have adequately handled reorientation of large ullage bubbles (Masica and Petrash, 1965).


The application of this phenomena is too limited to be worthy of summarization.


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.


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.

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.


The work reported is all based on 1-g data with no real effort made to relate to low-g.


Analytical treatment only, of a specialized subject not specifically applicable to in-orbit fluid transfer.


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.


The detailed analysis and testing 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**


Although the phenomena of liquid droplets evaporating off hot surfaces is important to tank childdown in fluid inflow, this data does not address gravity-sensitivity which is very important.


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.

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.


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.


The work is complex mathematically with results presented in a form that is difficult to use and terminology that is confusing.


Only applicable to fluid amplifier devices and therefore not useful in the current program.


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.


These results are also discussed in a summarized work by Symons 1971 in TM X-2348 where a more adequate correlation is developed.


No design data is presented and the geometry is not applicable to fluid transfer.

Data presented are applicable to specific commercial type cylinders and are not applicable to in-orbit transfer.


Mostly analytical and only applicable to 1-g conditions.

**FLUID OUTFLOW**


An experimental and analytical study of tank draining related to sloshing and vortexing was conducted which was not low-g oriented.


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.


*Interim Report, Final Report, Bizzell, June 1970 was summarized.*


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.


No pertinent information is given except that slosh baffles can be used to control vortexing.


A Lagrangian technique was employed in Bizzell, et al, 1970, which is summarized elsewhere.


Report is not readily available.


An internal document that is not readily available, see Ketchum, AIAA 70-1325, 1970.


Results are not presented in sufficient detail to be useful.


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.


No pertinent data was presented.


Early work of a qualitative nature has been superseded by more recent efforts.

Not too practical unless dielectrophoresis is used for acquisition as well, which is highly unlikely.


Presents a brief discussion on use of a distributor to provide for the vaporization of liquid entering a header, in order to equalize the chilldown of the system, however, no data are presented and insufficient information is given to add quantitatively to the state of the art.


Results are too specifically oriented to Agena to be of general use to other applications.


Two-fluid "low-g simulations" were run at relatively high Froude numbers; not enough details are presented to advance the state of the art.


Document not readily available (internal document).


Deals with the withdrawal of cylinders from liquid baths and is not applicable to the present program.


The overall systems analysis procedure appears useful, however, details of the specific contents of the analyses are not presented.

Deals with the withdrawing of cylinders from liquid baths and is not applicable to the current program.


Conclusions do not seem logical and results are not in a useful form.


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


Represents primarily a general survey of other work and is also discussed in other work by the same author, which is reviewed elsewhere.


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.


Essentially just a general discussion and rehash of other work.


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.


Does not contain data associated with low-g heat transfer problems.

Calculations of low-g heat transfer were by conventional means and applied specifically to the Agcna; the state-of-the-art with respect to technical capability was not advanced.


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).


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.


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.


Results of tests are discussed, however, specific data are not given and no pertinent conclusions are reached.


Detailed equations for heat transfer were developed without the means for solution and test data is not presented or even referred to.

Mainly general discussions with the only data presented being speculation based on existing technology.


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.


A general discussion of work done and potential work which should be done, without enough data presented to reach meaningful conclusions.


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


For the most current work on low-g convection see Grodzka and Bannister, 1974, which is summarized.


Applicable to detailed material study and not the specific state-of-the-art of low-g fluid behavior or cryogenic thermal control.


This work is adequately covered in a summarized paper by Grodzka and Bannister (1974).


This work is adequately covered in a summarized paper by Grodzka and Bannister (1974).

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.


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.


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.


Is primarily concerned with geophysical flows in a 1-g field and does not address the low-g problem.


Work applicable to the human respiratory system and not useful to the current study.


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.

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.),


This work has been expanded and updated in later reports (Forester, et al, 1970 and Barton, et al, 1972).


This work has been expanded and updated in a report by Barton, et al (1972).


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).


