This report presents a summarization and categorization of the pertinent literature associated with fluid management systems technology having potential application to in-orbit fluid transfer and/or associated storage. 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: fluid line dynamics and thermodynamics, low-g mass gauging, other instrumentation, stratification/pressurization, low-g vent systems, fluid mixing, refrigeration and reliquefaction, and low-g interface control and liquid acquisition systems. Reports which were reviewed and not summarized, along with reasons for not summarizing, are also listed. Low-g fluid behavior and cryogenic thermal control technology are presented in companion reports (NASA CR-134746 and NASA CR-134747) under this same contract.
FOREWORD

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

A summarization and categorization is presented of the pertinent literature associated with fluid management systems technology having potential application to in-orbit fluid transfer and/or associated storage. Low-gravity fluid behavior and cryogenic thermal control 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.


F. O. Bennett - Fluid Line Dynamics and Thermodynamics.

B. J. Campbell - Mass Gauging and Other Instrumentation.

# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  INTRODUCTION</td>
<td>1-1</td>
</tr>
<tr>
<td>2  FLUID MANAGEMENT SYSTEMS (GENERAL)</td>
<td>2-1</td>
</tr>
<tr>
<td>3  FLUID LINE DYNAMICS AND THERMODYNAMICS</td>
<td>3-1</td>
</tr>
<tr>
<td>4  MASS GAUGING</td>
<td>4-1</td>
</tr>
<tr>
<td>5  OTHER INSTRUMENTATION</td>
<td>5-1</td>
</tr>
<tr>
<td>6  STRATIFICATION/PRESSURIZATION</td>
<td>6-1</td>
</tr>
<tr>
<td>7  VENT SYSTEMS</td>
<td>7-1</td>
</tr>
<tr>
<td>8  FLUID MIXING</td>
<td>8-1</td>
</tr>
<tr>
<td>9  REFRIGERATION AND RELIQUEFACTION</td>
<td>9-1</td>
</tr>
<tr>
<td>10 INTERFACE CONTROL AND LIQUID ACQUISITION SYSTEMS (GENERAL)</td>
<td>10-1</td>
</tr>
<tr>
<td>11 CAPILLARY ACQUISITION</td>
<td>11-1</td>
</tr>
<tr>
<td>12 POSITIVE EXPULSION</td>
<td>12-1</td>
</tr>
<tr>
<td>13 OTHER INTERFACE CONTROL AND LIQUID ACQUISITION SYSTEMS</td>
<td>13-1</td>
</tr>
<tr>
<td><strong>Appendix</strong></td>
<td></td>
</tr>
<tr>
<td>A  AUTHOR INDEX OF SUMMARIZED REPORTS</td>
<td>A-1</td>
</tr>
<tr>
<td>B  REPORTS REVIEWED AND NOT SUMMARIZED</td>
<td>B-1</td>
</tr>
<tr>
<td>C  KEY WORDS USED IN NASA TAPE SEARCH</td>
<td>C-1</td>
</tr>
<tr>
<td>D  ABBREVIATIONS, DEFINITIONS AND NOMENCLATURE</td>
<td>D-1</td>
</tr>
</tbody>
</table>

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1.0 INTRODUCTION

This report presents a summarization and categorization of the pertinent literature associated with fluid management systems technology having potential application to in-orbit fluid transfer and/or associated storage.

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 a 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 work 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. Fluid Management Systems (General) — covering overall space storage and/or fluid transfer systems data which may be pertinent to in-orbit resupply and which do not fit into any of the following categories or contains information on more than one.

b. Fluid Line Dynamics and Thermodynamics — covering start/shutdown transients, two-phase flow surging, pumping, pressure drop and critical flow or choking, and line chilldown.

c. Mass Gauging — covering the various aspects of determining fluid quantity at low-g.

d. Other Instrumentation — covering liquid/vapor sensing at low-g, flowmetering, two-phase flow quality gauging, and temperature and acceleration measurement.

e. Stratification/Pressurization — covering fluid temperature stratification and tank pressurization with and without liquid outflow, with and without external pressurization with condensible and/or non-condensible gases, and with and without venting.

f. Vent Systems — covering analysis, design, fabrication and test of systems to vent and/or control fluid storage and/or receiver tank pressures at low-g.

g. Fluid Mixing — covering analysis, design, fabrication and test of systems to destroy fluid temperature stratification and/or minimize tank pressure rise by fluid mixing.

h. Refrigeration and Reliquefaction — covering systems to control tank pressure of space-stored fluids through refrigeration and/or reliquefaction.

i. Interface Control and Liquid Acquisition Systems (General) — covering systems and studies which consider various aspects of more than one of the following categories.

j. Capillary Acquisition — covering analysis, design, fabrication and test of systems using surface forces to control liquid orientation.

k. Positive Expulsion — covering bladders, bellows, diaphragms and pistons, with expanding or contracting surfaces to control orientation and/or to allow liquid expulsion at low-g.
l. Other Interface Control and Liquid Acquisition Systems—covering the use of centrifugal, electrical, and acoustic forces for liquid control.

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. Only that work having potential application to in-orbit fluid transfer and/or associated storage was included; e.g., under fluid line dynamics and thermodynamics all two-phase flow literature was not included.

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 FLUID MANAGEMENT SYSTEMS (GENERAL)

Covering overall space storage and/or fluid transfer systems data which may be pertinent to in-orbit resupply and which do not fit into any of the following categories or contains information on more than one.
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 analyses. This work is reported in five volumes; (1) executive summary, (2) technical report, (3) trade studies, (4) project planning data, and (5) cost estimates. A systems safety analysis was also accomplished and is reported in another three volumes under report number SD 72-SA-0054.

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

MAJOR RESULTS. -

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

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

COMMENTS. - Chen and Zukoski, 1968, was not obtained in time to be included in the literature review.
Figure 1. Connected Ullage

Nomenclature

\[v\] = outlet line velocity
\[a\] = acceleration
\[d\] = outlet line diameter
\[V\] = volume

\[
\frac{\text{RESIDUAL}}{(\text{DIA})^3} = \frac{v}{D^3}
\]

Figure 2. Residual Versus Froude Number for Various Tank Geometries
OBJECTIVE. - To perform an analytical assessment of potential methods for replenishing the auxiliary propulsion H₂, O₂ and N₂ cryogens which may be aboard an orbiting space station.

PERTINENT WORK PERFORMED. - This study included storage of supply fluid, transfer, and receiver tank pressure and temperature control. Systems considered were high pressure (supercritical), subcritical, and modular (transfer of the tanks). The baseline resupply requirement was 1,096 lb of H₂, 2480 lb of O₂ and 3,150 lb of N₂ to eight H₂, two O₂ and two N₂ bottles. The standard receiver tank was a 42.5 ft³ sphere containing liquid at 100 psia for station use. In addition to the baseline conditions, weight and performance data were generated for bottle diameters from 25 to 150-in. and transfer fluid quantities from 500 to 5,000 lb of H₂ and 1,000 to 10,000 lb each of O₂ and N₂. Transfer line lengths were 20 to 200 ft. and the maximum disturbing acceleration was 10⁻⁴g's. Both individual supply tanks for each receiver and a single supply for each fluid were considered.

Capillary screen, dielectrophoresis, bladders, bellows, diaphragms, and fluid vortexing methods of subcritical transfer were initially considered. On the basis of safety, weight and development potential only screen, metallic bellows, metallic diaphragm and paddle vortex sub-critical systems were selected for detailed analysis. The dielectrophoretic system was not chosen primarily on the basis of potential safety, since in O₂ there is still some question of electrical breakdown and combustion hazard associated with this high voltage system. Line and tank chilldown data are also presented and the feasibility of non-vent transfer was investigated for various operating conditions.

MAJOR RESULTS. -

1. Analysis of various high pressure supply heating and blowdown and receiver cooling schemes showed the only concept worthy of any consideration was one employing simple supply heating with increased receiver volume to allow for the reduction in transferred fluid density. Also, the final receiver fluid cannot be liquid since any requirement for condensation results in excessively high weight and power.

2. The surface tension and paddle systems were determined, on the basis of low weight and cost and high reliability and reusability, to have the best potential for the space station application. Typical system weight data are presented in Figure 1. Receiver tank weights are divided by 20 to reflect the fact that the receiver tanks stay fixed on the station for 20 supply cycles. Individual receiver weights are presented in Figure 2. The paddle vortex concept is illustrated in Figure 3.

COMMENTS. - The bellows work is reviewed under a separate summary.
Figure 1. Total H₂ Transfer System Weight (Supply + Receiver/20)

Figure 2. Receiver Weights for H₂ Transfer

Figure 3. Paddle Type Vortex System

Reproducibility of the original page is poor
OBJECTIVE. - Report on the findings and recommendations of existing literature on space-based propellant transfer techniques and determine possible alternatives.

PERTINENT WORK PERFORMED. - Results of the literature review showed that the recommended in-orbit transfer technique was, in general, the use of conventional liquid transfer (i.e., pumping) in conjunction with an artificially induced gravitational field.

Under the current program an analytical study was made of the feasibility of a "Thermal Bootstrap Transfer Process" as shown in Figure 1. Referring to Figure 1, the fluid is stored at equilibrium saturated conditions along the line E-E', at state point 1. This assumes no noncondensables; a requirement of this system. From state point 1, the fluid is introduced to a header where the temperature and pressure decrease along a constant enthalpy line to state point 2. The fluid is then compressed to a suitable state point, 3, such that its pressure and corresponding temperature differential allows the transfer of the heat of vaporization to the donor tank residual. After condensation the transfer fluid is subcooled to state point 4. The heat rejected between 3 and 4 is absorbed by the bulk supply fluid, causing evaporation from states 1 to E'. It is assumed that there is sufficient evaporation within the supply to maintain constant temperature and pressure. The process in the receiver tank follows two paths; (1) from points 5 to 6, where the fluid is retained in the liquid state by preventing its contact with the warm tank walls and (2) the fluid which is directed laterally contacts the tank wall and vaporizes to points 7 and 8. The fluid after expansion in the turbine is at state point 9. This turbine is used for fluid pumping from states 2 to 3.

MAJOR RESULTS. -

1. Calculations for hydrogen transfer indicated the thermodynamic feasibility of the process. This was based on a donor tank of 12,000 ft³, initially 95% full of liquid and transferring 8500 lb of LH₂ to a 400°F receiver tank.

2. Even though, for certain conditions, there is sufficient total receiver tank energy available, the available rate does not coincide with the demand rate, meaning the produced energy must be controlled, stored, or an auxiliary source, such as a gas generator used to heat the H₂ gas.
Figure 1. Transfer Process Schematic
3.0 FLUID LINE DYNAMICS AND THERMODYNAMICS

Covering start/shutdown transients, two-phase flow surging, pumping, pressure drop and critical flow or choking, and line chilldown.
WATERHAMMER AND SURGE CONTROL
Streeter, V.L., Wylie, E.B., Univ. of Michigan,

OBJECTIVE. - To review waterhammer and surge phenomena and discuss techniques for analyzing the transient-flow problems.

PERTINENT WORK PERFORMED. - The initiation and propagation of hydraulic transients is discussed. A review of pressure-pulse wave transmission investigations is presented. Two types of analytical approaches to the problem are reviewed; the "operational" method and the "numerical" method. In the operational method, the system propagation value and characteristic impedance are the most useful parameters for characterizing the fluid pipeline response. Models of differing degree of sophistication have been developed to handle specific problems. Figure 1 shows typical predicted transient responses for models with (a) no dissipation, (b) a linearized viscous loss (friction) term, and (c) both viscosity and heat transfer taken into consideration. Selecting a model for a particular application depends on the objective of the study, the values of pertinent dimensionless numbers, and the type of boundary conditions.

The numerical solution methods utilize finite-difference techniques to solve non-linear equations. Either the implicit technique, requiring simultaneous solution of a large number of equations, or the explicit technique, in which pressure and flow are determined incrementally at the computing sections, are used. The implicit procedure, while not limited to small time steps, can become very complex when a large number of equations are involved.

MAJOR RESULTS. -
1. The operational method offers advantages when the objective is to determine the system frequency response and resonating characteristics.
2. The numerical method is more flexible with regard to interfacing simple or complex pipeline systems with arbitrary boundary excitations.
3. The uncertainty of the acoustic speed during a transient is the greatest source of computational error. Only one-tenth percent of air by volume in a liquid can reduce the wavespeed by half.
4. Theory is available to devise valve motions or pump starting procedures which will minimize the effects of transients.
5. Devices such as accumulators, relief valves, surge tanks, etc. are available to reduce pressure fluctuations.
Figure 1. Transient response at valve in single pipeline
AN EXPERIMENTAL INVESTIGATION OF TWO-PHASE LIQUID OXYGEN PUMPING

OBJECTIVE. - To demonstrate the feasibility of pumping two-phase oxygen using a flight-configured (J-2) liquid oxygen pump.

PERTINENT WORK PERFORMED. - An analysis was performed of the J-2 engine liquid oxygen turbopump which indicated that at a speed approximately half the nominal 8000 rpm, the pump would operate in the two phase region. A blade blockage factor of 25 percent was predicted. Both high- and low-speed cavitation tests were performed to verify predicted performance. After attaining steady-state operating conditions, pump cavitation was initiated by slowly reducing the pressure in the run tank. Tests were continued until at least ten percent head loss had occurred. Nineteen successful tests were conducted, nine at speeds ranging from 6800 to 7650 rpm, and ten from 4320 to 4440 rpm. Two-phase operation was not achieved at the higher pump speeds, as predicted. Figure 1 shows a modified head coefficient plotted against net positive suction head (NPSH) for the high speed runs. The pump operated at progressively lower NPSHs as the liquid bulk temperature was increased. Two-phase conditions were successfully achieved during the final ten runs at the lower pump speeds. Figure 2 shows the results using a split abscissa, the right side being the pump inlet pressure minus the propellant vapor pressure, and the left side the percentage of vapor by volume at the pump inlet after two-phase conditions had been achieved. The experimental vapor handling capability of the pump was found to be significantly greater than predicted. Blade blockage of less than ten percent would be required (compared with the predicted 25 percent) to achieve the experimental vapor handling capability. No factors which could account for this discrepancy were found.

MAJOR RESULTS. -
1. The feasibility of pumping two-phase oxygen was demonstrated.
2. Using a standard J-2 engine turbopump, pump inlet vapor percentages of up to 50 were achieved before a ten percent reduction in pumping efficiency was encountered.
3. A practical two-phase pumping system for liquid oxygen could be developed.
Figure 1. Two-Phase Pump Performance

Figure 2. Pump Cavitation Performance
OBJECTIVE. - To analytically and experimentally investigate the effect of startup and shutdown transients on capillary collectors.

PERTINENT WORK PERFORMED. - A basic experimental study of simply configured capillary collectors (Figure 1) was conducted using horizontally mounted collectors and subcooled monoflorotrichloromethane (Freon 11). The test configuration, simulating a tank with a half-submerged collector tube, is shown in Figure 2. The collectors had a square cross section (0.75" x 0.75") with three of the four sides of Lucite and the remaining side of screen (Figure 3). The screened side was on top of the channel for tests with 200 x 400 and 325 x 2300 mesh. For greater visibility, the screened side was placed down for tests with 200 x 600 mesh screen. The length of feedline between the test tank and the control valve varied from 6.2 to 38 feet. Control valve opening times were 5 ms, 100 ms and 150 ms. An accumulator installed just upstream of the control valve, was used to attenuate the pressure surges. An incompressible nonlinear, viscous flow model was formulated specifically for analyzing gas ingestion during start transients in the test configuration. A shutdown transient analysis terminated when test results indicated that gas ingestion did not occur due to shutdown transients. Premature termination of the study prevented correlation of the start transient model with test results.

MAJOR RESULTS. -

1. High pressure surges due to shutdown did not produce like pressure surges in capillary collectors. Only trace amounts of vapor ingestion were observed in a few shutdown tests. Shutdown pressure surges were proportional to steady state flow rate and decreased with increasing valve opening time and accumulator volume. Although liquid spilling can occur due to shutdown transients, shutdown pressure surges do not appear to be a capillary device design problem.

2. Start transient flow caused substantial ingestion of gas into the capillary collector. Gas ingestion increased with increasing values of valve ΔP, and steady state flow-rate and decreased with increasing values of accumulator volume, line length, screen pore size, upstream line flow resistance and valve opening time.

COMMENTS. - Recent tests by Page, 1974, MMC (NAS8-30592), have indicated that shutdown and start transients did not produce capillary device gas ingestion. A comparison of the NAR results cited here and the Martin results was given in the 5th monthly progress report of NAS8-30592. The shorter time duration of the pressure spike above the bubble point and the lack of gas ingestion were explained by lower fluid density and velocity in the Martin study.
Figure 1. Capillary Collectors for Propellant Acquisition Under an Adverse Acceleration, Spherical Tank

Figure 2. Test Apparatus Schematic

Figure 3. Capillary Collector Tube
CRITICAL TWO-PHASE FLOW OF CRYOGENIC FLUIDS

OBJECTIVE. - To review analytical and experimental critical two-phase flow work since Smith (1962), and provide design recommendations and computational aids.

PERTINENT WORK PERFORMED. - Comparisons of critical single-phase and two-phase flow phenomena are made. Specific industrial applications where critical two-phase flow may be important are discussed. A thorough review of analytical models and experimental data for two-phase critical flow of fluids is presented. Most analyses approach the problem by starting with the well-understood critical flow of gases and incorporating differences or complications introduced by the presence of the liquid phase. Experimental results indicated that a description of liquid-gas distribution and flow velocities in all two-phase flows is difficult. Data in the critical flow region is essentially non-existent. A number of curves are presented showing predicted and measured critical mass flow rate as a function of fluid quality for various upstream pressures (Figure 1). It is left to the designer to choose the model that best fits his situation. In Figure 1, $P_o$ = stagnation pressure.

MAJOR RESULTS. -

1. The intuitive feel that critical two-phase flow velocities should lie somewhere between those of the gas and liquid in question is incorrect. Actual effective critical two-phase fluid flow velocity is much lower than that of either the gas or liquid.

2. With regard to critical two-phase flow, quality is a primary variable while system geometry is probably a secondary variable.

3. Although the assumptions of fluid homogeneity and thermal equilibrium are unlikely to be valid, models based on these assumptions produced reasonably good critical flow predictions.

4. The homogeneous mixture, non-equilibrium models (frozen flow) and the Henry (1968) model (Figure 1), appear to describe the critical flow process reasonably well. These models assume low mass transfer rates and low slip (gas-liquid velocity) ratios.

5. With respect to design utility, models which predict critical flows based on upstream (stagnation) conditions rather than on critical conditions, must be considered superior because data are much better known at the upstream location.
Figure 1. Two-phase orifice flow with nitrogen. Figure from Henry and Fauske (1971) with stagnation property curves of Moody (1965, 1969) added.
OBJECTIVE. - To test the hypothesis that the gas behavior primarily controls the critical (choking) and near-critical two-phase flow of two-component fluids for cases where essentially all the gas flows in separated and continuous streams.

PERTINENT WORK PERFORMED. - Experimental data were obtained with air-water mixture flows through an annular venturi. Both 0.0625 and 0.125-in. venturis were used. The ratio of liquid mass flow rate to gas mass flow rate was varied from 0.5 to 52.8, although visual observations indicated that the flow remained separated only to a mass flow ratio of 5. The measured critical pressure ratios varied from 0.52 to 0.62, approximately the values for isentropic and isothermal air flow, respectively. Shock waves in the diverging portion of the venturi exhibited behavior similar to that observed in all-gas flows. An analytical model was developed which consisted of a liquid film flowing at the tube wall and a gas core containing entrained liquid droplets. The sensitivity of calculated critical pressure ratios to variations in the parameters of droplet diameter, droplet drag coefficient, and interface heat transfer coefficient were found to be small. The effective gas flow area was adjusted to account for waves and droplet distribution through the use of an empirically determined blocking factor. A computation procedure was developed to numerically integrate the flow equations through the venturi using the Runge-Kutta method.

MAJOR RESULTS. -

1. The concept that the gas flow behavior controls two-phase, two-component critical flow for higher quality (gas fraction) flow rates is substantiated by the experimental and analytical results.

2. Comparisons between predicted and measured pressures in the venturi are excellent, even for the very low quality runs (Figures 1 and 2). The downstream endings of the analytical curves indicate the point of critical flow. In Figures 1 and 2, subscripts f, fe, ff and g refer to liquid, entrained liquid, liquid film and gas respectively.
Fig. 1 - Pressure versus axial distance along venturi. Analytical curves and experimental points for medium and higher quality flow rates, \( \frac{1}{16} \) in. annulus venturi.

Fig. 2 - Pressure versus axial distance along venturi. Analytical curves and experimental points for lower quality runs, \( \frac{1}{32} \) in. annulus venturi.
OBJECTIVE. - To establish an improved B-factor calculation method and to tabulate computerized results for several fluids of interest.

PERTINENT WORK PERFORMED. - A review is presented of various approaches for calculating the so-called "B-factor," defined as the ratio of the volume of vapor to the volume of liquid involved in the cavitation process. Although the "quasi-static" theory upon which the proposed solution is based is deficient from a theoretical viewpoint, it is well established and has been shown to provide good results (report references). The assumptions of the "quasi-static" model are the same as those for an isentropic process. Thus the time-consuming incremental pressure calculation process is eliminated. The B-factor is expressed solely in terms of fluid properties and is calculated in a one-step procedure. A comparison of the relationship between the saturation temperature depression due to vaporization and B-factor for the model presented in this report (solid line) and the more-rigorous (but still approximate) model of Gelder et al (1966) is shown in Figure 1 for LN₂.

The "quasi-static" model was used to calculate B-factors for the various fluids in the report title, from just above the triple point temperature to just below the critical temperature. A sample page for LH₂ is shown in Table 1. TF₁ and PF₁ are the initial liquid saturation temperature and pressure, respectively, and DTV and DPV are the reduction in the saturation properties of the liquid involved in the cavitation process. B is the B-factor. The error produced by successive linear interpolations in the table is shown to be less than ten percent.

MAJOR RESULTS. -
1. A simplified one-step, isentropic cavitation model is developed and shown to yield results similar to those of more rigorous, incremental-calculation models.
2. Tables of B-factors are provided over the full range of saturated liquid temperatures for He, H₂, N₂, F₂, O₂, H₂O, and Refrigerant 114 (C₂Cl₂F₄).

COMMENTS. - B-factor data are important for determining the relative ease with which various fluids can be transferred in the saturated state by pumping. For a particular transfer case the data is used to determine the actual driving pressure required to pump a given vapor fraction of two-phase fluid.
### Table 1. B Factors for Parahydrogen

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<td>IP (%)</td>
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#### Figure 1. B-factor and corresponding temperature depressions resulting from vaporization of liquid nitrogen
PRESSURE DROP OF TWO-PHASE FLOW IN A PIPELINE 
WITH LONGITUDINAL VARIATIONS IN HEAT FLUX 
Shen, P. S., Jao, Y.W., University of Toronto, 
Advances in Cryogenic Engineering, Vol. 15, June 1969

OBJECTIVE. - To determine the pressure drop of two-phase nitrogen in a pipe with longitudinal variations in heat flux, and to compare results with those predicted by the Martinelli-Nelson (1948) correlation.

PERTINENT WORK PERFORMED. - Pressure drop in transfer systems is considerably higher for two-phase flow than it is for single-phase liquid flow, due to the reduction in flow area for each phase and the interaction of the phases. Tests were performed using liquid nitrogen flowing through uninsulated and partially insulated copper tubes of varying diameter to determine the effect on two-phase pressure drop. Results were tabulated and checked against the Martinelli-Nelson correlation (Figure 1). Here \( \phi_{tt} \) is the square root of the ratio of two-phase pressure drop to liquid phase pressure drop. The parameter \( X_{tt} \) is a function of liquid and gas phase densities and viscosities, and is inversely proportional to fluid quality (vapor fraction).

MAJOR RESULTS. -

1. The experimental results support the use of the Martinelli-Nelson correlation for two-phase flow of nitrogen.

2. Two-phase flow of nitrogen is similar to that of other, non-cryogenic, fluids; (e.g. water.

3. The quality of a fluid flowing in a pipeline is a primary parameter in the determination of two-phase pressure drop.
Figure 1. Comparison of Two-Phase (Diabatic) Pressure Drop Data of Liquid Nitrogen With Martinelli-Nelson Prediction

\[ X_{lt} = \left( \frac{\rho_v}{\rho_\ell} \right)^{0.571} \left( \frac{\mu_\ell}{\mu_v} \right)^{0.143} \left( \frac{1}{X} - 1 \right) \]
TRANSIENT FLOW OF CRYOGENIC FLUIDS

OBJECTIVE. - To develop an analytical method and a computer program to predict the cooldown characteristics of cryogenic transfer lines.

PERTINENT WORK PERFORMED. - An analytical model was developed, a computer program written ("COOLDOWN"), and an experimental program conducted. The author discusses previous work done in the field with a number of references. Transient flow tests were performed in LH$_2$ and LN$_2$ using 0.625 and 0.215 inside diameter flow lines of various lengths. Length-to-diameter ratios investigated ranged from 480 to 3840 (Figure 1). Tests were performed with the incoming liquid either subcooled or saturated with respect to the pipe pressure. The computer program uses short time steps initially to determine the magnitude and period of early pressure and flow transients, and then longer time steps in a "quasi-steady" mode to predict total cooldown times. The flow is assumed to be one-dimensional, the phases are in thermal and mechanical equilibrium, there is no axial conduction along the pipe, and there is no heat transfer from the external environment to the pipe.

MAJOR RESULTS. -

1. Initial line surges are considerably greater for subcooled liquid than for saturated liquid.

2. In the higher density LN$_2$, peak surge was larger and occurred later than in LH$_2$.

3. At lower pressures the computer program predicts peak surge levels reasonably well, but overpredicts as the critical pressure is approached (Figure 2).

4. Peak surges caused reverse flow rates ten times greater than the initial forward flow rate (Figure 3). Computer predicted peak flows were more accurate in the forward direction.

5. Cooldown of long pipelines is controlled primarily by restrictions to gas flow rather than by heat transfer.

6. Cooldown times are longer for saturated incoming fluid than for subcooled fluid, due to the large amount of vapor evolved.

7. Cooldown time is proportional to line length and inversely proportional to the inlet pressure (Figure 4).

8. Surging is aggravated by liquid subcooling, high liquid density, long transfer lines, and rapid valve openings.
All Figures: Experimental Runs

- Computed with $T_{in} = 20.5\,^\circ K$

![Diagram of experimental setup](image)

Figure 1. Cooldown Experimental Facility

- Liquid Supply Vessel
- Pressurizing Gas Supply
- Remotely Controlled Pressure Regulator
- Experimental Pipeline
- Instrument Stations
- Instrument and Control Leads
- Expansion Bellows
- Receiver Vessel and Vent Stack
- Rolling Platform
- Blast Wall
- Control Shed

Figure 2. Subcooled Liquid Hydrogen Maximum Pressure Surge at Station 1 of Transfer Line A

- $P_m = 2.5$ atm.abs. or 25 psig.
- $4.2$ atm.abs. or 50 psig.
- $5.9$ atm.abs. or 75 psig.
- $7.6$ atm.abs. or 100 psig.
- $9.3$ atm.abs. or 125 psig.
- $11$ atm.abs. or 150 psig.

![Graph of pressure surge](image)

Figure 3a. Typical Inlet Flow Surge for Subcooled Liquid Nitrogen.
Transfer Line A, $P_m = 75$ psig.

![Graph of inlet flow surge](image)

Both Figures: Experimental Peak Values

Figure 3b. Typical Inlet Flow Surge for Subcooled Liquid Hydrogen.
Transfer Line A, $P_m = 75$ psig.

![Graph of inlet flow surge](image)

Figure 4. Cooldown Time for Subcooled Liquid Nitrogen Showing the Effect of Length

![Graph of cooldown time](image)
A STUDY OF COOLDOWN OF METALS, FLOW
INSTABILITY, AND HEAT TRANSFER IN TWO-PHASE
FLOW OF HYDROGEN, Manson, L., Miller, W. S.,

OBJECTIVE. - To provide information on transient, two-phase hydrogen childdown
of both coated and uncoated transfer lines, and on flow instability and heat transfer
in two-phase flow.

PERTINENT WORK PERFORMED. - Five different metals were used to fabricate one-
foot long tubes with different heat contents (Table 1). Three tubes were subsequently
coated with 0.01-inch thick Kel-F trifluorochloroethylene on the inside diameter.
An equation was developed expressing coating thickness to reduce cooldown time as
a function of coating material thermal conductivity and average heat transfer coefficient
for the uncoated tube for (a) the entire cooldown and (b) the nucleate boiling portion
of the cooldown. Heat transfer and flow phenomena during cooldown of metal tubes in
two-phase hydrogen flow are closely coupled. Modifications of single-phase heat
transfer correlations to adapt them to two phase flow are not valid. Although
two-phase correlations yield reasonable results at the initiation of cooldown (high
wall temperatures), agreement in the low-wall-temperature region was not as good.
Experimental stability results obtained in this study were not predictable by existing
empirical correlations (Figure 1).

MAJOR RESULTS. -
1. Thin, insulating coatings will shorten cooldown times when the heat transfer
   coefficients in forced-convection film boiling are low relative to those in the
   nucleate boiling region (Figure 2).
2. Coatings can be used to reduce the rate of heat addition to a fast-moving hydrogen
   stream, and to promote flow stability.
3. To suppress flow instabilities in subcooled liquid, relatively high flow rates were
   required. Much lower flowrates were required for saturated fluid flow.
4. Stability maps (Figure 1) are restricted to the system investigated. System
damping was high, making it difficult to define conditions which lead to instabilities.
<table>
<thead>
<tr>
<th>Group</th>
<th>OD/ID</th>
<th>Od X Monel</th>
<th>K Monel</th>
<th>Ti-5-Al</th>
<th>Alum.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUP I</td>
<td>.75/.50</td>
<td>.75/.50</td>
<td>.65/.50</td>
<td>.55/.50</td>
<td></td>
</tr>
<tr>
<td>Heat content</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 500-50 R, Btu</td>
<td>27.9</td>
<td>29.7</td>
<td>29.1</td>
<td>30.6</td>
<td>30.0</td>
</tr>
<tr>
<td>between 220-50 R, Btu</td>
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<td>5.4</td>
<td>6.5</td>
<td>6.7</td>
<td>6.5</td>
</tr>
<tr>
<td>GROUP III</td>
<td>.56/.50</td>
<td>.56/.50</td>
<td>.56/.50</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Heat content</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 500-50 R, Btu</td>
<td>6.0</td>
<td>6.3</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 220-50 R, Btu</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROUP IV</td>
<td>.36/.30</td>
<td>.36/.30</td>
<td>None</td>
<td>None</td>
<td>None</td>
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<td>Heat content</td>
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<tr>
<td>between 500-50 R, Btu</td>
<td>3.3</td>
<td>3.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 220-50 R, Btu</td>
<td>0.6</td>
<td>0.6</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 1. Stability Map for Low Pressure Hydrogen Experiments

Figure 2. Cooldown of Coated and Uncoated Vertical Plates in Saturated Liquid Nitrogen-Temperature vs Time
OBJECTIVE. - Provide analytical and empirical descriptions of transient phenomena in cryogenic transfer lines during chilldown. Work was also accomplished on receiver tank filling, 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. Basic elements of the computer model are illustrated in Figure 1. Mass, momentum and energy balances are applied to the pipe wall and flowing fluid. Pipe fluid length is broken into as many as 200 nodes. The finite difference calculation procedure consists of assuming a steady flow rate, calculating fluid conditions down the line, comparing calculated exit pressure with receiver pressure, and adjusting the flow until agreement is reached. Wall temperatures are constant over each time step and are updated at the end of each time step based on the heat removed. Two-phase flow is assumed to be homogeneous, and boiling heat transfer is by superposition (forced convection heat transfer plus pool boiling per Breen and Westwater, 1962). Output data consist of line temperatures, fluid temperature, pressure, velocity and quality, and heat rates at each node as a function of time. Limitations are that line diameter and wall thickness are constant, line is perfectly insulated and flow is uniquely determined by specified inlet temperature and pressure and outlet pressure. The ability to handle choked flow for two phase as well as for vapor exit conditions was found to be important during testing and was added to the version used for line-receiver integration. Also, for this version, flow and pressure oscillations are calculated separately using a spring (gas)- mass (liquid) analogy. Correlations were made with test data from the present work (1/2-in. I.D. x 5/8-in. O.D. Cu., 28 ft and 17 ft vacuum jacketed lines with LN$_2$) and with NBS data (5/8-in. I.D. Cu., 200 ft vacuum jacketed line with LN$_2$ and LH$_2$). Typical data are presented in Figures 2, 3 and 4.

MAJOR RESULTS. -

1. Better agreement was obtained between measured wall temperature time histories for long lines (L/D > 3800 for LH$_2$ and > 475 for LN$_2$) than short lines. As the L/D ratio is decreased, transient chilldown is increasingly dominated by pressure and flow surges in the fluid. Predictions of overall chilldown time were within ±15% of test data.

2. Agreement between predicted and measured frequency and magnitude of pressure and flow oscillation was generally between ±10%.

COMMENTS. - Substantiation of statement (2) was not obvious from data presented.
Figure 1. Flow Model for Transfer Line Chilldown Analysis

Figure 2. Line Temperature History with Subcooled Liquid Nitrogen at a Driving Pressure of 24.8 psia

Figure 3. Comparison Between Computed and Measured Line Temperature Histories with Saturated Liquid Hydrogen at a Driving Pressure of 5.1 atm.

Figure 4. Comparison Between Computed and Measured Line Temperature Histories with Subcooled Liquid Hydrogen at a Driving Pressure of 5.1 atm.
OBJECTIVE. - To determine the conditions under which buoyancy influences the critical heat flux level of a vertically-flowing, two-phase heat transfer system.

PERTINENT WORK PERFORMED. - Tests were performed in which LN\textsubscript{2} was flowed vertically through a resistance-heated, 0.505-in. inside diameter, 12-in. long steel tube. At a constant inlet pressure, power input to the heaters was gradually increased until the condition of criticality was established. Inlet pressures ranged from 50 to 240 psia, inlet velocities from 0.5 to 11.0 feet per second, and fluid subcooling from 12 to 51 Fahrenheit degrees. Each set of conditions was run both in the upward and downward directions to determine the effect of buoyancy on critical heat flux. Test data were plotted in the form of critical heat flux versus inlet velocity for upward and downward flow at a given inlet pressure (Figure 1). Below a certain velocity, approximately 7 ft/sec in Figure 1b, buoyancy affected the level of the critical heat flux. Above this point, the flow direction apparently had no effect. It was postulated that below the critical velocity, in the "buoyancy-dependent" zone (Figure 2) the flow may have been annular-dispersed, characterized by liquid droplets in a gaseous core surrounded by a liquid annulus on the tube wall. Above the critical velocity in the "buoyancy-independent" zone, the flow was said to change to bubbly or slug flow. No data are presented to support this flow regime identification.

MAJOR RESULTS. -

1. Under certain conditions, the critical heat flux level for upward flow is significantly higher than that for downward flow.

2. Buoyancy effects on critical heat flux increased with decreasing inlet pressure and subcooling, but decreased with increasing inlet velocity. Above certain velocities buoyancy effects were erased by fluid momentum.

3. For upward flow, with pressure above 150 psia, above an inlet velocity of 5 ft/sec, an increase of pressure increases the critical heat flux, while below 5 ft/sec there is a decrease in the critical heat flux with increased pressure.
Figure 1. Critical heat flux as function of inlet velocity for upward and downward flow of liquid nitrogen.

Figure 2. Susceptibility of liquid nitrogen flow system to buoyant effects on critical heat flux.
DIGITAL DISTRIBUTED PARAMETER MODEL FOR ANALYSIS
OF UNSTEADY FLOW IN LIQUID-FILLED LINES

OBJECTIVE. - To develop a numerical distributed-parameter solution for unsteady flow in liquid systems that is in a form general enough to be applied to a variety of system configurations.

PERTINENT WORK PERFORMED. A numerical solution of the momentum and continuity equations is developed using an approach similar to that used in the method of characteristics solution. This approach is termed the wave-plan solution. Incremental pressure pulses are computed from incremental flow rate changes, propagated through the system at sonic speed, and partially reflected and partially transmitted at all geometrical and physical discontinuities in the fluid network. With the wave-plan analysis; viscous friction effects are easily included, perturbing functions of any form may be used, nonlinear relations are easily included, and both transient and steady-state responses to disturbing functions are given. Digital computer subroutines have been written for the most common types of discontinuities which can then be combined to obtain models for various liquid flow systems. Subroutines representing a terminal flow orifice, an internal (friction) orifice, and a diameter discontinuity are described in the appendices.

Two detailed examples are presented, showing responses of straight and tapered lines to periodic sinusoidal flow disturbances. For the straight line example, comparison between analytical and available experimental data indicate very good agreement between wave shapes and magnitudes. The tapered line, approximated by a series of diameter discontinuities (Figure 1), exhibited large variations in resonant frequency (Figure 2) with the line taper factor, \( \delta \) (\( \delta = 0 \) for a straight tube). The line taper factor is defined as one-half the difference between the line exit and entrance diameters. This would indicate that some control could be exerted over the dynamic response of a flow system by the judicious choice of tapers.
Step-diameter-change approximation to tapered line.

Reservoir conduit system with tapered line

Figure 1. Tapered Line Model

Figure 2. Variation of Resonant Frequency with Taper Factor
OBJECTIVE. - To develop analytical models for predicting the limiting flow rate of two-phase, saturated hydrogen, nitrogen, and oxygen.

PERTINENT WORK PERFORMED. - Three models of saturated, two-phase fluid flow were developed: (1) homogeneous, thermal equilibrium; (2) separated-phase, thermal equilibrium, vapor-choking; and (3) homogeneous, metastable (phases homogeneous but insufficient time to achieve thermal equilibrium). For the homogeneous model the flow is assumed to be one-dimensional, horizontal, steady, and adiabatic. Model (2) assumes the flow is choked when the velocity of the vapor phase as predicted by the Martinelli-Nelson 1948 correlation reaches the sonic velocity for the vapor phase. Based on the equations developed for model (1), curves of mass limiting flux are presented as a function of pressure and quality (vapor fraction) for $H_2$, $N_2$, and $O_2$. An example for hydrogen is shown in Figure 1. In the development of model (3), the additional assumptions of incompressible liquid and ideal gas were made, which, particularly for $H_2$, limit the useful results to relatively low reduced ($P/P_{critical}$) pressures. The models were selected to bracket actual flow cases. A summary of the available experimental, two-phase, choking studies up to 1962 are presented in Figure 2 in the cross-hatched areas. Here the measured critical mass flux (flow rate per unit area) ratioed to the flux predicted by the homogeneous thermal equilibrium model (HO) is plotted against fluid quality. The idealized models were used to generate the dotted curves shown in Figure 2.

MAJOR RESULTS. -

1. For low fluid qualities, the homogeneous, thermal equilibrium (1) and homogeneous, metastable (3) models tend to bracket the experimental data (Figure 2).

2. For higher qualities (>0.2), the separated-phase, thermal equilibrium model (2) predicts the experimental results with reasonable accuracy.
Subscripts: \( PR \) = reduced pressure
\( HO \) = homogeneous, thermal equilibrium
\( MET \) = homogeneous metastable

Figure 1. Mass limiting flow predictions at the point of choking for \( H_2 \); homogeneous, thermal equilibrium model.

Subscripts: \( HO \) = homogeneous thermal equilibrium
\( MET \) = homogeneous metastable

Figure 2. Comparison of experimental two-phase, choking studies with curves from the idealized solutions of this paper.
4.0 MASS GAUGING

Covering the various aspects of determining fluid quantity at low-g.
DEVELOPMENT OF A ZÉRO-G GAUGING SYSTEM
Bupp, F. E., TRW, AFRPL TR-74-5, Report No. 16740-6003-RU-00, January 1974

OBJECTIVE. - Development of a practical, accurate method of gauging storable propellants in zero-g environment using nucleonic techniques.

PERTINENT WORK PERFORMED. A nucleonic propellant gauging system has been designed, fabricated and tested to meet the particular requirements of the Orbital Maneuvering System (OMS). Pertinent design characteristics for this system are presented in Table I. The nucleonic gauging system as designed consists of an array of gamma ray emitting radio-isotope sources (Cs-137) and a corresponding array of cadmium telluride (CdTe) radiation detectors along with peripheral electronics for signal conditioning, input multiplexing, count accumulating, system processing (computer) and display. Figure 1 shows a schematic of the complete experimental test arrangement. Testing has been limited to the one "g" configuration, however analytical evaluations have been performed projecting performance in the zero "g" condition on cylindrical tanks with hemispherical ends and postulating predictable ullage geometry.

MAJOR RESULTS.
1. Verification of system performance in a one "g" environment to a specified accuracy of ±0.5% over a range of 50% of total propellant capacity has been demonstrated.
2. Propellant gauging over the full-to-empty-tank conditions with a completely external system configuration has proven impractical because of required source energy limitations, dose rate, electronic speeds and dynamic range.
3. Propellant behavior in complex tanks featuring baffles, brackets, etc. would be unpredictable and would require system characterization through extensive investigation/calibrations.
# Table I. Synthesis of a Nucleonic Zero-G Gauging System for the OMS Tanks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total System Error</td>
<td>&lt;0.35 percent (all loadings up to 50 percent)</td>
</tr>
<tr>
<td>Response Time</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Total System Weight (Includes Flight Processor/ Display)</td>
<td>&lt;20 pounds</td>
</tr>
<tr>
<td>Number of Source-Detector Pairs</td>
<td>4</td>
</tr>
<tr>
<td>Pair Positions</td>
<td>1 on tank axis ( R = 0 )</td>
</tr>
<tr>
<td></td>
<td>3 at 120° ( (12.0 \text{ in.} &lt; R &lt; 19.5 \text{ in.}) )</td>
</tr>
<tr>
<td>Source Type</td>
<td>Cs-137 (Custom Capsule)</td>
</tr>
<tr>
<td>Strength</td>
<td>1.4 Ci (MMH)</td>
</tr>
<tr>
<td></td>
<td>6.5 Ci ( (\text{N}_2\text{O}_4) )</td>
</tr>
<tr>
<td>Collimators ( (k \geq 0.01) )</td>
<td>Depleted Uranium</td>
</tr>
<tr>
<td>Dose Rate (Average over hemispherical end at empty tank)</td>
<td>0.05 mr/hr (MMH)</td>
</tr>
<tr>
<td></td>
<td>0.24 mr/hr ( (\text{N}_2\text{O}_4) )</td>
</tr>
<tr>
<td>Signal Conditioning Electronics</td>
<td>(&lt; 10^5 \text{ cps} )</td>
</tr>
<tr>
<td>Nominal Maximum Speed</td>
<td>GdTe ( (0.2 \text{ cm x 2.5 cm}^2) )</td>
</tr>
<tr>
<td>Detector</td>
<td>Charge Sensitive Preamplifier</td>
</tr>
<tr>
<td>Input Stage</td>
<td>Double Differentiation/Double Integration</td>
</tr>
<tr>
<td>Shaping Stages</td>
<td>0.25 ( \mu \text{sec/Pole Zero Compensation} )</td>
</tr>
<tr>
<td>Time Constant</td>
<td>(&lt; 8.6 \text{ keV FWHM} )</td>
</tr>
<tr>
<td>Amplifier Noise Characteristic ( (4 \text{ pf}) )</td>
<td>Fixed Window</td>
</tr>
<tr>
<td>Discriminator</td>
<td>0.25 ( \mu \text{sec/volt square} )</td>
</tr>
<tr>
<td>Output Pulse</td>
<td>21-stage binary: COS/MOS</td>
</tr>
<tr>
<td>Interface Counter</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Experimental Arrangement: Nucleonic Gauging Tests
DEVELOPMENT OF ISOTHERMAL RIGS, FINAL REPORT
Kaminskas, R. A., Malone, D. J., TRW, NASA CR-124314,
NAS8-28574, April 1973

OBJECTIVE. - To design a Resonant Infrasonic Gauging System (RIGS), to fabricate
same and perform an evaluation test program.

