REPORT NO. GDC-DDB70-006
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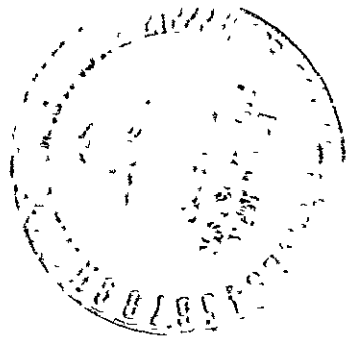
LOW GRAVITY PROPELLANT CONTROL USING CAPILLARY DEVICES IN LARGE SCALE CRYOGENIC VEHICLES

DESIGN HANDBOOK

GENERAL DYNAMICS
Convair Division



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August 1970

Prepared Under
Contract NAS8-21465
CONVAIR DIVISION OF GENERAL DYNAMICS
San Diego, California

FOREWORD

This design handbook for cryogenic capillary devices was prepared under NASA/MSFC Contract NAS8-21465, DCN-8-52-10174 (1F) and S-1 (1F). The report was edited and compiled by M. H. Blatt, Project Manager. Personnel contributing to the report were M. H. Blatt - Fluid Design, J. A. Stark - Thermal Design and L. E. Siden - Structural Design. The text was reviewed by Convair personnel including R. E. Tatro, F. Merino, J. Goldsberry and K. R. Burton. The study was performed under the technical direction of Leon J. Hastings, NASA/MSFC, R-P&VE-PT.

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INTRODUCTION

Expulsion of a fluid from a propellant tank in low gravity requires a means of positively controlling the liquid/vapor interface. Studies of both cryogenic and noncryogenic vehicle missions have indicated the usefulness of utilizing capillary devices to accomplish this propellant control. Based on the promising future for cryogenic capillary devices for positive expulsion in large scale vehicles this design handbook has been compiled.

The information is arranged in four chapters. The first chapter summarizes the contents of the remainder of the handbook with stress placed on the most significant design principles and the main problem areas. The fluid, thermal and structural design chapters which follow, deal with each of these subjects by presenting a detailed summary of the design approach, followed by a flow chart of the steps required for developing a final design and concluding with a detailed discussion of individual design principles and technical problem solutions. The volume is written so that a person with casual interest in cryogenic capillary devices can read only the first chapter if he chooses. Additional information can be obtained in discrete intervals by reading first the chapter summary then the design flow chart description and finally the detailed technical discussions in each chapter. The volume can thus be assimilated at four distinct levels depending on the readers interest. Carefully reading the entire volume should give the capillary device designer sufficient information upon which to base a design for the mission conditions being considered.

1

CRYOGENIC CAPILLARY DEVICE DESIGN

The objective of a capillary device for propellant control in large scale cryogenic vehicles is to provide liquid for engine restart or propellant transfer under adverse gravity conditions. The main fluid design task for a restart application is to contain sufficient liquid to maintain continuous liquid flow until the tank contents can be settled. For a propellant transfer application the principal fluid design goal is the maintenance of continuous contact with the main liquid body regardless of the direction of the vehicle acceleration. The thermal design goal is to prevent vaporization of liquid from within the capillary device. Practical fabrication considerations are to achieve a structurally sound configuration which can be readily manufactured and assembled. These three main areas for consideration; fluid design, thermal design and structural design must be consolidated into an overall design which achieves minimum weight, cost and complexity while satisfying mission requirements.

Chapters 2, 3 and 4 explain the principles behind achieving sound designs in these three areas. This chapter will summarize the salient points of each of these three chapters and then discuss areas where conflicts exist between fluid, thermal and structural design considerations.

From the standpoint of fluid design there are two basic types of devices, propellant transfer and restart. A propellant transfer device can operate in a low gravity environment by maintaining continuous contact with the liquid while the restart device relies on supplying liquid which acts to settle the main body of liquid and thus refills the capillary device.

The propellant transfer device, by nature, must have a large surface area and conform to the tank shape in order to contact the wetting propellant. In addition to maintaining a large surface area for fluid contact it is essential to devise low pressure drop paths from the main body of liquid to the transfer line in order not to exceed the pressure drop which will be maintained by surface tension forces at the capillary barrier. Residuals should be minimized by scavenging the device with linear acceleration while the capillary device is still full and relatively small amounts of liquid remain in the tank. Two configurations, which have been proposed for propellant transfer applications are a screen liner which is concentrically placed inside the tank and a channel reservoir configuration depicted in Figure 4-1. The screen liner is advantageous fluid dynamically since it covers the entire tank surface area for contact and flow. The channel reservoir configuration while covering only a small fraction of tank surface (20 to 50%) will operate successfully with the reservoir providing propellant

flow in the unlikely event that the channels should be uncovered. The residuals, if scavenging is used, should be similar for both types of device, however weight penalties will be somewhat higher for the channel-reservoir configuration. In spite of this disadvantage, thermal considerations favor use of channel reservoir configurations for capillary device applications.

For restart requirements, the capillary device will be a compact configuration with minimum surface area to minimize weight and hydrostatic head requirements. These devices may operate under high gravity conditions, thus spilling is a potential problem. The critical factor in sizing the restart device, and unfortunately the most difficult, is the determination of volume requirements based on settling of the liquid from its pre-restart configuration to a positioning covering the feedline area where the capillary device is situated. The collected fluid must refill the capillary device for a multiple restart mission. For a single restart the collected fluid need only assure that the liquid level in the capillary device does not fall below the pull-through height. Screen selection and configuration is based on the criteria of minimizing residuals, spilling and vapor ingestion and maximizing ease of refill.