Strictly analytical with no specific application to low-g heat transfer.


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.


This subject is adequately covered in a summarized paper by Grodzka and Bannister (1974).


This work is adequately covered in a summarized paper by the authors in 1974.

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.


This is only brief work and purely analytical speculation as to the actual effects of variation in gravity.


This work has been superseded by more recent work; e.g., Thuraisamy (1972), which uses a similar numerical technique.


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.


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.


Strictly analytical with limited application.


This work is covered sufficiently in the summary prepared for NASA TR R-386, Anon. (1972).

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.


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.


This work has been superseded by more recent and comprehensive data associated with the Apollo program.


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.


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.


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.


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.

Later work on this subject is reviewed elsewhere.


This is only a progress report.


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.


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.


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**


The information presented is only of a general discussionary nature and is not significant without more correlation with actual data.


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.

This work is quite general and is also discussed by the same author in later references which are reviewed elsewhere.


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.


Covers the same work as reported in NASA CR-2270 by Lienhard and Dhir (1973).


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.


This subject is adequately covered in other reports which have been summarized.


The discussion is general and only refers to other work which is reviewed elsewhere.


Pertinent aspects are covered in other work and a more complete survey of this subject is presented by Siegel, 1967, which is summarized.

This work is included in more detail in later reports by the same authors (e.g., Merte 1964), which are reviewed elsewhere.


This work is adequately summarized in NASA TN D-4301, dated February 1968, by Cochran, et al.


This work is reported in NASA TN's, which are reviewed elsewhere.


This work is adequately summarized in NASA TN D-4301, dated February 1968, by Cochran, et al.


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).


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.


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.
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.


No new test data was presented and the correlations made with existing data were not extensive enough to reach any final conclusions.


This subject is adequately covered in other reports summarized elsewhere.


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.


This work is included in a 1970 report by the author which is summarized.


Does not appear to have verified the techniques and does not present much data. Looks like mostly theory.


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.

The analysis provides only unconfirmed conclusions and does not in itself add to the current state-of-the-art of low-g boiling.


Data and conclusions of primary interest are contained in a report by Merte (1970), NASA CR-103047.


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 \(-0.03 \text{ and } 1g\)" 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.


This work is reported in greater detail by McGrew (1966) in NASA CR-652 which report is summarized.


The data presented is insufficient to support any meaningful conclusions.


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.

In its essentials this work is covered by the authors in other reports; e.g. (Mertc 1970) which is summarized.


New data presented comes from Mertc (1970), NASA CR-103047, which is summarized.


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.


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).


The effect of gravity on pool-boiling is only briefly discussed and then only in terms of other work which is reviewed elsewhere.


More significant data related to the low-g problem are presented in other reports reviewed elsewhere.


The major results obtained here are further evaluated along with additional data by Keshock and Siegel, (1964), which report is summarized.

The data here is covered by Siegel (1967), which report is summarized (ref. Lienhard 1970 and 1973).


This work has been superseded by more complete data which includes quantitative as well as qualitative results.


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.


It was concluded that over the range of conditions tested, mass velocity 134-328 Kg/m²·sec and \( q_w = 70-600 \text{ KW/m}^2 \), 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.


This work has been superseded by better data.


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


B-56
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.


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.


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.


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.


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.


No low-g test data is presented or even referred to and thus, as applied to low-g, the data presented is only speculation.


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.


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.


The information presented is only qualitative and is covered more thoroughly in later work at NASA-LeRC, which reports are reviewed elsewhere.


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.


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


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.


This work is strictly -1g; for more pertinent work, see Labus and Aydelott (1972 and 1974), which reports are reviewed elsewhere.


This is the same information as reported under Contract NAS8-11328, which work is reviewed elsewhere (McGrew and Larkin, 1966).

This testing, along with analysis, was covered in more detail in later reports, such as Bradshaw, et al (1970).


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.


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.


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.