PERTINENT WORK PERFORMED. - A resonant infrasonic gauging system has been
designed based on analytical and breadboard work performed in connection with pos-
sible use of such a system on the Apollo SPS tanks. Two prototype sensor (driver and
follower piston) designs were fabricated. These units were adapted to perform on a
30-gallon tank and on a 100-gallon tank. A complementary electronic control system
was designed and fabricated which provided drive, frequency and phase control to the
bellows drive motor. The resonant frequency of the RIGS system is related to the
ullage volume, and hence to the propellant volume, by the following equation:

\[ f = \frac{1}{2} \sqrt{\frac{A^2 \gamma P_u}{M V_u} + \frac{K_B}{M}} \]

where:
- \( f \) = resonant frequency
- \( K_B \) = spring constant of the bellows
- \( A \) = area of piston
- \( \gamma \) = ratio of specific heats of
  the ullage gases
- \( M \) = mass of the piston
- \( V_u \) = ullage volume
- \( P_u \) = system static pressure

A test program has been performed with the following objectives: (1) evaluate in gen-
eral the accuracy with which the system operates as a propellant gauging system, (2)
determine the effect of ullage gases specific heats on system accuracy, and (3) deter-
mine the effect of surface tension screens upon the accuracy of the RIGS system.

MAJOR RESULTS. -

1. Test results of performance of the system are shown in Figure 1, which displays sys-
tem resonant frequency vs. tank fluid in gallons.

2. The low resonant frequency of these systems require exceedingly low bellows spring
constants. This presents difficult design problems which can only be overcome by
electronic augmentation which simulates added mass and permits higher (practical)
values of spring constants.

3. The existing designs are too slow for following transient conditions. This too, can
   be overcome by suitable redesigns of the electronic control system.

4. The system was found to operate in essentially the isothermal mode with errors
due to specific heat ratios held to less than 1.0%.
Figure 1. RIGS Test Data
OBJECTIVE. – Build and deliver two breadboard RF Gauging Systems for gauging a full-scale and a one-tenth-scale S-IVB tank. To test and evaluate these systems, and, from empirical and analytical data results, develop scaling law determinations and methods for determining system error.

PERTINENT WORK PERFORMED. – Two complete breadboard RF gauging systems have been designed and fabricated along with scaled tanks for testing and evaluation. Criteria have been established for optimizing operational frequency bands as a function of tank parameters and propellant dielectrics. Several types of RF tank probes have been investigated with the result that the spiral antenna configuration was chosen as providing best overall gauging results. Tank configuration, structural materials, linings, and perturbations have been studied relative to their effect upon the tank quantity factor (Q). System electronics, including RF sources, RF isolators, mode detection, mode processor and output methods have been designed and refined to a reliable operable system. The mathematical model for RF gauging developed under NAS8-18039 has been further refined to make it more responsive to various input parameters, such as tank Q, dielectric properties and internal tank perturbations.

Testing and evaluation to investigate the feasibility of the system have been performed in the following areas: (1) propellant loading, (2) bubbling and sloshing effects, (3) propellant type vs. optimum frequency band, (4) tank/propellant orientation, (5) tank configuration/perturbation effects, and (6) LO2, LN2 and LH2 testing.

Follow-on progress reports published since this report cover extensive data reduction and analysis efforts.

MAJOR RESULTS. –

1. The tests performed using the RF gauging system as developed and fabricated have demonstrated that RF gauging is a feasible and practical approach to propellant gauging in spacecraft.

2. Significant progress was made in system implementation, including RF probe design and electronic mode processing.

3. In-depth understanding has evolved regarding system implementation and gauging system interface with tank configuration variables.

4. Experimental data has lead to an updating of the mathematical model that improves response correlation of experimental and theoretical results.

5. Results of LH2 testing indicate that the gauge shows promise of high accuracy, as concluded from dynamic test data, and that it is rapidly approaching the test equipment accuracies.
OBJECTIVE. - To summarize the results of a study evaluating several candidate propellant gauging systems suitable for use on the Space Shuttle vehicle, with the exception of the radio frequency gauge approach.

PERTINENT WORK PERFORMED. - The problems presented by zero g on the Space Shuttle vehicle have been delineated and reviewed. The desirability of effecting propellant settling prior to gauging has been established and means for effecting this have been reviewed. The following types of gauging have been reviewed and evaluated; Gamma Ray attenuation, Resonant Infrasonic Gauging (RIGS), Ultrasonic Devices, Ultrasonic Probe, Light Attenuation, Titration (Radioactive and Inert Gas) and Capacitive gauging. In each case the operating principle is reviewed, applicability, and performance limitations are detailed and a summary evaluation of the method is presented. Acoustic pumping and destratification by spraying techniques for propellant positioning for simplifying propellant gauging are also reviewed.

MAJOR RESULTS. -

1. Ultrasonic methods appear possible but would require extensive development and testing to establish feasibility.

2. Light attenuating, titration, radioactive traces, inert gases, and capacitance gauging are not considered as possible gauging systems for the Space Shuttle.

3. Table 1 tabulates the only practical ways of gauging LH₂ in zero-g conditions. Only nuclear, infrasonic and RF gauging are considered as being viable approaches.

4. If propellant settling techniques are employed, capacitance or ultrasonic means could be used. Also, liquid settling would simplify the nuclear gauge approach by reducing the number of source-detector pairs required.
<table>
<thead>
<tr>
<th></th>
<th>True Zero-g</th>
<th>Propellant Settling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LH₂ Tanks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank without Screens</td>
<td>Nuclear (RF)</td>
<td>Nuclear (RF) Level Measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LO₂ Tanks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank without Screens</td>
<td>Nuclear RIGS (RF?)</td>
<td>Nuclear RIGS Level Measurement (RF?)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank with Screens</td>
<td>Nuclear RIGS</td>
<td>Nuclear RIGS Level Measurement</td>
</tr>
</tbody>
</table>

* Radio Frequency (RF) gauging was included only on the basis of other work.*
OBJECTIVE. - To provide a propellant gauging system for the Manned Orbital Laboratory (MOL) to insure conservation of sufficient propellant for de-orbit. To meet this requirement a pressure volume temperature (PVT) gauging concept is used.

PERTINENT WORK PERFORMED. - The system consists essentially of propellant tanks featuring bladder propellant control and high pressure helium tanks. Both tanks are instrumented for measurement of pressure and temperature. Figure 1 shows the general arrangement of the system and Figure 2 shows the propellant gauging assembly schematic.

Performance of the system is predicated upon calculating changes in the pressurant remaining in the high pressure helium bottle based upon its monitored pressure and temperature. The mass of helium in the propellant tank ullage bladder is equal to the mass that has left the high pressure bottle. Measurement of pressure and temperature in the pressure tank ullage together with calculated mass and estimated ullage composition is used to calculate a change in ullage volume. Measurement of propellant temperature allows conversion to propellant mass.

MAJOR RESULTS. -

1. The basic elements and operating principles of PVT propellant gauging concept are presented with an outline of its successful application to the MOL spacecraft.

2. Figure 3 is a block diagram of the Gauging Program for a single system. In addition to the gauging function, provision is made for leak detection self check.

COMMENTS. - Application of this system to significantly larger propellant volumes/masses poses problems which makes this approach to propellant gauging look very questionable.
Figure 1. Propellant Systems—Gen. Arrangement

Figure 2. Propellant Gauging Assembly

Figure 3. Gauging Program
OBJECTIVE. - To design and fabricate operational subcritical cryogenic storage systems for ground test (Phase I), and to evaluate the performance of follow-on subcritical hardware in earth orbit (Phase II).

PERTINENT WORK PERFORMED. - Operational concepts for the storage of subcritical cryogenic fluids and the delivery of single-phase (vapor) were developed. During Phase I two subcritical systems were fabricated by AiResearch and tested which employed regenerative heat exchangers for pressure control and electrical heaters for rapid depletion. A capacitance gage matrix was installed in the tanks for fluid quantity measurements. Thermodynamic and vibration tests of the Phase I devices indicated that the concept warranted verification in a low-gravity environment.

The Phase II subcritical storage and supply system (Figure 1) was a self-contained package having all components necessary to store liquid nitrogen for extended periods and deliver the vapor phase under the environmental conditions of orbital flight. The tank was a spherical dewar on the order of 25 inches inside diameter. Two systems were fabricated, one for orbital evaluation and the other for qualification testing and flight system backup. An electrical heater was used to replace the regenerative heat exchangers to minimize system complexity. The system was flown aboard Apollo Mission AS-203 in July 1966. It exhibited good pressure control and stability, and the heat exchanger outlet temperature and the delivery temperatures were significantly above saturation. The capacitance gage successfully monitored the quantity of fluid in the tank throughout the test.

MAJOR RESULTS. -

1. A flightweight, subcritical cryogenic storage system was designed, fabricated and successfully tested in earth orbit.
2. This was the first successful orbital test of a three-dimensional wire matrix mass gaging device.
3. Single-phase vapor was consistently delivered by the system throughout the test.
Figure 1. Phase II Subcritical Nitrogen System
5.0 OTHER INSTRUMENTATION

Covering liquid/vapor sensing at low-g, flowmetering, two-phase flow quality gauging and temperature and acceleration measurement.
OBJECTIVE. - To survey the literature on cryogenic flowmetering to establish the state-of-the-art of oxygen flowmetering in liquid and gaseous states.

PERTINENT WORK PERFORMED. - A comprehensive summary of information available on liquid and gaseous oxygen flowmetering was made along with an evaluation analysis of commercial meters. Design information and performance characteristics have been presented for the following types of flowmeters: Screw Impeller Volumetric Flowmeter, Rotating Vane Volumetric Flowmeter, Oscillating Piston Meter, Head Meters and Orifice Meters. In addition, information on the following types of flowmeters is also presented: Angular Momentum Type, Turbine, and Vortex Shedding. For each type of meter the principle of measurement is presented, along with design and analysis data supported by operational characteristics and tabulated performance summaries. Each flowmeter review is followed by a summary and conclusions.

MAJOR RESULTS. -

1. A graphic presentation of the flow ranges of the various types of cryogenic flowmeters is shown in Figure 1. Figure 2 presents the (3σ) precision characteristics of the flowmeter types shown in Figure 1.

2. Analysis shows that the existing state-of-the-art for oxygen service leaves a great deal to be desired when measurements must be made to a total uncertainty of less than ±2.0%.

3. A serious problem exists in the use of surrogate fluids in establishing performance and calibration data. The science of surrogate system applications has not been developed to a point where such substitutions can be made without introducing significant errors.

4. Prevailing problems associated with measurement of cryogenic oxygen flow are as follows:
   a. Lack of Standardization and interlaboratory comparison of existing reference facilities.
   b. Technology deficiency regarding surrogate test/calibration errors.
   c. The need for large flow reference systems to support present and future needs.

Figure 1. Flow Ranges of Cryogenic Meters—Experimental Data from the Literature

Figure 2. Precision of Cryogenic Flowmeters—Experimental Data from the Literature
OBJECTIVE. - To summarize the current state of the art in cryogenic temperature measurements at liquid oxygen temperatures and to summarize performance characteristics of resistance thermometers, thermocouples and filled systems types.

PERTINENT WORK PERFORMED. - An excellent summary has been made of the state of the art of cryogenic thermometry in the range of liquid oxygen, nitrogen and hydrogen temperatures. An overview of the International Practical Temperature Scale (IPTS-68) relative to both older and contemporary temperature scales is presented along with operational graphs. Techniques of low temperature thermometry are reviewed, including problems of thermal conduction and thermo electric error sources. Basic design considerations and performance characteristics of the following types of thermometers are presented: resistance (metals and non-metals), platinum, indium, copper, carbon, and germanium. Also covered are the various types of thermocouples, vapor pressure thermometers and gas thermometers.

MAJOR RESULTS. -

1. Figure 1 is presented as a summary of the principal instruments that can be effectively used between the temperatures of 4° and 300°K.

2. Figure 2 presents absolute temperature coefficient of resistance versus temperature for several types of resistance thermometers and also one junction diode.

3. Indium exhibits all the desirable characteristics required of a resistance thermometer element for cryogenic ranges. It is recommended that the anisotropic behavior of indium be studied with the purpose of constructing reproducible thermometers for which Cragoe Z functions might allow precise resistance temperature from only a few calibration points.

4. The very desirable characteristics of fast response time, size, ruggedness and high sensitivity, warrant needed development of the thin film carbon type thermometers. These units require further studies to understand their transport properties and to standardize methods of deposition of materials and substrates.
Figure 1. Graphic Summary of the Approximate Range of Use of Several Temperature Transducers Between 4 and 300K. The Shaded Area Represents the Temperature Range Between the Triple Point and Critical Point of Oxygen.

Figure 2. Comparative Absolute Values of the Temperature Coefficient of Resistance (K⁻¹) Versus Temperature (K) for Several Resistance Thermometers and one Junction Diode.
AN EVALUATION OF SEVERAL CRYOGENIC TURBINE FLOWMETERS.

OBJECTIVE. - To conduct performance evaluation tests on each of several types of volumetric and mass cryogenic turbine type flowmeters to determine their performance, accuracy, rangeability, long term stability, and boundary operational characteristics.

PERTINENT WORK PERFORMED. - Tests were performed utilizing the new NBS cryogenic flow facility which provides for dynamic gravimetric measurement of liquid nitrogen flow. Accuracy of mass flow measurement is estimated as being ±0.18%. Eight flowmeters representing five manufacturers were tested. Five were turbine type standard volumetric meters and three were volumetric meters combined with a compensation device that measured or inferred the fluid density whereby the volumetric output from the turbine meter was converted to mass output.

The performance of the flowmeters in liquid nitrogen is evaluated by reporting the precision and bias of the meters before and after an 80-hour stability test and by defining the extent of temperature, pressure, flow rate, subcooling, and time order (wear) dependencies. Meters were evaluated at flow rates from 20 to 210 gallons per minute, pressures from 32 to 112 Psia and temperatures from 72° to 90°K. Flow meter performance was plotted relative to the 1972 Conference on Weights and Measures tentative code for Cryogenic Liquid Measuring Devices which specified a maintenance tolerance of +2% and -4%. The deviation was calculated from the vendors "K" factor supplied with the meter. The reported bias on each meter was obtained by evaluating the mathematical model at rated maximum flow rate at 80°K. The mathematical model used is: \( y = \mu + aT + bT^2 + c\ln + d\ln^2 + e\theta \) where; \( y \) = Bias in %, \( \mu \) = constant, \( T \) = Temperature, \( m \) = mass flow rate in lbs/sec, and \( \theta \) = time order term. The coefficients \( a, b, c, d \) and \( e \) give an indication of the dependency of the corresponding terms and were reported for each rangeability test when significant.

MAJOR RESULTS. - Table 1 is a summary of the test results showing the performance of the eight turbine flowmeters. As a result of these tests:

1. All meters showed good bias stability but somewhat large bias values at the start of tests.
2. The precision (3 \( \sigma \)) values were good with the exception of the Type Z meter.
3. Some of the meters showed statistically detectable temperature and flow rate dependencies.
4. All meters showed a trend to overregistration and a loss of precision with subcooling.
5. Turbines were sensitive to overspeeding during cooldown which could result in bearing damage.
6. K factors were found to be a function of the cryogen in which the meters are operated. For maximum accuracy they must be individually calibrated in the fluid in which they will be used.

5-6
Table 1. Turbine Meter Performance Summary

<table>
<thead>
<tr>
<th>Meter Identification</th>
<th>N (Volume Basis)</th>
<th>O</th>
<th>P</th>
<th>Q</th>
<th>R</th>
<th>S</th>
<th>V</th>
<th>Z (Mass Basis)</th>
<th>Z (Volume Basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision (3σ) at start, %</td>
<td>±0.69</td>
<td>±0.84</td>
<td>±0.54</td>
<td>±0.57</td>
<td>±1.02</td>
<td>±0.78</td>
<td>±1.11</td>
<td>±1.80</td>
<td>±0.57</td>
</tr>
<tr>
<td>Precision (3σ) at end, %</td>
<td>±0.66</td>
<td>-</td>
<td>±0.48</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>±2.40</td>
<td>±0.87</td>
</tr>
<tr>
<td>Bias at start, %</td>
<td>+3.82</td>
<td>+2.20</td>
<td>+0.10</td>
<td>+1.30</td>
<td>+1.93</td>
<td>+1.59</td>
<td>+0.42</td>
<td>+0.83</td>
<td>+1.08</td>
</tr>
<tr>
<td>Bias at end, %</td>
<td>+3.85</td>
<td>-</td>
<td>+0.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.64</td>
<td>+1.23</td>
</tr>
<tr>
<td>Liquid Volume Metered During Stability Test</td>
<td>384,000 gal.</td>
<td>810,000 gal.</td>
<td>280,000 gal.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>624,000 gal.</td>
<td></td>
</tr>
<tr>
<td>Stability Test</td>
<td>(1,453,600 l)</td>
<td>(3,066,200 l)</td>
<td>(1,059,900 l)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(2,362,100 l)</td>
<td></td>
</tr>
<tr>
<td>Max. Test Flow Rate</td>
<td>80 gpm (54/s)</td>
<td>80 gpm (54/s)</td>
<td>180 gpm (113.4/s)</td>
<td>120 gpm (7.6 l/s)</td>
<td>225 gpm (14.2 l/s)</td>
<td>14.5 lbs/s (6.6 kg/s)</td>
<td>130 gpm (8.2 l/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Subcooling, K</td>
<td>6</td>
<td>14</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Operating Principle</td>
<td>Compensated Turbine</td>
<td>Turbine</td>
<td>Turbine</td>
<td>Compensated Turbine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size, in. (cm)</td>
<td>1-1/4 (3.2)</td>
<td>1-1/2 (3.81)</td>
<td>1-1/2(3.81)</td>
<td>2 (5.08)</td>
<td>1-1/2 (3.81)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: This table is a highly condensed summary of the results of an extensive testing program. In this table it has not been possible to present some information that may be important in some applications. For example, some of the meters tested had statistically detectable temperature and flow rate dependencies. These additional details are presented in the appendices of the original report.

* Meter failed during this test.
INSTRUMENTATION FOR LIQUID HYDROGEN DENSITY MEASUREMENTS USING AN OPEN-ENDED MICRO-WAVE CAVITY

Smetana, J., Wenger, N. C., NASA-LeRC
NASA TN D-6415, July 1971

OBJECTIVE. - Development of an instrumentation system, based on the resonant characteristics of an open-ended microwave cavity, for measuring the density of liquid hydrogen and, in conjunction with a suitable volumetric flowmeter, for measuring total mass flow rate or mass transfer.

PERTINENT WORK PERFORMED. - Design parameters for open-ended resonant cavities have been established. Dielectric constants for liquid hydrogen as a function of density are established and correlated with open-ended cavity resonant characteristics. The effects of two-phase hydrogen (bubbles) on dielectric constant and density measurements have been reviewed. A prototype model of a flow line section featuring a built-in resonant cavity has been designed, fabricated and tested. Two resonant frequency measurement electronic systems have been designed and fabricated, these are: Resonant Frequency Tracking System (REFTS) and Cavity Tuned Oscillator (CTO). Both systems have been performance evaluated and relative merits of each have been determined. Limited systems testing has established system accuracies and limitations.

MAJOR RESULTS. -

1. Steady state liquid hydrogen density measurements can be made to an accuracy of 0.1% using the open-ended microwave cavity principle.

2. A practical flow line section with built-in resonant cavity has been fabricated and tested which demonstrates capability for making liquid density measurements to ±1.0% accuracy.

3. Two automatic resonant frequency measurement systems have been designed, both of which have demonstrated suitability for the application.

4. Acceptable two-phase density measurements can be made where the flow of liquid/gas is in a known configuration; however, problems associated with the measurement of random and slug flows have not been resolved in the investigation.
PERFORMANCE CHARACTERISTICS OF LIQUID-VAPOR
SENSORS OPERATING IN A REDUCED GRAVITY ENVIRONMENT

OBJECTIVE. - To experimentally investigate the liquid retention and response characteristics of certain liquid-vapor sensors when operating in low gravity environments.

PERTINENT WORK PERFORMED. - The complicated nature of fluid characteristics in low-g environments prevented analytical predictions, hence all results were derived from MSFC drop tower test data. This facility provided test durations of approximately four seconds and gravity levels ranging from $5 \times 10^{-4}$ to 0.03 of standard Earth gravity. The experiments were executed by initially locating the sensor unit below the liquid level in a transparent container of petroleum ether, then during the test, slowly pulling the sensor above the liquid level. Sensor reaction to this procedure was recorded by a motion picture camera and simultaneously electrical signals indicative of sensor performance were obtained by telemetry.

MAJOR RESULTS. -

1. Seven types of liquid vapor sensors for use in low gravity environments have been experimentally investigated. Results of the tests definitely demonstrated that most of the sensors performed unreliably in low gravity environments. In general, during the low gravity test periods the probe sensing elements retained sufficient liquid to prevent sensor identification of the true (liquid or vapor) environment. The quantity of liquid trapped by each sensor was dependent on gravity level and probe geometry. Table I is a Summarization of Test Results, tabulating sensor types, acceleration levels, sensor orientation and sensor performance.

2. Test data revealed that, except for the optical and spiral types which performed successfully in the orientation tested, all other types were unsatisfactory for use in low gravity environments. Flight test data on the liquid-vapor capacitance type sensor manufactured by Transonics and a concentric ring type sensor manufactured by Minneapolis Honeywell Corp, which were monitored by camera in flight, verified the unsatisfactory performances observed during this investigation.

COMMENTS. - This investigation demonstrates that zero-g performance of liquid-vapor sensors, and possibly other sensors that may be required in low-g fluid transfer systems, may present operational problems requiring careful investigation.
<table>
<thead>
<tr>
<th>Acceleration Level, ( a/\text{ge} )</th>
<th><strong>Sensor Type</strong></th>
<th><strong>Sensor Orientation</strong></th>
<th><strong>Sensor Performance</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>Concentric Ring</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.01</td>
<td>Concentric Ring</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.01</td>
<td>Concentric Ring</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.03</td>
<td>Concentric Ring</td>
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<td>Unsuccessful</td>
</tr>
<tr>
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<td>Trans-Sonics</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.01</td>
<td>Trans-Sonics</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.01</td>
<td>Trans-Sonics</td>
<td>Horizontal</td>
<td>Successful</td>
</tr>
<tr>
<td>0.01</td>
<td>Trans-Sonics</td>
<td>Horizontal</td>
<td>Successful</td>
</tr>
<tr>
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<td>Trans-Sonics</td>
<td>Horizontal</td>
<td>Successful</td>
</tr>
<tr>
<td>0.001</td>
<td>Trans-Sonics</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.001</td>
<td>Acoustic</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
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<td>Acoustic</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
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<td>Acoustic</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.001</td>
<td>Bendix (Light Prism)</td>
<td>Horizontal</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.001</td>
<td>Bendix (Light Prism)</td>
<td>Horizontal</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.001</td>
<td>Bendix (Light Prism)</td>
<td>Horizontal</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.001</td>
<td>Bendix (Light Prism)</td>
<td>Horizontal</td>
<td>Successful</td>
</tr>
<tr>
<td>0.001</td>
<td>Bendix (Light Prism)</td>
<td>Horizontal</td>
<td>Successful</td>
</tr>
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<td>Flat Cable</td>
<td>Vertical</td>
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</tr>
<tr>
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<td>Flat Cable</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
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<td>Flat Cable</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
<td>0.0005</td>
<td>Printed Circuit</td>
<td>Vertical</td>
<td>Unsuccessful</td>
</tr>
<tr>
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<td>Printed Circuit</td>
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<td>Unsuccessful</td>
</tr>
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<td>Spiral Probe</td>
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</tr>
<tr>
<td>0.0005</td>
<td>Spiral Probe</td>
<td>Horizontal</td>
<td>Successful</td>
</tr>
</tbody>
</table>
CRYOGENIC TEMPERATURE MEASUREMENT USING PLATINUM RESISTANCE THERMOMETERS


OBJECTIVE. - Evaluation of commercial platinum resistance thermometers (PRT) in order to satisfy need for accurate, reliable sensors to measure cryogenic temperatures.

PERTINENT WORK PERFORMED. - The resistance-temperature function for pure strain free platinum above 90°K is accurately expressed by the Callendar-Van Dusen equation. Below 90°K, nonlinearity in the resistance-temperature (R-T) relations is best expressed by Corruccini who used R-T relations in terms of resistance differences (\(Z_T\) functions). These functions are best established by reference to NBS calibration primary reference standard PRT. An evaluation of commercial PRT units has been made based on \(Z_T\) functions derived from multipoint calibrations of statistical samples compared with standard \(Z_T\) functions. Use of the \(Z_T\) function automatically normalized the PRT calibrations in terms of nondimensional resistance ratios and at the same time canceled out the effects of residual resistance. The average error in the 20°K to 90°K range for primary reference NBS standards is taken to be less than 0.005°K. Based on and utilizing the foregoing concepts a comprehensive survey was made of the performance characteristics of commercially available platinum resistance thermometers. Other features tested were; reliability, residual ratios, repeatability and self heating. Tested units included twelve basic commercial types, three Lewis Research specified improved types and a unit of poor quality. Instrumentation and procedures for improved calibrations in the cryogenic ranges were detailed.

MAJOR RESULTS.

Evaluation of three types of commercial PRT transducers demonstrated that resistance difference ratio "Z" functions based at 20.20°K and at 77.4°K conform to the primary reference PRT to within ±0.04°K. Accuracy in the range of 77.4°K to 273.15°K was found to be the same. Table I presents a detailed tabulation of data along with the corresponding data of a Primary Standard NBS thermometer.
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Reliability</th>
<th>Temperature, T, °K</th>
<th>Residual Repeatability, ( \frac{R_{20}}{R_{77}} )</th>
<th>Self-heating in liquid nitrogen, ( \frac{\circ\text{K}}{\text{mW}} )</th>
<th>Cost, dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>3</td>
<td>5000 945</td>
<td>25.5</td>
<td>2.7</td>
<td>190</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>3</td>
<td>200 38.2</td>
<td>.96</td>
<td>.01</td>
<td>100</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>2</td>
<td>500 95</td>
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<td>.2</td>
<td>80</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>0</td>
<td>1340 260</td>
<td>18</td>
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<td>280</td>
</tr>
<tr>
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<td>5</td>
<td>0</td>
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<td>435 83</td>
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</tr>
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<td>7.6</td>
<td>20</td>
</tr>
<tr>
<td>E</td>
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<td>1.68</td>
<td>15.7</td>
<td>330</td>
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<td>12</td>
<td>2</td>
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<td>190</td>
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<td>25.5 4.81</td>
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<td>2.29</td>
<td>450</td>
</tr>
</tbody>
</table>

*Nominal values.*
OBJECTIVE. - This paper presents the design and operational principles used in nucleonic gauges built by Industrial Nucleonics Corporation for the measurement of density and quality of low temperature hydrogen. Performance data for both types of gauges are presented and evaluated.

PERTINENT WORK PERFORMED. - The fast response cryogenic (LH$_2$) densitometer built for NASA was a modified commercial quality meter built for Douglas Aircraft Corp. The cryogenic quality meter was built to NASA Saturn specifications, to measure the quality of two-phase saturated hydrogen vented from the S-IVB stage of the Saturn vehicle. The densitometer gamma radiation source was Cesium 137 with a multiplate ionization chamber detector. The quality meter radiation source was Am-241 with a Sodium Iodide crystal detector coupled to an EMI photomultiplier tube. The densitometer was tested at the Instrument Development Branch Test Laboratory of Geo. C. Marshall Space Flight Center. In testing for LH$_2$ density, measurements were made of density, vapor pressure and temperature. Liquid hydrogen density was calculated by means of the following equation:

$$\rho(T) = 8.440 \times 10^{-2} - 2.230 \times 10^{-4} T - 2.183 \times 10^{-5} T^2$$

The quality meter was performance evaluated in connection with the flight of the S-IVB stage of the Saturn flight of June 1966. The equation defining quality was as follows:

$$Q = \frac{\text{Vapor (Mass)}}{\text{Liquid (Mass)} + \text{Vapor (Mass)}}$$

MAJOR RESULTS. -

1. Performance of the densitometer was checked through LH$_2$ changes associated with the following: Temperature changes, venting, supercooling, and restabilization. Figure 1 shows a plot of these results against calculated values. Static accuracies of ±0.3% and dynamic accuracies of ±3.0% were demonstrated under laboratory conditions.

2. Performance of the densitometer in LH$_2$ slush demonstrated accuracies of 0.5%.

3. Performance of the quality meter during the S-IVB flight demonstrated encouraging results during high level mass-flow (80%) liquid conditions and showed good correlation with TV data taken during venting periods.

4. The suitability of nucleonic methods of instrumentation for density and quality measurements has been demonstrated for space operations. It has been proposed to modularize these systems and to extend their application to include flow rate measurement of two-phase flow.
Figure 1. Time Varying Liquid Hydrogen Density Data
AN EXPERIMENT TO TEST LOW LEVEL ACCELEROMETERS

OBJECTIVE. - To devise and define a technique for testing/calibrating micro-g accelerometers.

PERTINENT WORK PERFORMED. - A method has been proposed and analyzed which provides a practical means of testing accelerometers under otherwise weightless conditions with inputs from $10^{-5}$ g to 1g. Basic to this proposal is that the testing is to be performed in an aircraft flying a parabolic arc so as to produce a zero-g condition for discrete periods. A free floating centrifuge is proposed along with a gyro controlled gimbal on which a speed clocked camera is mounted for determining angular velocity. The test accelerometer, power supplies and accelerometer output recording means are mounted in a counter-balanced configuration as an integral part of the centrifuge. An error analysis has been conducted to determine the effect of angular velocity uncertainty, effective radius length uncertainties, and aerodynamic effects.

MAJOR RESULTS. -

1. A free floating zero-g centrifuge has been proposed for testing/calibrating micro-g accelerometers under essentially weightless conditions in the range of $10^{-5}$g to 1g levels.

2. Means for manipulating and monitoring a micro-g centrifuge and for acquisition of accelerometer data has been outlined.

3. The accuracy of calibration levels is 0.1% of the input acceleration in the range of 0.1 to 0.0002 g's increasing up to 0.7% at $10^{-5}$g's.

4. The programmed system is amenable to design refinements which can extend the lower limits of the experiment to meet the requirements of tomorrow's low-level accelerometers.
6.0 STRATIFICATION/PRESSURIZATION

Covering fluid temperature stratification and tank pressurization with and without liquid outflow, with and without external pressurization with condensible and/or non-condensible gases, and with and without venting.
OBJECTIVE. - Determine the effects of various physical parameters on helium presurant gas requirements during initial pressurization and during expulsion of \( \text{LH}_2 \) and compare test results with an analytical model.

PERTINENT WORK PERFORMED. - Testing was accomplished in a 3.96-m (13-ft.) diameter 2219-T87 aluminum alloy spherical tank located in a vacuum chamber. Tests were conducted for a range of liquid outflow rates (1.73 to 4.32 Kg/sec) at a constant pressure of \( 34.47 \times 10^4 \text{N/m}^2 \) (50 psia) using a hemisphere type injector. Data were also obtained for pressurization of the tank from 1 atm. to 50 psia with no outflow at various pressurant inflow rates (2.48 \( \times 10^3 \) to 8.96 \( \times 10^3 \) \text{N/m}^2-sec) for initial tank ullages of 5, 28, 55, and 75% of total tank volume. In addition to pressure data, temperatures were recorded throughout the tank. An unsuccessful attempt was made to measure the concentration of helium and hydrogen gas at five positions in the tank.

The basic analytical program developed by Roudbush, 1965 (TN D-2585), and illustrated in Figure 1, was used for comparison with the test data. Modifications made to the basic program were accomplished to allow application to arbitrary symmetric tank shapes, and an attempt was made to incorporate heat transfer from the gas to the liquid. The treatment of internal hardware (e.g., tank baffle and instrumentation) was also modified to correspond to the treatment of heat transfer to the tank wall.

MAJOR RESULTS. -

1. Increasing the inlet gas temperature and/or the pressurization rate with no outflow reduced pressurant requirements.

2. The trends for various inlet gas temperatures and liquid outflow rates were consistent with results using hydrogen as the pressurant (Stochl, et al, 1969). The ratio of ideal to actual pressurant for similar test conditions was 8.3% lower for helium than for hydrogen. The trends were also consistent with those from smaller tank (1.52-m-dia.) tests indicating that scale effects are predictable.

3. For the range of test conditions used, the analytical program and assumptions adequately predicted pressurant gas requirements during the initial pressurization as well as during the expulsion period; within 2.1% for the 300K inlet temperature and within 7.0% for the 168K case. Tank wall heating predictions were within 19.3%, however, the prediction of liquid heating was not good (average deviation of 41.9%).
(1) The ullage gas is nonviscous.

(2) The ullage gas velocity is everywhere parallel to the tank axis and does not vary radially or circumferentially.

(3) The tank pressure does not vary spatially.

(4) The ullage gas temperature does not vary radially or circumferentially.

(5) The tank wall temperature does not vary radially or circumferentially.

(6) No heat is transferred axially in either the gas or the wall.

(7) No condensation or evaporation occurs.

(8) No heat is transferred from the gas to the liquid.

Figure 1. Pertinent Computer Program Characteristics (Roudebush, 1965)
TRANSIENT PRESSURE RISE OF A LIQUID-VAPOR SYSTEM IN A CLOSED CONTAINER UNDER VARIABLE GRAVITY

OBJECTIVE. - Develop an analytical model and correlate with actual flight data for prediction of pressure rise in a closed cryogenic container at low-g.

PERTINENT WORK PERFORMED. - The analytic problem was formulated in terms of the transport equations for a cylindrical tank with an axial body force and a symmetrically imposed external heat flux (Figure 1). The tank ends are assumed adiabatic. The temperature and velocity distributions are determined using a finite-difference method, which is coupled with an integral form of the energy equation to determine pressure rise. The procedure takes into account the possibility of incipient and nucleate boiling. For convection heat transfer it is assumed that laminar conditions prevail. When the temperature of the wall in contact with the liquid exceeds the saturation temperature by a specified amount, nucleate boiling is initiated. The boiling model considers that all vapor formed proceeds directly to the ullage space without interaction with the liquid. All properties are assumed constant except the density in the body-force term, and viscous dissipation is neglected. In the vapor region an ideal gas is assumed. The processes in the liquid and vapor regions are coupled at the interface by evaporation or condensation depending on the relative rates of diffusion heat transfer. The governing equations are made non-dimensional and placed in finite difference forms, along with boundary conditions for solution.

Calculations were made for the Saturn AS-203 hydrogen tank as approximated by a cylinder 6.7-m-dia. by 8.9-m-high, 1/3 filled with liquid. The total energy input was approximately 9 Kcal/sec., however, since some uncertainty existed as to heat flux distribution this was varied in the computer model. Also, different wall materials were used to assess their influence (Table 1). The effective acceleration was \( a/g = 1.7 \times 10^{-4} \) and the superheat for nucleate boiling to take place was 0.55°C. Comparisons between computer and flight data are presented in Figure 2.

MAJOR RESULTS. - Comparison of the computer model with the flight data was not good. This was thought to be due primarily to three factors; (1) having flat ends, the distribution of heating in relation to the liquid and vapor volumes was not satisfactorily simulated, (2) Interaction of vapor bubbles with the liquid, neglected here, would tend to increase the pressure-rise rate and (3) neglecting \( \Delta p/\Delta t \) time in the vapor space would produce lower densities and hence lower pressure.
Figure 1. Container Coordinate System

Figure 2. Computed Pressure Rise

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Nucleate Boiling Permitted</th>
<th>Wall Material</th>
<th>qw - watts/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Liquid</td>
<td>Vapor</td>
</tr>
<tr>
<td>B-H 47</td>
<td>Yes</td>
<td>Polyurethane</td>
<td>.0521</td>
</tr>
<tr>
<td>B-H 56</td>
<td>Yes</td>
<td>Aluminum</td>
<td>.0202</td>
</tr>
<tr>
<td>B-H 71</td>
<td>No</td>
<td>Aluminum</td>
<td>.0202</td>
</tr>
</tbody>
</table>

Table 1. Parameters for Computer Runs
EVALUATION AND APPLICATION OF DATA FROM LOW-GRAVITY ORBITAL EXPERIMENT, Bradshaw, R. D., et al, GD/C GDC-DDB70-003, 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 represurization, closed tank pressure rise, liquid level phenomena during venting (venting effects) and propellant sloshing. Only the closed tank pressure rise work will be discussed here. Pressure rise correlations were performed for the hydrogen tank for the 4th orbit of the AS-203 flight. Two different analytical models were used to predict the flight data. The first model is basically the Saturn II pressurization program described in the summarized report by Nein and Thompson, 1966 (TND-3177). For discussions here, this model is referred to as the P3542 program.

The second model is the REPORTER program developed under Contract NAS8-20165 by Walburn, et al, 1967. This program represents a First Law thermodynamics analysis with capacity for a 10 node problem, permitting temperature stratification in the ullage; however, for the current application only a single ullage and a single liquid node were used. Prior to the actual pressure rise analysis, considerable effort was expended in obtaining and verifying the external heating for input to the thermodynamic models. The heat transfer analysis within the forward skirt area proved difficult because of an undefined absorptivity $\alpha$ for the Mylar insulation on the forward dome. This absorptivity was estimated to be anywhere from 0.05 to 0.55 with a nominal value chosen as 0.20.

MAJOR RESULTS. -

1. Comparisons of analytical predictions with test data are presented in Figure 1, showing fairly good agreement, depending on the value of absorptivity used for the $\text{H}_2$ tank dome. Case 1 for the P3542 program corresponds to a total ullage heating, as calculated by the program, of 50,160 Btu while for Case 2 this is 55,800 Btu. The actual estimated heat input from a detailed analysis using a heat conduction program was 53,700 Btu. Matching of the heat flux calculated in P3542 with that predicted is a cut-and-try process.

2. Both programs are dependent on good data for ullage heating and both are inadequate relating to liquid stratification and propellant boiloff contributions.
Figure 1. Comparison of Predicted Pressures With AS-203 Pressure History During Long Term Coast
PRESSURANT GAS REQUIREMENTS FOR THE PRESSURIZED DISCHARGE OF LIQUID HYDROGEN FROM PROPELLANT TANKS

OBJECTIVE. - Experimentally determine the effect of various physical parameters on pressurant gas requirements and demonstrate the capability of analysis to predict these requirements during expulsion of LH₂.

PERTINENT WORK PERFORMED. - Testing was accomplished for: (1) two 5-ft (0.3-in. and 0.161-in. 6061 Al Aly wall) and one 13-ft (0.50-in. 2219 Al Aly wall) diameter spherical tanks, (2) three different injector geometries (hemispherical and radial diffusers and a straight pipe), (3) inlet gas temperatures of 300°, 500°, and 640° R, (4) tank pressures of 35, 50, and 75 psia, (5) liquid outflow rates of 0.5 to 12 lb/sec, and (6) expulsions with and without slosh. In all cases, expulsion was at constant pressure using GH₂. Initial ullage was 5% and expulsion was stopped at 95% liquid expulsion. The criteria for comparison was the ratio of ideal pressurant mass (no energy loss to walls or liquid) to the actual pressurant mass used. Testing was done in a vacuum chamber and fluid temperatures, tank pressure and liquid outflow and pressurant inflow rates were measured. Individual energy losses to the tank wall, internal hardware and liquid were determined.

MAJOR RESULTS. -

1. Of all test variables, the inlet gas temperature had the strongest effect (Figure 1). Also, in all cases the amount of pressurant required increased for increasing expulsion time (Figure 2). Changing tank pressure level does not alter the ratio of ideal to actual pressurant.

2. The use of a straight pipe injector decreases pressurant requirements over that of the diffuser types (Figure 3). This decreased pressurant requirement is due to reduced tank wall heating and greater amounts of liquid evaporation.

3. The major heat sink is the tank wall, where 40 to 50% of the total energy is absorbed; 15 to 20% is absorbed by the liquid.

4. Sloshing of the liquid at its natural frequency causes a significant increase in pressurant requirement (Figure 4). Although the use of antislosh baffles decreases the wave height, it also causes more liquid splashing which cools the ullage gas.

5. In general, the analytical program of Roudebush, 1965, was able to predict pressurant requirements within ±10% for all no slosh tests except for the straight pipe injector data which was within ±30%.
Figure 1. Pressurant Mass Ratio as a function of Inlet Temperature for Two Tank Sizes

\[ P_T = \text{Tank Pressure} \]
\[ \dot{\omega} = \dot{W} = \text{Outflow Rate (lbs/sec)} \]

Figure 2. Pressurant Mass Ratio as a function of Expulsion Time for Two Tank Sizes

Figure 3. Pressurant Mass Ratio as a function of Expulsion Time for Three Injector Geometries

Figure 4. 13' Tank Pressurant Gas Requirements Under Slosh Conditions
OBJECTIVE. - To develop a stratification and pressurization model and computer code.