Recommended thermal design techniques to prevent vapor formation in cryogenic capillary devices are to employ the cooling capacity of a thermodynamic vent system while using mixing to reduce fluid temperature gradients. The primary consideration is whether the vent fluid cooling capacity is sufficient to prevent vapor from forming without requiring vent flow in excess of the normal boiloff rate. The screen liner design because of its large surface area previously mentioned requires excessive fluid to be vented causing an unnecessary tank pressure reduction. Other important factors to be considered in the thermal design are the effect of heat transfer variations caused by changes in gravity level and liquid-vapor interface orientation on cooling configuration design and the sensitive relationship between fluid mixing and heat transfer to the capillary device. Mixing should be sufficient to reduce temperature gradients caused by free convective flow,however the forced flow pattern caused by the mixer should not cause increases in the heat transfer coefficient between the tank fluid and start basket which counteract the temperature gradient reduction. Cooling and/or venting of transfer lines which contact the capillary device contained fluid must be accomplished to prevent vapor formation in the feedline from displacing liquid in the capillary device. Wicking may be utilized for propellant transfer capillary devices to replace evaporated propellant.

The primary structural considerations are designing the capillary device to resist impingement loads, screen pressure drops and deflections which could cause structural failure of the configuration or alteration of the screen micron rating. Important factors to be incorporated into the design are repairability and ease of assembly. Any repairs required should be made possible without removing the capillary device from the tank. Assembly procedures should, if possible, consider installing the capillary device into the tank in assemblies or subassemblies in order to minimize activity and handling of the capillary device. The design should consider the filtration properties of the screen and propellant cleanliness to eliminate screen clogging problems which might otherwise

occur. Attachment of the screen to the structural supports should preserve the wicking path of the fluid, where required for a large surface area. All seals and connections in between the capillary device and the tank contents should not reduce the bubblepoint of the screen.

In general, fluid, thermal and structural considerations are compatible in striving towards minimum weight, high reliability and ease of fabricability. Conflicts which must be resolved include selection of maximum surface area for fluid transfer and minimum surface area for thermal control. Configurations which are desirable structurally and allow use of minimum gauge material may be unfeasible hydrodynamically. From a fluid design viewpoint the feedline should be wet as far back towards the engine as possible; placement of bellows, heat exchanger coils and control screens is not always structurally feasible to achieve this aim. Cooling capacity of the vent fluid may also limit the amount of fluid contained in the feedline. Placement of a capillary device in a desirable hydrodynamic location may be impeded by excessive heat transfer in this area. Each capillary device design will have unique conflicts and tradeoffs which must be resolved to satisfy mission requirements.

2

FLUID DESIGN

This chapter provides information and techniques for generating a capillary device design based on fluid mechanical considerations. The applicability of the discussion is to all cryogenic liquid supply demands which might be required of a capillary device.

There are two general classifications of missions for which capillary devices are designed. One type of mission is a restart mission where fluid supplied by the capillary device is used to restart an engine and provide thrust for settling the main body of liquid. The other case is typified by a lack of settling; thus requiring continuous low gravity transfer as might occur in an orbital propellant transfer mission.

For the restart or settling case the capillary device can be fairly small in size since it must contain only enough liquid to maintain continuous liquid flow until the main body of liquid is settled and collected over the outlet. The capillary device design for the low gravity period prior to engine restart must minimize vapor formation which could force liquid from the capillary device. The most stringent fluid mechanic design requirements are during the initial restart and during collection and refilling. The relatively high gravity levels experienced during restart and the entrance of vapor into the top of the capillary device induce tendencies for spilling of liquid from the capillary device which may be undesirable for tank shapes where this spilled liquid will then be inaccessible to the outlet. The settling period is typified by high velocity fluid initially being incident on the capillary device and aft bulkhead. The capillary device is thus subjected to high impingement loads and the possibility of vapor entrained by the high velocity liquid, entering the capillary device.

During refill the fluid being collected enters the capillary device through the side screen. However, liquid may have completely wetted the capillary device during the settling process causing some entrained vapor to be trapped in the capillary device. Section 2.9 shows the fluid configuration which might be expected during tank draining. It is desirable to drain the main pool of liquid in preference to the capillary device in order to retard vapor pullthrough. The areas for concern mentioned here are evaluated in detail in this chapter and methods are suggested for overcoming these problems.

The low gravity fluid transfer mission capillary device cannot rely on being refilled by settled fluid. It must therefore remain full during transfer by maintaining continuous contact with the main liquid pool at all times. This requires a relatively large screen surface area distributed over the inner surface of the tank to intersect

the liquid regardless of the orientation or acceleration. The large surface area of this device makes it inherently more difficult to cool than the smaller restart device. However, since there is continuous contact with the main liquid pool, wicking along the capillary control surfaces may be utilized in some cases to replace liquid evaporated from the screen surface without depleting the liquid from within the device.

Propellant transfer devices are typically liner, channel or tube configurations. Liners are most efficient fluid mechanically since they present large surface area for liquid flow and large internal area to minimize pressure drop. Thermally the channel concept is most efficient since it can be cooled using normal tank boiloff as discussed in Chapter 3. Collector tubes are applicable for low flow rate, high percent fill applications such as providing liquid to a thermodynamic vent system inlet prior to engine restart. Liners may be useful for the same type of application where the entire lower surface is not immediately adjacent to the tank wall.