This work is covered in greater detail by Walburn, et al, 1968, which report is reviewed below.


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.

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


The effects of gravity were not considered.


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.


Results of analyses and test of single component fluids CO₂ and SF₆ are presented, but gravitational effects were not explored to the extent necessary to arrive at meaningful conclusions relevant to the current program.


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.


Low-g effects were not considered.


Experiments were conducted with hydrazine and monomethylhydrazine at temperatures between 275.4 and 353.2K, however, low-gravity effects were not considered.


B-60
Orbital flight tests are planned for 1975, however, no low-g data have been obtained to date on this program.


The effects of low-g were not considered.


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

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADL</td>
<td>Arthur D. Little</td>
</tr>
<tr>
<td>AFAPL</td>
<td>Air Force Applied Physics Laboratory</td>
</tr>
<tr>
<td>AFFDL</td>
<td>Air Force Flight Dynamics Laboratory</td>
</tr>
<tr>
<td>AFOSR</td>
<td>Air Force Office of Scientific Research</td>
</tr>
<tr>
<td>AFRPL</td>
<td>Air Force Rocket Propulsion Laboratory</td>
</tr>
<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
</tr>
<tr>
<td>AMRL</td>
<td>Aerospace Medical Research Laboratory</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>CPIA</td>
<td>Chemical Propulsion Information Agency</td>
</tr>
<tr>
<td>GD/C</td>
<td>General Dynamics Convair</td>
</tr>
<tr>
<td>GD/FW</td>
<td>General Dynamics Fort Worth</td>
</tr>
<tr>
<td>GE</td>
<td>General Electric</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>LMSC</td>
<td>Lockheed Missiles and Space Company</td>
</tr>
<tr>
<td>LTV</td>
<td>Ling Temco Vought</td>
</tr>
<tr>
<td>MACDAC</td>
<td>McDonnell Douglas Aircraft Company</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MMC</td>
<td>Martin Marietta</td>
</tr>
<tr>
<td>NAR</td>
<td>North American Rockwell</td>
</tr>
<tr>
<td>NASA-GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>NASA-JSC</td>
<td>Johnson Space Center (Formerly MSC)</td>
</tr>
<tr>
<td>NASA-KSC</td>
<td>Kennedy Space Center</td>
</tr>
<tr>
<td>NASA-LeRC</td>
<td>Lewis Research Center</td>
</tr>
<tr>
<td>NASA-LRC</td>
<td>Langley Research Center</td>
</tr>
<tr>
<td>NASA-MSFC</td>
<td>Marshall Space Flight Center</td>
</tr>
<tr>
<td>NBS</td>
<td>National Bureau of Standards</td>
</tr>
<tr>
<td>NRC</td>
<td>National Research Corporation</td>
</tr>
<tr>
<td>STL</td>
<td>Space Technology Laboratory</td>
</tr>
<tr>
<td>SRI</td>
<td>Stanford Research Institute</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>SwRI</td>
<td>Southwest Research Institute</td>
</tr>
<tr>
<td>TRW</td>
<td>Thompson Ramo Woolridge</td>
</tr>
<tr>
<td>WPAFB</td>
<td>Wright Patterson Air Force Base</td>
</tr>
</tbody>
</table>