PERTINENT WORK/MAJOR RESULTS. - The computer code developed results from work at LMSC under various company and contracted programs, including NAS8-11525 (Hurd, 1966 and Chin, 1965 and 1964). The model treats a draining axisymmetric (single-valued radius) vessel which can have variable acceleration and asymmetric heating. The liquid is treated stepwise-in-time and is broken into stratified layers with quasi-steady turbulent (1/7 power profile) boundary layer flow (Figure 1). Earlier versions included laminar boundary layers, however, computations were unstable. Asymmetric heating is treated by breaking the vessel into wedges about the center-line. Direct bulk (nuclear) heating can be included. Pressurization or venting is treated continuously with time and the ullage is coupled with the liquid and wall through mass and/or energy transfer. The ullage is a single vapor node (no non-condensibles) as is the wall. The liquid surface is flat and the isotherms are horizontal, except in the boundary layer (assumed thin compared to vessel radius). Each of the azimuthal wedges has its own boundary layer and, based on experimental data from NAS8-11525, is assumed to have no edge effects. The boundary layer on each wedge initiates from its inversion point (arbitrarily chosen or determined from a balance between buoyant and pressure forces). Below the inversion point, simple mixing with the adjacent bulk fluid is assumed. The surface liquid layer is limited to a specified minimum mass by combining layers as needed.

After each step of liquid stratification, pressurization is considered. Pertinent aspects are illustrated in Figure 2. Compression heating of the liquid, determined to be important during LH$_2$ testing in a 40-in dia tank at LMSC, is included. Previous test work (references not given) indicate that flows at the L/V interface are complex and therefore heat transfer coefficients at the interface are input to the program and must be estimated or determined from empirical data. The energy balance at the interface is:

\[ h_{fg} \Delta h_s = \dot{Q}_{us} - \dot{Q}_{ls} = \left[ h_{us} (T_u - T_s) - h_{ls} (T_s - T_L) \right] A_s. \]

If \( \dot{Q}_{us} > \dot{Q}_{ls} \) evaporation will occur and if \( \dot{Q}_{us} < \dot{Q}_{ls} \) condensation will occur. It is assumed that subcooled ullage or superheated liquid cannot occur and is prevented by appropriate liquid evaporation.

At the end of each time step the following are output: temperature, mass thickness and position of each layer remaining; temperature and mass of each layer drained; ullage pressure, temperature and mass; wall temperature; mass transfer at L/V interface; mass of pressurant added or mass of vapor vented.

* Subscripts u, s and L refer to the ullage, liquid surface and liquid bulk, respectively.
Fig. 1. Configuration at Beginning of Time Steps

Fig. 2. Configuration for Liquid-Ullage Wall Coupling
EMPIRICAL CORRELATIONS FOR PRESSURE RISE IN
CLOSED CRYOGENIC CONTAINERS, Blatt, M. H., GD/C
Journal of Spacecraft and Rockets, Vol. 5, No. 6, June 1968

OBJECTIVE. - To define a simple method of predicting pressure rise in a closed
cryogenic tank subjected to external heating under both 1-g and "zero-g" conditions.

PERTINENT WORK PERFORMED. - A logical relationship between pressure rise and
tank conditions for a stratified fluid was postulated to be \( \Delta P/\Delta t = C_1 (\dot{Q}/MS)^C_2 \), where
M is total fluid mass and S is percent ullage. A least squares fit was then made of
available data for which the above parameters were known. In the case of LH\(_2\) at
"zero-g", a total of 10 data points were available from SIVB-203 and Aerobee flights.
For LH\(_2\) at 1-g, NASA/LeRC, Los Alamos, Aerobee and AC-9 (Atlas-Centaur) data
provided 5 points. For LO\(_2\) at 1-g, insufficient data was found to attempt a correlation.
At 0-g, Atlas-Centaur provided 3 data points. The maximum percent deviation was
+89/-35% for zero-g H\(_2\), +42/-15% for 1-g H\(_2\) and +6/-1% for zero-g O\(_2\).

MAJOR RESULTS. - The following equations were developed from the least square
fit:

\[
\begin{align*}
\text{LH}_2 \text{ - "zero-g"} & \quad \Delta P/\Delta t = 86 (\dot{Q}/MS)^{0.975} \quad \text{Eqn. 1} \\
\text{LH}_2 \text{ - 1-g} & \quad \Delta P/\Delta t = 98 (\dot{Q}/MS)^{1.02} \quad \text{Eqn. 2} \\
\text{LO}_2 \text{ - "zero-g"} & \quad \Delta P/\Delta t = 1450 (\dot{Q}/MS)^{1.14} \quad \text{Eqn. 3}
\end{align*}
\]

In the above equations, \( \Delta P/\Delta t \) is in psi/hr, \( \dot{Q} \) = total heat input in Btu/hr, M in LB
and S in percent. These equations are shown plotted in Figure 1, along with data for
homogeneous pressure rise for comparison. The homogeneous pressure rise equations
are:

\[
\begin{align*}
\text{LH}_2 & \quad \Delta P/\Delta t = 1.13 (\dot{Q}/M)^{1.01} \quad \text{Eqn. 4} \\
\text{LO}_2 & \quad \Delta P/\Delta t = 3.58 (\dot{Q}/M) \quad \text{Eqn. 5}
\end{align*}
\]

These homogeneous equations are approximations and are only accurate at ullage vol-
umes where the energy and mass contributions of the ullage are negligible.

COMMENTS. - The equations developed are based on a fairly small amount of data
and should, therefore, only be used where it is required to determine an approximate
pressure rise with a minimum of calculation.
Figure 1. Comparison of Tank Pressure Rise Rate Correlations
EFFECT OF GRAVITY ON SELF-PRESSURIZATION
OF SPHERICAL LIQUID-HYDROGEN TANKAGE

OBJECTIVE. - To examine information from several experimental programs in order to understand the thermodynamic history of liquid-hydrogen tankage at both normal and reduced gravity.

PERTINENT WORK PERFORMED. - Heat transfer test data, primarily in the form of non-vented pressure rise rates, are reviewed from a series of Aerobee flights, an Atlas passenger pod flight and 1-g tests with variations in heat distribution (Aydelott, 1967). In all cases the test tank was basically the same configuration (Fig. 1); consisting of a 9-in (23-cm) dia CRES inner sphere containing the LH₂, an intermediate sphere with electric heating coils and an outer vacuum jacket. Two simple pressure rise models are presented for comparison with the test data; (1) homogeneous and (2) surface evaporation which assumes all the energy absorbed goes to evaporating liquid and maintaining the vapor at a temperature corresponding to saturation at the total pressure while the liquid temperature remains constant.

MAJOR RESULTS. -

1. Overall, the location of heat input relative to the liquid and vapor was the most important factor in determining pressure rise rates. This is illustrated for the 1-g case in Figure 2.

2. Under reduced-gravity the pressure rise was greatly affected by the liquid configuration, with totally wetted walls producing the lowest rise rate. The liquid configuration was in turn dependent on the heat transfer rate and distribution, on the percent liquid fill and possibly on the existence of internal instrumentation. High heat-transfer rates and low liquid filling decreased the wetted area and increased pressure rise rates (Figure 3). Also, a small unidirectional acceleration decreased the wetted area and increased the rise rate. Oscillatory or random disturbances decreased the rise rate.

3. In general, pressure rise rates at 1-g quiescent were greater than at low-g (Fig. 4) since (a) the wetted wall area increased with decreasing g-level and (b) as g-level is reduced, convective heat transfer is diminished and boiling enhanced, with an increasing bubble population acting to cause more complete liquid mixing.

COMMENTS. - Statement 3b above appears to be mostly speculation with no real quantitative verification within this report.
Figure 1. Apparatus for Typical Aerobee Experiment

Figure 2. Effect of Heat-Transfer Rate and Distribution

Figure 3. Pressure as Function of Heat Added; Comparison of Normal-Gravity and Reduced-Gravity Tests. Uniform Heating Configuration

Figure 4. Pressure as Function of Total Heat Added for Reduced-Gravity Tests. Uniform Heating
AN EQUATION FOR THE PREDICTION OF CRYOGENIC PRESSURANT REQUIREMENTS FOR AXISYMMETRIC PROPELLANT TANKS


OBJECTIVE. - Develop a simple equation for prediction of pressurant requirements to maintain essentially constant pressure outflow of settled cryogenic fluids.

PERTINENT WORK PERFORMED. - The form of the equation and the dimensionless groups employed were obtained from the theories of Gluck and Kline, 1962, and Arpaci, et al, 1961. The coefficients were derived by fitting more than 125 theoretical points obtained by the generalized pressurization computer program described by Epstein, et al, 1965, and Nein and Thompson, 1966, over the range of variables presented in Table 1. The deviations of the pressurant requirements predicted by the program from those obtained from the equation were less than 7%. The equation was also compared with a considerable amount of test data. The final equation is presented below.

\[
\frac{w_p}{w_p^0} = \left( \frac{T_0}{T_s} - 1 \right) \left[ 1 - \exp(-p_1 C p_o) \right] \left[ 1 - \exp(-p_3 S p_o) \right] + 1 \times \exp \left[ -p_5 \left( \frac{1}{1 + C} \right)^{\frac{Sp_o}{1 + S}} \right] Q p_o
\]

where

\[
w_p^0 = \rho_o \Delta V, \quad C = \frac{(\rho c_p t) w}{(\rho c_p t) D} \left( \frac{T_s}{T_o} \right), \quad S = \frac{h c_t}{(rt) o D} \left( \frac{T_s}{T_o} \right), \quad Q = \frac{\dot{q} t}{(\rho c_p t) D T_0}
\]

\[D = \text{equivalent tank diameter. (Diameter of a cylindrical tank having same total volume and wall surface area as tank under investigation)}\]

\[h_c = \text{gas-to-tank-wall-free-convection heat transfer coefficient. (Calculated at film temperature equal to } (T_o + T_s)/2 \text{ and temperature difference equal to } T_o - T_s)\]

\[p = \text{tank pressure during liquid expulsion}\]

\[p_1, p_2, \ldots, p_n = \text{fitted constants (Table 2)}\]

\[\dot{q} = \text{heat flux from ambient to tank wall, per surface area of wall}\]

\[t_w = \text{wall thickness}\]

\[T_o = \text{pressurant inlet temperature}\]

\[T_s = \text{saturation temperature of propellant at initial tank pressure. (Equivalent to the initial wall temperature)}\]

\[w_p = \text{total pressurant mass}\]

\[w_p^0 = \text{total pressurant mass under conditions of zero heat and mass transfer}\]

\[\frac{w_p}{w_p^0} = \text{collapse factor}\]

\[\Delta V = \text{expelled liquid volume}\]

\[\theta \tau = \text{total liquid outflow time}\]

\[\rho = \text{density}\]

\[\text{Subscripts}\]

\[G \text{ refers to gas}\]

\[W \text{ refers to wall}\]

\[\text{Superscript}\]

\[O \text{ refers to variables at a temperature equal to inlet pressurant temperature and a pressure equal to tank pressure during explosion}\]

MAJOR RESULTS. - The capability of Equation 1 to predict accurate total pressurant requirements, \(w_p\), over the range of application (Table 1) was demonstrated by close agreement between experimental and theoretical results (Figures 1 and 2).
Table 1. Ranges of Variables Covered in Computer Program

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical tank diameter</td>
<td>5–30 ft</td>
</tr>
<tr>
<td>Ellipsoidal tank diameter</td>
<td>5–30 ft</td>
</tr>
<tr>
<td>Cylindrical tank diameter</td>
<td>4–35 ft</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>0.1–1 in.</td>
</tr>
<tr>
<td>Ratio of pressurant inlet temperature</td>
<td>2–15</td>
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<tr>
<td>to propellant saturation temperature</td>
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</tr>
<tr>
<td>Total outflow time</td>
<td>200–500 sec</td>
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<td>Ambient heat flow</td>
<td>0–10,000 Btu/ft²-hr</td>
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Table 2. Constants for Use in Equation (1)

<table>
<thead>
<tr>
<th>Pressurant</th>
<th>Propellant</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
</tr>
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<tbody>
<tr>
<td>$H_2$, He</td>
<td>$H_2$</td>
<td>0.330</td>
<td>0.281</td>
<td>4.26</td>
<td>0.857</td>
<td>1.50</td>
<td>0.312</td>
<td>0.160</td>
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<td>$O_2$, $N_2$, He</td>
<td>$O_2$</td>
<td>0.775</td>
<td>0.209</td>
<td>3.57</td>
<td>0.790</td>
<td>0.755</td>
<td>0.271</td>
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<td>$N_2$, He</td>
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<td>$F_2$, He</td>
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</table>

Figure 1. Comparison of Predicted Cryogenic Pressurant Requirements with Data from Small Cylindrical Tanks

Figure 2. Comparison of Predicted Cryogenic Pressurant Requirements with Data from Flight-Size Tanks

OBJECTIVE. - Develop accurate methods for prediction of pressurization gas requirements for cryogenic propellant tanks.

PERTINENT WORK PERFORMED. - A long series of experiments was conducted at NASA-MSFC using five basic tank configurations; (1) Saturn I, S-I stage with five interconnected LOX tanks (L/D = 7), with one having a diameter of 105-in. and four having diameters of 70-in, (2) Saturn I, S-IV stage, spherical LOX and cylindrical LH$_2$, 260-in. dia tanks, (3) 6.5-ft dia by 39-ft long cylindrical LOX tank, (4) 13-ft dia by 26-ft long cylindrical LOX tank, and (5) 1-ft dia by 3-ft long cylindrical LOX tank. Tank pressures and in most cases internal fluid temperatures were measured. For the LOX tank cases, pressurization was either with GN$_2$, GO$_2$, or He. Sloshing of tank configurations 3, 4 and 5 was also accomplished.

The analytical model used to correlate the test data was developed at Rocketdyne for the Saturn II vehicle (Epstein and Georgius, 1964). Pertinent elements are illustrated in Figure 1. Pressurization can either be with evaporated propellant and/or a non-condensable gas. The ullage gas temperature, composition, and properties are considered functions of time and of axial, but not radial or circumferential, distance. The tank and fluid can be divided into a large number of horizontal nodes. The experimental data was used to obtain empirical coefficients required in the program, as well as to define modifications which were made in the methods of handling fluid-wall and gas-liquid heat transfer and gas-liquid mass transfer.

MAJOR RESULTS. -

1. Prepressurization with helium reduces pressure decay during liquid sloshing near the critical frequency (Figure 2). It is assumed that helium acts as a buffer between the splashing liquid and condensable pressurant.

2. Under normal conditions helium pressurant must be introduced into a tank at a temperature 1.1 times higher than GO$_2$ to obtain the same ullage mean temperature.

3. The S-II computer program, as modified and utilizing recommended coefficients, can predict total and transient pressurant requirements and ullage temperature gradients within ±5%. A typical comparison is presented in Figure 3.

4. No significant radial ullage temperature gradient occurs, even in tanks with anti-slosh baffles, and the strongest influence on pressurant weight is exerted by pressurant inlet temperature, for which no diminishing return occurs within a temperature range compatible with common tank materials.
Figure 1. Pertinent Computer Program Elements

Figure 2. Comparison Between Ullage Pressure Loss For He and GN₂ Prepressurants Under Liquid Slosh and Non-Slosh Conditions in Tank Configuration 3

Figure 3. Comparison Between Experimental and Computed Pressurant Flowrate, S-I Stage LOX Tank Flight Test, Oxygen as Pressurant
7.0 VENT SYSTEMS

Covering analysis, design, fabrication and test of systems to vent and/or control fluid storage and/or receiver tank pressures at low-g.
OBJECTIVE. - To thoroughly evaluate performance of the zero-g hydrogen tank vent system previously developed under Contract NAS3-7942 (Sterbentz, August 1968).

PERTINENT WORK PERFORMED. - Both analysis and 1-g testing were accomplished; (1) Full scale testing in $H_2$ in two different size tanks (41.5 inch sphere and 100 inch oblate spheroid), (2) development of analytical models to correlate the test data, (3) small scale testing with methane, Freon, $LN_2$ and $LH_2$ and associated analysis of condensation at a moving liquid/vapor interface, and (4) definition of flight testing to verify system performance. Fluid mixing was evaluated by the time to reduce tank pressure to equilibrium, with and without venting, following pressurization with $H_2$ gas or with helium, each at 140*$^\circ$R and 530*$^\circ$R. Pressure was increased from 17 to 28 psia or 17 to 36 psia prior to mixing. Ability to maintain mixed fluid conditions was evaluated by comparing pressure change rates at equilibrium with those calculated from Equ. 1, Table 1. In addition to tank size, tank pressure and pressurant, the parameters in Table 2 were varied. A total of 732 tests were accomplished in 1500 hours of testing. Test plans for the 110 inch tank included television coverage of fluid circulation, but the camera did not work, with reasons not given. Testing was also accomplished in the 110 inch tank for configurations (3) and (4), Table 2, to simulate the effect of vapor which could be trapped at a ring baffle. This was accomplished using a series of 12 boxes attached to a ring in the tank.

MAJOR RESULTS. -

1. Greater mixer flow was required to mix with side mount than with bottom mount. In the 41.5 inch tank, 20 to 30% of the liquid must be circulated for bottom mounting and 80 to 90% for side mounting. In fact in the 110-in. tank side mount, at the low flow, no pressure control could be accomplished, with and without the crossover duct. Using similarity relationships and experimental data, mixing time was found to be inversely related to the jet momentum, and is predicted to be directly proportional to acceleration (Equ. 2, Table 1).

2. Depressurization rates from mixing alone are significantly reduced when helium is present (Figure 1). However, following complete mixing, helium appears to have no effect on the vent down rate.

3. A theory previously developed (Sterbentz, Aug. 1968) for condensation at a moving liquid-vapor interface appears to have included the proper variables and parameter groupings (Equ. 3, Table 1).

COMMENTS. - The final form of the mixing time equation (Equ. 2, Table 1) appears to be more empirical than analytical and correlation with test data using other fluids and other tank shapes would be required to develop confidence in its use. Even though performance evaluation of a zero-g vent system was the objective, only 1-g testing was accomplished.
Table 1. Pertinent Equations

\[
\begin{align*}
\frac{dP}{ds} &= 1.23 \left[ \rho_0 - (M_0 \lambda - 3.41P) \right] \\
&= \frac{1}{\rho_L \mu} \frac{1}{V_T} \left( 1 - \frac{V_u}{V_T} \right) \\
&= \frac{1}{\rho_L \mu} \frac{1}{V_T} \left( 1 - \frac{V_u}{V_T} \right)
\end{align*}
\]

(1)

Good for \( \rho_0 \) only (basic report contains derivation which could be applied to other fluids).

\[
Q_m = \frac{(A/N_u)^{0.5}}{V_n} = 0.52 + (1/4)^2
\]

(2)

\[
N_L = C_1 \left( \frac{\text{Re Pr} \mu}{N} \right)^{0.5}
\]

(3)

where

- \( P \) = pump power, watts
- \( M_0 \) = vent flow rate, lb/hr
- \( \lambda \) = latent heat of vaporization
- \( Q_0 \) = external heating, Btu/hr
- \( \rho_L \) = liquid density, lb/ft³
- \( L \) = length of condensing surface
- \( dP/ds \) = differential pressure change per unit time, psi/hr
- \( V_u \) = ullage volume, ft³
- \( V_T \) = total tank volume, ft³
- \( t_m \) = mixing time, sec
- \( A_0 \) = liquid vapor interface area, ft²
- \( A_1 \) = area of jet exit, ft²
- \( \dot{V}_1 \) = liquid velocity at jet exit, ft/sec

The factor of 1.23 in Eq (1) is determined by fitting experimental data to theoretical predictions.

**Figure 1. Comparative Effect of Pressurant on Tank Pressure Response at 70 Percent Ullage - 41.5 in. (1.05 cm) Tank**

**Table 2. Test Conditions**

<table>
<thead>
<tr>
<th>General</th>
<th>Mixer Flowrates - 2.5, 3.5 and 5.5 CFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent Flowrates - 0, 1.5, and 2.5 LB/HR</td>
<td></td>
</tr>
<tr>
<td>Ullage Volumes - 5, 25, 70 and 95%</td>
<td></td>
</tr>
<tr>
<td>41.5-in. Tank</td>
<td></td>
</tr>
</tbody>
</table>
| Vent System Location/Mixer Orientation -
(1) On Tank Bottom with Mixing Jet Directed at L/V Interface |
(2) On Side of Tank with Jet Directed Across Tank at the Centerline. |
| External Heating - 124 to 170 Btu/hr |
| 110-in. Tank |
| Vent System Location/Mixer Orientation -
(1) and (2) same as for 41.5-in Tank |
(3) Side Mounted with a Duct to Distribute the Jet to the Other Side of the Tank |
(4) Same as (3) except Radial Inlet Nozzle Added to insure Taking Fluid from Along Tank Wall |
| External Heating - 185 to 218 Btu/hr |
OBJECTIVE. - Definition of a representative in-space propellant logistics system and its operation.

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

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

MAJOR RESULTS. -

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

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

COMMENTS. - Chen and Zukoski, 1968, was not obtained in time to be included in the literature review.
Figure 1. Connected Ullage

Nomenclature

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

Figure 2. Residual Versus Froude Number for Various Tank Geometries
RESEARCH AT STANFORD ON THE CONTAINMENT OF LIQUID
HELUM IN SPACE BY A POROUS PLUG AND ON A LONG
HOLD-TIME DEWAR FOR THE GYRO RELATIVITY EXPERIMENT
NASA-MSFC, March 1972

OBJECTIVE. - To develop a porous plug for zero-g venting of superfluid liquid helium.

PERTINENT WORK PERFORMED. - A porous plug was formed from a tightly wound
roll of 0.5 mil aluminum foil, the mean spacing between layers being about 10,000
angstroms. The plug was sealed between the helium chamber and an exhaust line
leading to vapor-cooled shields (Figure 1). Under a pressure difference, superfluid
helium (below 2.17K) flows through the pores of the plug and evaporates, causing
refrigeration which cools the dewar by means of the high thermal conductivity of the
plug. During test, stable operation was achieved with the dewar in both upright and
inverted positions, without appreciable variation in boiloff rate. Figure 2 shows
predicted and observed operating curves for the system in the upright position, the
temperature being varied by an auxiliary heater. The unstable regime was found to
set in at 1.8K rather than around 2.1K as expected. This was most likely due to an
inaccurate estimation of critical velocity which arose from assuming a uniform spacing
between layers.

MAJOR RESULTS. -

1. A unique, porous plug device was developed and successfully demonstrated, which
separates helium gas and liquid phases under zero-g conditions.
HELUM GAS FROM SUPERFLUID PLUG

BYPASS LINE

FILL LINE

CRYOGENIC VALVES

HELIUM CONTAINER (4" DIAM)

GAS COOLED ALUMINUM HEAT SHIELDS

SUPERFLUID PLUG

COTTON WICK

Figure 1. Cross-Section of Invertible Dewar

-3

OBSERVED, PREDICTED (APPROXIMATELY)

STABLE FLUID OPERATION

MASS FLOW RATE THROUGH ALUMINUM FOIL PLUG AS FUNCTION OF BATH TEMPERATURE

Figure 2. Flow Data for the Porous Plug
OBJECTIVE. - To perform thermodynamic simulation tests and to update an existing analytical model for conducting preliminary design analyses of space vent-free cryogenic storage systems.

PERTINENT WORK PERFORMED. - A previous contract (Murphy and Rose, 1968) investigated techniques for utilizing vented hydrogen to cool and maintain a no-vent condition in a fluorine tank during long duration space missions. To verify the analytical model a liquid hydrogen and liquid nitrogen (simulating liquid fluorine) test article, shown schematically in Figure 1, was produced. A vent heat exchanger system representative of an airborne design consisted of 13 ft of copper tubing inside the 4-ft diameter, spherical LH$_2$ tank, 50 feet silver brazed to the outside of the stainless steel LH$_2$ tank, and 50 ft brazed to the 3-ft diameter LN$_2$ tank. Both tanks were blanketed with one inch of aluminized Mylar/nylon net multilayer insulation.

The test program was designed to generate similar thermodynamic processes at conditions that were as close as possible to those expected on an actual flight system. The most significant test was a 34-hour run which demonstrated the feasibility of the vent heat exchanger system. During two periods of operation at a venting rate of 0.4 lbs/hour, the hydrogen tank pressure fell at the rate of 8 and 4 psi per hour, respectively, and the nitrogen pressure dropped at the rate of 2.5 and 1.7 psi per hour, respectively. The test demonstrated that for representative venting rates a significant decrease in hydrogen and nitrogen pressures can be obtained.

MAJOR RESULTS. -

1. The vent-free cryogenic storage system was shown to be feasible.

2. The potential for using a wall exchanger vent system to control H$_2$ tank pressure was demonstrated.

COMMENTS. - The major problem with demonstrating low-g performance of a wall exchanger system at 1-g is the differences in heat transfer coefficients and the fact that the liquid and vapor are in fixed locations at 1-g. These problems were not addressed by the work presented here.
Figure 1. Propellant System Schematic
ANALYSIS OF ZERO GRAVITY RECEIVER TANK VENT SYSTEMS

OBJECTIVE. - To define and design an optimum vent system for use in an orbital propellant transfer receiver tank at low gravity.

PERTINENT WORK PERFORMED. - Comparisons were made of bulk heat exchanger, surface tension, mechanical separator, wall-mounted heat exchanger, and mechanical separator/wall-mounted heat exchanger combination systems for venting a 0.99 m³ (35.2 ft³) aluminum receiver tank. Weight, reliability, and cost data was generated. Weight data was generated for hydrogen qualities from 0.1 to 0.9 during chilldown, and for ten transfers including nine chilldowns, from 190.9K (325 R) and one from 250K (450R), Figure 1. Data was also generated for a single transfer (Figure 2). The wall heat exchanger was analyzed in more detail to determine thermal performance during chilldown. A review of film and transition boiling heat transfer data was made (Figure 3) to obtain the most accurate data for a computer program used to calculate temperatures during chilldown. Three basic configurations were analyzed for a cylindrical hemispherically ended tank; exchanger coils closely spaced on the tank cylinder, evenly distributed over the cylinder and distributed over the upper dome and cylinder. In addition to receiver venting studies, a bulk heat exchanger vent system was designed for supplying vapor to a partial reliquefaction system under development by MSFC.

MAJOR RESULTS. -

1. The mechanical separator has the best potential for achieving receiver tank venting where qualities above 0.1 are present at the vent. At the end of fill, when the quality may be below 0.1, the tank should be locked up and the pressure allowed to rise with subsequent ventdown through the low-flow orbital heat exchanger system. Design of a mechanical separator proceeded to receipt of vendor quotes.

2. For a wall exchanger, distribution over both the dome and cylindrical sections is required; tank surface area in contact with the vent gas should be at least 50%. For the single chilldown, added weight of a wall exchanger was only slightly less than the savings in vented propellant (Figure 1). For the multiple-transfer case, the net weight savings was significantly greater (Figure 2).

3. Bulk heat exchanger integration with the reliquefaction system resulted in a bulk exchanger weight of 5.66 kg (12.5 lb.) with a regulated inlet pressure to the exchanger of 163,000 ±8,950 N/M² (23.7 ± 1.3 psia) for a vent flow rate of 4,900 kg/sec. (3.0 lb/hr).

COMMENTS - It is noted that the receiver data was based on relatively high flow rates [0.75 kg/sec. (10 lb./min.)] without consideration of inlet flow baffling.
<table>
<thead>
<tr>
<th>Figure 1. Comparative system data — vent inlet quality 0.1.</th>
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<tr>
<td><strong>Total Hardware Weight, lb</strong></td>
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<tr>
<td>148.2</td>
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<tr>
<td>Total Childdown Loss, lb</td>
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<td>Total Fill Loss, lb</td>
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<td>Total Chill Plus Fill Losses, lb</td>
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<tr>
<td>Total Weight, lb</td>
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<tr>
<td>Relative Reliability, Failures x 10^-6</td>
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<td>Relative Cost; Lowest Cost</td>
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<td>Tank Volume Displaced, ft^3</td>
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<th>Figure 2. Comparative system data — vent inlet quality 0.1, single transfer.</th>
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<td>Childdown Loss, lb</td>
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<td>Fill Loss, lb</td>
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<td>Chill Plus Fill, lb</td>
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<tr>
<td>Total Weight, lb</td>
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<table>
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<tr>
<th>Figure 3. Film boiling heat transfer coefficients.</th>
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<tbody>
<tr>
<td>1. LEONHARD, 1966</td>
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<td>2. CHENOWETH, 1967</td>
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<td>3. GIARRATANO, 1965</td>
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<td>4. BREEN, 1962</td>
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<td>5. GIARRATANO, 1965</td>
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<td>6. BRENTARI, 1965 AND BRENTARI, 1964</td>
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<table>
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<tr>
<th>$h_f$ (Btu/hr-ft²-F)</th>
<th>$T_w - T_e (^{\circ}F)$</th>
<th>$T_w - T_e (^{\circ}F)$</th>
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</table>

7-11
ZERO-GRAVITY TEST OF AN ADVANCED SURFACE-TENSION PROPELLANT ORIENTATION AND ULLAGE VAPOR VENTING DEVICE

OBJECTIVE. - To determine the functional capabilities of a representative liquid propellant surface tension orientation and vapor venting system.

PERTINENT WORK PERFORMED. - The system configuration tested resulted from analysis, 1-g tests and trade-offs conducted under Contract AF 04(611)-9901 (Boraas, et al, 1965). This device (Figure 1) uses a plain "pie pan" screen (1), as the containment device. A vent region is between the contoured baffle (2) and the inner wall of the tank. When direct venting takes place, such as when gas is located at (a), it is via the screened holes at (3), the circumferential openings in the baffle (4), and the screened openings (5). The screens at (3) are designed to prevent liquid from entering the contoured passage during non-vent conditions. When gas is not at (a) while venting, liquid at (5) will be drawn into the contoured passage. This passage is designed to prevent liquid from reaching the screens at (5), however, should this occur accidentally, the screens at (5) are of high solidity to keep liquid out of the small chamber (6) under all conditions. This chamber (6) then serves as a source of liquid-free gas. The standpipe (7) is designed to increase the amount of time that direct gas venting is possible. The plate (8) functions as a capillary to retain some liquid above (1) to insure good liquid-to-liquid contact across the containment screen (1). The containment and vent screens are 200 x 200 mesh. Testing was accomplished using a KC-135 aircraft operating at low-g (free floating capsule) for periods of 3 to 15 sec. The test tank was a 12-in. diameter transparent sphere. The test fluid was a solution of water and isopropyl alcohol. A total of 120 maneuvers were accomplished, however, they all did not provide acceptable zero-g time. Fluid behavior, fluid expulsion and vapor venting tests were conducted at fill levels of 80, 50, 30 and 10%.

MAJOR RESULTS. -

1. The use of surface-tension screens for liquid orientation was successfully demonstrated.

2. Liquid free venting was accomplished, indicating that capillary traps can be utilized to increase the effectiveness of the vent. However, for these tests the vent rate and volume of gas to reduce tank pressure was extremely low and since there is no means of insuring that the underside of the vent baffle will not be covered with liquid successful operation is very mission dependent. Also there is no way of guaranteeing that the vent baffle screen will remain wetted throughout a mission and there is the possibility of forcing some liquid through the vent on every vent cycle. Therefore, without total liquid orientation, efficient venting is based only on probability.
Figure 1. Test Model Configuration E
OBJECTIVE. - To develop and demonstrate the effectiveness of a liquid propellant thermal conditioning type low-g vent system to control cryogenic $\text{H}_2$ tank pressure.

PERTINENT WORK PERFORMED. - The subject vent system operates by throttling the vent fluid to a low pressure and temperature to exchange heat with the bulk tank fluid to vaporize any liquid present at the vent inlet. Such a system can thus vent vapor even though the inlet is 100% liquid. Initially, parametric weight and performance data were generated for the individual system components; fluid removal unit (liquid only, liquid-or-vapor), expansion valve, heat exchanger (compact and wall types), mixer (electric drive, AC and DC and turbine drive), and pressure switch. Comparisons were made and optimum systems defined for the $\text{H}_2$ tanks on three different vehicles; (1) Earth/Lunar logistics, 134 days coast, (2) Earth/Mars Kickstage, 220 days, and (3) Earth/Mars manned, 220 days. Details of this work are presented in an interim report (Sterbentz, et al, 1967). The resulting system is illustrated in Figure 1. For the vent system to properly control tank pressure, any bulk liquid cooled within the exchanger must be thermally mixed with the ullage vapor. Fluid mixing 1-g testing was accomplished using a two-dimensional flow setup (closely spaced horizontal transparent plates in the form of a circle). A full-scale vent system design was generated for the vehicle (2) requirements, hardware fabricated and 1-g testing accomplished. A brushless DC motor was recommended for the pump drive, but since none were available for $\text{H}_2$ service, an AC motor was used in the test. Pertinent system design characteristics are presented in Table 1. The major testing was accomplished in a 110-in.-dia. oblate spheroid tank with the vent package at two different locations; (1) suspended 15 in. from the top (mixer flow directed down), and (2) at the tank side (mixer flow across tank centerline). Testing was accomplished with the top mount at $\text{H}_2$ ullage volumes of 5 and 50% and at 5, 27, 50, and 75% ullage with the side mount. The package was instrumented with temperature and pressure probes but bulk fluid stratification was not determined.

MAJOR RESULTS. -

1. The vent system as designed and built controlled tank pressure efficiently in a 110-in.-dia. $\text{H}_2$ tank whether immersed in gas or liquid, and there was no discernible difference in performance whether the mixing flow was in the same direction or perpendicular to the gravity vector. Typical pressure control is illustrated in Figure 2.

2. From the two-dimensional testing, the critical Weber number for a jet ($\sigma U^2 D_j / \rho$) to circulate liquid around a spherical tank = $4(1 + 0.16 \, H/D_j)$ where $H$ is distance from the jet nozzle to the opposite tank wall.
Table 1. Pertinent System Operating Parameters

External Heating = 11.5 Btu/hr nominal
Vent Cycle = On-off with vent flow of 1.4 lb/hr.
Inlet Pressure Range = 17 to 28 psia with nominal control to 18 ± 1.2 psia.
System Weight = 15 lb
Exchanger Vent Pressure = 4 ± 0.4 psia
Mixer Design Exit Velocity = 5 ft/sec

Figure 1. Selected Liquid Propellant Thermal Conditioning System Schematic

Figure 2. "110-in. dia. Tank, Unit-Side Mounted, Submerged in Liquid"
OBJECTIVE. - To design and fabricate operational subcritical cryogenic storage systems for ground test (Phase I), and to evaluate the performance of follow-on subcritical hardware in earth orbit (Phase II).

PERTINENT WORK PERFORMED. - Operational concepts for the storage of subcritical cryogenic fluids and the delivery of single-phase (vapor) were developed. During Phase I two subcritical systems were fabricated by AIResearch and tested which employed regenerative heat exchangers for pressure control and electrical heaters for rapid depletion. A capacitance gage matrix was installed in the tanks for fluid quantity measurements. Thermodynamic and vibration tests of the Phase I devices indicated that the concept warranted verification in a low gravity environment.

The Phase II subcritical storage and supply system (Figure 1) was a self-contained package having all components necessary to store liquid nitrogen for extended periods and deliver the vapor phase under the environmental conditions of orbital flight. The tank was a spherical dewar on the order of 25 inches inside diameter. Two systems were fabricated, one for orbital evaluation and the other for qualification testing and flight system backup. An electrical heater was used to replace the regenerative heat exchangers to minimize system complexity. The system was flown aboard Apollo Mission AS-203 in July 1966. It exhibited good pressure control and stability, and the heat exchanger outlet temperature and the delivery temperatures were significantly above saturation. The capacitance gage successfully monitored the quantity of fluid in the tank throughout the test.

MAJOR RESULTS. -

1. A flightweight, subcritical cryogenic storage system was designed, fabricated and successfully tested in earth orbit.

2. This was the first successful orbital test of a three-dimensional wire matrix mass gaging device.

3. Single-phase vapor was consistently delivered by the system throughout the test.
**Design parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure range</td>
<td>130 - 170 psia</td>
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<tr>
<td>Delivery pressure</td>
<td>60 ± 5 psia</td>
</tr>
<tr>
<td>Relief pressure</td>
<td>220 ± 20 psia</td>
</tr>
<tr>
<td>Proof pressure</td>
<td>360 psia minimum</td>
</tr>
<tr>
<td>Burst pressure</td>
<td>480 psia minimum</td>
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<tr>
<td>Maximum filled weight</td>
<td>275 lb</td>
</tr>
<tr>
<td>Liquid nitrogen capacity</td>
<td>128 lb</td>
</tr>
<tr>
<td>Standby time, nonvented, at 160°F</td>
<td>30 hr</td>
</tr>
<tr>
<td>Ambient temperature range</td>
<td>-65 to +160°F</td>
</tr>
<tr>
<td>Delivery rate</td>
<td>1.25 ± 0.13 lb/hr</td>
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<tr>
<td>Total electrical power available, prelaunch</td>
<td>28 V dc, 400W</td>
</tr>
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<td>Total electrical power available, postlaunch</td>
<td>28 V dc, 174W</td>
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<td>Maximum filled weight</td>
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<td>Liquid nitrogen capacity</td>
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<td>Total electrical power available, prelaunch</td>
<td>28 V dc, 400W</td>
</tr>
<tr>
<td>Total electrical power available, postlaunch</td>
<td>28 V dc, 174W</td>
</tr>
<tr>
<td>Maximum filled weight</td>
<td>275 lb</td>
</tr>
<tr>
<td>Liquid nitrogen capacity</td>
<td>128 lb</td>
</tr>
<tr>
<td>Standby time, nonvented, at 160°F</td>
<td>30 hr</td>
</tr>
<tr>
<td>Ambient temperature range</td>
<td>-65 to +160°F</td>
</tr>
<tr>
<td>Delivery rate</td>
<td>1.25 ± 0.13 lb/hr</td>
</tr>
<tr>
<td>Total electrical power available, prelaunch</td>
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</tr>
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</tr>
<tr>
<td>Delivery rate</td>
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<tr>
<td>Total electrical power available, prelaunch</td>
<td>28 V dc, 400W</td>
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<tr>
<td>Maximum filled weight</td>
<td>275 lb</td>
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<tr>
<td>Liquid nitrogen capacity</td>
<td>128 lb</td>
</tr>
<tr>
<td>Standby time, nonvented, at 160°F</td>
<td>30 hr</td>
</tr>
</tbody>
</table>
OBJECTIVE. - To define, design, fabricate and test a prototype heat exchanger vent system capable of controlling tank pressure while discharging only \( \text{GH}_2 \), even though the system and/or its inlet is in 100\% \( \text{LH}_2 \) as may be encountered in space at low-g.

PERTINENT WORK PERFORMED. - In the system definition phase, trade-offs were made to determine the type of heat exchange (bulk vs wall), type of pump drive (electric vs turbine), optimum vent flow rate, vent cycle, and fluid mixing criteria. Basic design requirements were to control tank pressure to \( 17 \pm 1 \) psia with external heating of 20-30 Btu/hr over 14 days. The resulting system is shown schematically, as setup for test, in Figure 1. Operation is by throttling the vent inlet to a low pressure and temperature and flowing through the heat exchanger to vaporize any liquid which may be present. Operation is intermittent to minimize total pump power input to the tank. The pump provides forced convection exchanger flow as well as liquid temperature destratification. Deactuation and actuation of vent and pump are controlled by a pressure-switch. Testing was at 1-g with hydrogen in a 40-in. dia. by 84-in. long superinsulated CRES tank. The system was located 22 in. from the tank bottom and tests performed with the mixing flow (exchanger warm side outlet) directed (1) radially (2) downward and (3) upward. In each case testing was performed with the unit in vapor (13 in. \( \text{LH}_2 \) level) and liquid (49 in. and 70 in. levels). The 3-way valve (Fig. 1) provided either liquid or vapor inlet at all tank liquid levels. Both steady state and transient performance of the system was determined. In addition to the Figure 1 instrumentation, temperatures were measured throughout the tank fluid with platinum resistance sensors.

MAJOR RESULTS. -

1. Feasibility and efficiency of the concept was demonstrated. No liquid was vented under all design operating conditions. A typical tank pressure trace is presented in Figure 2.

2. Tank fluid mixing and liquid/ullage coupling were found to be important for efficient pressure control. Operation with the system in liquid and the mixing flow directed down was inefficient and in fact, at a \( \text{LH}_2 \) level of 70-in., tank pressure was not controlled (Figure 3). Flow directed at the L/V interface was best for mixing with radial flow next.

3. An apparent freezing of \( \text{LH}_2 \) in the throttle valve during one of the tests was solved by locating the shutoff valve downstream of the heat exchanger and external to the tank.
Table 1. Pertinent Vent System Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Cycle</td>
<td>Intermittent (on 1/30th of total)</td>
</tr>
<tr>
<td>Vent Flow</td>
<td>3 lb/hr</td>
</tr>
<tr>
<td>Pump Power</td>
<td>7 watts</td>
</tr>
<tr>
<td>Throttling Pressure</td>
<td>5 psia</td>
</tr>
<tr>
<td>Test System Wt.</td>
<td>11 lb. Est.</td>
</tr>
<tr>
<td>Flight Wt.</td>
<td>8.2 lb</td>
</tr>
<tr>
<td>Pressure Switch</td>
<td>17 ± 1 psia with 0.5 psd max deadband</td>
</tr>
</tbody>
</table>

Figure 1. Basic Vent System Test Schematic

Figure 2. Tank Pressure (Second Test Series, 9.6 to 11.0 Hours)

Figure 3. Tank Pressure (Third Test Series, 21.5 to 22.5 Hours)

LEGEND

AL - System Actuates with Liquid Inlet
LG - Cycled Inlet from Liquid to Gas
GL - Cycled Inlet from Gas to Liquid
AG - System Actuates with Gas Inlet
STUDY OF ZERO-GRAVITY, VAPOR/LIQUID SEPARATION

OBJECTIVE. - To define the best method(s) of separating vapor from liquid in order to permit vapor-only venting of cryogenic propellant tanks operating at low-g.

PERTINENT WORK PERFORMED. - Analyses were accomplished and preliminary designs were developed on four primary methods of liquid/vapor separation; (1) heat exchange where the vent fluid is throttled to a low pressure and temperature and allowed to exchange heat with the tank fluid to vaporize any liquid initially present in the vent, (2) mechanical—employing a rotating element for centrifugal separation, (3) dielectrophoresis—utilizing an electric field to separate liquid from vapor (both total liquid control and local separator devices were considered), and (4) surface tension—utilizing fluid surface forces to orient the liquid in a tank with baffles or screens, or to effect local separation at the vent. Other methods including vent fluid rotation or vortexing, "hydrogen sublimation", and magnetic positioning were considered, but not studied in detail or included in the predesign comparisons.