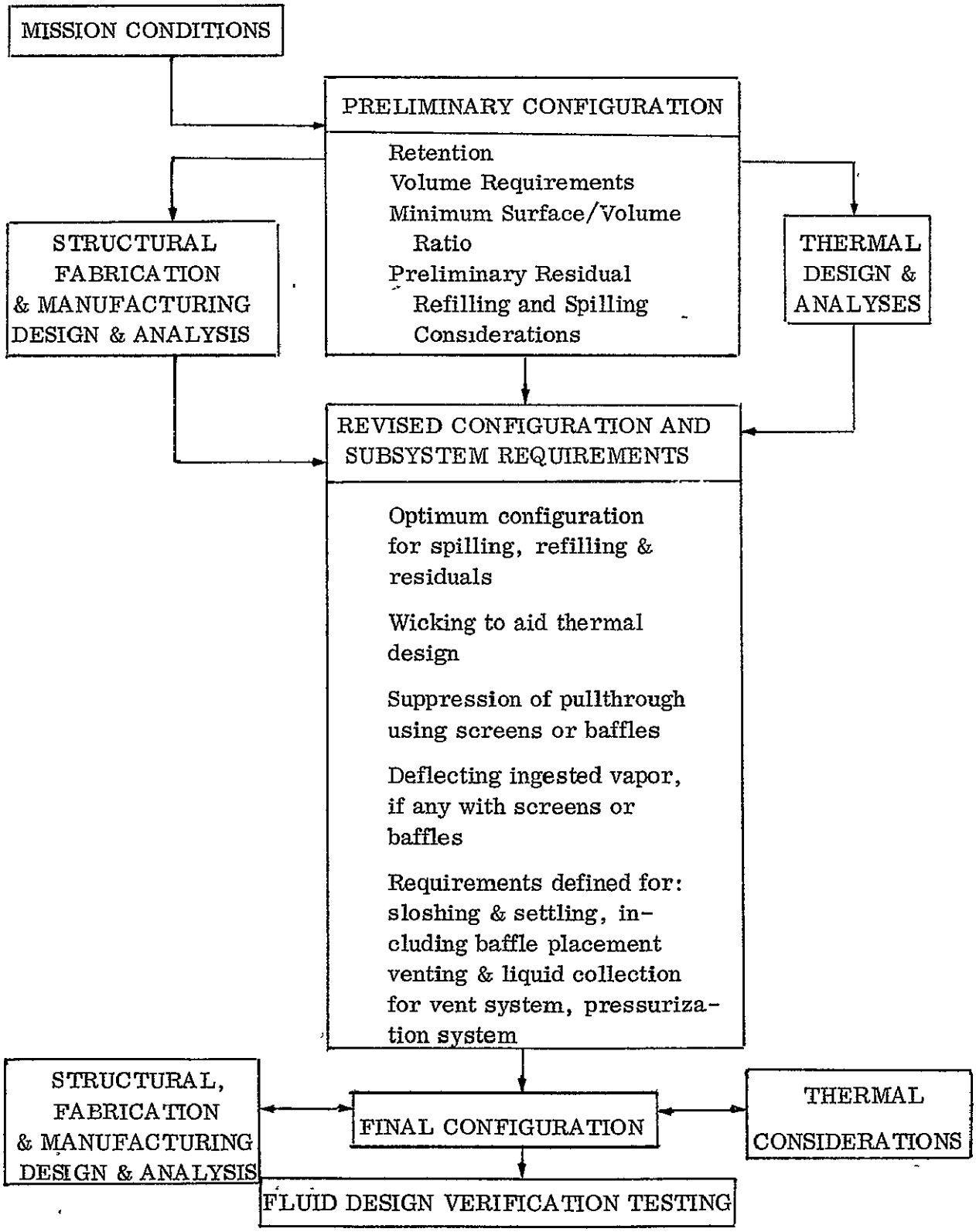
The main fluid dynamic problems with a propellant transfer type capillary device occur toward the end of the propellant tank draining period. At this point there is a relatively small amount of liquid and pressure drop across the screen surface and inside the channel can exceed the surface tension pressure of the capillary control device. Minimization of the tank residuals may require the use of scavenging, or liquid settling, during the final stages of transfer. This requires that consideration be given to settling, spilling, residual and pullthrough suppression.

FLUID ANALYSIS FLOW DIAGRAM

The initial effort should be to determine the preliminary configuration and based on mission conditions, to determine the hydrostatic loads, impingement forces and flow conditions under which the capillary device must operate. Select screen meshes and configuration dimensions for successful fluid retention based on static and dynamic fluid conditions. This configuration should contain sufficient volume for a restart sequence or provide sufficient surface area for contact with the main pool of liquid, as in a propellant transfer application. Thermal considerations require that the surface area be minimized to allow effective cooling. Thus, for a propellant transfer application, the surface area must be selected to satisfy the competing fluid dynamic and thermal design criteria. The initial configuration should also reflect preliminary considerations to minimize residuals, spilling and vapor ingestion and difficulties in refilling (for a multiple transfer case).

The preliminary configuration should then be evaluated thermally and structurally to assess any changes which may be required. These changes, for example, revisions in allowable surface area to permit cooling or revisions in surface shape to permit reduction in structural loading, must then be evaluated from a hydrodynamic standpoint.