D.2 GLOSSARY OF TERMS

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>Attitude Control System</td>
</tr>
<tr>
<td>Al Aly</td>
<td>Aluminum Alloy</td>
</tr>
<tr>
<td>AS-203</td>
<td>Apollo Saturn No. 203 Flight Vehicle</td>
</tr>
<tr>
<td>CRES</td>
<td>Corrosion Resistant Steel</td>
</tr>
<tr>
<td>F&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Fluorine</td>
</tr>
<tr>
<td>FEP</td>
<td>Teflon Polymer-Hexafluoropropylene</td>
</tr>
<tr>
<td>GHe</td>
<td>Gaseous Helium</td>
</tr>
<tr>
<td>GH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Gaseous Hydrogen</td>
</tr>
<tr>
<td>GN&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Gaseous Nitrogen</td>
</tr>
<tr>
<td>GO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Gaseous Oxygen</td>
</tr>
<tr>
<td>He</td>
<td>Helium</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>LEM</td>
<td>Lunar Excursion Module</td>
</tr>
<tr>
<td>LHe</td>
<td>Liquid Helium</td>
</tr>
<tr>
<td>LH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Liquid Hydrogen</td>
</tr>
<tr>
<td>LM</td>
<td>Lunar Module</td>
</tr>
<tr>
<td>LN&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Liquid Nitrogen</td>
</tr>
<tr>
<td>LO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Liquid Oxygen</td>
</tr>
<tr>
<td>LOX</td>
<td>Liquid Oxygen</td>
</tr>
<tr>
<td>MMH</td>
<td>Monomethyl Hydrazine</td>
</tr>
<tr>
<td>MLI</td>
<td>Multilayer Insulation</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Nitrogen Tetroxide</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Oxygen</td>
</tr>
<tr>
<td>S-IIb</td>
<td>Saturn Two B Vehicle</td>
</tr>
<tr>
<td>S-IVC</td>
<td>Saturn Four C Vehicle</td>
</tr>
<tr>
<td>------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Superfloc</td>
<td>Trade Name of GD/C Tufted Insulation System</td>
</tr>
<tr>
<td>TFE</td>
<td>Teflon Polymer – Polytetrafluoroethylene</td>
</tr>
<tr>
<td>T/M</td>
<td>Telemetering</td>
</tr>
<tr>
<td>TPS</td>
<td>Thermal Protection System</td>
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</table>

**D.3 NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>area</td>
</tr>
<tr>
<td>a</td>
<td>acceleration</td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat at constant pressure</td>
</tr>
<tr>
<td>$C_V$</td>
<td>specific heat at constant volume</td>
</tr>
<tr>
<td>D, d</td>
<td>diameter</td>
</tr>
<tr>
<td>$F_{tu}$</td>
<td>ultimate tensile stress</td>
</tr>
<tr>
<td>G</td>
<td>mass flow flux, m^3/A</td>
</tr>
<tr>
<td>g</td>
<td>gravity or gravitational constant</td>
</tr>
<tr>
<td>$g_o$</td>
<td>gravitational constant</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient or specific enthalpy</td>
</tr>
<tr>
<td>$h_f$</td>
<td>film heat transfer coefficient</td>
</tr>
<tr>
<td>$h_{fg}$</td>
<td>latent heat of vaporization</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity</td>
</tr>
<tr>
<td>L</td>
<td>length</td>
</tr>
<tr>
<td>m</td>
<td>mass</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>mass flow rate</td>
</tr>
<tr>
<td>N</td>
<td>speed, rpm</td>
</tr>
<tr>
<td>$N_{Bo}$, Bo</td>
<td>Bond number</td>
</tr>
<tr>
<td>$N_{Fr}$, Fr</td>
<td>Froude number</td>
</tr>
<tr>
<td>$N_{Gr}$, Gr</td>
<td>Grashof number</td>
</tr>
<tr>
<td>$N_{Re}$, Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$N_{Pr}$, Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$N_{We}$, We</td>
<td>Weber number</td>
</tr>
</tbody>
</table>
OD  outside diameter
P, p  absolute pressure
q, 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
\alpha  thermal diffusivity
\rho  kinematic surface tension
\gamma_s  slosh damping coefficient
\Delta H  head
\zeta  damping ratio
\theta  contact angle
\mu  dynamic viscosity
\nu  kinematic viscosity (\mu/\rho)
\rho  density
\sigma  surface tension
\omega  frequency or angular velocity

Subscripts
c  critical
gas
initial, inside
jet
liquid
conditions at normal gravity (l-g)
stagnation, outside
propellant
saturation
tank
ullage
vapor
wall
infinity