Predesigns including weights, power, reliability and pertinent operating characteristics were generated for the four basic systems above for three vehicle/mission cases; (1) S-IVB stage with continuous venting during a 4-1/2 hour coast with retention of the existing settling provisions, (2) S-IVB stage without constraints and (3) a cryogenic service module (CSM) with a multiple restart, 205 hr mission. Existing work was reviewed and existing data used where available. Otherwise new data were generated. In the S-IVB work only the hydrogen tank was considered, while for the CSM both \( \text{H}_2 \) and \( \text{O}_2 \) tanks were considered, though emphasis was on the hydrogen application.

MAJOR RESULTS. -

1. It was concluded that the heat exchange system is the most promising for the three vehicle/mission cases considered (Tables 1 and 2). The mechanical separator was a close second on most of the selection criteria except performance in 100% liquid. The dielectrophoretic and surface tension systems were consistently poorer on all of the selection criteria.

2. Total liquid control by surface tension or dielectrophoresis was not competitive for the venting application alone, due to the high weights involved.

3. Following selection of the heat exchange system as the most promising a significant amount of parametric and detailed design data were generated over a wide range of \( \text{H}_2 \) operating conditions. Coupling of the exchanger vent with a reliquefaction system was also briefly considered.
### Table 1. Comparison of Zero-g, Vapor/Liquid Hydrogen Separation Systems for Cases I and II (S-IVB)

<table>
<thead>
<tr>
<th>CRITERION</th>
<th>RELATIVE RATING (Lowest Rating is Best)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEAT EXCHANGE SYSTEM</td>
</tr>
<tr>
<td>System hardware weight (as equivalent pounds payload decrease)</td>
<td>78</td>
</tr>
<tr>
<td>Change in weight of vented propellant (as equivalent pounds payload decrease)</td>
<td>-11</td>
</tr>
<tr>
<td>Relative system components failure rate (10^-6 failures per mission)</td>
<td>307</td>
</tr>
<tr>
<td>Current feasibility of successful system operation (on 1 to 3 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
<tr>
<td>Availability of design data (on 1 to 2 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
<tr>
<td>Performance of system in 100-percent liquid (on 1 to 4 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
<tr>
<td>&quot;Complexibility&quot; - measure of complexity of device and difficulty of development to successful operational status (on 1 to 2 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2. Comparison of Zero-g, Vapor/Liquid Hydrogen Separation Systems for Case III (CSM)

<table>
<thead>
<tr>
<th>CRITERION</th>
<th>RELATIVE RATING (Lowest Rating is Best)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEAT EXCHANGE SYSTEM</td>
</tr>
<tr>
<td>System hardware weight (as equivalent pounds payload decrease)</td>
<td>13</td>
</tr>
<tr>
<td>Change in weight of vented propellant (as equivalent pounds payload decrease)</td>
<td>2</td>
</tr>
<tr>
<td>Relative system components failure rate (10^-4 failures per mission)</td>
<td>164</td>
</tr>
<tr>
<td>Current feasibility of successful system operation (on 1 to 3 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
<tr>
<td>Availability of design data (on 1 to 2 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
<tr>
<td>Performance of system in 100% liquid (on 1 to 4 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
<tr>
<td>&quot;Complexibility&quot; - measure of complexity of device and difficulty of development to successful operational status (on 1 to 2 scale - not relative magnitudes)</td>
<td>1</td>
</tr>
</tbody>
</table>
8.0 FLUID MIXING

Covering analysis, design fabrication and test of systems to destroy fluid temperature stratification and/or minimize tank pressure rise by fluid mixing.
HEATER-MIXER FOR STORED FLUIDS

OBJECTIVE. - Devise a system for improved mixing of stored fluids.

PERTINENT WORK PERFORMED. - The system shown in Figure 1 was conceived. As shown in Figure 1, an auxiliary chamber is immersed in the fluid stored in a larger fluid storage vessel. A heating element is wound on the wall of the auxiliary chamber. The auxiliary chamber is connected in fluid communication with the main storage vessel by means of a jet nozzle. The wall of the auxiliary chamber is heat cycled to produce a corresponding expansion and contraction of the fluid within the auxiliary chamber to produce heating and mixing of the stored fluid by means of jetting the expanded fluid to and fro relative to the stored fluid contents of the vessel.

Figure 1. Thermal Fluid Mixing System
OBJECTIVE. - To thoroughly evaluate performance of the zero-g hydrogen tank vent system previously developed under Contract NAS3-7942 (Sterbentz, August 1968).

PERTINENT WORK PERFORMED. - Both analysis and 1-g testing were accomplished:
1. Full scale testing in H₂ in two different size tanks (41.5 inch sphere and 100 inch $\sqrt{2}$ - oblate spheroid),
2. Development of analytical models to correlate the test data,
3. Small scale testing with methane, Freon, LN₂ and LH₂ and associated analysis of condensation at a moving liquid/vapor interface, and
4. Definition of flight testing to verify system performance.

Fluid mixing was evaluated by the time to reduce tank pressure to equilibrium, with and without venting, following pressurization with H₂ gas or with helium, each at 140°F and 530°F. Pressure was increased from 17 to 28 psia or 17 to 36 psia prior to mixing. Ability to maintain mixed fluid conditions was evaluated by comparing pressure change rates at equilibrium with those calculated from Equ. 1, Table 1. In addition to tank size, tank pressure and pressurant, the parameters in Table 2 were varied. A total of 732 tests were accomplished in 1500 hours of testing.

Test plans for the 110 inch tank included television coverage of fluid circulation, but the camera did not work, with reasons not given. Testing was also accomplished in the 110 inch tank for configurations (3) and (4), Table 2, to simulate the effect of vapor which could be trapped at a ring baffle. This was accomplished using a series of 12 boxes attached to a ring in the tank.

MAJOR RESULTS.

1. Greater mixer flow was required to mix with side mount than with bottom mount.
   - In the 41.5 inch tank, 20 to 30% of the liquid must be circulated for bottom mounting and 80 to 90% for side mounting. In fact in the 110-in. tank side mount, at the low flow, no pressure control could be accomplished, with and without the crossover duct. Using similarity relationships and experimental data, mixing time was found to be inversely related to the jet momentum, and is predicted to be directly proportional to acceleration (Equ. 2, Table 1).

2. Depressurization rates from mixing alone are significantly reduced when helium is present (Figure 1). However, following complete mixing, helium appears to have no effect on the vent down rate.

3. A theory previously developed (Sterbentz, Aug. 1968) for condensation at a moving liquid-vapor interface appears to have included the proper variables and parameter groupings (Equ. 3, Table 1).

COMMENTS. - The final form of the mixing time equation (Equ. 2, Table 1) appears to be more empirical than analytical and correlation with test data using other fluids and other tank shapes would be required to develop confidence in its use. Even though performance evaluation of a zero-g vent system was the objective, only 1-g testing was accomplished.
Table 1. Pertinent Equations

\[
\begin{align*}
\frac{dP}{dz} &= \frac{1.98 \left[ \frac{C_v}{\rho} - (\rho_d \lambda - 3.61) \right]}{ho_L V_T \left( \frac{1}{V_U} - \frac{1}{V_U^T} \right)} \\
&= \frac{1}{0.36 \left( \frac{V_U}{V_U^T} \right)} \\
&= \frac{1}{1 + \frac{\rho}{\rho_L} \left( \frac{V_U}{V_U^T} \right)} \\
&= \frac{1}{1 + \frac{\rho}{\rho_L} \left( \frac{V_U}{V_U^T} \right)} \\
&= \frac{1}{1 + \frac{\rho}{\rho_L} \left( \frac{V_U}{V_U^T} \right)}
\end{align*}
\]

*Note for \( \rho_4 \) only (Basic report contains derivation which could be applied to other fluids).

\[
\begin{align*}
\left( \frac{A_U}{A_U^T} \right)^{\frac{1}{2}} &= \frac{1}{52^2} \left( \frac{1}{A_U^T} \right)^{\frac{1}{2}} \\
&= \frac{1}{52^2} \left( \frac{1}{A_U^T} \right)^{\frac{1}{2}} \\
&= \frac{1}{52^2} \left( \frac{1}{A_U^T} \right)^{\frac{1}{2}}
\end{align*}
\]

\[
\begin{align*}
\text{Nu} &= C_4 \left( \Re \Pr \text{Nu}_4 \right)^{\frac{1}{2}} \\
&= C_4 \left( \Re \Pr \text{Nu}_4 \right)^{\frac{1}{2}} \\
&= C_4 \left( \Re \Pr \text{Nu}_4 \right)^{\frac{1}{2}}
\end{align*}
\]

where:

- \( \rho \) = pump power, watts
- \( d \) = fluid density, lb/ft³
- \( V \) = Vent flow rate, lb/hr
- \( V_T \) = total tank volume, ft³
- \( t_m \) = mixing time, sec
- \( \text{Nu} \) = Nusselt No. = \( \frac{h_m L}{k_L} \)
- \( \text{Nu}_4 \) = condensation heat transfer coefficient
- \( \Delta \) = differential pressure change per unit time, psi/hr
- \( \Delta T \) = temperature difference between liquid and vapor
- \( \text{Nu}_4 \) = zero-gravity condensation No. = \( \frac{L}{(C_L L/2)} \)
- \( \Lambda \) = liquid vapor interface area, ft²
- \( \alpha \) = area of jet exit, ft²
- \( \beta \) = liquid velocity at jet exit, ft/sec
- \( \sigma \) = liquid velocity at interface
- \( \lambda \) = latent heat of vaporization
- \( \rho \) = density of vapor, lb/ft³
- \( \phi \) = constant derived from theory equal to 1.12 (Ref. Sterbentz 1968)
- \( \gamma \) = constant of fluid
- \( \rho_d \) = density of dispersed phase
- \( \lambda_d \) = thermal conductivity of dispersed phase
- \( \alpha_d \) = thermal diffusivity of dispersed phase
- \( \sigma_d \) = surface tension of dispersed phase

Table 2. Test Conditions

| Mixer Flowrates | 2.8, 3.8 and 5.5 CFM |
| Vent Flowrates | 0, 1.5, and 2.5 LB/HR |
| Ullage Volumes | 5, 25, 70 and 85% |

61.5-in. Tank

Vessel System Location/Mixer Orientation

1. On Tank Bottom with Mixing Jet Directed at L/V Interface
2. On Side of Tank with Jet Directed Across Tank at the Centerline.

External Heating - 124 to 170 Btu/hr.

110-in. Tank

Vessel System Location/Mixer Orientation

1. Same as for 61.5-in Tank
2. Same as (1) except Radial Inlet Nozzle Added to Insure Tank Entry from Along Tank Wall
3. External Heating - 185 to 218 Btu/hr.

Figure 1. Comparative Effect of Pressurant on Tank Pressure Response at 70 Percent Ullage - 41.5 in. (1.05 cm) Tank
OBJECTIVE. - Verify the validity of utilizing small-scale-tank mixing parameters in the design of full-scale-tank mixers and apply previously developed mixing techniques (Poth, et al, 1968) to the design of $\text{LO}_2$ mixer systems.

PERTINENT WORK PERFORMED. - Mixing tests were conducted in a 10-ft-dia. by 20-ft-high tank using non-pressurized water as the test fluid. Jet mixing was employed where liquid was taken from the bottom of the tank and introduced back into the tank: bottom as an axial jet directed at the liquid/vapor interface. The tank had a flat bottom and open top. The data obtained consisted of temperature histories and observed jet motion. Comparisons were made with the data from small scale tests with water in 1-ft-dia by 2-ft-high closed (hemispherical top) tanks with concave and convex bottoms (Poth, et al, 1968).

Hot water was used to induce stratification layers from 0.5 to 19.5-ft-thick. Jet diameters were 0.875 and 0.625-in., as scaled up from the small-tank tests. Flow rates were varied from 11.7 to 136.5 gpm. Data from 52 test runs are reported. Correlations were made for three basic parameters; (1) time for jet to move from nozzle exit to liquid surface, $\theta_j$, (2) effects of buoyancy on mixing time, and (3) time, after mixing begins, to reach a specified percent of the completely mixed condition.

MAJOR RESULTS. -

1. Both small and large scale data for jet transit time correlated well with the equation; $\left( \frac{V_0}{D_0/2} \right) \theta_j = 0.152 \left( \frac{Z_b}{D_0/2} \right)^2$. Nomenclature are defined in Table 1.

2. Data on the effects of buoyancy on mixing time agreed with that of the small scale tests (Figure 1) and it is concluded that buoyancy effects can be neglected when predicting low-g mixing times.

3. In the large-scale tests, stratification thickness was found to be an important variable affecting mixing time and a different correlation was necessary to produce a good data grouping (Figure 2).
Figure 1. Effect of Buoyancy on Mixing; Large and Small Scale Water Tests

\[ V_0 = \text{nozzle exit velocity} \]
\[ D_0 = \text{nozzle exit diameter} \]
\[ D_t = \text{tank diameter} \]
\[ b = \text{constant, 0.25} \]
\[ N_{i*} = \left[ a \beta (T_s - T_b)/l \right] z_b^3/(V_0 D_0)^2 \]
\[ I_{m_i} = 1 - \left[ (T_s - T_m)/l \right] / (T_s - T_b) \]
\[ \theta = \text{time to mix after pump turned on} \]
\[ \theta_j = \text{jet transit time} \]
\[ \theta_1 = \text{time after mixing begins} \]
\[ T_s = \text{liquid surface temperature} \]
\[ T_b = \text{bulk temperature} \]
\[ T_m = \text{mean fluid temperature} \]
\[ z_b = \text{distance from nozzle to liquid surface} \]

Subscript:
\( i = \text{initial} \)

Table 1. Nomenclature

Figure 2. Correlation of the Dimensionless Time Required for Temperature Stratification or Ullage Pressure to Reach 10% of its Initial Value Versus N, Large and Small Tank Tests
A STUDY OF CRYOGENIC PROPELLANT MIXING TECHNIQUES
Experimental Data, Poth, L.J., et al, GD/FW, FZA-439, NAS-20330
November 1968.

OBJECTIVE. - Develop technology required for prediction of thermal stratification of cryogenic fluids at low-g and means by which equilibrium can be achieved (mixing).

PERTINENT WORK PERFORMED. - The first annual report of this contract (Poth, Sept. 1967) selected jet mixing as the preferred type of mixing. The present is concerned with application to large cryogenic vehicles. Scaling data is emphasized as well as primary problems occurring in the application of data from one-g testing. Various stratification models considered are illustrated in Figure 1. Extensive consideration is given to the mixer power drive and the state-of-the-art in this field. Mixing tests used water with dye-injection in the jet and tank temperature measurements for 58 non-pressurized open-tank tests and only tank temperature measurements in 20 pressurized closed tank tests. A brief bench-type study of low Bond number mixing was also performed in small size tubes with water although modeling difficulties occurred.

MAJOR RESULTS. -

1. Feasibility of jet mixing was established and mixing times were correlated with the product of fluid power times outlet diameter (Fig's 2, 3). Increased nozzle size for a given power reduces mixing time. Conventional vane axial pumps proved adequate, however fluid power available from a given pump can be doubled with a more efficient brushless dc motor. This motor also desirably speeds up with vapor, which promotes ullage de-encapsulation.

2. System weights for a manned Mars vehicle are given in Table 1 where the final comparison variable is converted to an initial mass in earth orbit (IMIEO).

3. In addition to ullage encapsulation of the mixer, ullage breakup by the mixer is important. Active mixing was observed to occur in regions distant from the mixer. This led to design specification for mixers at both ends of the tank. However, the more stringent design performance criteria is ullage encapsulation.

4. Extensive design data are presented in the appendices for a range of mixer systems from small tanks to that for a manned Mars vehicle.

5. Additional work is required in pressure-temperature response mechanisms, boiling at heat shorts, ullage break-up, and buoyancy. Further development of brushless dc mixers is required. Experimentally, ullage encapsulation and ullage break-up must be examined in reduced gravity. Large tank tests are required to extend scaling, and orbital experiments should be defined to verify low-g mixing theory.
Table 1
MAXIMUM WEIGHT SUMMARY
(EXCLUDING STRUCTURAL SUPPORTS, ETC)
FOR BRUSHLESS D.C. MOTOR DRIVEN PUMP
INCLUDING ULLAGE ENCAPSULATION CRITERION

<table>
<thead>
<tr>
<th></th>
<th>EARTH ESCAPE STAGE</th>
<th>MARS BRAKING STAGE</th>
<th>MARS ESCAPE STAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EARTH ORBIT</td>
<td>EARTH TO MARS ORBIT</td>
<td>EARTH TO MARS ORBIT</td>
</tr>
<tr>
<td>Fuel Cell Weight, lbs.</td>
<td>5.8</td>
<td>1.73</td>
<td>1.09</td>
</tr>
<tr>
<td>Boiloff Weight, lbs.</td>
<td>59.5</td>
<td>6.7</td>
<td>14.2</td>
</tr>
<tr>
<td>Pump Weight, lbs.</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Weight Per Tank, lbs.</td>
<td>69</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Weight Per Stage, lbs.</td>
<td>276</td>
<td>84</td>
<td>27</td>
</tr>
<tr>
<td>Δ Imice Per Stage, lbs.</td>
<td>497</td>
<td>263</td>
<td>122</td>
</tr>
<tr>
<td>Total Δ Imice, lbs.</td>
<td></td>
<td></td>
<td>948</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of Simplified Stratification Models for Typical Nuclear Flight Module Conditions

Figure 2. Correlation of Dimensionless Time
For Δ(T_e - T_0) to Reach 0.1 of its Initial Value: Open Tank Test

Figure 3. Correlation of Axial Jet Mixing Time Ratio
for Δ(T_e - T_0) / Δ(T_e - T_1) = 0.2: Open Tank Test
OBJECTIVE. - To determine the minimum jet inlet velocity to maintain a stable flow pattern as a function of tank size, acceleration level, and test fluid in spherical tanks in reduced gravity.

PERTINENT WORK PERFORMED. - A series of fluid flow tests were performed in the LeRC 2.2 sec drop tower with acceleration levels of $10^{-5}$, 0.005, 0.01, 0.02, and 1.0 g's to define thermal conditioning flow profiles. The flow patterns and container sizes are shown in Figure 1; the test fluids were ethanol and water. Test coverage was primarily photographic. In one-g tests, the velocity was increased until the critical velocity was reached and the flow reached the tank top in a uniform, steady manner. In low-g, this was achieved by bracketing the conditions on successive drops. At velocities lower than critical, a center core did not form and fluid collected near the tank inlet.

MAJOR RESULTS. -

1. The velocity required to maintain a flow circulation can be correlated in the form $V = C \left( \frac{R}{\delta} \right)^{1/2}$ where $\delta$ is the initial jet thickness and $V$ is the mean jet inlet velocity. The correlation for water is shown in Figure 2 where the tank radius nondimensionalizes the abcissa and reduces the data to a single line. For ethanol, $C = 37$ and for water, $C = 41$.

2. The strong influence of gravity is shown in Figure 3. The range of low-g test data for ethanol are shown and the one-g correlation is given. A modified jet inlet velocity, $V/(R/\delta)^{1/2}$, can be used to normalize the data; the correlation with acceleration level is shown in Figure 4. At lower than $4 \times 10^{-3}$ g’s, the critical jet velocity for complete circulation is independent of acceleration level. At higher accelerations, the critical velocity is proportional to $(ng/g)^{0.43}$ indicating a departure from the expected Froude relation of slope 0.5.

COMMENTS. - The definition of critical velocities for inflow patterns has impact on fluid-mixing design.
Continuous layer of liquid along tank wall (adjustable range)

Figure 1. Desired Circulation Pattern

Figure 2. Velocity Required to Maintain Flow Circulation as Function of Wall Jet Ratio \( R/\delta \) in Normal Gravity Environment With Water

Figure 3. Velocity Required to Maintain Flow Circulation as Function of Wall Jet Ratio \( R/\delta \) in Low-Gravity Environments With Ethanol

Figure 4. Effect of Gravity on Flow Circulation Requirements for 10-, 20-, and 30-Centimeter-Diameter Tanks. Test Fluid, Ethanol
ZERO GRAVITY PROTOTYPE VENT SYSTEM

OBJECTIVE. - To define, design, fabricate and test a prototype heat exchanger vent system capable of controlling tank pressure while discharging only GH₂, even though the system and/or its inlet is in 100% LH₂ as may be encountered in space at low-g.

PERTINENT WORK PERFORMED. - In the system definition phase, trade-offs were made to determine the type of heat exchange (bulk vs wall), type of pump drive (electric vs turbine), optimum vent flow rate, vent cycle, and fluid mixing criteria. Basic design requirements were to control tank pressure to 17 ± 1 psia with external heating of 20-30 Btu/hr over 14 days. The resulting system is shown schematically, as setup for test, in Figure 1. Operation is by throttling the vent inlet to a low pressure and temperature and flowing through the heat exchanger to vaporize any liquid which may be present. Operation is intermittent to minimize total pump power input to the tank. The pump provides forced convection exchanger flow as well as liquid temperature destratification. Deactuation and actuation of vent and pump are controlled by a pressure-switch. Testing was at l-g with hydrogen in a 40-in. dia. by 84-in. long superinsulated CRES tank. The system was located 22 in. from the tank bottom and tests performed with the mixing flow (exchanger warm side outlet) directed (1) radially (2) downward and (3) upward. In each case testing was performed with the unit in vapor (13 in. LH₂ level) and liquid (49 in. and 70 in. levels). The 3-way valve (Fig. 1) provided either liquid or vapor inlet at all tank liquid levels. Both steady state and transient performance of the system was determined. In addition to the Figure 1 instrumentation, temperatures were measured throughout the tank fluid with platinum resistance sensors.

MAJOR RESULTS. -

1. Feasibility and efficiency of the concept was demonstrated. No liquid was vented under all design operating conditions. A typical tank pressure trace is presented in Figure 2.

2. Tank fluid mixing and liquid/ullage coupling were found to be important for efficient pressure control. Operation with the system in liquid and the mixing flow directed down was inefficient and in fact, at a LH₂ level of 70-in., tank pressure was not controlled (Figure 3). Flow directed at the L/V interface was best for mixing with radial flow next.

3. An apparent freezing of LH₂ in the throttle valve during one of the tests was solved by locating the shutoff valve downstream of the heat exchanger and external to the tank.
Table 1. Pertinent Vent System Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Cycle</td>
<td>intermittent (on 1/30th of total)</td>
</tr>
<tr>
<td>Vent Flow</td>
<td>3 lb/hr</td>
</tr>
<tr>
<td>Pump Power</td>
<td>7 watts</td>
</tr>
<tr>
<td>Throttling Pressure</td>
<td>5 psia</td>
</tr>
<tr>
<td>Test System Wt.</td>
<td>11 lb.</td>
</tr>
<tr>
<td>Est. Flight Wt.</td>
<td>8.2 lb</td>
</tr>
<tr>
<td>Pressure Switch</td>
<td>17 ± 1 psia with 0.5 psi min. deadband</td>
</tr>
</tbody>
</table>

Figure 1. Basic Vent System Test Schematic

Figure 2. Tank Pressure (Second Test Series, 9.0 to 11.0 Hours)

Figure 3. Tank Pressure (Third Test Series 21.3 to 22.5 Hours)

**LEGEND**

- **AL** - System Actuates with Liquid Inlet
- **LG** - Cycled Inlet from Liquid to Gas
- **GL** - Cycled Inlet from Gas to Liquid
- **AG** - System Actuates with Gas Inlet
9.0 REFRIGERATION AND RELIQUEFACTION

Covering systems to control tank pressure of space-stored fluids through refrigeration and/or reliquefaction.
ANALYSIS, DESIGN, AND DEVELOPMENT OF A PARTIAL HYDROGEN RELIQUEIFIER

OBJECTIVE. - To design, fabricate, and test a partial hydrogen reliquefier characteristic of flight type units.

PERTINENT WORK PERFORMED. - Various thermodynamic cycles which included a compressor, an expander, various numbers of heat exchangers, and a para-ortho hydrogen converter were analyzed. The converter was included to permit venting equilibrium hydrogen, which is at a higher energy state than para hydrogen, to achieve a greater heat sink per pound of vented fluid and thus increase the fraction of the feed that can be reliquefied. A computer program was used to analyze the various cycle configurations. It was concluded that the single most important factor affecting the fraction of the feed reliquefied is the split of the feed between the compressor and expander loops. The selected configuration and design point conditions for 29.4 psia tank or feed pressure are shown in Figure 1. Characteristics for a 22 psia feed pressure are presented in Figure 2.

Positive displacement machinery was used due to the low flow rates involved. The expander and compressor pistons, mounted on a common crankshaft, have filled Teflon rings and sealed bearings. The heat exchangers are the finned-tube type, and the ortho-para catalyst is contained in segments between sections of one of the heat exchangers (Figure 3). Four tests of the reliquefier were made at LH$_2$ temperature with four different compressor piston ring designs. In none of the tests was a good seal achieved, and it was concluded that a rather extensive design modification would be required to solve this problem.

MAJOR RESULTS. -

1. A hydrogen reliquefaction system was designed and fabricated to reliquefy approximately 43 percent of the feed gas flow at rates of 1.72 to 1.37 lbs/hr, depending on the feed pressure.

2. Attempts to provide an adequate seal for the compressor piston were unsuccessful.

COMMENTS. - The overall system weight is not given in the report. Data from Sexton, et al, 1971, listed under "Fluid Management Systems (General)" in Appendix B indicates the weight for this system is 200 lbs and requires 300 watts of power.
Figure 1. Design Point Conditions (29.4 Psia Feed Pressure)

Figure 2. Design Point Conditions (22 psia Feed Pressure)

Figure 3. Test Heat Exchanger IV with Para-Ortho Hydrogen Conversion Catalyst
INVESTIGATION OF EXTERNAL REFRIGERATION SYSTEMS
FOR LONG TERM CRYOGENIC STORAGE
Jensen, H.L., et al, LMSC, NASA CR-114920,
NAS9-10412, February 1971

OBJECTIVE. - To gather data on and investigate external-refrigeration systems for cooling cryogenic storage systems in long term space applications.

PERTINENT WORK PERFORMED. - Data were developed with the intent of providing the designer with sufficient basic information to conduct rapid and accurate cryogenic refrigeration system studies. Reports, data sources, and development programs on small cryogenic refrigerators were reviewed. For long term (more than six months) application it was found that non-vented systems show an advantage over vented systems having no self-contained external refrigeration. Since cryogenic refrigerators operate at relatively low efficiencies, the power supply and heat rejection devices become important. A general lack of data on failure characteristics was found which would be applicable to cryogenic and space applications.

The study presents basic information to obtain external autonomous refrigerator performance, weight, and size (Figure 1). Means of estimating performance-reliability tradeoffs are presented, as well as methods for computing tank surface temperatures and radiator heat rates. Data are presented on weights of cryogenic tanks and vacuum shells so that the designer can obtain trends and weight increments in conducting tradeoff studies. Weight estimating relationships for heat exchangers, helium circulation compressors, cryogenic heat pipes, and power sources are presented. A large range of the pertinent parameters was given to make the data useful for a large variety of space-oriented studies.

A handbook was prepared (LMSC-A984158) which is an extraction from the final report. It is intended to provide the designer with a concise statement of the information and procedures necessary to conduct system trade-off studies.

MAJOR RESULTS. -
1. A handbook of design information and procedures for conducting tradeoff studies on refrigeration systems was developed.
Figure 1. Summary of Refrigerator Weights vs Refrigeration for Various Cycles at 20°K and 4.2°K
INVESTIGATION OF GAS LIQUEFIERS FOR SPACE OPERATION

OBJECTIVE. - To determine the thermodynamic cycles best suited for use in space for the liquefaction and reliquefaction of helium, hydrogen, nitrogen, fluorine, and oxygen at rates from 1 to 1000 lbs per day.

PERTINENT WORK PERFORMED. - A survey is presented of the mode of operation, performance, and efficiency of the following cycles: cascaded compressed vapor cycles, systems using Joule-Thompson (J-T) cooling only, systems using expansion engines, Stirling cycle systems, Taconis cycle systems, and miscellaneous other systems. Data on the subject gases are presented followed by a theoretical survey of the relative efficiencies of liquefaction and reliquefaction for ideal reversible cycles. Charts and graphs presenting significant data on actual thermodynamic cycles used for refrigeration and reliquefaction are included which are based on conservative estimates of the current state of the art and optimistic estimates of the probable future state for the period 1965-70. Weights and volumes of existing compressors, motors, and expanders are presented. Detailed qualitative (Table 1) and quantitative (Table 2) comparisons of all the promising cycles are made on the basis of performance, weight, volume, reliability, and compatibility with the space environment. Definitive conclusions are arrived at which serve to permit specific recommendations for future action.

MAJOR RESULTS. -

1. A useful comparison of thermodynamic cycles for space liquefaction and reliquefaction of cryogenic fluids has been assembled.

2. Based on the data given, the Stirling cycle systems were recommended for reliquefaction and/or liquefaction of N2, O2, and F2 for all production rates.
Table 1. Qualitative Cycle Comparison

<table>
<thead>
<tr>
<th>Main Causes of Inherent Irreversibility</th>
<th>Systems Employing One Expansion Engine Only</th>
<th>Systems Employing Multi-Stage Expansion Engines</th>
<th>Systems Employing Expansion Engines Plus J-T Expansion</th>
<th>Stirling Cycle</th>
<th>Taconis Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer at unequal heat capacity.</td>
<td>Heat transfer at unequal heat capacity.</td>
<td>J-T Expansion.</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Transfer of latent for sensible heat (reliquefaction).</td>
<td>Transfer of latent for sensible heat (reliquefaction).</td>
<td>None</td>
<td>None</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|----------------------------------------|-----------------------------|-------------------------------|-------------|-------------------------------|

|----------------------------------------|----------|-------------|---------------------------------|

<table>
<thead>
<tr>
<th>Major Disadvantages in Space Environment</th>
<th>None</th>
<th>Large number of components.</th>
<th>None</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Large number of components.</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Reliquefaction of H₂ at 1000 (100) lbs/day

<table>
<thead>
<tr>
<th>System</th>
<th>Single J-T with Liquid No Precooling at 67%</th>
<th>Systems with One Expander(t)</th>
<th>Compound Systems with Two J-Ts.</th>
<th>Stirling Cycle with H₂ J-T.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coeff. of performance</td>
<td>Cons.</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Opt. (Est.)</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Required input power.</td>
<td>Cons. (Est.)</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Cons. (Low)</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Compressor and motor weight. lb.</td>
<td>Cons. (up)</td>
<td>16900</td>
<td>16900</td>
<td>16900</td>
</tr>
<tr>
<td>Cons. (low)</td>
<td>16900</td>
<td>16900</td>
<td>16900</td>
<td>16900</td>
</tr>
<tr>
<td>Compressor, motor and liquefier weight lbs</td>
<td>Cons. (up)</td>
<td>19300</td>
<td>19300</td>
<td>19300</td>
</tr>
<tr>
<td>Cons. (low)</td>
<td>19300</td>
<td>19300</td>
<td>19300</td>
<td>19300</td>
</tr>
<tr>
<td>Radiator weight, lbs.</td>
<td>Cons.</td>
<td>26200</td>
<td>26200</td>
<td>26200</td>
</tr>
<tr>
<td>Opt. (Est.)</td>
<td>26200</td>
<td>26200</td>
<td>26200</td>
<td>26200</td>
</tr>
<tr>
<td>Total weight of compressor, motor, liquefier and radiator lbs</td>
<td>Cons. (up)</td>
<td>31100</td>
<td>31100</td>
<td>31100</td>
</tr>
<tr>
<td>Cons. (low)</td>
<td>31100</td>
<td>31100</td>
<td>31100</td>
<td>31100</td>
</tr>
<tr>
<td>Power generation subsystem weight, lbs</td>
<td>Cons.</td>
<td>7700</td>
<td>7700</td>
<td>7700</td>
</tr>
<tr>
<td>Opt. (Est.)</td>
<td>7700</td>
<td>7700</td>
<td>7700</td>
<td>7700</td>
</tr>
<tr>
<td>Radiator area. sq. ft.</td>
<td>Cons. (up)</td>
<td>4800</td>
<td>4800</td>
<td>4800</td>
</tr>
<tr>
<td>Cons. (low)</td>
<td>4800</td>
<td>4800</td>
<td>4800</td>
<td>4800</td>
</tr>
<tr>
<td>Compressor Volume. cu. ft.</td>
<td>Cons. (up)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Cons. (low)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Compressor and liquefier volume. cu. ft.</td>
<td>Cons. (up)</td>
<td>3550</td>
<td>3550</td>
<td>3550</td>
</tr>
<tr>
<td>Cons. (low)</td>
<td>3550</td>
<td>3550</td>
<td>3550</td>
<td>3550</td>
</tr>
<tr>
<td>NO DATA AVAILABLE</td>
<td>NO DATA AVAILABLE</td>
<td>NO DATA AVAILABLE</td>
<td>NO DATA AVAILABLE</td>
<td>NO DATA AVAILABLE</td>
</tr>
</tbody>
</table>

9-7
10.0 INTERFACE CONTROL AND LIQUID ACQUISITION SYSTEMS (GENERAL)

Covering systems and studies which consider various aspects of more than one of the following categories.
ZERO GRAVITY LIQUID TRANSFER SCREEN

OBJECTIVE. - Describe a liquid transfer device for transferring liquid from one container to another in zero gravity.

PERTINENT WORK PERFORMED. - The liquid transfer device operates as follows: A spiral shaped screen (Figure 1) is rotated so that the surface tension created between the liquid in the container and the spiral shaped screen member directs the liquid out an exit port. The perforated screen is utilized so that back pressure created by the spiral shaped member can be relieved by allowing the contained liquid to pass through the spiral shaped member minimizing the back pressure. The transfer device adds very little heat to the liquid being transferred and minimizes the amount of venting required during transfer. The rotating shaft is turned by an electric motor. The periphery of the screen spirals are reinforced with a metal band.

COMMENTS. - This device combines the two concepts selected for propellant transfer in Stark, 1972. This concept should have high efficiency and low weight. The back pressure control attributes of the spiral screen could be useful in a case where fairly low transfer rates are required.
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OBJECTIVE. - To perform an analytical assessment of potential methods for replenishing the auxiliary propulsion $H_2$, $O_2$ and $N_2$ cryogens which may be aboard an orbiting space station.

PERTINENT WORK PERFORMED. - This study included storage of supply fluid, transfer, and receiver tank pressure and temperature control. Systems considered were high pressure (supercritical), subcritical, and modular (transfer of the tanks). The baseline resupply requirement was 1,096 lb of $H_2$, 2480 lb of $O_2$ and 3,150 lb of $N_2$ to eight $H_2$, two $O_2$ and two $N_2$ bottles. The standard receiver tank was a $42.5 \text{ ft}^3$ sphere containing liquid at 100 psia for station use. In addition to the baseline conditions, weight and performance data were generated for bottle diameters from 25 to 150-in. and transfer fluid quantities from 500 to 5,000 lb of $H_2$ and 1,000 to 10,000 lb each of $O_2$ and $N_2$. Transfer line lengths were 20 to 200 ft. and the maximum disturbing acceleration was $10^{-4}g'$s. Both individual supply tanks for each receiver and a single supply for each fluid were considered.

Capillary screen, dielectrophoresis, bladders, bellows, diaphragms, and fluid vortexing methods of subcritical transfer were initially considered. On the basis of safety, weight and development potential only screen, metallic bellows, metallic diaphragm and paddle vortex sub-critical systems were selected for detailed analysis. The dielectrophoretic system was not chosen primarily on the basis of potential safety, since in $O_2$ there is still some question of electrical breakdown and combustion hazard associated with this high voltage system. Line and tank chilldown data are also presented and the feasibility of non-vent transfer was investigated for various operating conditions.

MAJOR RESULTS. -

1. Analysis of various high pressure supply heating and blowdown and receiver cooling schemes showed the only concept worthy of any consideration was one employing simple supply heating with increased receiver volume to allow for the reduction in transferred fluid density. Also, the final receiver fluid cannot be liquid since any requirement for condensation results in excessively high weight and power.

2. The surface tension and paddle systems were determined, on the basis of low weight and cost and high reliability and reusability, to have the best potential for the space station application. Typical system weight data are presented in Figure 1. Receiver tank weights are divided by 20 to reflect the fact that the receiver tanks stay fixed on the station for 20 supply cycles. Individual receiver weights are presented in Figure 2. The paddle vortex concept is illustrated in Figure 3.

COMMENTS. - The bellows work is reviewed under a separate summary.
Figure 1. Total H₂ Transfer System Weight (Supply + Receiver/20)

Figure 2. Receiver Weights for H₂ Transfer

Figure 3. Paddle Type Vortex System
OBJECTIVE. - Determine promising concepts of total capillary acquisition for LO$_2$/LH$_2$ space shuttle main propulsion, attitude control and auxiliary power requirements. Perform bench tests to determine critical characteristics of capillary barrier materials. Specify testing required to verify system performance.

PERTINENT WORK PERFORMED. - Several thermal control concepts were analytically evaluated. Use of mixing, vehicle rotation, tank wall heat exchangers and heat pipes were examined for controlling thermal stratification. Thermodynamic vent system cooling capacity to condense vapor trapped in a capillary device was considered. Concepts considered for cooling of LO$_2$ with LH$_2$ were regenerative cooling, catalytic conversion from para to orthohydrogen, double walled tankage, vapor cooled shields, pumping of LH$_2$ over the LO$_2$ tank, a surge tank of cooled oxygen for periods when the hydrogen tank is not venting and internal mixing. A major consideration was prevention of freezing of LO$_2$ with the LH$_2$ coolant.

Vapor bubble collapse and condensation rates were determined analytically. A thermal stratification, self pressurization model was developed considering a laminar boundary layer, wall conduction, stratified liquid and vapor and a mixing region between the stratified liquid and the bulk subcooled liquid. Collector tube flow losses were computed.

Tests were run to determine screen pressure drop, bubble point, wicking rate, dewicking rate and collector flow losses. Dewicking tests were designed to qualitatively assess the ability of a screen to remain wetted when the liquid level supporting the wicking fluid is lowered.

MAJOR RESULTS. -

1. An active thermal protection system combining a thermodynamic vent system and vapor cooled shields was selected.

2. Screen configurations consisting of screened compartments were designed for the LO$_2$ and LH$_2$ tanks. Collector tubes were used in the LH$_2$ tank to supply inlet flow for thermodynamic vent system cooling.

3. Dewicking height properties of a capillary barrier material can be more critical than the bubble pressure.

4. Removal of trapped vapor pockets within the liquid by pressurization in low gravity did not appear practical due to long collapse times for large bubbles.

5. Figure 5.3-1, in the report, discussed recommended ground based and orbital tests.

COMMENTS. - Dewicking test results intuitively should yield test results similar to bubble point tests. Observed differences may be due to poorly controlled test conditions.
OBJECTIVE. Summarize the state of the art and developmental history of positive expulsion devices.

PERTINENT WORK PERFORMED. - The presentation was divided into seven chapters; Bellows, Cryogenic Bladders, Elastomeric Bladders, Teflon Bladders, Metal Diaphragms, Pistons and Surface Tension devices. Each chapter deals with definition of the positive expulsion concept, design features, programs, development history, current state of the art, problem areas and recommendations for future development.

MAJOR RESULTS. -

1. Bladders had been used as an expulsion device on more space vehicle programs than any other device. Fourteen flight programs had used Teflon bladders and nine programs had used elastomeric bladders. About 6,000 Teflon bladders and about 500 rubber bladders had been supplied for flight vehicles.

2. Surface tension screens had been used on six flight programs with 500 flight tests up to 1971.

3. Metal bellows had been used on six flight programs with 400 flight tests up to 1971.

4. One piston tank and one metal diaphragm tank had completed flight tests. Pistons had been used in 60 Lance hot firing tests which included several flight tests. A metal diaphragm was flight tested on an Army Missile.

5. Controlled folding devices should be considered for long life applications since they minimize three corner folds that shorten bladder or diaphragm life.

6. All the expulsion devices discussed in the report have high expulsion efficiency (96 to 99%). The major differences between the device are the differential pressure required for expansion.

7. Expulsion device testing should simulate actual operating conditions as closely as possible in order to eliminate scaling errors that have occurred in past programs.

8. Additional testing to evaluate dissolved gas and bubble formation in propellant expulsion tanks was recommended.

COMMENTS. - All flight tests were conducted with storable propellants. The fluid transfer system designer should examine this report to see if existing devices can be useful in accomplishing fluid transfer.
OBJECTIVE. - Survey and evaluate propellant management techniques for the Apollo Spacecraft Propulsion System.

PERTINENT WORK PERFORMED. - Six categories of propellant management systems were evaluated: non-metallic bladders and diaphragms, metallic diaphragms, capillary devices, sliding seal pistons, metallic bellows and miscellaneous systems. Primary system goals were passive operation, high volumetric expulsion efficiency, low weight and pure liquid delivery to the tank outlet. Secondary system goals were; insensitivity to; propellant slosh, acceleration direction, engine duty cycle and off loading requirements, multicycle capability, series tankage capability, and no hardware change from the configuration described in Table 1 and Figure 1. Evaluation criteria were adaptability, reliability, state of the art, weight, development time and cost, expulsion efficiency, passive operation, slosh control, series tankage capability, pressurant gas ingestion, and adaptability to low g mass gauging systems.

MAJOR RESULTS. -

1. The non-metallic bladder material for fuel and oxidizer was chosen to be Teflon laminate based on low weight and material compatibility. A collapsing, single cell bladder of 10 mils thickness was selected.

2. A 10 mil thick Teflon laminate was chosen for the reversing non-metallic diaphragm.

3. A sliding sleeve, ring reinforced metallic diaphragm using a vent port to facilitate filling on the ground was the most promising metallic bladder or diaphragm configuration.

4. A capillary acquisition device consisting of a double compartment start basket with a screen liner in the bottom compartment was selected.

5. A center guided piston, sealed along the center guide rod and tank wall, was chosen for the piston design.

6. A titanium bellows design with a redesigned titanium tank was chosen for the bellows design.

7. Electrical systems, chemical foam systems, acoustic force systems and separate restart tanks were briefly considered but rejected, generally due to low level of technology development.