Table 2-1. Fluid Analysis Flow Diagram



An evaluation of the effect of thermal and structural requirements upon hydrodynamic performance will indicate necessary changes in fluid design. At this time it is also efficient to optimize the location, size and type of capillary control surfaces based on spilling, refilling and residual performance as evaluated by the INGASP and DREGS2 programs. Pullthrough suppression, wicking and vapor deflection considerations should be incorporated into this design. Subsystem requirements should be defined so that capillary device operation will not be jeopardized. The use of baffles for controlling sloshing and settling, a thermodynamic vent system for controlling tank pressure and cooling the capillary device, pressurization with low temperature pressurant and collector tubes or channels to provide liquid inlet to a thermodynamic vent device are the major subsystem items which influence capillary device performance.

The results of the fluid design effort will be a final configuration which will also reflect thermal, structural, fabrication and manufacturing design effort. For design verification, a test program should be developed at this time to prove that the capillary device will satisfactorily perform under mission conditions.

SUMMARY OF FLUID DESIGN SECTION

Retention

The criteria for surface tension induced interface stability and support for screens, tubes and perforated plates are presented. Surface tension support is considered in the context of resisting hydrostatic forces, dynamic impingement forces and flow pressure drop. Results are presented parametrically in a series of graphs and tables.

Screen Flow

Pressure drop correlations are presented for dutch twill and square weave screens which are applicable to both cryogenic and non cryogenic fluids. Tables are presented which give pertinent screen geometry and flow coefficients for dutch twill and square weave screens.

A discussion of calculation of vapor penetration into a propellant transfer capillary device is presented.

Wicking

Results of screen wicking tests run at Convair are presented in empirical form since theoretical models studied proved inadequate for predicting screen wicking. Comparisons between parallel plates and dutch twill screens are given.

Settling and Sloshing

A technique is suggested for determining settling time by dividing the fluid motion into four phases; liquid motion from the low gravity orientation to the aft end of the tank, turbulence and recirculation subsequent to striking the aft bulkhead, slosh wave decay, and rise of entrained vapor from the collected fluid. Techniques are briefly described for shortening the settling period for the purpose of refilling a capillary device.

Spilling and Vapor Ingestion

A technique for detecting and evaluating spilling and vapor ingestion is presented. The INGASP program, presented in Appendix A, is a computer model for predicting spilling, vapor ingestion and refilling. Use of the program for selecting screen areas on the S-IVC LO_2 start basket is described.

Refilling (Capillary Device)

Equations for evaluating refilling are presented and methods of hastening start basket refill and minimizing trapped vapor such as use of a standpipe or refill valve are discussed.

Tank Filling

Filling of a tank containing a capillary device on the ground and in orbit is considered. It is likely that settling of the liquid will be required to efficiently fill the tank in orbit.

Residuals

Pullthrough and interface shape correlations are presented along with methods of reducing residuals in tanks containing capillary devices. Discussion centers around use of screens to resist pullthrough and flow through capillary restart devices and propellant transfer devices during tank draining. The DREGS2 program equation development is briefly described with a listing of the program presented in Appendix B.

Entrained Vapor Impingement

This section discusses the use of hydrophilic screens in deflecting vapor which has entered the capillary device away from the feedline.

Venting

The hazards of tank blowdown are discussed with equations presented for predicting tank pressures during a large pressure drop as requirement for an ullaging-blowdown sequence. The consequent bulk boiling can be eliminated with a relatively constant pressure thermodynamic vent system.

Pressure Collapse

Equations are developed which may be used to compute the collapse of a hot ullage due to mixing or circulation upon restarting the engine. Bulk boiling due to ullage pressure decay can be estimated and adjustments made to the pressurant system design to permit less ullage stratification if necessary.

2.1 RETENTION

The primary purpose of a capillary device for controlling propellants is to retain liquid in a given position when subjected to adverse forces. Retention against adverse accelerations is governed by both stability and support criteria.

For a liquid-vapor interface to be stable, the Bond number, $Bo = \frac{\rho g D^2}{4\sigma} \leq K$ where K is a constant depending upon the type of capillary barrier and the contact angle between the fluid and the type of capillary barrier used. The contact angle is zero for propellants and containment materials currently of interest. For zero contact angle, with a circular cylinder, the value of K is 0.842 as determined experimentally by Masica, Petrash and Otto in Reference 2-1. This result verified the findings of Bretherton, Reference 2-2 who obtained this constant using both theoretical and experimental methods. For a circular hole, as in a perforated plate, Martin, Reference 2-3, showed experimentally that K = 0.84. Other experiments, Reference 2-3, showed that K = 0.45 for a square weave screen where D is the open width of the square weave screen. No information is currently available on the value of K for dutch twill screens. Typical stability curves are given for screens and plates in Figure 2-1.