8. Table 2 compares the systems evaluated. A capillary device was selected as the recommended technique (Figure 2). A non-metallic bladder was the second choice.
Figure 1. Oxidizer and Fuel Tanks

Figure 2. No Hardware Limitation Capillary Design

Table 1. Propulsion System Characteristics

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Non-metallic</th>
<th>Metallic</th>
<th>Design A</th>
<th>Design B-2</th>
<th>Capillary Retention</th>
<th>Sliding Seal Pieces</th>
<th>Metallic Bellows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expulsion Efficiency, %</td>
<td>Cylindrical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric Efficiency within Tank Envelope, %</td>
<td>Rolling Diaphragm</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Pressure Ingestion</td>
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<td>Hardware Changes</td>
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<td>Duty Cycle Limitations</td>
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<td>Off-Load Propellant Limitations</td>
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<tr>
<td>Cycle Life</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Propellant Exposure Tolerance, Yr (1-Yr Goal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Series Tankage Capability</td>
<td></td>
<td></td>
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<tr>
<td>State-of-the-Art</td>
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<tr>
<td>Development Time and Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 2. Propellant Control Systems Evaluation Summary

10-11
STORABILITY DEMONSTRATION PROPELLANT
FEED SYSTEMS

OBJECTIVE. - To design, fabricate, test, and deliver to AFRPL twenty-three storable prepackaged propellant systems (SPPS) containing acquisition devices for a long-term storability demonstration.

PERTINENT WORK PERFORMED. - Each of the 15-gallon tanks contains either a Surface Force Orientation (SFO) device or a Rolling Diaphragm (RD) positive expulsion device. The 2219 aluminum tanks, 30 in. long and 13.75 in. in diameter, were subsequently loaded with MHF-5, N₂O₄, or C₁F₅ prior to shipment.

The SFO device was required to be compatible with the propellants and pressurants for five years. It was not required to expel propellant in a negative gravity field, due to the unavailability of fine micron screen. The device consists of an aluminum alloy screen welded to a waffle-patterned backup plate. This assembly was circumferentially welded to the tank liquid outlet head prior to final tank assembly (Figure 1). MHF-5 was successfully expelled by the system during three demonstration tests.

The RD device had to meet the same requirements as the SFO device and be leak free. The RD shell and center tube are 0.032-in., 1100 aluminum alloy, bonded to the center guide and outer wall with silicone rubber adhesive (Figure 2). During testing, problems with shell collapse, piston cocking, and weld leakage were encountered and design changes made. The final four demonstration tests were successful.

One of the three pressurization subsystems was a liquid propellant gas generator consisting of a gas/hydrazine system separated by a bellows supplied by Metal Bellows Company.

MAJOR RESULTS. -

1. Twenty-three propellant storage systems were developed complete with acquisition and pressurization systems.
Figure 1. Propellant Tank With Surface Force Orientation Device

Figure 2. Propellant Tank With Rolling Diaphragm Device
OBJECTIVE. - To design, fabricate, test, and deliver two identical surface tension and two dielectrophoretic (DEP) propellant orientation units for orbital flight test.

PERTINENT WORK PERFORMED. - Phase I of this program included the experiment definition, analysis, preliminary design, and the orbital test plans for both a surface tension and a DEP propellant orientation device. The surface tension device used allyl alcohol as a test fluid to simulate performance with N₂O₄, N₂H₄/UDMH, or other storable propellants. The partial control concept, rather than total control, was selected since it yields lighter system weights. The three-component device, shown in Figure 1, consists of a truncated cone with holes located around the bottom for liquid containment over the drain, a flat plate over the drain for reducing fluid velocities and pull-through height, and a multi-baffled vent device. The spherical, Lexan test tank is 12-in. in diameter. The liquid containment device is designed to be stable in all directions for acceleration levels up to 10⁻³g₀.

The dielectrophoretic device was designed to demonstrate liquid orientation capability. Liquid withdrawal, vapor venting, liquid collection times, anti-pullthrough characteristics and the effect on slosh frequencies were to be determined. The DEP device was installed in a 16-in. diameter Lexan sphere (Figure 2). The minimum electrode spacing of 3 cm, and the spacing ratio of 2:1 were selected to provide the widest range of test voltages and accelerations. Greater than 10⁻³g₀ adverse accelerations can be tolerated with an electrode potential difference less than 100 kv. The electrode assemblies and the high-voltage power supplies were fabricated by Dynatech Corp. However, the DEP experiment was terminated early in the fabrication phase for unspecified reasons.

MAJOR RESULTS. -

1. Two surface tension and two dielectrophoretic liquid orientation experiments were designed for orbital testing, complete with transparent tanks, lighting systems, and cameras.

2. In phase II of this program the two surface tension packages were delivered to AFRPL.

COMMENTS. - A surface-tension venting device similar to that used here was subjected to aircraft zero-g tests. The results were reported by Bovenkerk, 1969, summarized under vent systems.
VENT - 7.6 IN.
VENT DEVICE

DRAIN

ORIENTATION CONE AND PULL-THROUGH SUPPRESSION PLATE

Figure 1. Surface Tension Orientation Device

\[
\frac{S_{\text{MAX}}}{S_{\text{MIN}}} = 2
\]

SPACE VENT

\[ S_{\text{MAX}} = 2.4 \text{ in. (6 cm)} \]

SPACE DRAIN

\[ S_{\text{MIN}} = 1.2 \text{ in. (3 cm)} \]

Figure 2. Selected Electrode Configuration.
11.0 CAPILLARY ACQUISITION

Covering analysis, design, fabrication and test of systems using surface forces to control liquid orientation.
WICKING OF LIQUIDS IN SCREENS

OBJECTIVE. - Analytically and experimentally determine the magnitude of wicking rates of liquids in screens.

PERTINENT WORK PERFORMED. - An analytical model was developed based on surface forces and Poiseuille flow that expressed the wicking velocity in terms of the geometry of the screen, and the surface tension and viscosity of the liquid. Data was obtained to evaluate the correlation constant $C$, representing all the screen geometric parameters, in the equation $V_w = (C/L) \left( \sigma/\mu \right)$, where $L$ is the distance between the wicking liquid/vapor interface and the liquid source and $V_w$ is the wicking velocity. Equations were generated for determining the local and uniform heat flux that could be intercepted by wicking flow in order to prevent drying out of a screen and loss of retention capability. $Q/W = (\delta \rho \lambda/2) (C/L) \left( \sigma/\mu \right)$ (local heat source) and $Q/A_s = (\rho \lambda/2) (C/L^2) \left( \sigma/\mu \right)$ (uniform heat source). See Table 1 for nomenclature.

Thirteen screen meshes were evaluated experimentally using methanol and ethanol as the test fluids. Tests were run in a horizontal wicking chamber on the ground and in a drop tower test package. Wicking displacement was measured visually as a function of time using a small scale having divisions of 0.1 cm. For the drop tower package, photographic data was used to measure displacement. Capillary pumping delivered liquid to the screen in the drop test package after the system entered zero gravity. Low wicking rates and short test times impaired the accuracy of many of the drop tower tests.

MAJOR RESULTS. -

1. Values of the correlation constant $C$ were empirically determined and are shown in Table 2 for the ten dutch weave screens tested.

2. The square weave screens tested (150x150, 200x200 and 400x400) did not wick.

3. Predicted screen wicking capability (from equations 2 and 3) for preventing screen drying is shown in Figures 1 and 2 for local incident heat flux and uniform heat flux.

COMMENTS. - Results of Paynter, et al, 1973, indicate that order of magnitude increases in wicking can be obtained using screen plate combinations compared to using screen alone.
Figure 1. Maximum Local Incident Heat Flux as Function of Distance From Liquid Source. Wicking Flow Perpendicular to Warp Wires; Test Liquid, Hydrogen

Figure 2. Maximum Uniform Heat Flux as Function of Distance From Liquid Source. Wicking Flow Perpendicular to Warp Wires; Test Liquid, Hydrogen

<table>
<thead>
<tr>
<th>Screening Process</th>
<th>Mesh Size, ( D_s ) ( \mu \text{m} )</th>
<th>Screen Thickness, ( t ) ( \mu \text{m} )</th>
<th>Correlation Constant, ( c ) ( \mu \text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20x250 Twilled-weave Dutch</td>
<td>30</td>
<td>685</td>
<td>1.7</td>
</tr>
<tr>
<td>30x300 Twilled-weave Dutch</td>
<td>37</td>
<td>430</td>
<td>0.71</td>
</tr>
<tr>
<td>159x400 Twilled-weave Dutch</td>
<td>37</td>
<td>147</td>
<td>1.5</td>
</tr>
<tr>
<td>200x400 Twilled-weave Dutch</td>
<td>30</td>
<td>135</td>
<td>0.97</td>
</tr>
<tr>
<td>30x700 Twilled-weave Dutch</td>
<td>40</td>
<td>254</td>
<td>0.42</td>
</tr>
<tr>
<td>159x400 Twilled-weave Dutch</td>
<td>21</td>
<td>147</td>
<td>0.19</td>
</tr>
<tr>
<td>200x400 Twilled-weave Dutch</td>
<td>14</td>
<td>135</td>
<td>0.11</td>
</tr>
<tr>
<td>325x300 Twilled-weave Dutch</td>
<td>10</td>
<td>61</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 1. Nomenclature

11-3
OBJECTIVE. - To analyze, design, fabricate and test a multipurpose full scale liquid hydrogen acquisition and thermal control system (start tank) as part of the NASA/MSFC auxiliary propulsion system breadboard.

PERTINENT WORK PERFORMED. - A screen device, consisting of a 24 inch diameter 24 inch. long rolled spot welded 250 x 1270 stainless steel annular screen was designed and fabricated to sustain an outflow rate of 7.5 lb/sec for 5 seconds against 1-g. The device fit into a 6061 T6 aluminum cylindrical pressure vessel 34.5 inches high and 29 inches in diameter (Figure 1). The thermodynamic vent system (TVS) consisted of flow control orifices (viscojets) and externally wall mounted dip brazed helical coils on the cylindrical tank wall (0.25 in. D X 70 ft long in two 35 ft paths).

MAJOR RESULTS. -

1. The screen device performed successfully for both overhead and submerged diffusers using cold gas pressurization. Pressurization with warm hydrogen gas and, to a lesser extent, warm helium gas produced a marked decrease in retention capability.

2. Thermodynamic vent system flow control was achieved. Viscojet pressure loss predictions compared to actual viscojet and TVS pressure loss are shown in Figure 2.

3. Simulated low-g restart was achieved, involving IDU outflow followed by refill with simultaneous outflow.

4. Screen sealing with polyurethane adhesive and filling of gaps between the cooling tubes and the start tank wall with a conducting epoxy were successfully demonstrated with no adverse effect due to LH2 immersion and repeated thermal cycles.

5. Two phase refill was demonstrated indicating that completion of settling is not required before start tank refill can be initiated.

6. A conical screen feedline barrier (shown in Figure 3) was successfully tested, using warm helium flow into the feedline at .004 lb/sec. This was equivalent to heating under the most severe conditions anticipated.

7. Malfunction of the submerged ball valves occurred repeatedly and seriously hampered testing.

COMMENTS. - A scarcity of quantitative comparisons of analytical predictions and test data detract from this report. Empirical relations generally are not shown. Perhaps this is due to test data being limited by ball valve actuation problems.
VENT TUBE

LEVEL SENSORS

COVER

SCREEN DEVICE

REFILL DIFFUSER

PRESSURANT DIFFUSER

Figure 1. Conical Screen Feedline Barrier

Figure 2. Flowrate Dependence of Viscojets

Figure 3. Vapor Barrier Screen
OBJECTIVE. - Perform analytical and design studies to develop acquisition system designs for an advanced Cryogenic Space Shuttle Auxiliary Propulsion System (CSS/APS) and an Advanced Space Propulsion Module (ASPM) similar to a Space Tug.

PERTINENT WORK PERFORMED. Screen acquisition system sizing procedures were developed and implemented in computing pressure differentials during system operation. Fully distributed channel (FDC) and start tank concepts were designed for the Space Shuttle and ASPM. The FDC concept, using cold pressurant, remains full of liquid until the high acceleration reentry period. Pressurization tradeoffs and feed system transient flow analyses were performed for the FDC. A localized pressure isolated channel (LPIC) acquisition concept (start tank) was devised to minimize pressurization system weight by permitting warm pressurant to be used in the main tank. Designs were presented incorporating refilling with settled fluid and vacuum vent refilling (Figure 1) for refilling between settling burns. Extensive calculations were performed to optimize insulation, venting, pressurization and acquisition system requirements for both vehicles over a range of possible missions. Both a screen ring and smaller screen device were fabricated for integration into a NASA owned 105-inch tank. Settling analysis, based on empirical correlations, predicted vehicle acceleration requirements for ASPM six-burn missions.

MAJOR RESULTS. -

1. Pump shutdown could cause backflow and ingestion of expanding, two phase fluid into the contained fluid. Pump bypass can be used to minimize backflow and pressure surge. Valve opening and closing effects were analytically found to cause pressure waves that could degrade screen performance (Figure 2).

2. Circular screened channels are recommended for good retention and low weight.

3. Thermal management studies indicate that vapor cooled shields are desirable for vented tanks such as the ASPM LH2 tank to control incident heating into the tank contents. For unvented tanks (CSS/APS) internal mixers are recommended to control propellant stratification.

4. Acquisition concepts must be compared on an overall feed system basis. Figure 3 illustrates the subsystem elements that should be included in the comparison.

5. For the six-burn missions analyzed, liquid settling has a lower weight penalty than the surface tension acquisition system.

COMMENTS. - The fully distributed channel and vacuum refill start tank concepts are most applicable to low-g fluid transfer. Techniques used to optimize insulation thickness and compare vented tanks to unvented tanks should be useful in designing supply tanks.
Figure 1. Main Tank Propellant Acquisition for Start Tank Vacuum Refill

Figure 2. LH₂ Acquisition Subsystem Shutdown Pressure History

<table>
<thead>
<tr>
<th>Distributed Channel</th>
<th>Pressure Isolated Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooled Shield</td>
<td>Internal Mixer</td>
</tr>
<tr>
<td>Cold Helium</td>
<td>Thermal Control:</td>
</tr>
<tr>
<td>— Pressurization</td>
<td>111°K GH₂ Pressurization</td>
</tr>
</tbody>
</table>

| Weight | Higher weight | Minimum weight |
| Reliability | Fewer parts | Uses rotating machinery for propellant mixing |
| Completely passive | Has potential retention breakdown correlation capability (+30 to 45 kg) |

| G-independent | All thermal aspects and critical flow characteristics can be tested on the ground | Internal mixer and refill involves some potential low-g uncertainties |
| Technology Status | In hand | Internal mixer involves some potential low-g uncertainties |
| Head potential for reqd screen mesh | About at limit of finest available mesh | Good safety factor with relatively coarse mesh |
| Fabrication capability | Must have access to all interior mesh | Tank within a tank fabrication |
| Pump bypass compatibility | Must dump all pump bypass | Could be handled with minimum or no dumping |
| Offloading | Severe limited capability | Complete flexibility |

Figure 3. Overall Basic Concept Comparison
OBJECTIVE. - Develop experimental information to establish design criteria in the areas of (1) basic screen characteristics; (2) screen acquisition device fabrication problems, and (3) screen surface tension device operational failure modes.

PERTINENT WORK PERFORMED. - Evaluations were made of gas tungsten arc welding and roll spot welding of stainless steel plate and screen sandwiches, rivetted trapezoidal channel assemblies, screen element attachment by screws and nutplates and repairing of screen characteristics and operational failure modes.

MAJOR RESULTS. -

1. Screen bubble point tests with LH\textsubscript{2} and GHe gave inconsistent results. Using GH\textsubscript{2} pressurant, results were consistent and directly comparable to isopropyl alcohol results.

2. Flow losses using screen mesh and perforated plate were between 10 and 30\% higher than losses with screen alone. Inserting a coarse mesh spacer screen between the plate and fine mesh screen reduced the pressure drop to that of the screen alone.

3. Degradation of bubble point due to pleating was found to be less than 20\%, as shown in Figure 1. Considering total flow area of the screen, pressure losses were not measurably affected by pleating.

4. Deflection tests indicated no significant bubble point degradation and no load cycle dependence.

5. Warm gas can seriously reduce the retention capability of fine mesh screen, as shown in Figure 2.

6. Direct heat transfer to a screen supporting saturated LH\textsubscript{2} did not cause reduction in retention capability as anticipated.

7. Screen vibration (using screen samples having natural frequencies much greater than the maximum shaker frequency) had an unpredictable effect on retention capability (see Figure 3).

8. Multilayer screen barriers cause trapped gas to be forced downstream into the propellant feed system. The bubble point of the multilayer unit must be exceeded to expel this gas, creating a possible gas ingestion problem in the capillary feed.

9. Large screen devices can be bubble point tested with a film condensation method.

10. Settling tests indicated that momentum refill should not be relied upon for capillary device refilling.
Figure 1. Bubble Point Performance of Pleated Screens

Figure 2. Influence of Warm \( \text{GH}_2 \) Above Screen Retaining \( \text{LH}_2 \)

Figure 3. Longitudinal Vibration Effects on Bubble Point for Liquid Columns
SIMILARITY TESTING OF SPACECRAFT CAPILLARY PROPELLANT MANAGEMENT SYSTEMS
DeBrock, S.C., LMSC, AIAA Paper No. 73-1228, Nov. 1973

OBJECTIVE. - Demonstrate the use of similarity testing for verifying the performance of spacecraft capillary propellant management systems.

PERTINENT WORK PERFORMED. - Since capillary forces do not dominate most full scale propellant management systems in a 1-g laboratory environment, the model scale, acceleration environment, propellant flow rate and/or test fluid properties must be adjusted to maintain the same balance of forces found in the prototype. Dimensionless groups may be used to yield identical scaled performance from the model to the prototype.

The various test methods available for similarity testing are compared in Table 1. Descriptions of bench testing used for surface tension devices were given for evaluating; surface tension by the Sugden Method, transient acceleration loading (shock) effects on capillary device retention; transient propellant withdrawal, propellant reorientation and sump refill.

Drop tower tests were described for; determining initial low g propellant orientation, time required to deorient the propellant, and associated propellant motion.

MAJOR RESULTS. -

1. Similarity test methods have been proven to successfully predict prototype performance. In the Agena development program, expulsion efficiency tests with plastic sumps and water were compared to subsequent full scale propulsion subsystem hot firings. Other examples of similarity test comparison methods are given in Table 2.

2. Similarity test techniques have been used to accurately predict flight performance as shown in Table 3.
### Table 1. Similarity Test Approach Comparison

<table>
<thead>
<tr>
<th>Type</th>
<th>Approach</th>
<th>Application</th>
<th>Strengths</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-g Bench</td>
<td>Use dimensionless group to scale model size, test fluid properties and test conditions.</td>
<td>Evaluate propellant withdrawal, bulk static and dynamic behavior.</td>
<td>Conveniences; controlled test conditions; rapid burn-around and low cost;</td>
<td>Must size becomes small at low prototype accelerations; does not duplicate low-g test conditions.</td>
</tr>
<tr>
<td>Immiscible Test Fluids</td>
<td>Incompatible test fluids with similar densities reduce body forces.</td>
<td>Evaluate bulk propellant configurations.</td>
<td>Conveniences; controlled test conditions; rapid burn-around and low cost;</td>
<td>Limited to static bulk evaluations.</td>
</tr>
<tr>
<td>Electromagnetic Field</td>
<td>Colloidal suspension of magnetic particles &quot;suspended&quot; by electromagnetic field.</td>
<td>Evaluate propellant withdrawal, bulk static and dynamic behavior.</td>
<td>Variable body forces. Model size limited by size of magnetic discs; cannot provide low-g simulation of gas or vapor phase, impaired visibility.</td>
<td></td>
</tr>
<tr>
<td>Aircraft Testing</td>
<td>Keplerian trajectories used to produce weightlessesses.</td>
<td>Evaluate propellant withdrawal, bulk static and dynamic behavior.</td>
<td>Produces true low-g environment for relatively long periods.</td>
<td>Poor control of g magnitudes and initial conditions; relatively expensive and time consuming.</td>
</tr>
<tr>
<td>Drop Tower</td>
<td>&quot;Free fall&quot; of test platform.</td>
<td>Evaluate propellant withdrawal, bulk static and dynamic behavior.</td>
<td>Precise control of test conditions; reasonable test environment; variable body forces.</td>
<td>Relatively short test period; small models for modest facilities.</td>
</tr>
<tr>
<td>Orbital Test</td>
<td>Use orbital vehicle test lab.</td>
<td>Evaluate propellant withdrawal, bulk static and dynamic behavior.</td>
<td>Long test periods to test for low-g environment.</td>
<td>Variable required special test environment or the total vehicle must experience test g's.</td>
</tr>
</tbody>
</table>

### Table 2. Similarity Test Comparison

<table>
<thead>
<tr>
<th>Vehicle Event</th>
<th>Capillary System Parameter Monitored</th>
<th>Similarity Test Method</th>
<th>Results</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-g Coast</td>
<td>Propellant bulk configuration</td>
<td>Two liquid neutral buoyancy; low-g drop tower</td>
<td>02: Low-g configuration has been correlated between two liquid neutral buoyancy vs. drop tower tests; (b) high-impact tests of a common design have shown the same results at 1/6 and 1/12 scale with different test fluids.</td>
<td>(a) &gt; 1&lt;br&gt;(b) &gt; 12</td>
</tr>
<tr>
<td>Low-g Engine Startup</td>
<td>Arresting or low-g surface dip</td>
<td>1-g bench</td>
<td>1-g bench tests of similar designs have been conducted with water and kerosene at scales of 1/6, 1/12, and 1/6 and show identical results.</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Propellant Reorienta-</td>
<td>Propellant reorientation mode and time</td>
<td>Low-g drop tower; 1-g bench</td>
<td>Low-g drop tower and 1-g bench tests have been conducted with water and kerosene at scales of 1/6, 1/12, and 1/18 and show similar results when normalized to the same scale and g test fluid.</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Refill of Capillary Devices</td>
<td>Separation of entombed propellant from gas and gas expansion</td>
<td>Low-g drop tower; 1-g bench</td>
<td>Engine gas ingestion</td>
<td>&gt; 70</td>
</tr>
<tr>
<td>Expulsion Efficiency</td>
<td>Arresting of high-g surface dip</td>
<td>Full scale 1-g bench, full scale test firing</td>
<td>Residual propellant free from 1-g hot fire tests agreed with 1/2 full scale water flow bench test results within ±10%</td>
<td>Bench = 15&lt;br&gt;Hot firing = 6</td>
</tr>
</tbody>
</table>

### Table 3. Similarity Test Comparison With Flight Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-g Coast</td>
<td>Static Propellant Bulk Configuration</td>
<td>Two liquid neutral buoyancy; low-g drop tower</td>
<td>Vehicle lateral and axial acceleration</td>
<td>Accelerometer</td>
<td>(a) ≤ 10&lt;br&gt;(b) ≤ 10</td>
<td></td>
</tr>
<tr>
<td>Vehicle Maneuver/</td>
<td>Bulk Propellant retention within capillary devices</td>
<td>Low-g drop; 1-g bench</td>
<td>Engine gas ingestion</td>
<td>Pump inlet and thrust chamber pressure transducers</td>
<td>Gas-free engine restart after many days of vehicle Maneuvers verified propellant re-&lt;br&gt;tection capability</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Low-g Engine start-</td>
<td>Arresting of low-g surface dip</td>
<td>1-g bench</td>
<td>Engine gas ingestion</td>
<td>Pump inlet and thrust chamber pressure transducers</td>
<td>Gas-free engine restart after many hours of vehicle coast verifies low-g surface pressure performance</td>
<td>&gt; 70</td>
</tr>
<tr>
<td>Steady Engine firing</td>
<td>Steady low-g gas burning</td>
<td>1-g bench</td>
<td>Engine gas ingestion</td>
<td>Propellant feed system and thrust chamber pressure transducers</td>
<td>Gas-free low-g engine propellant feed contaminants predicted performance</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Propellant Reorienta-</td>
<td>Propellant de-</td>
<td>Low-g drop tower; 1-g bench</td>
<td>Vehicle Axial acceleration</td>
<td>Accelerometer</td>
<td>Vehicle axial accelerometer showed initial acceleration overshoot during propellant reorientation followed by acceleration undershoot as mass impacted tank bottom.</td>
<td>≥ 10</td>
</tr>
<tr>
<td>Refill of Capillary Devices</td>
<td>Separation of entombed propellant from gas and gas expansion</td>
<td>Low-g drop tower; 1-g bench</td>
<td>Engine gas ingestion</td>
<td>Pump inlet and thrust chamber pressure transducers</td>
<td>Gas-free engine restart verified propellant refill during prior engine burn.</td>
<td>&gt; 70</td>
</tr>
<tr>
<td>Expulsion Efficiency</td>
<td>Arresting of high-g surface dip</td>
<td>Full scale 1-g bench, full scale test firing</td>
<td>Propellant head and chamber pressure transducers</td>
<td>Pump inlet and propellant tank pressure transducers</td>
<td>(a) Rapid pump inlet pressure decay indicated acceleration overshoot and undershoot during propellant refill.</td>
<td>&gt; 12</td>
</tr>
</tbody>
</table>
OBJECTIVE – Define the design parameters for an earth orbital maneuvering system (OMS) passive acquisition/expulsion device through analysis and testing.

PERTINENT WORK PERFORMED – Fuel and oxidizer trap (start basket) designs were selected for satisfying mission requirements. Ground testing was conducted to provide support information for the design activity. Lateral screen stability and bubble point tests were conducted with multiple screen barriers. Centrifuge testing was used. Testing was conducted with 180 x 180, 200 x 1400 and 325 x 2300 mesh screens. These represent the finest meshes available in titanium, aluminum and stainless steel respectively. Gas penetration data was obtained in centrifuge tests conducted at accelerations above those required to exceed the retention capability of a single screen layer. A quantitative model was developed for predicting multiple screen breakdown under lateral acceleration. A small scale model complete screen liner and subscale trap were fabricated and used to study ground handling requirements and procedures. Acceptance tests, functional inspections, and propellant loading and draining procedures were investigated in bench tests. Acceptance testing consisted of bubble point and drip testing. Bubble point testing was conducted by submerging the screen liner in methanol and pressurizing while rotating the liner. The same model was used to study shock and vibration during ground handling. Screen liner flaws were repaired with eutectic solder. Drip tests were conducted by filling the liner with liquid, lifting it out of the bath and rotating the liner so that it supported increasing hydrostatic head. Liquid dripping out of the liner denoted the retention limit of the 80 x 700, 250 x 1370 and 325 x 2300 mesh screens tested. Remote bubble point tests were also run with a spray technique, measuring the pressure differential across the wetted liner.

MAJOR RESULTS –

1. Recommended joining methods for surface tension devices are shown in Table 1. Resistance welding is the most desirable method. High temperatures caused by fusion welding can destroy the screen.

2. Possible failure modes of screen devices are shown in Table 2.

3. Data presented in Figure 1 illustrates the deviation from additive bubble point capability of multiple dutch twill screen layers.

4. A generalized relationship of the breakdown characteristics of multiple screen barriers under high lateral accelerations, indicated that multiple-screen barriers of fewer layers than required for lateral stability can be designed to provide barrier breakdown transients on the order of minutes rather than seconds.

5. Testing demonstrated loading and ground handling of liner and trap devices.
Table 1. Recommended Joining Methods for Surface Tension Devices

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Stainless Steel</th>
<th>Aluminum</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen-to-Screen welding</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Screen to Plate welding</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Resistance Welding</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fusion Welding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Beam Welding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazing</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soldering</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Fastening</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 2. Causes of Failure of Surface Tension Devices

- Loss of Working Capability - Clogged by Contamination or Corrosion, Fracture of Screen Wire
- Unsatisfied Pressure Imbalance
- Recurrent Thermal Cycling - Expansion and Contraction of Liquid
- Excessive Evaporation
- Excessive Vibration
- Excessive Weight on Screen
- Low Engine Speed
- Clogging of Ports by Contamination or Corrosion
- Erection of Pressure by Corrosion, Erosion
- Structural Loads
- Excessive Accelerations
- Structural Failure - Excessive Structural Loads, Fatigue due to Vibration, Load
- Change in Liquid Properties (Surface Tension, Density, Contact Angle) - Variation with Temperature, Contamination, Corrosion Products
- Excessive Pressure Imbalance
- Excessive Pressure Loss within Membrane
- Hydraulatic Head - Excessive Accelerations
- Fine Area Change - Structural Failure, Corrosion
- Fine through Screen - Clogging due to Contamination or Corrosion
- Friction Losses - Structural Failure, Corrosion
- Excessive Root Valve Leaks
- Thermal Environment - Corrosion Products

Figure 1. Bubble Point Data from Multiple-Screen Tests

(S = Spacing between screens)
OBJECTIVE. - Experimentally determine the screen bubble point, flow-through pressure loss, and pressure loss along rectangular channels lined with screen on one side. Using the correlated experimental data, determine the optimum system characteristics of a full wall screen liner.

PERTINENT WORK PERFORMED. - Initially, a conceptual tankage design for a screen liner system integrated with an internal thermodynamic vent system (TVS) was developed (Figure 1). A comprehensive survey of screens for use in the wall screen liner was performed. Ten screens were selected based on type of weave, anticipated bubble point, and pressure drop for flow-through the screen. Bubble point tests were then conducted for these screens using 3 cm circular specimens bonded with polyurethane adhesive into a holding fixture. Bubble point testing with isopropyl alcohol was conducted prior to assembly in the LH₂ dewar. All ten samples were mounted together and were visible through windows at the bottom of the Dewar. With the LH₂ level above all the specimens, each specimen was pressurized with GH₂ until bubbles appeared. Pressure differentials were measured with a manometer and a hook gauge. An apparatus was designed to simultaneously provide flow-through pressure loss data with channel flow loss data. Screens were placed normal to the flow in the inlet section and parallel to the flow in the channel sections as shown in Figure 2. Testing was conducted using LH₂ saturated at 50 psia. Flow rate was measured with a turbine flow meter and pressure was measured with a water manometer and a pair of electronic hook gauges. The tankage system shown in Figure 1 was analyzed for tank sizes ranging from 50 to 5000 ft³, inflow rates of 1%/min, outflow rates of 1 and 0.01%/min and TVS flowrate of 1 and 0.1%/min. An optimum weight system was determined for each tank size and flow rate analyzed.

MAJOR RESULTS. -

1. Bubble point data for the ten screens tested is shown in Table 1. φ' is defined by the equation \( \phi' \sigma / g_c D = H \) where H is the supported head.

2. Flow loss correlations for flow normal to the screens tested are tabulated in Table 2.

3. Friction factors for the screens obtained from the channel flow test data, correlated fairly well with the relative roughness and Reynolds number as depicted by Moody graphs presented in Appendix B of the report for each of the screens tested.

4. Maximum screen liner performance was obtained with 325×2300 screen, but for some cases 150×150 screen provided the lowest weight system. For long duration missions (300 days) pump efficiency was very important because pump boiloff became the design driver.
Table 1. Alcohol and 34.5 N/cm² (50 psia) LH₂ Bubble-Point Test Data

<table>
<thead>
<tr>
<th>Screen</th>
<th>Presented bubble point in psig</th>
<th>Presented bubble point in pressure of 50 psig</th>
<th>LH₂ data</th>
<th>Manufacturer's stated alcohol data</th>
<th>D</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>325 x 2,300 (0.0011 x 0.0023)</td>
<td>13.90</td>
<td>6.5008</td>
<td>21.10</td>
<td>6.6602</td>
<td>0.4615</td>
<td>10</td>
</tr>
<tr>
<td>200 x 1,400 (0.0006 x 0.0019)</td>
<td>16.55</td>
<td>16.51</td>
<td></td>
<td>6.3117</td>
<td>0.2377</td>
<td>14</td>
</tr>
<tr>
<td>100 x 1,600 (0.0003 x 0.0025)</td>
<td>7.73</td>
<td>7.73</td>
<td></td>
<td>0.1155</td>
<td>0.1765</td>
<td>20.4</td>
</tr>
<tr>
<td>720 x 20 (0.0016 x 0.0041)</td>
<td>7.02</td>
<td>7.82</td>
<td></td>
<td>0.3764</td>
<td>0.1875</td>
<td>24</td>
</tr>
<tr>
<td>115 x 100 (0.0003 x 0.0020)</td>
<td>6.70</td>
<td>4.76</td>
<td></td>
<td>0.1824</td>
<td>0.1826</td>
<td>26</td>
</tr>
<tr>
<td>53 x 150 (0.0007 x 0.0031)</td>
<td>3.45</td>
<td>3.30</td>
<td></td>
<td>0.0317</td>
<td>0.0582</td>
<td>15</td>
</tr>
<tr>
<td>150 x 150 (0.0020 x 0.0029)</td>
<td>2.23</td>
<td>0.0400</td>
<td>2.25</td>
<td>0.0161</td>
<td>0.0160</td>
<td>105</td>
</tr>
<tr>
<td>24 x 110 (0.0004 x 0.0021)</td>
<td>1.600</td>
<td>1.605</td>
<td></td>
<td>0.1452</td>
<td>0.0300</td>
<td>155</td>
</tr>
<tr>
<td>60 x 60 (0.0030 x 0.0030)</td>
<td>0.998</td>
<td>0.996</td>
<td></td>
<td>0.0221</td>
<td>0.0220</td>
<td>253</td>
</tr>
<tr>
<td>40 x 40 (0.0020 x 0.0020)</td>
<td>0.623</td>
<td>0.502</td>
<td></td>
<td>0.0133</td>
<td>0.0176</td>
<td>361</td>
</tr>
</tbody>
</table>

General breakdown: 1.4%.

Single wire breakdown: 0.6%.

Table 2. Flow Loss Correlation

<table>
<thead>
<tr>
<th>Screen</th>
<th>( d ) (in)</th>
<th>( b ) (in)</th>
<th>( c ) (in)</th>
<th>( D ) (in)</th>
<th>( A )</th>
<th>( B )</th>
<th>( H ) (in of 50 psig)</th>
<th>( V ) (in/sec)</th>
<th>( T ) (in/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 x 10</td>
<td>0.00025</td>
<td>0.000073</td>
<td>0.000215</td>
<td>0.000002</td>
<td>0.0451</td>
<td>0.542</td>
<td>2.220</td>
<td>0.00239</td>
<td>0.0063</td>
</tr>
<tr>
<td>100 x 10</td>
<td>0.00025</td>
<td>0.000073</td>
<td>0.000215</td>
<td>0.000002</td>
<td>0.0451</td>
<td>0.542</td>
<td>2.220</td>
<td>0.00239</td>
<td>0.0063</td>
</tr>
<tr>
<td>50 x 10</td>
<td>0.00025</td>
<td>0.000073</td>
<td>0.000215</td>
<td>0.000002</td>
<td>0.0451</td>
<td>0.542</td>
<td>2.220</td>
<td>0.00239</td>
<td>0.0063</td>
</tr>
<tr>
<td>25 x 10</td>
<td>0.00025</td>
<td>0.000073</td>
<td>0.000215</td>
<td>0.000002</td>
<td>0.0451</td>
<td>0.542</td>
<td>2.220</td>
<td>0.00239</td>
<td>0.0063</td>
</tr>
<tr>
<td>15 x 10</td>
<td>0.00025</td>
<td>0.000073</td>
<td>0.000215</td>
<td>0.000002</td>
<td>0.0451</td>
<td>0.542</td>
<td>2.220</td>
<td>0.00239</td>
<td>0.0063</td>
</tr>
<tr>
<td>10 x 10</td>
<td>0.00025</td>
<td>0.000073</td>
<td>0.000215</td>
<td>0.000002</td>
<td>0.0451</td>
<td>0.542</td>
<td>2.220</td>
<td>0.00239</td>
<td>0.0063</td>
</tr>
</tbody>
</table>

*Based on Eq. (1) of the reference.*

Figure 1. Conceptual Tankage Design

Figure 2. Flow-Loss Test Apparatus
OBJECTIVE. - Design passive acquisition/expulsion systems for subcritical storage of cryogens in the Space Shuttle Orbiter and the Space Tug propulsion systems.

PERTINENT WORK PERFORMED. - The dual screen liner (DSL) approach was chosen as the baseline for this study. The basic DSL concept, shown in Figure 1, was designed to provide liquid free vapor in the outer annulus for venting, vapor free liquid for expulsion between the two spherical screens and near continuous control of the bulk propellant in the inner sphere. Venting of the vapor annulus must be performed within the bubble point of the outer screen liner in order to assure that liquid does not enter this region during venting. Communication screens, with lower bubble point than the screen liners, are used to vent the inner sphere to the outer annulus. A channel/liner system was examined for reducing residuals. The system relies upon wicking to keep the liner wet between channels. The channels replace the liquid annulus. Use of a weeping tank concept with a permeable membrane vented to vacuum, to control pressure over a wider pressure band than the basic DSL concept was considered. The DSL concept was also applied to cryogenic feedlines as shown in Figure 2.

Information was presented in four basic categories related to cryogenic acquisition system evaluation and design: (1) Fluid Mechanics (2) Thermal and Thermodynamics (3) Structures and (4) Configuration and Size. Computer models were constructed to predict outflow capability and used to generate parametric data. Subscale DSL tests conducted with noncryogens on the KC-135 aircraft qualitatively demonstrated system expulsion capability. Analyses were conducted for evaluating start transients, screen to screen joining and screen to plate joining were accomplished with spot welding, brazing and soldering. Welding is the superior method. Series feed tankage was selected over parallel feed tankage based on lower weight and complexity. A development plan was presented including an orbital test program (see Tables VI-1 to VI-4 of the report).

MAJOR RESULTS. -

1. Bubble collapse times computed for LH$_2$ and LO$_2$ are shown in Figure 3.

2. Screen to screen joining and screen to plate joining were accomplished with spot welding, brazing and soldering. Welding is the superior method.

3. Series feed tankage was selected over parallel feed tankage based on lower weight and complexity.

4. A development plan was presented including an orbital test program (see Tables VI-1 to VI-4 of the report).
Figure 1. Basic DSL Concept

Figure 2. Screen Liner Cryogenic Feedlines

Figure 3. Collapse Time for Spherical Vapor Bubble in Subcooled Liquid (Prisnyakov) 11-17
OBJECTIVE. - Verify cryogenic system design for the dual screen liner (DSL) concept with subscale ground tests.

PERTINENT WORK PERFORMED. - Low g tests were conducted in a KC-135 using plexiglas models and noncryogenic fluids. These tests evaluated DSL expulsion, bubble collapse, and capillary pumping. One g bench tests were run to determine multilayer screen layer bubble point, temperature dependency of bubble point in LN₂ and LO₂, vapor flow pressure loss across wetted screen and screen/plate barriers, prevention of screen breakdown while venting within a ΔP band, screen/plate wicking, fine mesh screen structural capability, nonvisual bubble point test techniques, feedline screen liner operation and vibration effects on screen retention. Tests were conducted on a DSL in a 25 in. diameter spherical tank (Figure 1) using liquid hydrogen and liquid nitrogen as test fluids.

MAJOR RESULTS.
1. Except for some bubbles observed during flow initiation, the low gravity aircraft tests demonstrated low-g gas free liquid expulsion. The initial gas ingestion occurred because of vapor trapped in the device during high g loadings.
2. Bubble collapse test data compared fairly well with theoretical collapse time predicted by $\gamma = 1 - 2 \epsilon / \sqrt{\Delta H}$ (see Table 1 for nomenclature).
3. Multilayer screen layers must be maintained in a wetted condition using wicking or capillary pumping in order to provide additive bubble points.
4. Screen bubble point depends upon temperature, as shown in Figure 3.
5. Lower vapor flow pressure drops occur for wetted screen/perforated plate than for wetted screen alone. (Figure 2).
6. Bubble point-rewetting tests indicate that once vapor penetrates a wetted screen, pressure drop must be dropped to 57% of the bubble point to assure rewetting and resealing of the screen.
7. Order of magnitude increases in wicking distance were obtained for screen/plate combinations compared to screen alone.
8. For sinusoidal vibration tests, retention failure corresponded to model resonance. Hydrostatic analysis successfully predicted screen retention capability during random vibration.
9. Cryogenic tests successfully demonstrated DSL expulsion capability in -1g with both cold and warm gas pressurization. Venting could not be successfully demonstrated because of adverse thermal stratification.
**Figure 1.** Assembly Dwg for 63.5 cm (25 in.) Subscale Model

**Figure 2.** Methanol Screen and Perforated Plate Data Adjusted to Common Bubble Point

\[
Ja = \frac{\text{Jacob No.}, (\rho \frac{A_c}{C_p} \Delta T)/[\rho_V \lambda]}{r_b} \\
\Delta T = T_{sat} - T_b \\
\epsilon = 1 + \frac{\rho_V}{\rho_L} (2Ja - 1) \\
\lambda = \text{latent heat of evaporation} \\
\rho_V = \text{vapor density} \\
\rho_L = \text{liquid density} \\
\tau_H = \frac{4Ja^2 \alpha t}{\pi r_0^2}
\]

**Table 1.** Nomenclature

11-19
OBJECTIVE. - Select a surface tension propellant management system for the Viking 75 Orbiter.

PERTINENT WORK PERFORMED. - Mission requirements were analyzed in order to provide gas free propellant to the engine and to position propellant symmetrically about each tank centerline for spacecraft center of mass control. The entire device had to be installed and removed through a 9 in. drain access hole. Several candidates (Figure 1) were evaluated with the selection rapidly narrowed to a choice between truncated central cross and a central baffle concepts. Both concepts act to position propellant over the outlet, drive the ullage bubble radially outward and forward, locate the propellant center of mass on the tank axis, stabilize the ullage bubble on the tank centerline at the forward end of the tank to reduce disturbance during pressurization, and provide vent port access to the vapor for relief valve depressurization of the tanks. The central baffle concept, while structurally more complicated, was selected over the central cross because of its greater ability to control the ullage and minimize slosh disturbances. A typical mission operational sequence is shown for the central baffle design in Figure 2.

The baffles are configured to cause vapor to move to an equilibrium position near the vent. This is illustrated in Figure 3 where the force driving the bubble to its equilibrium position is shown as a function of location along the tank centerline. Bubble motion, caused by reorientation or disturbing accelerations, is damped by the surface forces between the contained fluid and the solid surfaces. An extended tube arrangement was selected for the pressurization/vent tube. A capillary channel of 0.01 in$^2$ cross sectional area, conforming to the inside of the tank, was used for capillary pumping of condensate from the cold forward end of the tank to the warm forward end.

A development test program was proposed using a functional matrix chart that is difficult to understand. (Much of this material was presented in DeBrock, 1973). A spherical tank baffle device was designed, fabricated from pure titanium sheet, and subjected to low frequency slosh vibrations in a 30 in. diameter plastic tank. Baffle elements were able to withstand the imposed structural loading. A furling tool was also designed and fabricated for installing a one piece baffle through a small propellant tank access hole.

MAJOR RESULTS. -

1. A passive design for providing fluid center of mass, vapor free liquid outflow and liquid free vapor for venting was developed.