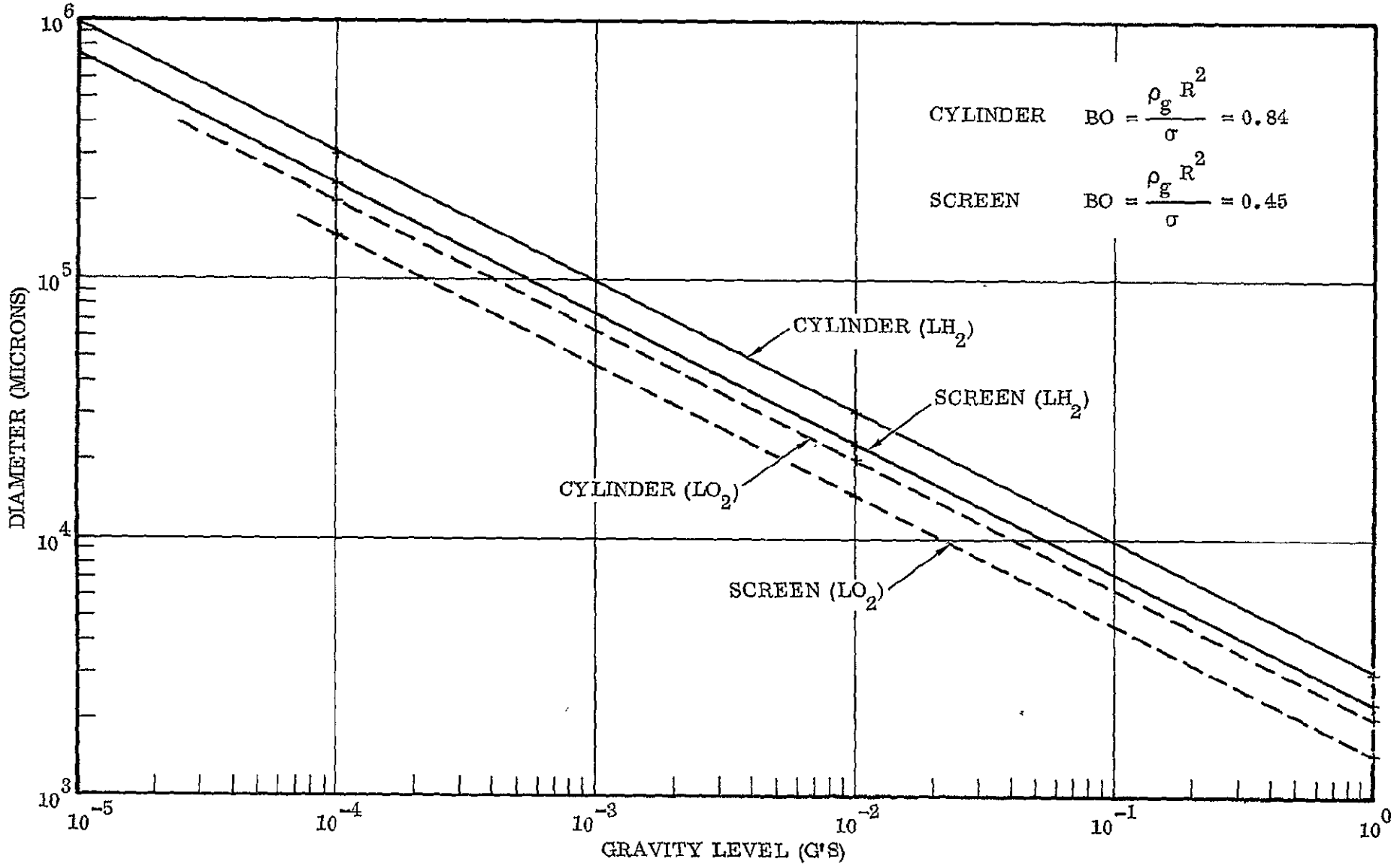


Figure 2-1. Stability Limit for Square Weave Screens and Circular Cylinders

Surface tension support is defined by

$\Delta P_\sigma = \frac{4\sigma}{D_{BP}}$ where D_{BP} is the bubble point. The bubble point is normally determined by submerging a box, with one side containing the screen to be tested and the other side containing a pressurizing means, 3/8ths of an inch below the surface of an isopropyl alcohol bath. This box, illustrated schematically below, is then pressurized until an air bubble breaks through the screen. The bubble point is thus a measure of the largest pore in the screen.

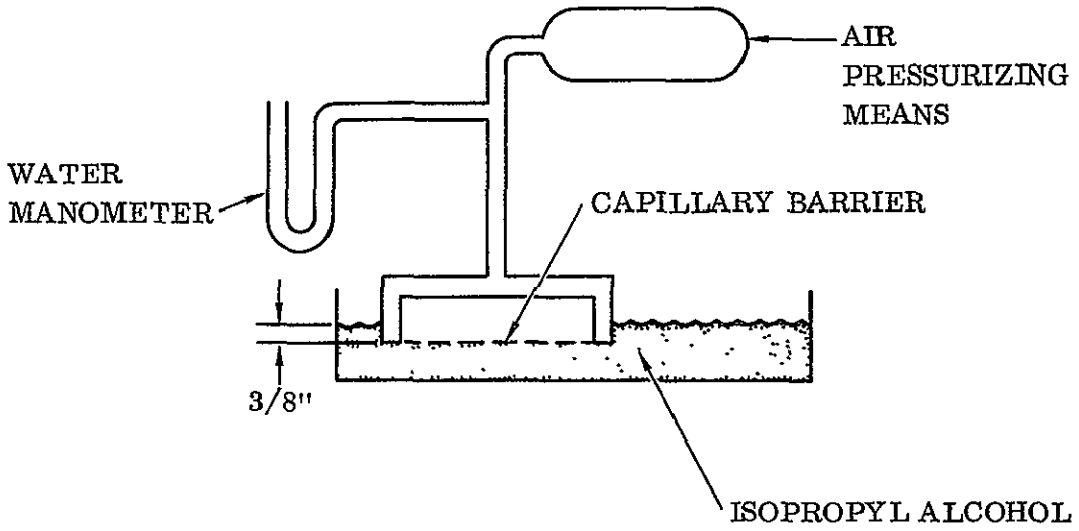


Figure 2-2. Bubble Point Test Set Up.

Normally the support criteria are more stringent than the stability criteria. For example, if the support requirement is to retain a given head of fluid against an adverse acceleration,

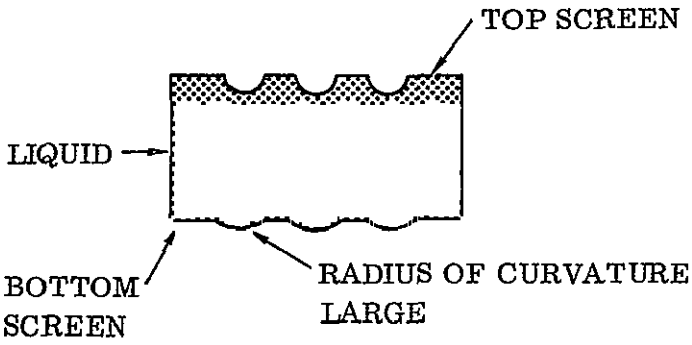
$$\Delta P = \frac{4\sigma}{D_{BP}} < \rho g h \text{ or } \frac{\rho g D_{BP}}{4\sigma} < \frac{1}{h} \quad \text{(support criteria)}$$

and for interface stability

$$\frac{\rho g D_{BP}}{4\sigma} < \frac{K}{D_{BP}}$$

Thus for stability criteria to be controlling $\frac{K}{D_{BP}} < \frac{1}{h}$, which is only the case for extremely large pores and small liquid heights. Evidently, for practical situations, stability criteria are satisfied more easily than support criteria.

For liquid propellants, which are good wetters, surface tension devices must be designed to keep vapor out rather than keep liquid in. This is because liquid will wet a screen or perforated plate so that surface tension forces holding the liquid in are very small. This is illustrated by the sketch below, where no appreciable liquid depth would be supported by the bottom screen if the top screen were removed. With the top screen in place, the liquid cannot leave the enclosure through the bottom screen, unless vapor enters through the top screen. This will occur only if the pressure difference across the top screen exceeds surface tension pressure. Support of liquid columns is illustrated by the plots shown in Figure 2-3.



Surface tension support pressure must also be balanced against fluid inertia forces and fluid flowing pressure drop. Inertial forces are given by

$$\frac{\rho V^2}{2c}$$

Fluid momentum is important in sloshing and settling problems where vapor can enter the basket if impinging at a high enough velocity. Fluid velocities can be obtained by using the MAC model technique (Reference 2-4) described in Section 2.4. Figure 2-4 illustrates the case where vapor is impinging on the surface and the case where vapor entrained in liquid is impinging on the capillary device. If it is not possible or practical to prevent vapor from entering the start basket it may still be possible to ensure successful system operation by deflecting vapor from the outlet as described in Section 2.10.

In many cases a primary retention criteria is whether fluid flowing through a screen will produce a pressure drop exceeding that of the surface tension retention pressure of the screen. In this case $\Delta P_\sigma = \Delta P_{flow}$. Flow pressure drops for square weave and dutch twill screens were obtained in a Convair IRAD test program and are presented in Section 2.2, along with bubble point data for dutch twill screens tested. Bubble point for square weave screens was assumed equal to the open width of the screen. The equation $\Delta P_\sigma = \Delta P_{flow}$ was solved, for fluids and screens of interest in order to obtain fluid velocity which satisfies this equation. Results are presented in Tables 2-2 and 2-3. These results are important in minimizing vapor penetration into a capillary device during draining as discussed in Section 2.6.

The 200 × 600 screen allowed maximum dutch twill screen fluid velocity while a 400 × 400 screen allowed maximum velocity for a square weave screen. In general, square weave screens, although they have large pores with resultant low surface tension pressure, have low pressure drops compared to the tortuous path of the dutch twill screen and thus allow higher flow velocities through the screen before exceeding the surface tension retention pressure.

Characteristically the bubble point diameter is lower than the average capillary diameter used in calculating screen flow losses. This apparently anomalous fact is because the average capillary diameter is measured by forcing mercury into the screen sample and determining the average diameter on a volume basis. Pores in screens generally have minimum diameter in the middle of the screen while porosimeter measurements include the larger diameters downstream and upstream.