2. Fabrication and structural evaluation studies indicated the feasibility of the crossed baffle design.
Figure 1. Candidate Concepts

Figure 2. Typical Operating Sequence of Viking Propellant Management

Figure 3. General Profile of Baffle Driving Capability
AN INTEGRATED START TANK FOR CRYOGENIC PROPELLANT CONTROL
Blackmon, J.B., Castle, J.N., MACDAC, 12th JANNAF Liquid Propulsion Meeting, Nov. 1970

OBJECTIVE. - Develop the preliminary design of an integrated start tank/screen retention system, and compare this system with settling techniques and other capillary acquisition systems.

PERTINENT WORK PERFORMED. - An LH$_2$ start tank composed of off-the-shelf hardware was designed consisting of an auxiliary pressure vessel containing a screen retention device located in the main propellant tank with one fill and one vent valve as shown in Figure 1. The design is integrated with a thermodynamic vent system. The start tank provides; quick restart, good thermal protection of the screen retention device, refill ability at low and high g, normal gravity checkout capability, and liquid inlet for a thermodynamic vent system. Warm helium pressurization is employed for the main liquid hydrogen tank and cold helium for the start tank. Operationally, the start tank provides liquid delivery to the feedline and main engines. Main engine thrust settles the propellant. The main tank is pressurized to 2 to 3 psi greater than the start tank after liquid has cleared from the top of the tank. After the main tank is settled, the start tank refill and vent valves are opened and the main tank fluid refills the start tank while supplying engine outflow. Between burns, a vapor bypass line is provided in the feedline to vent vapor back to the start tank, maintaining the feedline full of liquid. Vacuum refill was described for refilling the start tank in low-g. Pressure rise rate curves for the start tank were utilized to determine thermal conditioning requirements. A small scale model ground demonstration start tank was fabricated and successfully fluid dynamically tested using water as the test fluid. Settling and refill were simulated using a large balloon to initially hold liquid away from the start tank. Breaking the balloon initiated settling. Settling work reported is similar to Blackmon et al, 1968.

MAJOR RESULTS. -
1. The major advantages of the start tank compared to partial and total control screen devices are more direct pressure and screen control and small head requirements for the screen retention surfaces.

2. The start tank hardware weight is higher than a start basket but the pressurization system weight is lower since hot gas pressurization may be used in the main tank when a start tank is employed for settling the main tank liquid.

3. Start tank weight estimates as a function of volume are shown in Figure 2.

COMMENTS. - Figure 2 is presented merely to illustrate the general weight trend of start tank components. Burge and Blackmon, 1973 gives more detail weight breakdowns.
Figure 1. MDAC Start Tank Schematic

Figure 2. Start Tank Volume (Ft$^3$)
OBJECTIVE. - Experimentally determine the effect of flight vibration environments on the performance of a spherical surface propellant expulsion screen.

PERTINENT WORK PERFORMED. - An 11.6 inch diameter spherical test screen of pleated 250 × 1370 mesh 304L stainless steel dutch twill wire cloth was mounted in a spherical Plexiglas test tank. The tank screen assembly was mounted to an exciter capable of a 5-2000 Hz frequency range and a one-inch peak-to-peak stroke. The fluid outlet was at the top of the tank. Testing was conducted using isopropyl alcohol and Freon 113. Simulated launch vibration tests using both sinusoidal and random vibration were conducted. Specific conditions run for each test are specified in Table 1. Operating vibration tests were conducted by imposing random vibration levels on the test model as tabulated in Table 2. Frequency was increased as a function of time for both launch and operating vibration tests. Data was evaluated by summing the gravitational and vibrational acceleration vectorially and comparing the resultant pressure differential due to acceleration with the pressure retention capability of the screen.

MAJOR RESULTS. -

1. Screen retention capability was evaluated in Figure 1 for low frequency range vertical sinusoidal vibrations by comparing the pressure differentials during vibration to the retention pressure, \( \Delta P_o \), where \( \Delta P_o = \phi (2\sigma/d) \). (\( d \) is the bubble point of 17 microns and \( \phi \) is normally assumed to be 1.36). At low frequency, data agreed fairly well with theory.

2. Large pressure differentials, compared to the retention pressure were required to produce retention failure when using low frequency lateral sinusoidal vibrations.

3. High frequency range data indicates that, above a threshold frequency simple hydrostatic theory is insufficient for predicting screen performance under sinusoidal vibration. Retention was maintained even though peak pressure due to accelerations were above the bubble point pressure. The author postulated that this was caused by surface elasticity effects or reduced transmissibility due to gas bubbles trapped between the screen and the tank wall.

4. Screen resonant frequency was found to vary directly with screen pressure differential (Figure 2). Violent screen failure at high frequency was attributed to screen resonance.

5. Hydrostatic theory appeared to predict performance during random vibration tests.

COMMENTS. - This work illustrated that additional testing was required in improving upon hydrostatic theory and in investigating screen resonance.
Table 1. Simulated Launch Vibration Test Matrix

<table>
<thead>
<tr>
<th>TEST FLUID</th>
<th>TANK PRESSURE</th>
<th>AXIS</th>
<th>MODE</th>
<th>LEVELS</th>
<th>FREQUENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISOPROPYL ALCOHOL</td>
<td>30 PSIA</td>
<td>VERTICAL</td>
<td>RANDOM</td>
<td>6.55 G RMS</td>
<td>30-2000 Hz</td>
</tr>
<tr>
<td>ISOPROPYL ALCOHOL</td>
<td>30 PSIA</td>
<td>VERTICAL</td>
<td>RANDOM</td>
<td>6.55 G RMS</td>
<td>30-2000 Hz</td>
</tr>
<tr>
<td>ISOPROPYL ALCOHOL</td>
<td>30 PSIA</td>
<td>LATERAL</td>
<td>RANDOM</td>
<td>6.55 G RMS</td>
<td>30-2000 Hz</td>
</tr>
<tr>
<td>FREON 113</td>
<td>30 PSIA</td>
<td>VERTICAL</td>
<td>RANDOM</td>
<td>2.0 G RMS</td>
<td>30-2000 Hz</td>
</tr>
</tbody>
</table>

Table 2. Operating Vibration Test Matrix

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>TEST FLUID</th>
<th>TANK PRESSURE</th>
<th>FLOW RATE</th>
<th>AXIS</th>
<th>MODE</th>
<th>LEVEL</th>
<th>FREQUENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>ISOPROPYL ALCOHOL</td>
<td>30 PSIA</td>
<td>0.55 LB/SEC</td>
<td>VERTICAL</td>
<td>RANDOM</td>
<td>6.55 G RMS</td>
<td>30-2000 Hz</td>
</tr>
<tr>
<td>20</td>
<td>ISOPROPYL ALCOHOL</td>
<td>30 PSIA</td>
<td>1.50 LB/SEC</td>
<td>VERTICAL</td>
<td>RANDOM</td>
<td>6.55 G RMS</td>
<td>30-2000 Hz</td>
</tr>
<tr>
<td>21</td>
<td>ISOPROPYL ALCOHOL</td>
<td>30 PSIA</td>
<td>0.13 LB/SEC</td>
<td>LATERAL</td>
<td>RANDOM</td>
<td>6.55 G RMS</td>
<td>30-2000 Hz</td>
</tr>
<tr>
<td>22</td>
<td>FREON 113</td>
<td>30 PSIA</td>
<td>0.16 LB/SEC</td>
<td>VERTICAL</td>
<td>RANDOM</td>
<td>2.0 G RMS</td>
<td>30-2000 Hz</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of Theory and Test Results

Figure 2. Frequency - Pressure Correlation for Screen Resonance

11-25

OBJECTIVE. - Determine the feasibility of using cryogenic capillary devices for low gravity propellant control.

PERTINENT WORK PERFORMED. - Two missions were considered; a single restart mission for the LO₂/LH₂ S-IVC and a propellant transfer mission using a LOX tanker to fill an S-IIb.

Capillary devices were designed based on fluid and thermal analysis. The fluid analysis considered screen pressure drop, retention, settling spilling, vapor ingestion, refilling and venting. The thermal analysis considered both passive and active means for preventing vapor formation from within the capillary devices.

Bench tests were run using pentane and dutch twill (wicking) and square weave (non-wicking) screens of similar bubble point to qualitatively determine the retention capability of capillary burners subjected to evaporation.

Capillary device designs developed were compared to bladders, dielectrophoresis, and linear acceleration on the basis of cost, reliability, weight and manufacturing feasibility. Because of the uncertainty in predicting settling time for S-IVC conditions, comparisons were made over a range of settling times.

MAJOR RESULTS. -

1. The venting analysis demonstrated that significant quantities of vapor could be formed in the capillary device if pressure was not controlled within a narrow band. A thermodynamic vent system can be used for this purpose as well as to cool the capillary device and feedline.

2. The settling analysis demonstrated the importance of geysering, recirculation and turbulent dissipation when employing high Bond number settling.

3. Wicking screens have better retention capabilities than nonwicking screens when subjected to evaporation.

4. The LOX tanker system capillary design (Figure 1) compared favorably with other means of propellant control (Table 1). Bladders, although slightly lower in weight have permeability problems with cryogens and possible LO₂ impact problems.

5. The S-IVC LO₂ and LH₂ start baskets compared favorably with other means of propellant control (Figure 2).
Figure 1. Oxidizer Collector System

Figure 2. Equivalent Hardware Weight Comparison for S-IVC Mission Restart

Table 1. \( \text{LO}_2 \) Tanker Weight Comparisons

<table>
<thead>
<tr>
<th>TYPE OF PENALTY</th>
<th>SETTLING</th>
<th>SETTLING WITH SCAVENGING</th>
<th>ALUMINUM SURFACE TENSION (CHANNELS)</th>
<th>ALUMINUM SURFACE TENSION CHANNELS (STAINLESS SCREENS)</th>
<th>STAINLESS SURFACE TENSION (FULL LINER)</th>
<th>DIELECTROPHORESIS</th>
<th>ALL STAINLESS (SURFACE TENSION CHANNELS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VENT SYSTEM</td>
<td>10</td>
<td>10</td>
<td>25</td>
<td>25</td>
<td>50</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>TRANSFER SYSTEM</td>
<td>100</td>
<td>100</td>
<td>417</td>
<td>522</td>
<td>685</td>
<td>488</td>
<td>163</td>
</tr>
<tr>
<td>RESIDUALS</td>
<td>1,883</td>
<td>33</td>
<td>33</td>
<td>33</td>
<td>33</td>
<td>33</td>
<td>925</td>
</tr>
<tr>
<td>SECONDARY PROPULSION</td>
<td>700</td>
<td>1,467</td>
<td>777</td>
<td>777</td>
<td>777</td>
<td>-</td>
<td>777</td>
</tr>
<tr>
<td>ADDED PRESSURANT</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2,693</td>
<td>1,610</td>
<td>1,252</td>
<td>1,357</td>
<td>1,512</td>
<td>1,308</td>
<td>1,128</td>
</tr>
</tbody>
</table>

11-27
OBJECTIVE. - Analytically and experimentally evaluate fluid and thermal problems associated with cryogenic capillary propellant control devices.

PERTINENT WORK PERFORMED. - Fluid analysis of the S-IVC and LOX tanker missions (see Blatt, et al, Phase I, 1970) consisted of capillary device outflow, liquid settling, wicking, vapor impingement and refilling. Computer programs were formulated for analysis of wicking and outflow in order to correlate experimental data. Thermal analysis was devoted to detailed sizing of capillary device cooling configurations and consideration of destratification and mixing effects on cooling system operation. Systems designed for both missions used the normal boiloff capability of a thermodynamic vent system to maintain the contained liquid in a slightly subcooled condition. The feedline was maintained filled with liquid up to a conical screen barrier near the engine. The structural design effort consisted of developing weight estimates, support, attachment and cooling configuration details along with load analysis and assembly drawings. Normal gravity bench tests were conducted to evaluate capillary device draining, spilling and outflow in transparent scale model S-IVC tankage. Pullthrough suppression tests were run in simple cylindrical containers to verify the analytical procedures used for sizing pullthrough suppression screens. Wicking tests were run using horizontal screens and heaters to determine the capability of wicking screens in preventing screen drying.

MAJOR RESULTS. -

1. The LO$_2$ design for the S-IVC (Figure 1) consisted of a cylinder cone arrangement over the outlet. The LH$_2$ tank reverse bulkhead design consisted of a torus extending 60° on either side of the sidewall mounted outlet.

2. The LOX tanker design employed a reservoir over the outlet for maintaining liquid outflow when a disturbance caused liquid to be reoriented off the tank walls.

3. Scale model spilling tests were successfully correlated with the INGASP computer model predictions of vapor ingestion and spilling during capillary device startup (Figure 2).

4. Residuals tests were successfully correlated with the Dregs 2 computer model prediction of capillary device draining (Figure 3).

5. Outflow tests run with screen baffles indicated that interface shape during draining and screen flow pressure drops can be used to predict screen pullthrough suppression performance.

COMMENTS. - See Symons, 1974 for more extensive wicking data.
**Figure 1. Oxidizer Reservoir Structural Arrangement**

**Figure 2. S-IVC Scale Model Spilling Tests**

**Figure 3. S-IVC Scale Model Residual Test**

Correlation
OBJECTIVE. - Provide fluid, thermal and structural design information for cryogenic capillary propellant control device design.

PERTINENT WORK PERFORMED. - The work was divided into three areas: fluid, thermal and structural design. Short descriptions of the design requirements were followed by a flow chart for conducting the analyses and design in each area.

The flow chart for fluid analysis indicated that initially a preliminary capillary device configuration should be determined for the mission conditions based on retention capability, volumetric requirements, refilling and spilling considerations and maintaining minimum surface to volume ratio. The configuration should be revised and finalized based on additional analysis of wicking, pullthrough suppression, deflecting ingested vapor, sloshing, settling, venting pressurization, spilling, refilling and draining.

The fluid analysis chapter detailed methods of analyzing retention, screen flow, wicking, settling and sloshing, spilling and vapor ingestion, refilling, tank filling, residuals, entrained vapor impingement, venting, pressure collapse, and bubble dynamics.

The thermal analysis chapter detailed methods of analyzing active cooling of a capillary device with a thermodynamic vent system. After determining incident heating, vent flow rates, and heat balance on the tank and capillary device, a detailed definition of the cooling configuration should be determined based on mixing and cooling flow data over the full range of fluid conditions expected. A complete thermal analysis should then be done, using a thermal analyzer program, or the fin equations presented, in order to define the cooling tube locations, attachments, spacing, throttling pressures, mixing flow and mixer location and vent flow path. Mixing, heat transfer, and thermal control were dealt with in separate sections. Mixing, heat transfer, and vent system sizing equations were presented.

Structural and manufacturing considerations were discussed in the final chapter. Based on the vehicle tank geometry and hydrodynamic analyses, an overall profile and structural arrangement for the device should be determined. This should be used to examine external and internal loading conditions in order to establish materials requirements, gauges and sizes of supporting members, screen attachment methods, heat exchanger tube attachment methods and stiffener requirements. Specific sections dealt with loads, materials, screen attachments, heat exchanger attachments, configurations for minimum weight, and screen clogging.

A SURVEY OF CURRENT DEVELOPMENTS IN SURFACE TENSION DEVICES FOR PROPELLANT ACQUISITION

OBJECTIVE. - Survey current developments in capillary propellant acquisition devices.

PERTINENT WORK PERFORMED. - Analysis techniques, performance test methods, materials compatibility structural test methods, fabrication, handling, acceptance testing, and flight experience with capillary propellant acquisition devices were described.

Capillary devices were compared to other methods of expulsion. Capillary devices have the principal attributes of passiveness and consequent high reliability for long life missions. Advantages and disadvantages of other methods are presented in Table 1. Capillary acquisition device designs were described for; partial retention devices that rely upon settling for refill (Agena, Apollo, Mariner 71), and total communication approaches such as tank liners or channels (X-15 Flight Research Vehicle, 62 inch hydrazine gallery design and Viking).

Capillary system flight experience is summarized in Table 2. Characteristics of each of these flight proven systems were described. Fluids transferred by these systems ranged from Cesium to JP5.

Methods of analyzing capillary acquisition devices were described with a plethora of references cited. Areas considered were propellant surface shape, stability, liquid reorientation, start transients, and surface drainage dips. Additional work was recommended in the area of liquid reorientation and startup transients.

Performance testing was described, particularly related to model testing (See De Brock 1973). Descriptions were given of mission events to be evaluated, dominant variables and test methods. Use of these methods on Agena was described related to static and dynamic retention, transient propellant withdrawal, restart and geysering and refill during fluid reorientation.

Materials compatibility testing being conducted at JPL was described. Surface tension tests to determine the time dependence of surface tension with several propellant/material combinations were about to be conducted for screen materials.

Resistance spot welding techniques were described for fabricating screen devices. Subassembly procedures for capillary device installation and removal in the tank were described. Acceptance testing commonly consists of bubble testing.

COMMENTS. - The LEM and Transtage propellant restart devices cited in Table 2 have not actually been flight tested since propellant is settled with ACS engines prior to engine restart.

11-32
Table 1. Positive Expulsion System Comparison

<table>
<thead>
<tr>
<th>EXPULSION SYSTEM</th>
<th>STRONG POINTS</th>
<th>PROBLEM AREAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pistons</td>
<td>Positive displacement; variable initial ullage gas volumes</td>
<td>Heavy; leakage; jamming due to cocking or corrosion; limited to cylindrical tanks</td>
</tr>
<tr>
<td>Bladders</td>
<td>Much development and flight experience; adaptable to most tank geometries and initial gas ullage volume</td>
<td>Long term compatibility; gas permeation; poor expulsion efficiency; folding geometry conducive to pinhole leaks</td>
</tr>
<tr>
<td>Metallic Bellows</td>
<td>Good compatibility; predictable performance adaptable to varying tank geometries and initial ullage volumes</td>
<td>High weight; cocking during expulsion</td>
</tr>
<tr>
<td>Elastomeric Diaphragm</td>
<td>Good expulsion efficiency; trouble free and repeatable diaphragm geometry during expulsion</td>
<td>Poor wear characteristics during prolonged propellant slosh; poor long life compatibility; limited to spherical tank geometry with significant initial ullage volume</td>
</tr>
<tr>
<td>Metallic Diaphragm</td>
<td>Good compatibility; not sensitive to propellant slosh</td>
<td>Limited to spherical tank geometry with significant initial ullage volume</td>
</tr>
<tr>
<td>Rolling Diaphragm</td>
<td>Good compatibility; not dependent on initial ullage volume</td>
<td>High ΔP required for expulsion; limited to cylindrical tank geometry</td>
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</tbody>
</table>

Table 2. Summary of Flight Experience

<table>
<thead>
<tr>
<th>FLIGHT APPLICATION</th>
<th>BASIC FUNCTION</th>
<th>NO. OF FLIGHTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Agena</td>
<td>Propellant retention and propellant supply during low-g restarts</td>
<td>&gt;120</td>
</tr>
<tr>
<td>Apollo Service Module</td>
<td>Propellant retention and gas phase flow blockage during propellant settling</td>
<td>11</td>
</tr>
<tr>
<td>Apollo Lunar Excursion Module</td>
<td>Propellant retention in feed line</td>
<td>6</td>
</tr>
<tr>
<td>Transtage</td>
<td>Gas phase flow blockage during propellant settling</td>
<td>&gt;20</td>
</tr>
<tr>
<td>ATS Cesium Ion Propulsion Subsystem</td>
<td>Vapor phase propellant feed</td>
<td>3</td>
</tr>
<tr>
<td>MQM - 74A Drone</td>
<td>Gas phase flow blockage</td>
<td>322</td>
</tr>
<tr>
<td>Firebee II Drone</td>
<td>Gas phase flow blockage</td>
<td>9</td>
</tr>
</tbody>
</table>
EXPERIMENTAL INVESTIGATION OF CAPILLARY PROPELLANT
CONTROL DEVICES FOR LOW GRAVITY ENVIRONMENTS
Contract No. NAS8-21259, June 1970

OBJECTIVE. - Experimentally investigate the liquid/gas interfacial stability of perforated plate under an acceleration acting both normal and parallel to the surface, passive schemes for preventing the passage of settled propellants, and liquid filling of capillary annuli.

PERTINENT WORK PERFORMED. - All work was done in the Martin 2.1 second drop tower. Stability criteria tests for acceleration perpendicular to square weave screen and perforated plate were described thoroughly in Barksdale and Paynter 1968. Damping tests, similar to stability tests, were run with liquid initially below the level of the barrier. An acceleration was applied normal to the surface of the barrier to reorient the (flat surfaced) fluid to the opposite end of the transparent flat bottomed cylindrical tank. Barriers evaluated were; single and double perforated plate, single and double square weave screen, multi-tube and single tube configurations, and single layer Dutch-twill cloth.

The hydrostatic stability of Dutch-twill and square weave screen and perforated plates were evaluated for accelerations imposed parallel to the plane of the barrier material. Liquid initially was 1/4" or less above the barriers. A dimensionless number, \( \phi \), representing the ratio of acceleration to surface forces was used to delineate between stable and unstable interface behavior. \( \phi = a_L h/r \), where \( a_L \) = lateral acceleration, \( h \) = lateral distance (tank diameter), \( r \) is the pore radius and \( \beta \) is the dynamic surface tension. Twenty one drop tests were made using simple cylindrical and spherical glass specimens, with a concentric screen liner to provide a liquid flow annulus, for evaluating capillary refilling of annuli. Filling theory was presented for computing the capillary fill rate based upon surface tension and friction forces.

MAJOR RESULTS. -

1. Performance of porous barriers in damping settling flow was characterized into six flow regimes. (Table 1). Results shown in Figure 1, as a function of barrier Weber number, indicate that Dutch twill screens, because of their small pore size, resist the passage of settling flow. In Figure 1, \( \xi \) is the ratio of open to closed area.

2. For interface stability with accelerations parallel to the porous barrier, values of \( \phi \) were found to be; \( \phi \approx 1.1 \) for Dutch twilled screen and \( 0.85 < \phi < 0.95 \) for square weave screen. For perforated plate, \( 2.1 < \phi < 2.5 \) for \( 9.5 \leq \xi \leq 22.7\% \) and \( 1.2 < \phi < 1.7 \) for \( \xi = 36.2\% \).

3. For capillary filling of annuli comparison of data and predictions is shown in Figure 2. General conclusions were that perforated plate or square weave screen will be required to prevent wicking from impeding annulus filling.
Table 1. Damping Flow Regimes

A No liquid passes through the barrier;

B Some liquid (relatively little) passes during wetting of the barrier by liquid settling along the wall of the cylindrical specimen;

C The dome of the liquid column either penetrates the barrier, resulting in a sessile globule, or recedes completely;

D The central liquid mass penetrates the barrier as one or two columns that pinch off and stay above the barrier, but no additional liquid passes;

E Similar to D, but the columns are not completely pinched off;

F A considerable amount of liquid passes through most of the barrier surface, and there is a number of columns (streamers);

G A massive amount of liquid passes through the barrier with no apparent damping.

Figure 1. Damping Performance of Selected Barriers

Figure 2. Annulus Fill Time vs Liquid-to-Container Volume Ratio
OBJECTIVE. - Analytically and experimentally determine a critical Weber number for incipient gas passage through a rotating barrier during rotational maneuvers.

PERTINENT WORK PERFORMED. - A simple capillary barrier (Figure 1) for engine restart was analyzed to determine the effect of rotational maneuvers on liquid and vapor flow through the capillary barrier. Flow was taken to be incompressible, inviscid and irrotational. The cylindrical tank was filled to a height h just above the capillary barrier. A short duration, high torque angular impulse was applied instantaneously generating the rotation. For centerline clockwise motion the flow field tended to cause gas passage at the hole on the extreme right of the barrier. A model of this pore is shown in Figure 2. The critical case occurs when the interface is pulled just to the hemispherical shape. An equation was formulated relating the conditions at incipient gas passage through the barrier to the tank geometry and location of the axis of rotation. The barrier hole size does not enter into the relationship. The theory was limited by the assumption that the openness of the screen is one.

Experimental data was obtained in order to determine the influence of the critical Weber number on the openness ratio Op. Tests were conducted in 4.75" and 5.0" I.D. plexiglas model cylindrical tanks with hemispherical ends. Carbon tetrachloride was used as the test fluid. Twenty two useful tests were obtained from the KC-135 testing.

MAJOR RESULTS. -

1. Experimental data is shown in Figure 3 (see Table 1 for nomenclature) to delineate between stable and unstable barrier behavior as a function of actual Weber number, openness ratio and theoretical critical Weber number. Critical Weber number increases significantly with increasing openness ratio.

COMMENTS. - Results of this paper should be compared to lateral and normal stability and retention capability to formulate critical design criteria for barrier sizing for typical mission requirements.
Table 1. Nomenclature

- \( a \) = tank radius
- \( d \) = diameter of hole or perforation in capillary barrier
- \( F(t) \) = function of time in Bernoulli equation
- \( g \) = acceleration or gravity field
- \( h \) = height of the barrier above the tank bottom, where volume below barrier is taken as an equivalent right circular cylinder
- \( J_1 \) = Bessel function of first order and first kind
- \( l \) = normal distance from center of rotation to barrier
- \( O_a \) = ratio of hole area to total barrier area
- \( P \) = pressure; \( P_g \) = gas pressure
- \( q \) = velocity vector
- \( r \) = a cylindrical coordinate in inertial frame instantaneously coinciding with tank radial coordinate
- \( R \) = radius of curvature
- \( s \) = average height of liquid above capillary barrier
- \( t \) = time
- \( U \) = velocity in \( x \) direction
- \( V \) = volume of spherical segment
- \( W \) = velocity in \( Z \) direction
- \( W_{cr} \) = critical Weber number, value of Weber number at incipient gas passage through barrier
- \( W_k \) = velocity of liquid through barrier hole relative to tank velocity
- \( \langle W \rangle_R \) = average value of \( W_k \) during growth of interface to maximum size
- \( W_t \) = tank velocity in \( Z \) direction
- \( \tau \) = coordinate in inertial framework
- \( X \) = height of spherical segment
- \( Z \) = coordinate in inertial frame instantaneously coinciding with the tank axis, taken as positive in the downward direction
- \( \gamma \) = coefficient of bubble pressure term
- \( \theta \) = rotation rate about axis perpendicular to tank longitudinal axis
- \( \nu \) = kinematic viscosity
- \( \xi_0 \) = roots of \( J_1 \) (arg) = 0
- \( \rho \) = liquid density
- \( \sigma \) = liquid surface tension
- \( \phi \) = angular coordinate in inertial framework instantaneously coinciding with tank coordinate
- \( \Phi \) = velocity potential
- \( \Phi_f \) = final velocity potential for case of \( O_a \) approaching 1
- \( \Phi_i \) = initial velocity potential for case of \( O_a \) approaching 1

Figure 1. Model for Theoretical Development, a) Total Model, b) Interface Growth at Most Vulnerable Hole

Figure 2. Critical Weber number as a Function of Geometry and Position of Axis of Rotation

Figure 3. Normalized Capillary Barrier Stability Results
OBJECTIVE. - Develop capillary propellant management system designs for the oxidizer and fuel tanks of an Apollo spacecraft propulsion system.

PERTINENT WORK PERFORMED. - For design groundrules and configuration requirements, see Section 10.0, Barksdale, 1969. Identical designs were selected for both oxidizer and fuel tanks, although requirements for the oxidizer tank were more stringent. Designs were developed both for retrofit within the baseline tankage (Figure 1) and for a no-hardware limitation configuration (Figure 2). Device geometry was influenced mainly by containing sufficient fluid to perform 500 restarts independent of the system thrust profile. Screen sizing was primarily based on the acceleration environment. Analyses were conducted to support the design effort. These analyses considered screen static retention capability, hydrostatic stability at the screen, damping of liquid motion by capillary barriers, reorientation, refilling, and draining. The Marker and Cell technique was used to compute initial fluid motion during both reorientation and annulus draining. A plexiglass model of the existing Apollo spacecraft propulsion system, approximately one-fifth scale, was used with a model of the capillary device. Sixty-eight tests were conducted. Five drop tests were run demonstrating the retention capability of the coverplate screen assembly under a lateral acceleration environment. Seventeen resettle tests were conducted. These tests dropped liquid on the capillary device from a screened compartment that stabilized the liquid to be settled. The pressure supported liquid was released when the compartment vent valve was opened. Low gravity interface shapes were analytically determined for the liquid vapor interface in both compartments of the propellant trap. The configuration analyzed is shown in Figure 3. A series of 19 drop tests were run using 1/5 and 1/12 scale model tanks.

MAJOR RESULTS. -

1. No difficulties were experienced in filling the liner completely if the screen was dry before introduction of the fluid and the fill rate exceeded the screen wicking rate.

2. Liquid settling and capillary device refill tests demonstrated successful capillary device refilling during outflow.

3. Interface configurations found from drop tests demonstrated that sufficient liquid would contact the screens to accomplish low gravity restart.

COMMENTS. - The report does not discuss the correlation, if any, between the settling and interface configuration analyses and test.

11-38
Figure 1. Retrofit Design

Figure 2. No Hardware Limitation Design

Figure 3. Configuration for Computer Analysis
OBJECTIVE - Experimentally determine the Bond number stability criteria for square weave screens and perforated plates.

PERTINENT WORK PERFORMED - Tests were conducted over an acceleration range of 0.0013 to 0.055 g in Martin's 2.1 second drop tower facility. The acceleration was applied normal to the flat plates and screens tending to reorient the liquid from beneath the barriers to the opposite end of the 5 1/2" O.D transparent flat bottomed cylinders. Tests were conducted with 39 perforated plates and 13 square weave screens (Table 1, Figure 1). Two specimens were tested in each drop with the liquid level in the tanks sufficient to cover the barrier material and assure wetting prior to applying the destabilizing acceleration. Methanol, carbon tetrachloride and Freon TF were used as the test fluids. A literature search of hydrostatic stability was conducted and was presented in the Appendix of the report.

MAJOR RESULTS -

1. The theoretical critical Bond number \( (\alpha R^2/c) \) of 0.842 where \( R \) is the radius of the hole and \( \alpha \) is the dimensionless acceleration, delineating between stable and unstable liquid vapor interfaces at a perforated plate was compared to experimental data (Figure 2). Results agree fairly well between data and predictions.

2. The critical Bond number for square weave screen was experimentally found to be 0.45 where \( R \) is half the screen opening (Figure 3).

Figure 1. Typical Hole Layout Pattern for Plates With Constant Hole Size (See Table 1). N = Number of Holes per Hole Circle.
### Perforated Plate Barrier Specifications

**Plate No.** | **Matl.** | **Pore Size 1 (in.)** | **Pore Size 2 (in.)** | **Pore Size 3 (in.)** | **Thickness (in.)** | **T**<sub>1</sub> | **T**<sub>2</sub> | **T**<sub>3</sub> |
---|---|---|---|---|---|---|---|---|
1 | S.S. | 1.30 | 1.37 | 2.05 | 0.002 | 0.020 |
2 | S.S. | 0.60 | 1.17 | 1.70 | 0.005 | 0.087 |
3 | S.S. | 1.00 | 1.55 | 2.01 | 0.039 | 0.076 |
4 | S.S. | 0.80 | 1.65 | 2.11 | 0.039 | 0.076 |
5 | S.S. | 1.00 | 1.65 | 2.11 | 0.039 | 0.076 |
6 | Al | 1.30 | 1.70 | 2.30 | 0.002 | 0.020 |
7 | Al | 1.25 | 1.75 | 2.25 | 0.002 | 0.020 |
8 | Al | 1.00 | 1.00 | 1.00 | 0.002 | 0.020 |
9 | Al | 1.00 | 1.00 | 1.00 | 0.002 | 0.020 |
10 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
11 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
12 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
13 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
14 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
15 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
16 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
17 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
18 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
19 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
20 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
21 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
22 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
23 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
24 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
25 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
26 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
27 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
28 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
29 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
30 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
31 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
32 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |
33 | Al | 0.80 | 0.80 | 0.80 | 0.002 | 0.020 |

### E. Square Weave Screen Barrier Specifications

<table>
<thead>
<tr>
<th>Screen No.</th>
<th>Material</th>
<th>Wire Dia. (in.)</th>
<th>Open Width (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>S.S.</td>
<td>0.192</td>
<td>0.120</td>
</tr>
<tr>
<td>S-2</td>
<td>S.S.</td>
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<td>0.120</td>
</tr>
<tr>
<td>S-3</td>
<td>S.S.</td>
<td>0.192</td>
<td>0.120</td>
</tr>
<tr>
<td>S-4</td>
<td>S.S.</td>
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<td>0.120</td>
</tr>
<tr>
<td>S-5</td>
<td>S.S.</td>
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<td>0.120</td>
</tr>
<tr>
<td>S-6</td>
<td>S.S.</td>
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<td>S-7</td>
<td>S.S.</td>
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<td>S.S.</td>
<td>0.192</td>
<td>0.120</td>
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</table>

### Table 1. Foraminous Barrier Specification

<table>
<thead>
<tr>
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<th>Material</th>
<th>Wire Dia. (in.)</th>
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<tr>
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<td>S.S.</td>
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<td>S-4</td>
<td>S.S.</td>
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<td>S-5</td>
<td>S.S.</td>
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<td>0.120</td>
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<tr>
<td>S-6</td>
<td>S.S.</td>
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<td>0.120</td>
</tr>
<tr>
<td>S-7</td>
<td>S.S.</td>
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<tr>
<td>S-8</td>
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<tr>
<td>S-13</td>
<td>S.S.</td>
<td>0.192</td>
<td>0.120</td>
</tr>
</tbody>
</table>

### Notes:
- **S.S.** = stainless steel
- **Al** = aluminum
- **B** = brass

---

**Figure 2.** Stability Characteristics for Perforated Plate Barriers

**Figure 3.** Stability Characteristics of Square Weave Screen Barriers
12.0 POSITIVE EXPULSION

Covering bladders, bellows, diaphragms and pistons, with expanding or contracting surfaces to control orientation and/or to allow liquid expulsion at low-g.
ELASTOMERS FOR LIQUID ROCKET PROPELLANT CONTAINMENT
Martin, J.W., Green, H.E., TRW, AFML-TR-71-59 (Part II), F33615-71-C-1233, October 1973

OBJECTIVE. - To evaluate new elastomeric compounds for use as seal and positive expulsion diaphragm materials with hydrazine, dinitrogen tetroxide (N₂O₄), aircraft hydraulic fluids, and fluorinated oxidizers.

PERTINENT WORK PERFORMED. - Elastomers and applications evaluated included AF-E-332 for hydrazine expulsion, AF-E-411 for hydrazine seals, AF-E-124D for hydrazine and N₂O₄ expulsion, carboxynitroso rubber (CNR)/HYSTL composites for N₂O₄ expulsion, and two TRW-developed elastomers for hydraulic fluids. A new bladder fabrication technique was developed. A pressurized (1000 psi during forming) silicone rubber bag was formed to serve as the internal mandrel and a conventional two-piece female mold was used to form the outside surface. A 10.5-in. Mariner mold was used to produce bladders that exhibited uniformity and properties similar to those slab-molded under much higher pressure (Table 1). Three 4-in. AF-E-332 diaphragms were used to expel hydrazine 332 times at room temperature and 100 times at 160°F, and alcohol 100 times at -40°F, respectively, with no degradation. A 10.5-in. bladder made from the same material successfully expelled hydrazine with an expulsion efficiency of 99 percent. Long term storability test with hydrazine at 140°F indicated that the -332 material is highly compatible with the propellant (Table 2). A 4-in. bladder fabricated from AF-E-124D was unaffected by 500 room-temperature (RT) expulsion cycles with water and an additional 941 RT cycles with N₂O₄. This elastomer is characterized by good strength but susceptibility to creep after cure, high cure shrinkage, and better resistance to oxidation than any other elastomer (Table 3).

MAJOR RESULTS. -
1. A new, low-cost bladder fabrication technique was developed.
2. A new material, AF-E-332, apparently meets all of the present requirements for a hydrazine bladder or diaphragm elastomer. It is readily processable, not degraded by hydrazine up to 160°F, has no effect on fluid decomposition rate, and exhibits high cycle lifetime.
3. CNR and AF-E-124D, while not developed to the extent of AF-E-332, show excellent promise, particularly for use with N₂O₄.
Table 1. Hydrazine Permeability of 332-6 Bladder

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness, Inches</th>
<th>ΔP</th>
<th>Test Duration Hours</th>
<th>Rate, mg/cm²·hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab Molding</td>
<td>0.050</td>
<td>1 Atm</td>
<td>312</td>
<td>0.018</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.080</td>
<td>1 Atm</td>
<td>720</td>
<td>0.0055</td>
</tr>
</tbody>
</table>

Table 2. Pressure Rise Tests of AF-E-332 Bladders
(Hydrazine Storage at AFRPL)

<table>
<thead>
<tr>
<th>Bladder Tank No.</th>
<th>One Month, psi</th>
<th>Three Months, psi</th>
<th>Five Months, psi</th>
<th>Fifteen Months, psi</th>
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</thead>
<tbody>
<tr>
<td>S/N 008</td>
<td>9</td>
<td>15</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>S/N 010</td>
<td>8</td>
<td>14</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Corresponding</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tank Temperature</td>
<td>137</td>
<td>140</td>
<td>140</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 3. Retention of AF-E-124D Mechanical Properties
After 8 Days in N₂O₄

<table>
<thead>
<tr>
<th>Storage Temperature</th>
<th>Tensile Retained</th>
<th>Elongation Retained</th>
<th>Shore A Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>75°F</td>
<td>96%</td>
<td>100%</td>
<td>±0</td>
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<tr>
<td>120°F</td>
<td>95%</td>
<td>95%</td>
<td>-1</td>
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<tr>
<td>160°F</td>
<td>92%</td>
<td>96%</td>
<td>-3</td>
</tr>
<tr>
<td>200°F</td>
<td>51%</td>
<td>180%</td>
<td>-18</td>
</tr>
</tbody>
</table>

12-3
SURVEY OF MATERIALS FOR HYDRAZINE PROPULSION SYSTEMS IN MULTICYCLE EXTENDED LIFE APPLICATIONS
Coulbert, C.D., Yankura, G., JPL, NASA TM 33-561, September 1972

OBJECTIVE. - The objective of this report was to summarize and assess the existing information and data on materials compatibility with hydrazine monopropellant as applied to the requirements of Space Shuttle vehicle auxiliary propulsion systems.

PERTINENT WORK PERFORMED. - Materials were evaluated for application over a 10-year/100-mission operational lifetime with minimum refurbishment. The temperature range of interest spans the normal hydrazine liquid range (2 to 110°C). The two principal phenomena of concern in this study are (1) effect of materials on hydrazine decomposition, and (2) effect of hydrazine on material properties. However, for the shuttle mission, change in the hydrazine composition over a several year period may not be a problem, since the system will be used, drained, and refilled many times over the 10-year period. Of greater concern are the bladders, tanks, and seals which must survive the full vehicle life cycle. The three major types of metallic materials investigated are alloys of aluminum, titanium, and stainless steels. Non-metallic materials, for use as diaphragms, valve seats, or seals, were investigated with the best results being obtained with ethylene propylene rubbers (EPR) and ethylene propylene terpolymer (EPT) compounds.

The appendices of the report contain reproductions from a report by Martin on material compatibility with hydrazine, a report by Rocketdyne on hydrazine decomposition studies, a report by Pressure Systems, Inc., on EPT-10 properties as a function of hydrazine immersion time, and a summary of JPL elastomer physical property data.

MAJOR RESULTS. -

1. A number of commercial alloys of aluminum, titanium and stainless steel can be used in hydrazine systems for long-term storage.

2. EPR and EPT elastomeric compounds are the most promising for use with hydrazine. To date they have been judged satisfactory for one to two year mission applications with minimum cycling.

COMMENTS. - See the summary of the material study by Martin and Green (1973) for additional information on elastomeric materials.
OBJECTIVE. - To perform an analytical assessment of potential methods for replenishing the auxiliary propulsion, fuel cell, and life support cryogens which may be aboard an orbiting space station.

PERTINENT WORK PERFORMED. - For subcritical liquid transfer various types of expulsion techniques were analyzed and four were selected for detailed evaluation: surface tension, metallic bellows, metallic diaphragm, and paddle vortex systems. Detailed definitions and parametric weight data were developed for various configurations of each expulsion technique. Heat transfer, pressurization, fluid residual, and chill down analyses were made. For the bellows-type system, each configuration was required to contain a total liquid volume of 42.5 ft$^3$ and be capable of expulsion into a receiver tank at 100 psia. The bellows were assumed to be fabricated from 0.010-inch thick CRES 347, and be of the nested-hydroform type. High pressure helium was the assumed pressurant gas, and liquid hydrogen the fluid to be transferred.

Various bellows configurations were selected to determine the overall effects on system weight of bellows and pressurant bottle design and packaging, and bellows length to diameter (L/D) ratio. A configuration with a spherical, titanium helium bottle located inside the tank envelope, and a bellows L/D of 1.5 was found to result in minimum weight (Figure 1). For this configuration, parametric weight data were then generated over the range of propellant volumes from 4.7 to 1020 ft$^3$ and tank pressures from 50 to 500 psi. Weights of the total supply system (including LH$_2$) as a function of mass transferred are shown in Figure 2 for the various transfer techniques mentioned above, plus modular (tank exchange) and high pressure (supercritical) transfer methods.

MAJOR RESULTS. -

1. Compared with the other subcritical systems, the metallic bellows was found to have the highest weight and unit cost, and lowest potential reliability.

2. While possessing a high expulsion efficiency, \( \left( \frac{\text{fluid loaded} - \text{fluid remaining}}{\text{fluid loaded}} \right) \), the bellows system has a relatively low volumetric efficiency, \( \left( \frac{\text{total tank volume} - \text{unusable volume}}{\text{total tank volume}} \right) \).

3. It was recommended that the metallic bellows system not be a primary development target for this particular resupply application.
Figure 1. Bellows System, Configuration E

Figure 2. H₂ Supply System Weights Including Fluid (Wₑ₂)
INVESTIGATION OF THE FEASIBILITY OF DEVELOPING LOW PERMEABILITY POLYMERIC FILM
Hoggatt, J. T., Boeing Co., NASA CR-120892, NAS 3-13326, December 1971

OBJECTIVE. - To determine the feasibility of reducing the gas permeability rate of Mylar and Kapton films without drastically affecting their flexibility at cryogenic temperatures.