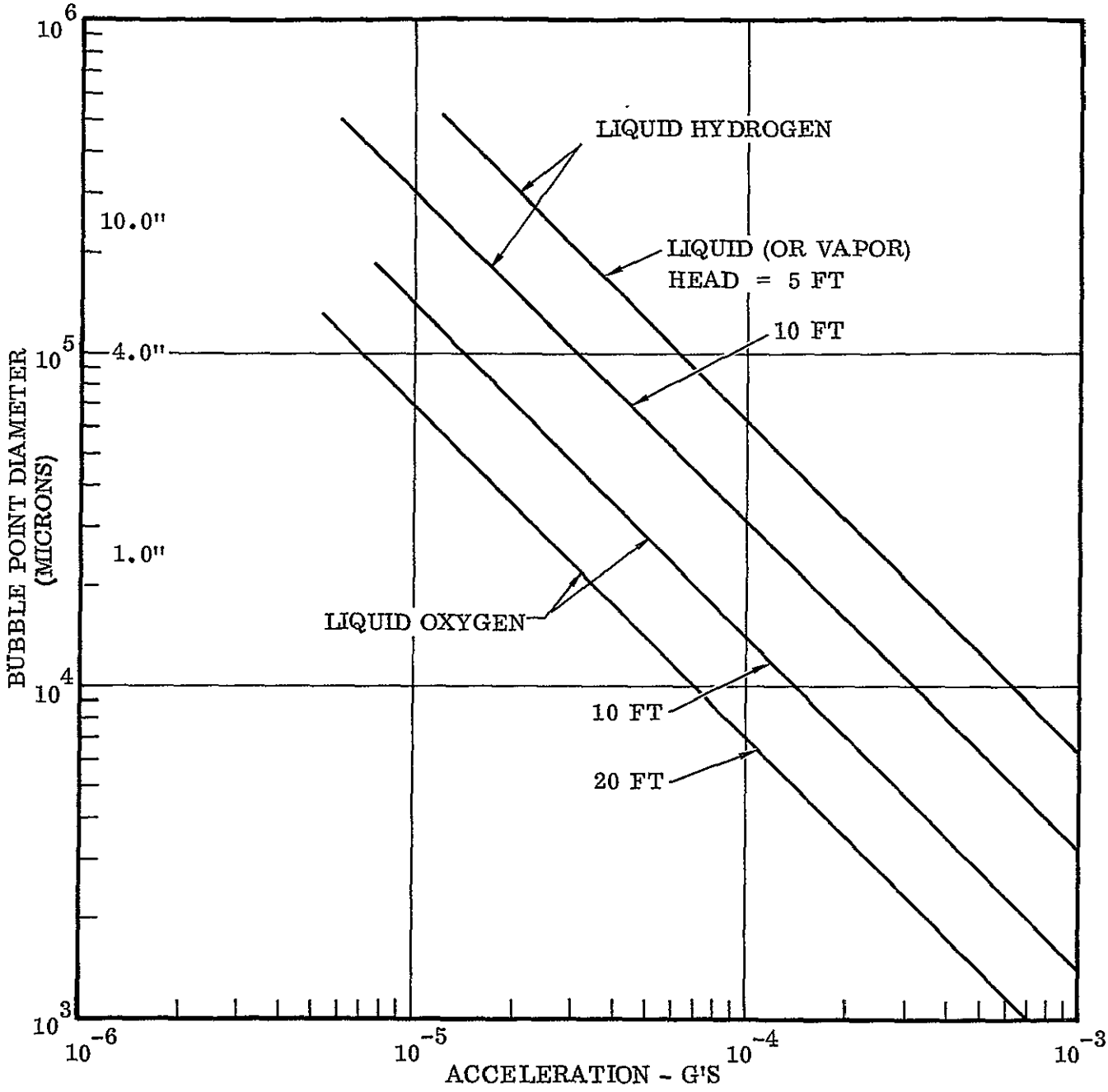


Figure 2-3. Liquid Head or Trapped Vapor Head Contained by Capillary Vs Acceleration