PERTIENENT WORK PERFORMED. - Both 1/4 and 1/2-mil Mylar and Kapton films were evaluated in this program. Each lot was characterized, the data serving as a basis for comparison in assessing the effects of metallizing and laminating on permeability and flexibility. Helium permeability at 21, -195, and -252°C and liquid hydrogen permeability at -252°C were measured with the materials in both unstressed and stressed (20 percent of ultimate) conditions. Stressing the films resulted in 1 to 3 orders of magnitude increase in helium permeability, but a decrease in LH₂ permeability. One side of each type of film was vacuum or sputter-metallized with aluminum or gold to a thickness of 5000 or 10,000 angstroms. Vacuum metallizing did not result in any reduction in permeability, while sputtered coatings reduce helium permeability by approximately two orders of magnitude. Metallizing was found to reduce the flex life of the film. The goldized Kapton films were formed into a two-ply laminate by stacking the sheets with the two metallized surfaces in contact with one another, and then applying heat (300°C) and pressure (84.4 kg/cm²) for five minutes to diffusion bond the two surfaces together. Diffusion bonded samples were subjected to the same types of permeability and flex testing.

MAJOR RESULTS. -
1. Diffusion bonding of sputtered coatings reduces the film helium permeability by at least four orders of magnitude over the plain film and appears independent of the thickness of the metallized coating (above 3000 angstroms).
2. Metallizing the films reduces the cryogenic flexibility slightly. The diffusion bonding process, however, did not appear to result in further flexibility reductions.
3. The laminate concept is applicable as a barrier ply for polymeric expulsion devices, cryogenic insulation systems, and as a space-stable bagging material where a combination of low permeability and flexibility is important.
4. Bladder permeability rates are shown in Table 1.
<table>
<thead>
<tr>
<th>Comment</th>
<th>Material</th>
<th>Film Stress 0%</th>
<th>Film Stress 20%</th>
<th>Film Thickness mils</th>
<th>Coating Thickness A×10⁻³</th>
<th>Total Specimen Thickness mils</th>
<th>Specific Permeability of Helium ( \frac{cc-mm}{cm²-sec-cm Hg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Film</td>
<td>Mylar</td>
<td>X</td>
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<td>.25</td>
<td>-</td>
<td>-</td>
<td>.25</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td></td>
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<td>.25</td>
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<td>.25</td>
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<td>(Sputtered One</td>
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<td>X</td>
<td>.50</td>
<td>-</td>
<td>-</td>
<td>.50</td>
<td>95.0 ( \times ) 10⁻⁹</td>
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<td>Side Only)</td>
<td>X</td>
<td>X</td>
<td>&quot;</td>
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<td>&quot;</td>
<td>7.2 ( \times ) 10⁻¹</td>
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<td></td>
<td>Mylar</td>
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<td></td>
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<td>Laminated Film</td>
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<td>.25</td>
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<td>-</td>
<td>.25</td>
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<td>(Sputtered Coating-</td>
<td>X</td>
<td>X</td>
<td>&quot;</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>428.0 ( \times ) 10⁻¹³</td>
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<tr>
<td>Diffusion bonded)</td>
<td>X</td>
<td>X</td>
<td>&quot;</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>1.68 ( \times ) 10⁻¹³</td>
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<tr>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>&quot;</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>.50</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
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<td>&quot;</td>
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<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>&quot;</td>
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<td></td>
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<td>X</td>
<td>X</td>
<td>.50</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>Laminated Film</td>
<td>Kapton</td>
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<td>X</td>
<td>.25</td>
<td>-</td>
<td>-</td>
<td>.50</td>
</tr>
<tr>
<td>(Vacuum Deposited</td>
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<td>X</td>
<td>.25</td>
<td>-</td>
<td>-</td>
<td>.50</td>
<td>9.7 ( \times ) 10⁻¹¹</td>
</tr>
<tr>
<td>Coating-Diffusion</td>
<td>X</td>
<td>X</td>
<td>.50</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>7.15 ( \times ) 10⁻¹¹</td>
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<tr>
<td>Bending)</td>
<td>X</td>
<td>X</td>
<td>.50</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>16.8 ( \times ) 10⁻¹¹</td>
</tr>
</tbody>
</table>

Table 1. Average Specific Permeability Rates at +70° F
EVALUATION OF METALLIC POSITIVE EXPULSION BELLOWS OPERATING PARAMETERS WITH CRYOGENIC PROPELLANTS

OBJECTIVE. - To determine the performance of an existing, seamless bellows configuration at cryogenic temperatures, and to revise existing design computer programs to incorporate characteristics associated with cryogenic temperatures.

PERTINENT WORK PERFORMED. - The bellows core design was identical to that developed for MMH and \( \text{N}_2\text{O}_4 \) expulsion on the Minuteman vehicle. A 7 mil seamless CRES 347 tube, 12.5 in. in diameter, was expanded into bellows forming dies by internal pressurization and then each convolution was compressed between two dies forming the root and crest bend radii and sidewall shape. A total of 22 bellows cores were manufactured in this manner by DK Aerospace division of MSL Industries, Inc. These were subsequently tungsten-inert-gas (TIG) welded to end plate closure assemblies by Bell. These assemblies were subjected to an extensive series of tests at cryogenic temperatures, which were identical to the standard Minuteman series performed at room temperature, to expose performance variations resulting solely from the low temperature exposure. The entire test matrix plus results at \( \text{LH}_2 \), \( \text{LO}_2 \), and room temperatures is shown in Table 1. The test program not only imposed the environments singly at various temperatures but also in combinations, with the sequence varied to determine if it had any effect on system performance.

MAJOR RESULTS. -

1. A 200 cycle expulsion test (Spec. No. 14) in \( \text{LH}_2 \) indicated that the bellows behaves the same at cryogenic temperature as it does at ambient temperature. No indication of fatigue-type damage was found.

2. A 45-day storage test in \( \text{LH}_2 \) indicated that the CRES-347 bellows material is completely compatible with the cryogenic liquid. The specimens were free of any type of embrittlement or corrosion.

3. The bellows life cycle at cryogenic temperatures is improved over that at ambient temperature.

4. Variation in the test sequencing had no detectable effect on results.

5. Overall, it has been shown that the metallic bellows operating parameters are unimpaired by exposure to either \( \text{LH}_2 \) or \( \text{LO}_2 \), and that ambient temperature design techniques apply.

COMMENTS. - A too-general interpretation of the second clause in the fifth result would be unwise. In general cryogenic temperature exposure introduces a whole new set of design considerations and the current results were for only one size and type of bellows.
<table>
<thead>
<tr>
<th>Test Spec.</th>
<th>LH₂ Test Sequence</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-test cycling</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>45-day LH₂ Storage</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Leak Test</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>LH₂ Test</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Vibration Test</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Incipient Leak Metall.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Expulsion Test</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Leak Test</td>
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<td>8</td>
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<tr>
<td>10</td>
<td>Buckling Test</td>
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</tr>
<tr>
<td>11</td>
<td>Expulsion Cycling</td>
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<tr>
<td>12</td>
<td>Expulsion Cycling</td>
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<tr>
<td>13</td>
<td>Leak Test</td>
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<td>14</td>
<td>Expulsion Cycling</td>
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<tr>
<td>15</td>
<td>Unused Expulsion</td>
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<tr>
<td>16</td>
<td>Failed at 856</td>
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<td>17</td>
<td>Room Temp Test</td>
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<tr>
<td>18</td>
<td>Failed at 856</td>
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</tr>
<tr>
<td>19</td>
<td>Failed at 856</td>
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<td>20</td>
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<td>21</td>
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</tr>
<tr>
<td>22</td>
<td>Failed at 856</td>
<td></td>
</tr>
</tbody>
</table>
OBJECTIVE. – To eliminate, or reduce, bladder permeation and the associated problem of bubble formation on the liquid side of the bladder.

PERTINENT WORK PERFORMED. – Permeation test specimens were fabricated by Dielectrix Corp. from laminates of TFE Teflon/aluminum film/and FEP Teflon (Table 1). The Teflon coatings were spray-deposited using Apollo and Lunar Orbiter technology. Samples of each material were subjected to fifty 2% strain cycles with specimen length recorded after each load application. Stress relaxation and recovery tests were performed by applying a 2% strain in various environments and recording stress levels as a function of time. Specimen recovery was measured as a function of time after removal from the machine. Finally a series of cyclic roll-fold tests were performed in water until total rupture of the laminates occurred. No permeability tests were performed on this contract.

Bubble formation tests were performed using degassed N₂O₄ as the propellant and helium as the pressurant. Model bladders were TFE/FEP Teflon laminates ten inches in diameter. The test tank was equipped with viewports for visual observation. Tests were conducted with wet (liquid-saturated) and dry bladders in both the up and down positions. In the up position the bladder folded around the standpipe creating sharp material folds.

MAJOR RESULTS. –

1. The 9 mil 20% codispersion/0.5 mil Al / 3 mil TFE laminate displayed the best structural properties.

2. Gas bubble formation in a N₂O₄/GHe Teflon bladder system is retarded by soaking the bladder. Bubble formation does not appear to be a problem for the present configuration Apollo tanks.

3. Bladder permeation rates are shown in Table 2.
Table 1. Laminates Tested

<table>
<thead>
<tr>
<th>Configuration Number</th>
<th>Laminate Construction</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>3 mil TFE-1/4 mil Al-3 mil FEP</td>
</tr>
<tr>
<td>2</td>
<td>3 mil TFE-1/2 mil Al-3 mil FEP</td>
</tr>
<tr>
<td>3</td>
<td>9 mil TFE-1/2 mil Al-3 mil FEP</td>
</tr>
<tr>
<td>4</td>
<td>6 mil TFE-1/2 mil Al-6 mil FEP</td>
</tr>
<tr>
<td>5</td>
<td>9 mil 20% Co-Dispersion-1/2 mil Al-3 mil FEP</td>
</tr>
</tbody>
</table>

Table 2. Comparison of Permeation Rates

<table>
<thead>
<tr>
<th>Permeant</th>
<th>Model Test</th>
<th>Full-Scale Test</th>
<th>ASTM Permeation Rate for Single Permeant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Bladder</td>
<td>Wet Bladder</td>
<td>Dry Bladder</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium</td>
<td>0.012</td>
<td>0.006-6 MIL</td>
<td>0.035 (N₂O₄ Tests)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.003-12 MIL</td>
<td>0.045 (MMH Tests)</td>
</tr>
<tr>
<td>N₂O₄</td>
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<td>0.082-6 MIL</td>
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<td></td>
<td></td>
<td>0.041-12 MIL</td>
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</tr>
<tr>
<td>MMH</td>
<td>-</td>
<td>-</td>
<td>0.002</td>
</tr>
</tbody>
</table>

NOTE: Units for permeation rates are scc/in.²/hr/psi for 6-mil Teflon unless otherwise indicated. Temperature is 70°F.

12-13
OBJECTIVE. - To determine the capability of polymeric materials as expulsion bladders to satisfy typical system requirements in a liquid oxygen environment.

PERTINENT WORK PERFORMED. - A total of ten 12-in. diameter spherical bladders were subjected to LO$_2$ expulsion testing, and an additional eight to dynamic modes of excitation. Barrier ply materials selected were 1/2-mil Kapton and 1/4-mil Mylar films, based on LO$_2$ impact tests conducted in Task I. A 3-mil Teflon fabric was selected as an abrasion and substrate ply material, used to reinforce the laminate and protect the barrier plies. The three bladder construction configurations consisted of (1) 10 plies with 12 gores per ply, (2) 5 plies with 6 gores per ply and (3) 5 plies with 12 gores per ply. The fabrication sequence is shown in Figure 1. Bladders were installed in the test tank and leak checked prior to filling. Leak checks were performed after every fifth cycle. Each bladder was repeatedly cycled until failure, defined as a leakage rate at -280F in excess of 200 scc/min. of GHe, or for 25 complete cycles. Four of the bladders, those with only 5 barrier plies, did not survive the first expulsion cycle, due to tears or ruptures of the laminate.

Slosh, vibration, impact, and burst tests were run on the remaining eight bladders to study the structural integrity and chemical compatibility of the polymeric bladders in an LO$_2$ environment. Slosh frequencies of 0-10 cps, vibration from 10-160 cps, acceleration up to 4 g's, and blunt impacts up to 216 ft-lbs of energy were imposed, as well as ballistic penetration by a 30.06 projectile.

MAJOR RESULTS. -

1. Kapton film, FEP-coated Kapton film, and TFE Teflon fabric were found to be LO$_2$ compatible. No evidence of LO$_2$ incompatibility occurred in any of the expulsion tests.

2. The 10-ply, 12-gore Kapton bladders gave the best overall performance, and were the only bladders to reach the program goal of 25 cycles with a leakage rate less than 200 scc/min.

3. The fill efficiency (LO$_2$ volume/tank volume) and expulsion efficiency of all bladders averaged 84 and 82 percent, respectively. Values of 99 and 98 percent, respectively, were obtained with water at room temperature.

4. Bladders withstood slosh and impact loadings without detriment. Lateral vibrational failures resulted from inadequate support of the bladder, and could be remedied by a slight redesign.
GORE PATTERNS
Cut From Flat Sheet

GORE LAYUP

Tape Adhesive
Gore Segments
Layup Hemisphere

LAYUP OF SINGLE BLADDER PLY

Mandrel

Helium in
Sealing Patch

Stems Installed
Mandrel Removed
Adhesively Sealed

COMPLETED BLADDER

Additional plys are layed up in same manner, Each ply is individually helium leak checked

Figure 1. Bladder Fabrication Sequence
DEVELOPMENT OF CRYOGENIC POSITIVE EXPULSION BLADDERS
Pope, D.H., Penner, J.E., Beech, NASA-CR-72115,
NAS3-6288, January 1968

OBJECTIVE. - To consolidate previous achievements in cryogenic laminated-bladder
technology and develop a system capable of 25 failure-free LH$_2$ expulsion cycles.

PERTINENT WORK PERFORMED. - After a review of previous material investigations,
the following materials were selected for laminate development: Mylar (Type C) film,
Kapton (Type H) film, polyethylene film, Dacron fabric, and Nomex paper. Techniques
for sealing the laminates included adhesive bonding, thermal sealing, and ultrasonic
welding. A total of 95 different laminate configurations were designed and 557 material
samples were fabricated for screening tests, which consisted of an initial permeability
test, a cryogenic flexibility test, and a final permeability test and failure analysis.
Based on this screening evaluation the five laminates shown in Figure 1 were used to
fabricate a total of ten 11.5-in spherical bladders for LH$_2$ expulsion testing. The
design consisted of twelve equal gore sections and a four inch cap section. The
bladders were mounted in a 12 liter, spherical, unsilvered glass dewar. Five LH$_2$
expulsion tests were performed followed by a permeability check. This cycle was
continued until a total of 25 expulsion cycles and 5 permeability checks had been
performed. Eight of the bladders survived the full 25 cycles, but all eight exhibited
post test leakage rates varying from 18 to 28,000 cm$^3$/min of GHe per minute (Table 1).
Bladder B206 produced the best all-around and most trouble-free performance,
although not the lowest leak rate.

MAJOR RESULTS. -
1. The goal of 25 failure-free expulsion cycles was not achieved.
2. Almost all of the operational problems of these multi-ply bladders can be attributed
   partly or entirely to interply inflation.
3. Outward expulsion (liquid outside bladder) virtually eliminated flow, fill, and
   expulsion problems due to interply inflation.
4. Satisfactory expulsion performance (avg. of 85%) was not as difficult to attain as
   satisfactory LH$_2$ fill performance (avg. of 71%). Percentages refer to the nominal
   capacity of the bladder.
5. Extensive data on bladders composed of ten or more individual plys has been
   obtained.
Table 1
TABULATION OF EXPULSION TEST RESULTS
(Based on inward expulsion testing observations)

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<thead>
<tr>
<th>PARAMETERS</th>
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<th>B103</th>
<th>B104</th>
<th>B105</th>
<th>B106</th>
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<td>1. My CYCLES</td>
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<tr>
<td>Number Completed</td>
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<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<td>% Expulsion</td>
<td>99.68</td>
<td>92</td>
<td>85</td>
<td>90</td>
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<td>86</td>
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<td>% Expulsion Left 10 Cycles</td>
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<td>93</td>
<td>93</td>
<td>94</td>
<td>93</td>
<td>90</td>
</tr>
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<td>Exclusion Behavior</td>
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<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Very Good</td>
<td>Excel</td>
</tr>
<tr>
<td>% Fill Behavior</td>
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<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
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<td>Flow Characteristics</td>
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<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
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<td>2. PERMEABILITY</td>
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<td>Post-Test Rate (cm/hr)</td>
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<tr>
<td>Flow-by-Flow Pattern</td>
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<td>3. INTRAPLY INFLATION</td>
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<tr>
<td>Installation b Removal</td>
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<td>4. BLADDER CONDITION AFTER TEST</td>
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<td>Near Site</td>
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<td>Good</td>
<td>Poor</td>
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<tr>
<td>At Polar Cap</td>
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<td>Good</td>
<td>Excel</td>
<td>Good</td>
<td>Excel</td>
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<tr>
<td>Other Areas</td>
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<tr>
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<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>At Polar Cap</td>
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<td>Good</td>
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<td>Comparative Perm.</td>
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<tr>
<td>At Site</td>
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<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
</tr>
<tr>
<td>At Polar Cap</td>
<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
<td>Excel</td>
</tr>
<tr>
<td>% Pigs Retrieved &amp; Effective</td>
<td>50.61</td>
<td>62</td>
<td>54</td>
<td>50</td>
<td>80</td>
<td>62</td>
</tr>
</tbody>
</table>

*After repair of stem seal leak, leakage immediately after 144 cycling was 428 g/min.
**Dissection of bladder after testing not performed.
MULTICYCLE METALLIC BLADDERS FOR CRYOGENIC FLUID STORAGE


OBJECTIVE. - To design, fabricate, and test 23-in. diameter multicycling metallic diaphragms for the storage and expulsion of 20 pounds of LH$_2$ from a spherical tank.

PERTINENT WORK PERFORMED. - Initially, two separate diaphragm configurations were considered; an expanding spherical type and a controlled collapsing hemisphere. The expanding type was discarded due to extreme fabrication difficulties (of the ten specimens processed, only two were considered suitable for test, and both failed prematurely). The hemispherical systems were the thin-shell, wire-reinforced reversing configuration developed by ARDE in prior in-house programs (Figure 1). Bladder structural parameters, shell contour, wire size and spacing, and brazing techniques were systematically studied and improved over the course of the program. AISI 321 stainless was selected as the shell material to avoid cryogenic-temperature embrittlement problems. Procurement problems forced the use of AISI 308 wire, the suitability of which had been demonstrated previously. Copper was selected as the joint brazing material. Six-inch diameter subscale diaphragms were fabricated to check out brazing and structural improvements which were subsequently incorporated into the 23-in. systems.

A total of six of the 6-in. and ten of the 23-in. development units were built and tested in water and LN$_2$ before the "modified hemispherical" (MH) configuration was developed (Figure 2). Two 6-in. MH units were built and water-tested, followed by fourteen 23-in. MH units tested in water, LN$_2$, and LH$_2$. An additional five 23-in. MH units were fabricated and delivered to the Air Force.

MAJOR RESULTS. -

1. The most significant improvements made were the use of the ductile copper braze and the use of a "modified hemispherical" diaphragm contour which reduced strain in the critical equator region and eliminated wire interference problems.

2. The modified-hemispherical diaphragms achieved six, five, and seven successful reversals with LH$_2$, LN$_2$, and water, respectively.

3. The MH type of metallic diaphragm has been demonstrated to be suitable for multicycle use with any fluid compatible with annealed stainless steel.
Figure 1. Typical Diaphragm Reversal Mode

Figure 2. Sketch of Modified Hemispherical Diaphragm Shell
13.0 OTHER INTERFACE CONTROL AND LIQUID ACQUISITION SYSTEMS

Covering the use of centrifugal, electrical, and acoustic forces for liquid control.
A DIELECTROPHORETIC LIQUID OXYGEN CONVERTER
FOR OPERATION IN WEIGHTLESS ENVIRONMENTS

OBJECTIVE. - To design a dielectrophoretic (DEP) orientation device for a liquid oxygen converter, to validate the analyses of the converter through experiments, to demonstrate system safety, and to evaluate the structural integrity of critical components.

PERTINENT WORK PERFORMED. - The principles of DEP and its effect on dielectric fluids are discussed, and the requirement to provide an electric field gradient to move a dielectric liquid toward an outflow port is explained. The so-called "bang-bang" region at the edge of the electrode array produces an intense field gradient which has a strong stabilizing effect on the liquid/vapor interface. Tests are described which show, for the first time, that it is possible to achieve stable DEP orientation of fluids with dc fields, as well as with ac fields. Four classes of electrode arrays were evaluated as shown in Figure 1 (liquid drawn to bottom of sphere). Tests revealed that the parallel disc configuration caused liquid separation, or slug formation, resulting in high residuals. The other three systems exhibited better, and equivalent, performance. The fanned disc configuration was selected for the zero-g experimental models since it was easier to fabricate. A 25 liter spherical, clear plastic model was constructed for tests with Freon 113 and a 2 liter glass vacuum Dewar model for LN₂ tests. KC-135 flights gave useful zero-g float times of 10 to 12 seconds. The results of both zero-g and low-g tests with the 25 liter device are shown in Figure 2 together with a curve developed from the stabilization analysis. Materials compatibility, electrical breakdown, and ozone generation tests were performed to evaluate system safety. A component development and optimization study resulted in a set of weight equations which are illustrated graphically in Figure 3.

MAJOR RESULTS. -
1. For the first time, it was demonstrated that dc electrical fields, as well as ac fields, will provide stable DEP orientation.
2. The stability test results for the 25-liter device compare well with predictions (Figure 2).
3. The materials were demonstrated to be compatible with oxygen for the selected design. Electrical breakdown and ozone generation problems can be avoided.

COMMENTS. - Stark, 1972, Section 10.0, has questioned the validity of the conclusions with regard to the safety aspects of the DEP system.
**Figure 1.** Four Classes of Total Orientation Electrode Arrays

**Figure 2.** Comparison Between Experimental and Theoretical Performance of the 25-Liter Dielectrophoretic Oxygen Converter with Freon 113 as the Simulant Liquid

**Figure 3.** Optimized System Weights for Dielectrophoretic Fluid Orientation Systems for Subcritical Oxygen Converters \( (V = \text{Voltage}) \)
OBJECTIVE. - Define the most feasible and promising conceptual technique(s) for transferring \( \text{LO}_2 \), \( \text{LH}_2 \), \( \text{N}_2\text{O}_4 \) and 50% hydrazine/50% UDMH in orbit.

PERTINENT WORK PERFORMED. - In general, analyses, tradeoffs and conceptual designs were based on existing technology. However, with respect to tank rotation for liquid orientation some analyses were performed which are not found elsewhere; at least not for the in-orbit transfer application. Only this aspect of the overall work reported will be summarized. The problem of rotation of a cylindrical tank and liquid about the longitudinal axis is treated. The rotational speed \( \Omega_c \) to insure collection of liquid on the tank wall was taken from the analysis of Seebold and Reynolds (1965) to be:

\[
\Omega_c = \sqrt{\left( \frac{\sigma}{\rho R^2} \right) (4 + 5 \rho a R^2/\sigma g)}
\]

where \( R \) is the tank radius, \( a \) acceleration in the axial direction and \( g \) the gravitational constant. The time for liquid spin-up, \( T \), was determined from the analytical work of Greenspan and Howard (1963) to be:

\[
T = \frac{L}{\nu \Omega_c^{1/2}}
\]

where \( L \) is the tank length. This analysis accounts for momentum transfer induced by secondary flows that exist at the ends of the tank. A purely viscous momentum transfer predicts a characteristic time of \( 4 R^2/\nu \). Using the Greenspan and Howard analysis the spin-up time for a 33-ft-dia. by 60-ft-long \( \text{H}_2 \) tank was 11 hours and for the purely viscous case the time was 300 days.

Equations were also developed to account for the use of radial vanes inside the tank to increase the viscous and form drag to reduce the liquid spin-up time. Assuming that the overall drag coefficient (\( \bar{C}_D \)) can be approximated by a constant average value, the equation for spin-up time was determined to be:

\[
T = \frac{36 \pi}{(N \bar{C}_D \Omega_c)}
\]

where \( N \) is the number of vanes and \( \bar{C}_D \) is the average drag coefficient for each vane. Assuming these vanes to be screen with \( \bar{C}_D = 0.44 \) and \( N = 4 \) the spin-up time for the large \( \text{H}_2 \) tank was determined to be approximately 1-min.

COMMENTS. - Testing was not accomplished here to verify the analyses.
OBJECTIVE. - Obtain an analytical approximation to the boundary layer discharge of liquid in a liquid-gas vortex separator and verify with experimental data.

PERTINENT WORK PERFORMED. - The analysis is based on a momentum integral method. The basic operation of the cyclone or vortex separator is illustrated in Figure 1, where a mixture of liquid and vapor is introduced tangentially into a cylindrical chamber causing a vortex-like motion which produces a centrifugal force field causing the liquid to move outward. Further, by a properly shaped exit for the liquid; e.g., a conical section, a secondary flow is generated. This secondary flow causes a pressure gradient which directs the liquid toward the apex of the cone where it exits, and should allow the vortex separation and outflow to be accomplished in a low-g field. The following assumptions were made in the analysis; (1) boundary layer flow in the cone is considered separately from the separation process in the cylindrical section, (2) the liquid has constant viscosity and density, (3) the flow is steady, and (4) the only body force acting is that of gravity and the axis of revolution of the separator is parallel to the line of action of gravity.

Testing was accomplished using air and silicone oils of different viscosities, to obtain results over a wide range of Reynolds numbers. The separator was 4.5 in. diameter with a cylindrical section 4.75 in. high. Different cone sections were tested with cone angles of 15° and 45° and outflow diameters of 0.052 to 0.228 in. Testing was performed for outflow with gravity and against gravity (unit inverted from that shown in Figure 1).

MAJOR RESULTS. -

1. An analytical approximation to the secondary flow rate in a vortex separator with a conical outflow section was obtained.

2. Operating with gravity and without evaporation, nearly 100% efficient liquid removal was obtained.

3. Operation against gravity gives evidence that the secondary flow can overcome an adverse body force and thus the unit should operate effectively at low-g. Actual inverted operation at 1-g however, was not efficient due to the considerable adverse static pressure gradient.

COMMENTS. - Using the basic analyses and test results presented here a small water separator for use in a low-g life support shower system was developed (Rosener, et al, 1971) (see Rejections). The final configuration, however, was significantly more complicated than that shown in Figure 1 and incorporated internal baffling to obtain an operational system.
Figure 1. Typical Vortex Separation
COLLECTION OF LIQUID PROPELLANTS IN ZERO GRAVITY WITH ELECTRIC FIELDS

OBJECTIVE. - To investigate the theory governing dielectrophoretic (DEP) fluid control, to conduct simulated and actual zero-g experiments, and to extrapolate results into the design of two DEP collection systems for a 250,000-lb LH₂/LO₂ space vehicle.

PERTINENT WORK PERFORMED. - Equations for dielectric force fields are developed, and a comparison between DEP and surface tension forces is made. Surface free-charge density and the resulting disruptive pressure forces are discussed, with emphasis placed on techniques for minimizing such disturbances. Although the maximum DEP force for a spherical electrode configuration is much greater than that of the cylindrical configuration due to greater electric field non-uniformity, electrical breakdown will occur at a lower voltage in the spherical system. Small scale one-g tests were performed using water drops suspended in a carbon tetrachloride/benzene mixture, followed by one-second zero-g tests performed with carbon tetrachloride in 250 ml flasks. Eight-to-ten second low-g (± 0.05g) tests were performed in an Aerocommander with a cylindrical electrode system and Dow Corning 200 oil. Tests were performed using both ac and dc fields, the latter resulting in appreciable stirring of the liquid due to free charges.

Plausible DEP orientation designs for a 250,000-lb LH₂/LO₂ space vehicle are discussed. Two separate ac-powered systems, one (I) designed to collect 1000 lb of LH₂ and 5000 lb of LO₂ over the tank outlets prior to restart (Figure 1) and the other (II) designed to settle half-full tanks (Figure 2), are compared. Resulting weight estimates are shown in Table 1. An auxiliary propulsion system designed for one restart and 15 vent cycles would, by comparison, weigh 2200 lb. The cylindrical electrode system collects the liquid from the tank walls to the center electrode, thereby imposing an insulating gas layer between the tank wall and liquid (Figure 3). DC fields could also be used to reduce temperature stratification, and tank pressure, by inducing free convection currents to stir the tank.

MAJOR RESULTS. -
1. Due to the problem of free charge disturbances in dc fields, only ac fields may be used for stable collection of liquids.
2. DEP systems have been shown to have a very low weight as compared to auxiliary propulsion systems for propellant orientation.
3. Propellant weight savings due to liquid orientation to the center of the tank and destratification by stirring more than offset the weight of the DEP system.
Table 1. Dielectrophoretic propellant collection
System Weights

<table>
<thead>
<tr>
<th>Weight</th>
<th>LH&lt;sub&gt;2&lt;/sub&gt;</th>
<th>LO&lt;sub&gt;2&lt;/sub&gt;</th>
<th>LH&lt;sub&gt;2&lt;/sub&gt;</th>
<th>LO&lt;sub&gt;2&lt;/sub&gt;</th>
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</thead>
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<td>51</td>
<td>24</td>
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<tr>
<td>Insulation</td>
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<td>42</td>
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<tr>
<td>Generator</td>
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<td>Battery</td>
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<td>Total</td>
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<tr>
<td>Total system</td>
<td>180</td>
<td>265</td>
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</tr>
</tbody>
</table>

Figure 1. Electrode Configuration I

Figure 2. Electrode Configuration II

Figure 3. Propellant Positioning for Decreasing Boil-Off Loss
APPENDIX A

AUTHOR INDEX OF SUMMARIZED REPORTS


Hord, J., Voth, R. O., "Tabulated Values of Cavitation B-Factor for Helium H₂, N₂ F₂, O₂, Refrigerant 114 and H₂O," February 1971, p. 3-12.


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 basically the same as described for the detailed summaries. The page location of each category is presented below.

<table>
<thead>
<tr>
<th>Category</th>
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<tbody>
<tr>
<td>General</td>
<td>B-2</td>
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<tr>
<td>Fluid Line Dynamics and Thermodynamics</td>
<td>B-8</td>
</tr>
<tr>
<td>Mass Gauging</td>
<td>B-13</td>
</tr>
<tr>
<td>Other Instrumentation</td>
<td>B-16</td>
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<tr>
<td>Pressure/Temperature Control Systems (General)</td>
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<td>B-45</td>
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<tr>
<td>Other Acquisition Systems</td>
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GENERAL


No new technology data are generated by this study which would be applicable to in-orbit fluid transfer.


Deals with equipment to be used in the performance of biochemical, hematological, and microbiological experimentation and data pertinent to in-orbit transfer is not presented.


This work has been superseded by more recent data.


Other than Volume IV of Phase I, which is summarized, no new technology data was found which was significant to in-orbit fluid transfer. The study consisted basically of design trade-offs and vehicle analyses using existing technology.


This is only a paper study using existing data and does not add to the state-of-the-art of the technology required for in-orbit fluid transfer.


Work in technology areas of interest is based on existing information and new technology data of significance to the current program is not presented.


Tradeoffs, analyses and weights are based on existing technology information.


This work as it pertains to in-orbit fluid transfer has been superseded by more recent work.

Photographic coverage is only qualitative and no comparisons are given between theory and test data.


Tradeoffs and analyses are based on existing technology data.


The primary application is to ground handling and technology data of significant interest to the current program is not presented.


General information only with no significant technology data presented.


Deals strictly with tank construction details, which is not within the scope of the current study.


This report contains an assessment of the performance of the various spacecraft systems during the first six months of orbit of the HEOS-1, launched in December 1968, but does not contain any data on low-g fluid system performance.


General survey only. None of the technology areas are covered in sufficient detail and the data are not current enough to be of significant use to the present program.


Analyses and tradeoffs were based on existing technology information. This report does not cover the testing phase of the program. (Ref. Burge, 1968 and Kelly, 1970).
Essentially all the significant test data obtained was associated with 1-g tank pressurization which, for purposes of the current program is covered adequately elsewhere.

None of the papers presented were of interest to the current study.

This is very early work in the field, which has been superseded by later and more complete information.

This is a good overview of the work accomplished and the resulting cryogenic storage systems for Apollo life support and power systems. However, technology details are not presented in depth and are covered better by summaries and/or reviews of the source material.

Existing technology was used to accomplish trade-offs for the specific vehicle requirements of this program.

Trade-offs and data presentation are based on existing technology.

This is a detailed piece of hardware which represents only one small part of the overall transfer system.

Deals with compressed gas storage systems with general discussions and does not advance the state-of-the-art.

Experiments on the storage of liquid helium in a cryostat on an orbiting satellite are briefly reported, however, the data are not sufficient to add anything to the state-of-the-art of technology required for in-orbit fluid transfer.


The work reported deals mainly with tankage details and did not get past the design stage.


Information specifically related to shuttle with no basic technology information that can be extrapolated to other systems.


Contains Space Shuttle APU system analysis and computer printouts of system performance without basic technology information useful to low g fluid transfer.


Work is based on existing technology data, with no new pertinent contributions made which would be applicable to in-orbit fluid transfer.


This was primarily an operations study and significant advancements were not made in the state-of-the-art of the individual technologies associated with in-orbit fluid transfer and overall transfer data of interest are the same as in Sexton, et al (1972), which is summarized.


The only data of significance was that associated with 1-g tank pressurization which, for purposes of the current program, is covered adequately elsewhere.

Information is concentrated in the engine area and no technology data are presented which would be useful to in-orbit fluid transfer.


This work is reported in greater detail in contract reports, i.e., Morgan, et al, 1968, NAS10-4606, which is summarized


This study did provide some interesting parametric data on fluid transfer systems, however, the work done was based on existing information and no actual advancement was made in the individual technology areas. With respect to the overall systems aspects, later studies having more current information have been performed and are reviewed elsewhere.


This is a multi-volume report covering overall optimization and integration of all potential space shuttle cryogenic systems, however, only existing technology data or technology developed elsewhere was used in the study.


The systems presented here are based on existing technology or assumptions about what could be built. No new technology data of interest to the current study are presented.


General discussions with specific technology data not given.


Simplified approach to overall thermal control optimization as a paper tradeoff study with no new technology data presented.


Presents results of a six month study to define a Versatile Upper Stage (VUS) vehicle capable of performing a variety of missions with only existing fluid system technology data used in the study.

Trade-offs, analyses and design are based on existing technology information.


Only existing technology was used in performing this study.


Problems and technical advancements associated with cryogenic liquid rocket propellant systems are discussed in general terms, with no new technology data presented.


This is a general survey paper which is similar to a more extensive report (Davis, et al, 1970, SP-247), which is reviewed elsewhere.


The only information which might be of interest is on a zero-g vent system, which work is presented in Salvinski (1965) reviewed under Vent Systems.


In general, only existing technology information was used in this study in the areas associated with in-orbit fluid transfer. Basic transfer system ideas are essentially the same as presented by Sexton, et al (1972) under the In-Space Propellant Logistics Study, which is summarized.


These papers were presented basically for the exchange of general information and pertinent work is covered more completely in other technical NASA and contractor reports which are reviewed elsewhere.


There was no data presented applicable to space vehicles, space transfer of fluids or low-g fluid behavior.

This is only a brief general review, without any specific new technology data presented.


Specific data are only presented on the space environment with respect to electromagnetic and particulate radiation and meteoroids.


General discussions only, without specific technology data presented.


The objective of the study was to provide safety guidelines and requirements for the operation of an Orbiting Propellant Depot. Only discussions and data of a general nature was presented with no specific technology information of use to the present study.


The work presented here is based only on existing technology data.


Presents general discussions only, with no quantitative data pertinent to advancing the state-of-the-art of technology associated with in-orbit fluid transfer.

**FLUID LINE DYNAMICS AND THERMODYNAMICS**


Due to its similarity with the summarized work of Steward (1968), this report was not summarized.

The information presented in this paper has been superseded by more recent work in this field.


Due to inaccuracies in calculated fluid and wall conditions, this material is of questionable use in the design of propellant lines.


Tests of the model against slug flow, as opposed to mist flow, showed significant deviations and thus the model cannot be generally applied to the prediction of cooldown times.


The object of this study was to investigate the cooldown requirements for the 18-in. diameter LH\textsubscript{2} and LO\textsubscript{2} transfer lines at the M-1 engine test facility, and is too specific to add to the general state-of-the-art.


This is early work in the field and the low-g aspects of the problem are only discussed in general terms.


Development of the wave-plan solution presented here is adequately summarized elsewhere.


This analysis is for a very idealized fluid condition, not pertinent to the low-g technology study.

This is a detailed study of one small area associated with fluid transfer which did not warrant summarization for the current program.


This study did not investigate the effect of gravity on pressure loss and heat transfer, the most important parameters.


This phenomenon is not pertinent to low-g fluid transfer.


For purposes of the current program this subject is adequately covered by Shen and Jao (1969), which report is summarized.


Pertinent data are covered in more recent reports, e.g., Smith, et al (1973) and Smith (1972) which reports are summarized.


This work is associated with engine feedlines and is not significantly applicable to in-orbit fluid transfer.


This work is associated with engine feedlines and is not significantly applicable to in-orbit fluid transfer.


This review is similar to that conducted by Smith, et al (1973).


This paper discusses fluid flow regimes and liquid/gas interface effects in general terms and does not add to the description of the current state-of-the-art of low-g fluid transfer.

The effect of coatings on transfer line cooldown time was covered in the summary of the report by Manson and Miller (1968).


The portion of this study dealing with line insulation was summarized under "Cryogenic Thermal Control Technology." The effect of line internal coatings was covered in the summary of the report by Manson and Miller (1968).


This paper is a good general discussion of many aspects of transfer line cooldown, however, the material presented does not add to the state-of-the-art in this field.


This report describes predictions of and test data for the cooldown of 10 and 12-in diameter cryogenic transfer lines at the Nuclear Rocket Development Station of the Los Alamos Scientific Laboratory and is too specific to contribute to the general state-of-the-art.


This work is too specific to add to the general state-of-the-art.


The objective of this study was to develop improved boost pump chilldown procedures for in-space restart and is not pertinent to the current technology study.


The observed conditions are not applicable to low-g fluid transfer.

Prediction of thermal stresses during cooldown is important, however, the limited extent of the analysis presented in this paper and the lack of experimental verification of the predictions make its value questionable.


The results presented in this paper are too tentative to be of use in the design of low-g transfer systems.


This paper is a general discussion of the design of liquid-fueled launch vehicles and does not contribute to the description of the state-of-the-art of low-g fluid transfer.


For purposes of the current program this subject is adequately covered in summarized reports such as Streeter and Wylie (1974) and Steward (1968).


Insufficient information is presented to evaluate the usefulness of the material in this paper.


This is an IRAD report not generally available.


The flow regime may be applicable for characterizing the flow in condensors and boilers in low gravity, however, no test data is presented to demonstrate that the correlations do indeed apply to low gravity. Also, the quantitative conditions for capillary slug flow are not specified, thus limiting the usefulness of the data.


This paper discusses the work performed by Steward (1968) at Colorado State Univ. entitled "Transient Flow of Cryogenic Fluids," which is summarized.

This paper discusses the work performed by Steward (1968) at Colorado State Univ. entitled "Transient Flow of Cryogenic Fluids," which is summarized.


This book is a generalized treatment of unsteady fluid flow. A later article by Streeter and Wylie (1973) dealing specifically with predicting and controlling water-hammer and surge is summarized in lieu of this text.


The purpose of this study was to evaluate by experiment an analytical method for estimating the vapor-to-mixture-volume ratio for two-phase hydrogen flow in a pump inlet annulus over a range of temperatures and flow rates, and has no direct application to low-g fluid transfer.


These POGO problems are not pertinent to low-g propellant transfer.


With respect to low-g heat transfer and in-orbit fluid transfer considerations no new data is presented.

MASS GAUGING


The results of this same investigation are contained in Report No. 16740-6003-RU-00, by Bupp (Jan. 1974), a summary of which is included elsewhere.


Mass quantity gauging has been more completely covered by the work done by Bendix in the report "Design, Development and Manufacture of a Breadboard Radio Frequency Mass Gauging System" (1972), which is summarized.

This idea has been developed more completely in later work.


The principle is presented that propellant mass can be derived from data obtained by monitoring the pressure and temperature of the mass of helium purge gas within an expulsion bladder and the pressure and temperature of the propellant in the tank by applying known gas laws, an idea which has been more completely developed in later works, (See Bliss, 1969, which is summarized).


The gas law method of propellant gauging has been covered in "MOL Propellant Gauging System" by Bliss, which report is summarized.


This work has been superseded by more recent extensive investigation and development in this area.


This presentation is of a general informative nature only and contributes no significant information to the basic technology.


This summary report on RF gauging for propellants under zero-g conditions is outdated by the extensive work done in this area since 1967.


The presentation of three proposed zero-g propellant gauging methods; Resonant Infrasonic Gauging, Nucleonic Gauging and Pulsed Ultra Sonic, is of a sketch/outline nature. These systems have been treated in depth in other papers.

This article presents the concept that, in a positive acceleration environment, accurate propellant gauging can be accomplished by utilizing an array of point level sensors in the propellant tank. Since this article was published, further and more detailed work has been accomplished.


A patent disclosure is presented which deals with a refinement in the infrasonic zero-g gauging method. The concept is a minor-refinement only and is of no special significance to low-g fluid transfer technology.


An elementary time accumulating system which sums the total fuel consumption of positioning engines based on known engine rates of usage is presented. The system is not considered applicable to low-g fluid transfer technology.


This subject has been completely covered in the report entitled, "Design, Development and Manufacture of a Breadboard Radio Frequency Mass Gauging System," (Anon. 1972), which is summarized.

Wheatley, J. C., Strait, S. F., "An All-Glass Liquid Helium Dewar Employing No Auxiliary Cryogens," U.C. San Diego, La Jolla, American Institute of Physics, Volume 43, Number 6, June 1972.

The principle advantage of this configuration is that of elimination of distortion of RF Fields (Used in scientific experiments). The idea is of a very specialized nature not applicable to in-orbit fluid transfer.
OTHER INSTRUMENTATION


This is a compilation of a wide variety of transducers which have been developed or improved under various NASA Aerospace programs. No items that could be related to the zero-g fluid transfer problem are included which are not more completely presented elsewhere.


The results of this work have already been well integrated into the state-of-the-art design technology for low-g instrumentation.


This report is supplementary to NBS SP-3084 (Mann, 1974) which is summarized.


This paper, contributes nothing to existing technology.


Deals with the measurement of atmospheric temperature and not applicable to the present study.


This unit is an excellent design for the intended wind tunnel application, but no particular application is seen for this type of accelerometer in Low-G Fluid Transfer Technology.


Although this paper presents a good review of cryogenic temperature measurement techniques, no pertinent information of particular use to low "g" space applications is presented.

This paper describes a technique which detects the phase (liquid or vapor) on the hot junction of a micro thermocouple and measures the temperature of each phase in steam-water two phase flow, which is a laboratory technique not applicable to space flight operations.


Information in this paper is of a general type indicating only areas of design requiring research and development rather than presenting solutions.


This is a standard type of a low-g accelerometer and does not in itself add to the overall state-of-the-art.


The neutron absorption method used in this investigation is already covered in the summarized report "Propellant Quantity Gauging System Under Zero-G" (Anon. 1971).


The refinements of micro-g bias error analysis in itself is considered as being of no special significance to the current program.


This paper is a review of commercial applications of cryogenic technology, present and future; not significant for space consideration.

This paper describes a method and a device for measuring the contact angle of a liquid at its interface with a solid, which is not significant with respect to instrumentation required in the operation of in-orbit fluid transfer systems.


This review is essentially for general information purposes only and does not contribute to the state-of-the-art of low g fluid transfer.


This paper is of a general information nature only and does not contribute to the state-of-the-art of low-g fluid transfer.


This paper is a study of factors which contribute to the difficulty of accurately measuring transient temperatures in cryogenic fluids and while this information supports the intelligent use of available temperature sensors, it contributes no significant information to the basic technology.


This report is a compendium of 158 resumes of instrumentation systems and experiments used or performed during space operations, none of which appear to be related to the problem of Low-G Fluid Behavior or Transfer Technology.


Data is of a very general nature with no indepth presentation.


Although this paper is considered as an excellent outline and is supported by an extensive bibliography, it adds no specifics to the current subject.

This subject is better covered in the report by J. P. Schelwe and B. Y. Cho, "Nucleonic Measurements of Cryogenic Densities and Qualities" July 1967, which is summarized.


This paper does not deal with the problems associated with space environments, space instrumentation or zero-g considerations.


Two phase density measurements using the open ended resonant cavity is more completely covered and reported in NASA Technical Note D-6415; "Instrumentation for Liquid Hydrogen Density Measurements using an Open-Ended Microwave Cavity," by Smetana J. and Wenger, N. C., July 1971, which report is summarized.


This NASA Technical Note describes the design, application and performance of a specially designed thermocouple arrangement for application to measuring ullage gas temperature profiles over LH$_2$ during pressurization and expulsion studies, an arrangement that is strictly for laboratory application.


This paper describes a 25 millimicrogal gravity meter which uses superconducting magnets at cryogenic temperature and is not significantly related to zero-g fuel transfer technology.


This work was reported by Smetana and Wenger (1971) which is summarized.


This method has been further investigated and reported in NASA TN D-6415; "Instrumentation for Liquid Hydrogen Density Measurements Using an Open-Ended Microwave Cavity; by Smetana J. and Wenger N. C., July 1971, which report ised. summarized.
PRESSURE/TEMPERATURE CONTROL SYSTEMS (GENERAL)


This is very early work in the field which has been superseded by later work.


Marshall Space Flight Center's research achievements in the thermal management areas of LH₂ storage in deep space and low orbit environments, including zero-g venting, destratification mixing, hydrogen reliquefaction and solar shields, are outlined in a brief review. Pertinent details are covered in the various contract reports which are reviewed elsewhere.


A technology program is discussed in which a hybrid (analog/digital) electronic controller is developed. This is detailed work for a specific engine feed application not of sufficient general application to in-orbit transfer to warrant summarization.

STRATIFICATION/PRESSURIZATION


Pertinent results of the overall Aerobee program, of which this is a part, are presented by Aydelott (1967). Also this data was included in a pressure rise rate correlation by Blatt (1968).


This data is included in the report by Aydelott (1967), which is summarized. Pressure rise data here also used in the correlation by Blatt (1968).


Except for an unsuccessful attempt to use a F₂/H₂ reaction for H₂ tank pressurization, the pertinent work reported here was based on existing state-of-the-art data.

This work has been refined and extended by Arnett and Voth (1972), which report is reviewed elsewhere.


This is a detailed stratification program limited to gravity levels where the liquid/vapor interface is flat.


By itself this work does not add to the state-of-the-art of low-g heat transfer or pressure control. Its relation to low-g work is covered by Aydelott (1967), which report is summarized.


The overall Aerobee flight work is adequately summarized by Aydelott (1967), which report is summarized. Also, this pressure rise data was correlated by Blatt (1968).


Pertinent results of the overall Aerobee and 1-g 9-in. tank tests are adequately summarized by Aydelott (1967). It is noted that the Flight 7 data was used by Blatt (1968) in a pressure rise correlation.


The data here is strictly 1-g and the evaluation of its usefulness at low-g must await further low-g testing than has been accomplished to date.


The pertinent aspect of this work, an attempt to apply the analysis to actual flight data, is reported by Merte, et al, 1970, which is summarized.

This is 1-g data with no demonstrated application to in-orbit low-g fluid management.


Zero gravity was not really treated in any detail and data which might be pertinent to in-orbit fluid transfer was elementary and/or superseded by more recent work.


This report deals with the specific development of a system using Fluorine injected into a hydrogen tank to accomplish controlled combustion and pressurization and is not of general interest to in-orbit transfer.


The key results of this work culminated in a computer model described in LMSC-A794909-A Vol. IV (Anon.), which is summarized.


This is a good review of the work accomplished up to 1964, however, significant work has been accomplished since and the only data presented here are for 1-g.


The pertinent aspect of this work, an attempt to apply the analysis to actual flight data, is reported by Merte, et al, 1970, which is summarized.


Only applicable to 1-g and nuclear heating with pressure rise not included.

1-g testing. Pertinent aspects of this work are presented in NASA TMX-52573, Stochl and DeWitt, 1969, which is reviewed elsewhere.


This work has been extended by Epstein and Anderson, 1967, which is summarized.


The current state-of-the-art of the computer program described here is represented by later work; e.g. the summarized report by Bradshaw, et al, 1970, (GDC-DDB-70-003) and the report by Nein and Thompson, 1966, (TN D-3177).


This is a useful compilation of design information associated with the various aspects of different types of pressurization systems, however, it is based on existing technology data and the state-of-the-art in 1966.


A cryogenic helium storage system was developed and tested. This work deals with detailed pressurization system hardware, which is beyond the scope of the current technology study.


The use of one propellant to react with another to accomplish tank pressurization is primarily applicable to engine feed systems and not of general interest to in-orbit fluid transfer.


The test data was obtained at 1-g and no attempt was made to apply the results to low-g.

A system is developed to generate hot nitrogen suitable for direct contact pressurization of both fuels and oxidizers of typical earth and space storable propellants. This work deals with detailed pressurization system hardware, which is beyond the scope of the current technology study.


This is just a brief survey of the state-of-the-art, which is adequately covered by individual works which are summarized.


Results of the overall Aerobee flight program are satisfactorily summarized by Aydelott (1967), which report is summarized.


The test data was obtained at 1-g and no attempt was made to apply the results to low-g.


Even though extensive testing was accomplished at 1-g, using Freon 113 in different size tanks, the results were only of a general nature and not significant to in-orbit fluid transfer, as compared to other work in this field. Satisfactory pressure scaling was only demonstrated for the simple case of liquid heating where the tank fluid would be essentially mixed.


Results of the overall Aerobee flight program are satisfactorily summarized by Aydelott (1967), which report is summarized.

Even though the effects of low-g are discussed and an acceleration term exists in the equations, this analysis is similar to those typically used for 1-g and no low-g test data are presented for verification.


Pertinent results of the overall Aerobee flight program are presented by Aydelott (1967), which report is summarized. Also, pressure rise data have been correlated by Blatt (1968).


This is a good, thorough treatment of interfacial heat and mass transfer, however, testing was only accomplished at 1-g and the basic results have been incorporated into later works which are summarized.


Pertinent results of the overall Aerobee flight program are presented by Aydelott (1967), which report is summarized.


Pertinent aspects of this work are reported under contracts NAS8-24982 and NAS8-20330, Poth, et al, 1968 and 1970 and in AIAA Paper No. 71-646, Poth and Van Hook, 1971, which reports are reviewed elsewhere.


See the summarized report by Aydelott (1967) for pertinent results of the overall Aerobee program. Also, pressure rise data have been correlated by Blatt (1968).

This is one-g data without particular application to in-orbit fluid management.


The current state-of-the-art of this work is represented by the summarized work of Stochl, 1970 (TN D-7019).


This work is reported in greater detail in TN D-2585 by Roudebush, 1965.


General discussions and trade-offs presented here are based on existing technology data.


1-g testing. This work has been expanded by testing in a 13-ft-dia. tank as reported in NASA TN D-7019, Stochl, et al, 1970, which is summarized.


1-g testing. Pertinent aspects of this work are summarized in NASA TM X-52573, Stochl and DeWitt, 1969, which is summarized.


1-g testing. Pertinent aspects of this work are summarized in NASA TM X-52573, Stochl and DeWitt, 1969, which is summarized.

This is the same as NASA TM X-52573 by Stochl and DeWitt, 1969, which is summarized.


This is 1-g data without any correlation to low-g. For additional work by the author on this subject, See Tatom, 1966, which report is reviewed below.


This is one of a fairly large number of reports containing 1-g stratification data, the low-g usefulness of which must await evaluation through low-g testing.


This report is identical to a paper presented by the authors at the 1963 Cryogenic Engineering Conference, which paper is reviewed above.


The summarized work of Epstein and Anderson, 1967 is taken to be representative of the state-of-the-art of pressurant predictions using relatively simple equations.


Computer programs were developed to predict internal tank thermodynamics and forces on a vehicle generated by venting. The current state-of-the-art of the thermodynamics model is represented by work presented in the summarized report by Bradshaw, et al, 1970 (GDC-DDB-70-003).

The design of external pressurization systems for supercritical cryogenic storage systems is investigated. Just one approach is presented which is mostly concerned with hardware details not peculiar to low-g operation.


Some H₂ tank data are presented from S-IVB flights 501 and 502, however, the data and its evaluation are not sufficient to draw meaningful conclusions other than that "more experimentation under carefully controlled conditions is necessary before accurate prediction of bubble-induced collapse is possible."


A semiempirical prediction method was developed for high-gravity environments for application to the LH₂ tanks of the Saturn booster stages. Low-g was not treated in any detail.

VENT SYSTEMS


The critical phase of this work was a low-g test of the most promising system selected here, which is covered by Bovenkerk (1969), which is summarized.


This program is concerned with the design and evaluation of a heat exchanger vent system for tank pressure control at low-g. This is only a quarterly report. It is expected that the final report will be out sometime in November or December 1974, under CR-134536.


The work reported here is essentially the same as that reported by the author in the May 1969 Low-G Seminar at MACDAC, which report is reviewed elsewhere and which is more readily available than the current work.

Mostly just a review of existing data. The only new item is the use of electroconvection to replace the mechanical pump in a bulk heat exchanger system, the performance of which is only speculation. The potential success of such a system would be allied with that of dielectrophoretic orientation, the technology of which is reviewed elsewhere.


An interesting survey and a good bibliography are presented, however, this work by itself does not advance the state-of-the-art of liquid/vapor separation as it applies to low-g venting systems or in-orbit fluid transfer.


It is noted that energy balances and testing were associated with an exchanger attached only in the ullage region of a tank operating at one-g and would not have the same characteristics as one required to operate at low-g with all liquid orientations. More significant work has been accomplished since; e.g., Page and Tegart, 1969 and Bullard, et al, 1973.


This is a specialized study with limited application. The general concept of non-vented oxidizer tanks is covered by the report by Murphy and Rose, 1968 which is reviewed elsewhere.


The significant aspects of this program are presented in greater detail by Salvinski, et al, 1965, which report is reviewed elsewhere.


This is only the first phase of a program which is covered in its entirety by Allgater, 1968, which report is summarized.

Tests were run in 1-g using LH$_2$ to demonstrate the feasibility of the thermodynamic heat exchanger low-g vent concept for use in the Centaur however, this is very early and only preliminary work on a subject which is covered more completely in later reports.


The center vent tube concept is based on locating the vent inlet at a point in the tank where vapor is expected to be under zero-g conditions with the important factor being liquid/vapor interface shape and non-wetting of the vent tube, which is covered more thoroughly in the Low-G Fluid Behavior volume.


The significant test phase of this work is reported by Page and Tegart, 1969, which is summarized. Also the current report is confidential.


The significant test phase of this work is reported by Page and Tegart, 1969, which summarized.


Technology details are not presented and the vent systems discussed here are covered in more detail in other work, e.g. Mitchell, et al, (1966), which report is summarized.


More recent and comprehensive work in this area is presented by Allgeier (1968), which is summarized.


This patent describes a typical storage system with insulation, throttling valve, and wall heat exchanger. See Page & Tegart (1969) and Allgeier (1968) for more detailed information on this subject area.
Two different versions of dynamic liquid/vapor separators are described for the low-g vent application. These particular units were built and tested under a GD/C contracted program which is covered by Mitchell, et al, (1966), which report is.


Work pertinent to the current program was conducted in the area of zero-g venting where a wall heat exchanger vent system was fabricated and tested using both LN₂ and LH₂, however, this is very early work on the subject and has been superseded by later work; e.g., Page and Tegart, 1969 and Bullard, et al, 1973.


This work is reported in greater detail in Report GDC-DDB67-006 by the authors, October 1966 which is summarized.


This work is covered in more detail by Mitchell, et al, 1966, which report is summarized.


This is an interim report; the significant phase of the work (testing and data analysis) is covered in the final report (Sterbentz, et al, 1968), which report is summarized.


Without test and further analysis the usefulness of this system, as compared to similar systems, is mere speculation.

Not enough data was presented to fully evaluate performance. Also, later and more advanced work on the subject is presented by Page and Tegart, 1969, and Bullard, et al, 1973.


This system is basically a gas supplier, with external heating available for liquid vaporization, rather than a low-g venting system.

**FLUID MIXING**


Mixing of two different liquids as proposed here is not pertinent to the current in-orbit-fluid transfer program.


This paper was never published and would therefore not be generally available. For some of the basic test results see Stark and Blatt, 1967, which report is summarized.


Even though this brief analysis does indicate the feasibility of providing some convective heat transfer by tank rotation, the work is only analytical and not extensive enough or with sufficient quantitative data to be useful in the current program.


This is only preliminary work on the problem, without experimental verification. For later work on this subject, see Catton, 1969, which is reviewed elsewhere.


This is a good basic jet mixing report, however, no attempt was made to relate the work to low-g. For work more directly applicable to in-orbit fluid management see Berenyi, et al, 1968 and Poth, et al, 1968, which reports are summarized.

B-32

Even though test data using water sloshing in a small Plexiglas cylinder at 1-g were obtained, the usefulness is only qualitative and limited in scope since an in-depth analysis was not made and the dimensionless temperature moment used to correlate the data was not even quantitatively defined. The basic conclusion was that stable nonplanar sloshing provided greater destratification than unstable nonplanar or stable planar sloshing.


This work is covered more thoroughly by Holmes and Krane (1969), which report is reviewed above.


The feasibility of using a small (0.5 to 2.5w) brushless dc motor to drive a cryogenic LH2 mixer was demonstrated. Increased efficiency over an ac motor was also indicated, however, some electronic failures occurred. Further details of this work are associated with component fabrication beyond the scope of the current program.


It was significant that bubble pumps did not effect a reduction in pressure rise rate, however, this report is not generally available.


This study is concerned with controlling the mixture ratio of two or more fluids such as hot and cold water coming together in two or more streams and is not applicable to the current program.


This work has been amplified and expanded from that presented here; Reference, Poth, et al, 1968, which is summarized.

This is the same work as reported under contracts NAS8-24882 NAS8-20330, Poth, et al, 1968 and 1970 and in AIAA Paper No. 71-646, Poth and Van Hook, 1971.


This work is covered in greater detail in contract reports, e.g., Van Hook and Poth, 1970, which report is summarized.


Taking fluid from different parts of a tank to obtain a mixed fluid flow to an engine is proposed along with some test data demonstrating the idea. This is not of primary significance to in-orbit fluid supply.


No quantitative data are presented and the qualitative data presented are not significant as compared to other work in this field; e.g., Poth, et al, 1968, which report is summarized.

REFRIGERATION & RELIQUEFACTION


This is the same work which is reported in greater detail by the authors in the contract NAS8-21203, 1972 final report.


General system and hardware characteristics, along with test results are adequately covered by the summary technical report under this contract (same author and date), which is summarized.

More extensive information of this type and more oriented to the current program is presented by Jensen, et al, 1971, which is summarized.


This was initial work on the subject which has culminated in the fabrication and test of a partial H₂ reliquefier as reported by Benning, et al, 1972, which report is summarized.


Results of an analytical study investigating the application of capillary pumping to the heat rejection loop of an advanced Rankine Cycle power conversion system are presented, however, the work was only analytical and Rankine Cycle power systems in themselves are not of interest to the current program.


This is the same work as reported by Gibson, et al, 1965, in the contract NAS8-5298 final report which is reviewed elsewhere.


This is the same work as reported by Gibson, et al, 1965, in the contract NAS8-5298 final report which is reviewed elsewhere.


Data of this type more specifically oriented to the current space application is presented by Jensen, et al, 1971, which report is summarized.

INTERFACE CONTROL & LIQUID ACQUISITION (GENERAL)


Data is not presented in a useful form. See Trump, et al, 1966, for more recent work on surface tension device storage means for providing liquid to the vaporizer.

The development of this concept is covered more thoroughly by Paynter and Page, 1973, which report is summarized.


Other more comprehensive studies of capillary force feed systems are summarized elsewhere.


The system uses magnetic forces as well as capillary force to deliver LO$_2$. Insufficient design information is presented to aid the fluid transfer system designer.


The report is a brief overview with information presented obtainable from other sources that have been summarized, e.g., Debrock, 1970.


The two techniques selected for detailed analysis have been subjected to considerable development since this program was completed.


This is only a general discussion of designs of tanks for space storage of cryogenic liquids and adds nothing to the current state-of-the-art of liquid expulsion techniques.


The material in this paper, as presented, is not directly pertinent to the low-g transfer study.

This paper discusses considerations which must be taken into account in designing a positive expulsion system. It does not, however, add to the state-of-the-art.


This program is an extensive review of all propellant acquisition and expulsion systems to 1962. Recent developments have made it obsolete.


Only general not-in-depth discussions are presented. For better data on this subject, see Rosener, et al, 1971, under "other acquisition systems."


Primarily deals with overall system description with no real details given. Does not add to the state-of-the-art.


The result of this program was an operational piece of hardware delivered to AFRPL. The Phase I portion of this study (Parmley, 1966), summarized elsewhere, presents the selection criteria and preliminary design information. The Phase II report presenting information on experiment definition and fabrication does not provide fluid transfer system design information.


Considerable improvement of surface tension devices has been made since this study was completed.


This paper provides a parametric comparison of the weights of three reaction control systems with general comments about relative advantages and development status of acquisition devices, however, the discussion of the various acquisition devices is too general in nature to be of use in the present study.

This work has been superseded by more recent investigations.


The basic application is for environmental control systems and similar devices have been built and tested under more current work reviewed elsewhere, e.g. Rosener, et al, 1974, under "other acquisition systems."


This discussion is very general with no significant data presented.


The material presented in this paper is not directly pertinent to the low-g propellant transfer study.


The material in this paper, as presented, is not directly pertinent to the low-g transfer study.


Liquid-gas separation by vortex and surface tension phenomena is discussed, however, insufficient details are given to be of use to the current program.

**CAPILLARY ACQUISITION**


This report is a synopsis of two other volumes of the study that were both individually summarized.

The report doesn't add to capillary acquisition knowledge. For a critique of neutral buoyancy see De Brock, 1973.


No design data was presented.


This report discusses the double liner concept for venting and outflow with cryogens. Test data presented is difficult to interpret. Reports by Paynter, and Page, 1973, that are summarized, adequately treat this subject.


The report describes Convair work on screen flow testing, settling, residual analysis, bubble motion and surface tension properties. However, screen flow pressure drop is adequately covered in Cady, 1973. Important information presented on draining is presented in Satterlee and Hollister, 1967. Settling work merely consolidates drop tower testing reported by NASA/LeRC and work on bubble motion, agglomeration, and vaporization is significant but is not directly usable without the computer program which is proprietary.


Very brief discussion makes evaluation of this work difficult for propellant orientation. Referenced reports giving details were classified. This report is summarized for the venting category.


Interesting concepts for nonwetting fluids are presented, however not much design information was presented. No testing was done to verify calculations.

This study is referenced by Bovenkerk, 1969, as containing more detailed information on surface tension devices for venting and acquisition.


This paper is a synopsis of reports by Burge, and Blackmon, 1973 that are summarized.


Concentric perforated plates for center of mass control in a very low gravity environment are discussed. Not enough details are given to be of value.


The report is qualitative with no design data or unique information presented.


The report describes galleries with screened windows (four 190° channels) in a 62" diameter hydrazine tank. System analysis and design are similar to that described in DeBrock 1970 and 1973. Bubble point acceptance testing was used for the welded assembly. The system is described in Heller, 1971, which is summarized. In fact, the device appears on the cover of that report.


This is an interim report. Final results are documented in DeBrock, November 1972, listed above.


Propellant management system is briefly described. Device is mainly a restart device, relying upon settling for a refill and thus not strictly applicable to low g fluid transfer. A sponge assembly providing low g refill capability is briefly discussed. Technical details of design, analysis and testing of the sponge are not given.

The information in this paper is contained in more recent reports.


No basic technology information is given and report is not generally available.


This report analytically demonstrated that cryogens will wet all known solids with a zero contact angle. The information in this basic report has become common knowledge in the field.


Basic data on wetting, appearing to apply to liquid metal alloys, from the example given. Detailed information of this type is not needed for designing liquid acquisition systems.


Information is not directly applicable to surface tension devices. Applicability appears related to solder or other metallic fluids.


The paper gives a good conceptual description of the use of porous material channels for passing liquid in low gravity. A portion of the liquid is throttled and used to subcool the remaining liquid flow. No data or design details are given, however.

Presents work done between 1967 and 1970 by GDC, Martin and University of Michigan on capillary acquisition, low gravity experimentation on the AS-203, interface stability with foraminous materials, and low gravity boiling heat transfer. Individual source materials are reviewed elsewhere.


This concept was examined in detail including ground based cryogenic testing in NAS9-12182, Paynter and Page, 1973.


The information in this paper is contained in more recent reports.


The report indicates that retention capability of a specific capillary material should be determined by testing (bubble point). Discussion and testing are interesting but specific information is not that useful.


An analysis of stability, retention, reorientation and refilling of the Apollo Service Module retention system was presented. The analysis was very specific and no unique design information was presented that could be used for general acquisition system design.


For orienting and supplying liquid, concept has limited applicability due to low flow rate capability. Very little data presented.


Internal document not available for normal distribution.

Symons, 1974, provides more pertinent information on wicking in screens.


The program will directly aid fluid transfer system design but since the program is still in progress only interim monthly reports have been issued.


This report is a consolidation of other volumes of NAS9-12182. These volumes, Paynter and Page, 1973, and Fester, 1973 are summarized.


More details of the dual screen liner (DSL) concept and the testing required are presented in Paynter and Page, 1973, a five volume study that is summarized.


The significant space data has been superseded, refined or assimilated into the literature, and the report is now obsolete.


Data is presented in more detail in Paynter, 1970, NAS8-21259.


Good basic report but results have been superseded by more current studies.


A small device using fibrous teflon and CRES screen was developed to separate hydrogen gas from hydrogenated water for life-support systems. In its present form it does not have application to in-orbit fluid transfer.

This system is basically a start basket relying on reorientation and settling for refill and is therefore not applicable to low g fluid transfer.


Only 1-g testing was accomplished while later work on this subject (Saunders 1970) included actual low-g testing.


The application is for environmental control systems and is not pertinent to in-orbit fluid transfer. Also, similar devices have been built and tested under more current work, reviewed elsewhere, e.g. Saunders, 1970.


The design and test plan details are not of general use in the design of transfer systems. No technology information is presented.


The concept discussed is similar to Viking 75. The summarized Viking 75 work by Dowdy and DeBrock, 1972 suffices for documenting this type of design.


A similar device is adequately described in Dowdy and DeBrock, 1972 which is summarized.


The more recent work in NAS9-12182, Paynter and Page, 1973, covers the dual screen liner approach adequately.

The paper discusses some pertinent current problems that are handled in more detail in other sources.

**POSITIVE EXPULSION**

Boeing, AIAA/Aerospace Conference, May 1968.

A 7.125 inch O.D. stainless steel bellows, 11 inches long was tested in LN$_2$. Cryogenic bellows evaluation

Techniques," Boeing, D2-22297, N64-32877, March 1964.

The purpose of this study was to experimentally evaluate metallic bellows and floating piston positive expulsion devices for cryogenic liquids in zero gravity. However, considerable number of improvements in bellows manufacturing techniques have been developed since 1964.


The objective of this task was to increase the expulsion cycle life of Apollo bladders by overcoming bladder-to-shell friction problems. Undersized bladders, similar to that used on the Lunar Module RCS tanks, were evaluated for this application. The bladders used are discussed in detail in Anderson, 1969 which is summarized.


Similar work, by the same author, Anderson, 1969 is summarized.


The work is similar to Anderson, 1969 in using aluminum coatings to inhibit permeation in N$_2$O$_4$ bladders. Also, see Hoggatt, 1971.

This contract provides groundwork for the later, comprehensive investigation by Pope and Penner (1968), which is summarized.

Bohler, D.M. (Lt.), "Chemical Supplies, Storage and Expulsion of Cryogenic Propellants," WPAFB, PCI 120/6 Section VI-A (Vol. 6, Background Material for the Study of the National Space Power Program, October 1964.

The paper gives a very brief overview of modes of containment, heat leak, zero gravity consideration and pumping. No design details are presented.


No useful material was presented in this brief synopsis.


A later and more comprehensive discussion of this topic is presented by Martin and Green (1973), which is summarized.


This report points out the problems associated with "free floating" rolling diaphragm pistons. Extensive redesign of this system was recommended. Other diaphragm concepts, such as Gleich 1967 are more worthy of attention.


See Hoggatt (1968) for more recent developments in LO₂ bladder technology.


The objective of this paper was to develop a method for analyzing fold strains produced by single and double folds. The metals, which are superior with regard to permeation resistance, are inferior with regard to fatigue resistance. The opposite is true of the elastomers. Intermediate plastics (Teflon) were unsatisfactory in both respects for extended duration missions. More complete studies of bladder material problems and characteristics are presented in Hoggatt, 1968 and 1971, Pope and Penner, 1968 and Anderson, 1969.

Tensile properties of EPT-10 and AF-E-332 were determined in air and liquid hydrazine using constant-strain-rate tensile tests over a range of temperatures and elongation rates. Results were used to predict time to rupture for these materials in hydrazine. Experimental results do not appear directly usable as design information.


The work is generally useful, however specific data on permeability related to fluid transfer is presented in Martin and Green, 1973 and Anderson, 1969 which are summarized.


The objective of this program was to evaluate a welded bellows assembly designed and fabricated by the Solar division of International Harvester. The work indicated that welding techniques for bellows core fabrication require considerable development. More promising are the formed bellows configurations discussed in Stark, 1972 and Lange and Hughes, 1971.


The report describing developments of thin films and cryogenic testing for brittleness, is too narrow in scope to be of use in fluid expulsion system design.


Bladder test results indicating permeation and diffusion of oxygen through the potable water tank bladder were presented. Results are specifically applicable to one bladder configuration and are not generally applicable to propellant transfer applications. No information is given here on bladder construction.


The only useful conclusion from this study it that welded bellows fabrication techniques require considerable improvement.

Evolution of a Teflon-glass laminate for an \( \text{LO}_2 \) gasket material is presented which is applicable to positive expulsion devices.


The objective of this paper was to discuss the characteristics of the three lobe collapsing bladder, however considerable progress has been made in the development of reusable, elastomer bladders since this paper was written.


The final report on this program, Gleich (1971) is reviewed elsewhere.


An Arde program involving cryogenic testing of diaphragms of similar design is summarized (Gleich, 1967).


An Arde program involving cryogenic testing of diaphragms of similar design is summarized Gleich, 1967).


The final report on this program Gleich, 1967 is summarized.


This is the first of a series of reports on this four-year contract. For summary and comments, see Sing (1966).


Dynamics and permeation investigations were conducted. This is an interim report.
This report indicates that considerable work is required before a usable rolling diaphragm will be available. Work presented in Gleich, 1967 and Martin and Green, 1973 presents the pertinent work done since that time.


See Hoggatt (1968), summarized elsewhere, for more recent and successful development of polymeric bladders for LO₂ expulsion.


Considerable development of polymeric expulsion bladders has occurred since this report was published.


The results of this task are included in the report by Hoggatt (1968), which is summarized.


This document is a handout showing viewgraphs and data on the various TRW systems, including diaphragms, bladders, and bellows and is not generally available.


This report has been superseded by more recent surveys of the state of the art.


The objective of this program was to design and fatigue test a welded CRES 347 bellows utilizing the "tilt-edge" configuration, however, the test verification program was not nearly as extensive as that performed by Lange and Hughes (1971).

This work provided groundwork for the later, comprehensive investigation by Pope and Penner (1968), which is summarized.


The problem of, and solution for polymeric film permeability were covered in more detail by Anderson (1969), summarized elsewhere.


Work was similar to Johnson and Bhuta, 1969 which is reviewed below.


Diffusion flow rates were analytically determined for laminated positive expulsion bladders. Results of the program are difficult to use since knowledge of the foil defects present in the bladder being evaluated is required. The report is thus not useful as a design tool.


This patent is very general in its description of the system and offers no useful information for this study.


Primarily a discussion of other work.


The analytical treatment of permeation in bladders indicates that pressurant and propellant vapor can result in formation of large gas bubbles on the propellant side of the bladder. No comparison is given with experimental data. Permeation is discussed in Martin and Green, 1973 and Anderson, 1969, which are summarized.

This paper is unnumbered and apparently not generally obtainable. Similar information is presented by Hellman (1969) of Thiokol in a readily-obtainable report.


This report only indicates that polymeric diaphragm development is far behind that of metallic diaphragms and that work in this area may not be as fruitful as in elastomeric or metallic diaphragms.


The objective of this program was to investigate elastomeric materials for OF$_2$ and B$_2$H$_6$ (Diborane) expulsion bladders, however, considerable development of elastomeric expulsion bladder materials has occurred since this report was written.


White (1971) provides later information on this study.


Centrifuge testing was conducted to evaluate Condor system start capability under axial and transverse load environments. The metallic collapsing expulsion bladders (Expellodyne) were evaluated using alcohol-glycol and Freon as the test fluids. The test was 81% successful. Bladder redesign was recommended. No design details were presented.


No specific information on the bellows expulsion system performance is presented.


This document is not generally available. More information on Teflon co-dispersions can be found in the report by Anderson (1969), summarized elsewhere.

B-51

The paper discusses the characteristics of bladder materials as a function of the relative composition of TFE (Polytetrafluoroethylene) and FEP (Hexafluoropropylene) Teflon. The fluid transfer system designer does not generally require information at this level of detail.


This contract provided groundwork for the later, comprehensive investigation by Pope and Penner (1968), summarized elsewhere.


No design data given. Report information is superseded by Heller, 1971.


The subject of laminated teflon bladders has been adequately treated in Hoggatt, 1971 and Anderson, 1969.


More recent and comprehensive materials development studies are reported by Martin and Green (1973) summarized elsewhere.


Actual responses deviated greatly from predictions, indicating that considerable refinement of predictive techniques is required. Because of this the usefulness of the reported is minimal.


Similar development work was carried out by Hoggatt (1971), summarized elsewhere.

A LOX compatible adhesive system for use in Kapton film bladder fabrication was selected from nine adhesives originally selected for screening. A Kel-F elastomeric adhesive was selected based on the three criteria of bonding strength, LOX impact compatibility and adequate flexibility at \(-320^\circ F\). Details of this nature are not required for the current program.


A metallic diaphragm is used to expel the fuel, \(N_2O_4\), from a 6-1/8 in. spherical tank. Very little information about the diaphragm appears in this paper.


The computer programs described in this report were revised on a later contract by Lange and Hughes (1971).


No new technology is reported in this patent.


This report is very brief and now technically obsolete.


This report is a bibliography of reports covering all phases of low g liquid behavior and supply and is not generally available, since it is an internal library document. Pertinent reports were ordered from those cited.


The report discusses preparation of tetrafluoroethylene oxide (TFEO) and polytetrafluorethane oxide (PTFEO) as well as several other fluoroelastomers. Fluid transfer system design does not require knowledte of these details.

This work is superseded by more recent work; i.e. AFE-332 is the recommended bladder material for hydrazine according to Martin and Green, 1973.


Discusses the same information presented in White, 1971.


The information provided on positive expulsion systems is comparatively sparse and not particularly useful.


A later report by Hoggatt (1971) summarized elsewhere, has made significant progress in the reduction of polymeric film permeability.


The composition, purity and decomposition of hydrazine was explored. Useful information was presented, but generally this is of limited applicability to the fluid transfer system design. Work of a similar nature is presented in Coulbert and Yankura, 1972 which is summarized.


An Arde program involving cryogenic testing of diaphragms of similar design has been summarized elsewhere (Gleich 1967).
OTHER ACQUISITION SYSTEMS


This study served as ground work for the more definitive investigation by Blackmon (1965), which is summarized.


This program establishes ground work for later work by Blackmon (1965), which is summarized.


The material in this report is included in that by Blutt and Hurwitz (1968), summarized elsewhere.


The specific application here is for a small water vortex separator for life support systems. No low-g testing was accomplished and the information presented is not significant to in-orbit fluid transfer.


No new technical data with regard to dielectrophoretic acquisition system performance is contained in this report.


Ten zero g aircraft flight tests performed on liquid expulsion tank produced inconclusive results. Neither surface tension or heat transfer considerations appear to have been adequately handled. No quantitative data was presented.

This report contains proprietary information and is not generally available.


A more complete discussion of this topic is contained in the report by Blutt and Hurwitz (1968), which is summarized.


The report by Blutt and Hurwitz (1968), summarized elsewhere, further develops many of the concepts reported herein.


Control of dielectric fluids has been discussed in considerable detail (Blutt and Hurwitz 1968), this paper does not add significant new data.


A more complete, and pertinent, discussion of this topic appears in Reynolds and Hurwitz 1969.


A positive pressure differential can be observed between a liquid in an open container and the atmosphere outside the container if the liquid is near its boiling point and its surface is subjected to an acoustic sound field. The omnidirectional pressure in the liquid however will not be sufficient to settle liquid at a predetermined location in the tank. The report generally discredits the work of Wessels in regard to using acoustical pumping for orientation.


Later work on this subject is reported by Fleeter and Ostrach, 1966 which is summarized.

No experimental evaluation of the centrifugal and static impingement separator devices proposed were made and no design data is given that would be useful to low g transfer system design.


The information in this report is the same as that by Melcher, et al (1969) reviewed below.


The pertinent details of this work included in the report by Blutt and Hurwitz (1968), which is summarized.


More recent work by the authors, in the same area, is reviewed above.


This work is oriented toward vortex liquid-gas separation where the liquid is to remain in the separator. For data on vortex separation which is more pertinent to in-orbit fluid transfer see the summarized report by Fleeter and Ostrach, 1966.


The magnetic technique is not well developed technology. No design data is presented. Magnetic particles could cause clogging problems when the fluid is used for its final purpose such as engine restart, cooling, etc.


The work reported here concentrated on the problem of potential adverse reactions between the pressurant and oxidizer and data pertinent to in-orbit fluid transfer was not presented.

This paper describes graphic experiments of dielectrophoretic action but does not relate directly to low-g acquisition.


This report discusses the dielectrophoresis phenomenon and has been superseded by more recent treatments of the subject.


The report by Blutt and Hurwitz (1969), which is summarized, provides more in depth analysis and more extensive experimental data on the oxygen converter system.


The material contained in this paper is included in the contract final report by Blutt and Hurwitz (1968), which is summarized.


The liquid-gas vortex separation work accomplished by Fleeter and Ostrach, 1966, was used here as a base to develop a separator for a space shower application. This unit is too small to be of specific application to fluid transfer and therefore the more basic work of Fleeter and Ostrach is summarized to represent this general technology.


Basic application is to space manufacturing and is not pertinent to the current program.


Same work as covered in Wessels, 1968.
Acoustical pumping forces are derived for a saturated liquid subjected to acoustic vibration. As indicated by Kramer, 1967, however, acoustical pumping can be used more readily for pressurization than for acquisition.


Same work as covered in Wessels, 1968.
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 | Y. Propellant Properties |
| B. Settling | Z. Venting |
| C. Expulsion Bladders | AA. Exhausting |
| D. Gravitation | BB. Interfacial Tension |
| E. Gravitational Effects | CC. Wetting |
| F. Reduced Gravity | DD. Interfaces |
| G. Weightlessness | EE. Instruments |
| H. Gravitational Fields | FF. Cryogenics |
| I. Propellant Transfer | GG. Liquid Flow |
| J. Fluids | HH. Water Flow |
| K. Liquids | II. Fluid Flow |
| L. Liquefied Gases | JJ. Vents |
| M. Heat Transfer | KK. Exhaust Systems |
| N. Thermodynamics | LL. Cryogenic Fluids |
| O. Liquid-Liquid Interfaces | MM. Liquid Sloshing |
| P. Liquid-Vapor | NN. Ullage |
| Q. Interface Stability | OO. Rotating Fluids |
| R. Liquid Surfaces | PP. Rotating Liquids |
| S. Hydrodynamics | QQ. Liquid-Vapor Equilibrium |
| T. Capillary Flow | RR. Free Boundaries |
| U. Inlet Flow | SS. Liquid Oxygen |
| V. Fluid Dynamics | TT. Liquid Hydrogen |
| W. Liquid Rocket Propellants | UU. Refueling |
| X. Fluid Mechanics | VV. Fuel Control |

C-2
WW. Acquisition
XX. Expulsion
YY. Flow
APPENDIX D

ABBREVIATIONS, DEFINITIONS AND NOMENCLATURE
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<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>
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<tr>
<td>GD/FW</td>
<td>General Dynamics Fort Worth</td>
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<td>GE</td>
<td>General Electric</td>
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<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>
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<tr>
<td>MACDAC</td>
<td>McDonnell Douglas Aircraft Company</td>
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<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<td>MMC</td>
<td>Martin Marietta</td>
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<td>NAR</td>
<td>North American Rockwell</td>
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<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>
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<td>NASA-LeRC</td>
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<td>NASA-MSFC</td>
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<td>NBS</td>
<td>National Bureau of Standards</td>
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<td>NRC</td>
<td>National Research Corporation</td>
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<tr>
<td>STL</td>
<td>Space Technology Laboratory</td>
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<td>SRI</td>
<td>Stanford Research Institute</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>ACS</td>
<td>Attitude Control System</td>
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<tr>
<td>Al Aly</td>
<td>Aluminum Alloy</td>
</tr>
<tr>
<td>AS-203</td>
<td>Apollo Saturn No. 203 Flight Vehicle</td>
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<tr>
<td>CRES</td>
<td>Corrosion Resistant Steel</td>
</tr>
<tr>
<td>$F_2$</td>
<td>Fluorine</td>
</tr>
<tr>
<td>FEP</td>
<td>Teflon Polymer-Hexafluoropropylene</td>
</tr>
<tr>
<td>GHe</td>
<td>Gaseous Helium</td>
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<tr>
<td>$\text{GH}_2$</td>
<td>Gaseous Hydrogen</td>
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<tr>
<td>$\text{GN}_2$</td>
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<td>$\text{GO}_2$</td>
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<td>Helium</td>
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<tr>
<td>$\text{H}_2$</td>
<td>Hydrogen</td>
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<tr>
<td>LEM</td>
<td>Lunar Excursion Module</td>
</tr>
<tr>
<td>LHe</td>
<td>Liquid Helium</td>
</tr>
<tr>
<td>$\text{LH}_2$</td>
<td>Liquid Hydrogen</td>
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<tr>
<td>LM</td>
<td>Lunar Module</td>
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<tr>
<td>$\text{LN}_2$</td>
<td>Liquid Nitrogen</td>
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<tr>
<td>$\text{LO}_2$</td>
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<td>LOX</td>
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<tr>
<td>MMH</td>
<td>Monomethyl Hydrazine</td>
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<tr>
<td>MLI</td>
<td>Multilayer Insulation</td>
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<tr>
<td>$\text{N}_2$</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>$\text{N}_2\text{O}_4$</td>
<td>Nitrogen Tetroxide</td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>Oxygen</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>S-II B</td>
<td>Saturn Two B Vehicle</td>
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D.2 GLOSSARY OF TERMS
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<tr>
<td>S-IVC</td>
<td>Saturn Four C Vehicle</td>
</tr>
<tr>
<td>SPS</td>
<td>Service Propulsion System</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>
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<tr>
<td>TPS</td>
<td>Thermal Protection System</td>
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### D.3 NOMENCLATURE

- **A**: area
- **a**: acceleration
- **C_p**: specific heat at constant pressure
- **C_v**: specific heat at constant volume
- **D, d**: diameter
- **F_{tu}**: ultimate tensile stress
- **G**: mass flow flux, \( \dot{m}/A \)
- **g**: gravitational constant
- **h**: heat transfer coefficient or specific enthalpy
- **h_f**: film heat transfer coefficient
- **h_{fg}**: latent heat of vaporization
- **k**: thermal conductivity
- **L**: length
- **m**: mass
- **\dot{m}**: mass flow rate
- **N**: speed, rpm
- **N_{Gr, Gr}**: Grashof number
- **N_{Re, Re}**: Reynolds number
- **N_{Pr, Pr}**: Prandtl number
- **OD**: outside diameter
- **P, p**: absolute pressure
- **q, \dot{Q}**: heat transfer rate
- **Q**: volume flow rate
R  radius
  t  time
  T  absolute temperature
  u  velocity
  v  specific volume
  V  volume
  W  weight
  \dot{w}  weight flow rate
  X  fluid quality
  Z  compressibility factor
  \alpha  thermal diffusivity
  \Delta H  head
  \mu  dynamic viscosity
  \nu  kinematic viscosity (\mu/\rho)
  \rho  density
  \sigma  surface tension

Subscripts
  c  critical
  g  gas
  i  initial
  j  jet
  \text{L, L}  liquid
  o  stagnation
  p  propellant
  s  saturation
  T  tank
  u  ullage
  v  vapor
  w  wall
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