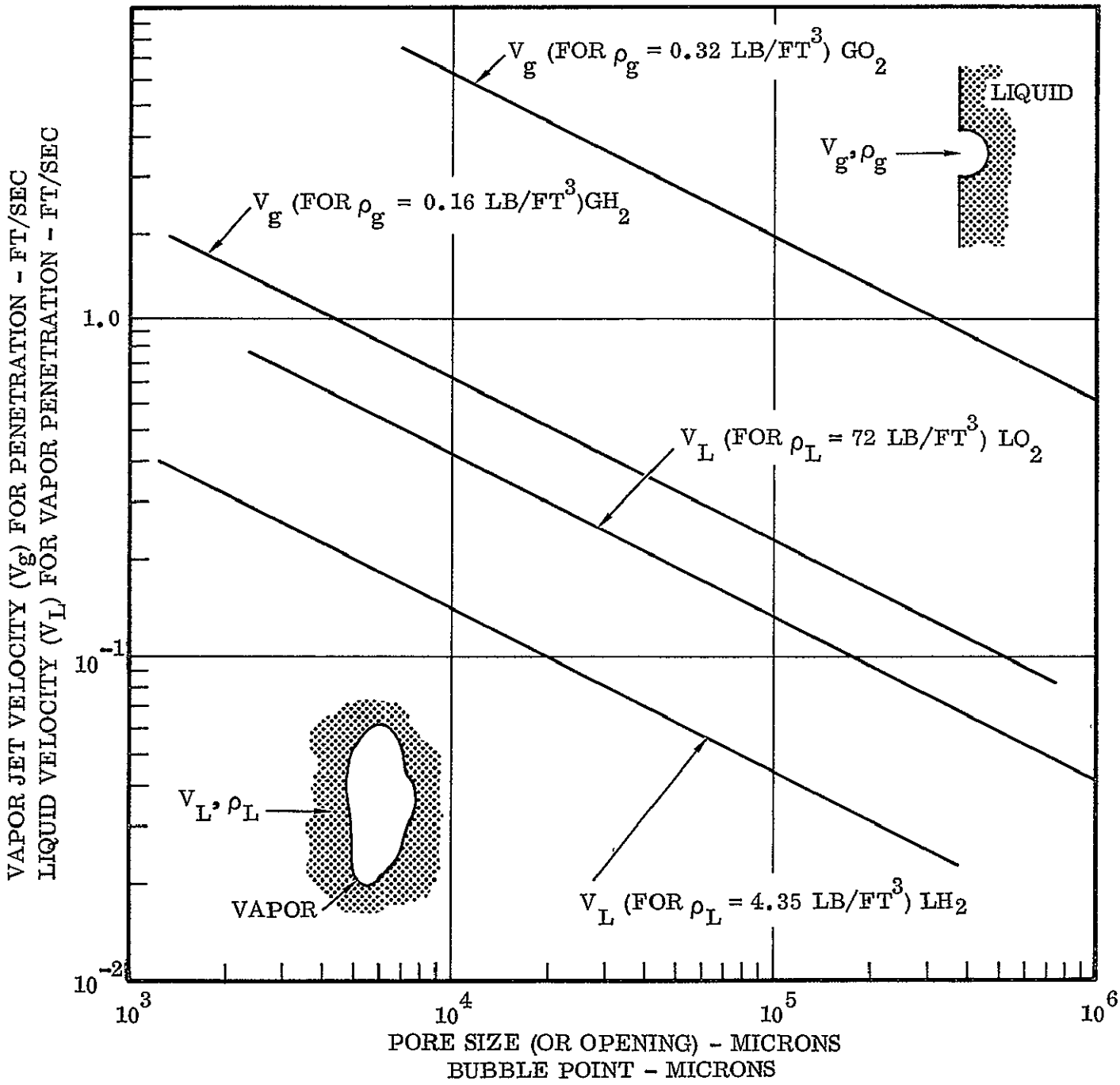


Figure 2-4. Velocity Requirements for Penetration of Vapor or Liquid Through a Wetted Screen or Plate

Table 2-2. Maximum Screen Velocity for Dutch Weave Screen Before Surface Tension Pressure is Exceeded

Maximum Velocity	Screen Mesh	Liquid	Maximum Velocity	Screen Mesh	Liquid	Maximum Velocity	Screen Mesh	Liquid
.468	200 × 1400	Oxygen	.193	150 × 700	Fluorine	.802	30 × 250	Water
.487	165 × 1400	Oxygen	.410	80 × 700	Fluorine	.730	20 × 250	Water
1.414	200 × 600	Oxygen	.153	50 × 250	Fluorine	.543	200 × 1400	Pentane
.219	165 × 800	Oxygen	.308	30 × 250	Fluorine	.589	165 × 1400	Pentane
.225	150 × 700	Oxygen	.270	20 × 250	Fluorine	1.810	200 × 600	Pentane
.481	80 × 700	Oxygen	.419	200 × 1400	Nitrogen	.297	165 × 800	Pentane
.176	50 × 250	Oxygen	.441	165 × 1400	Nitrogen	.291	150 × 700	Pentane
.358	30 × 250	Oxygen	1.324	200 × 600	Nitrogen	.604	80 × 700	Pentane
.312	20 × 250	Oxygen	.210	165 × 800	Nitrogen	.239	50 × 250	Pentane
.765	200 × 1400	Hydrogen	.211	150 × 700	Nitrogen	.463	30 × 250	Pentane
.785	165 × 1400	Hydrogen	.446	80 × 700	Nitrogen	.413	20 × 250	Pentane
2.238	200 × 600	Hydrogen	.169	50 × 250	Nitrogen	.771	200 × 1400	Methane
.340	165 × 800	Hydrogen	.337	30 × 250	Nitrogen	.806	165 × 1400	Methane
.354	150 × 700	Hydrogen	.296	20 × 250	Nitrogen	2.357	200 × 600	Methane
.273	50 × 250	Hydrogen	.848	200 × 1400	Water	.367	165 × 800	Methane
.465	30 × 250	Hydrogen	.956	165 × 1400	Water	.375	150 × 700	Methane
.488	20 × 250	Hydrogen	3.099	200 × 600	Water	.799	80 × 700	Methane
.391	200 × 1400	Fluorine	.538	165 × 800	Water	.295	50 × 250	Methane
.411	165 × 1400	Fluorine	.503	150 × 700	Water	.597	30 × 250	Methane
1.213	200 × 600	Fluorine	1.016	80 × 700	Water	.522	20 × 250	Methane
.190	165 × 800	Fluorine	.434	50 × 250	Water			

Table 2-3. Maximum Screen Velocity for Square Weave Screen Before Surface Tension Pressure is Exceeded

Maximum Velocity	Screen Mesh	Liquid	Maximum Velocity	Screen Mesh	Liquid	Maximum Velocity	Screen Mesh	Liquid
1.060	10 × 10	Methane	5.990	100 × 100	Nitrogen	3.286	325 × 325	Fluorine
2.122	20 × 20	Methane	7.045	200 × 200	Nitrogen	8.000	400 × 400	Fluorine
4.529	40 × 40	Methane	3.632	325 × 325	Nitrogen	0.861	10 × 10	Pentane
7.452	50 × 50	Methane	8.844	400 × 400	Nitrogen	1.724	20 × 20	Pentane
10.439	100 × 100	Methane	0.978	10 × 10	Hydrogen	3.680	40 × 40	Pentane
12.276	200 × 200	Methane	1.958	20 × 20	Hydrogen	6.056	50 × 50	Pentane
6.330	325 × 325	Methane	4.179	40 × 40	Hydrogen	7.071	80 × 80	Pentane
15.411	400 × 400	Methane	4.179	40 × 40	Hydrogen	8.482	100 × 100	Pentane
1.571	10 × 10	Water	6.876	50 × 50	Hydrogen	9.976	200 × 200	Pentane
3.147	20 × 20	Water	8.030	80 × 80	Hydrogen	5.144	325 × 325	Pentane
6.716	40 × 40	Water	9.632	100 × 100	Hydrogen	12.524	400 × 400	Pentane
11.050	50 × 50	Water	11.328	200 × 200	Hydrogen	0.631	10 × 10	Oxygen
15.479	100 × 100	Water	5.841	325 × 325	Hydrogen	1.264	20 × 20	Oxygen
18.204	200 × 200	Water	14.221	400 × 400	Hydrogen	2.698	40 × 40	Oxygen
9.387	325 × 325	Water	0.550	10 × 10	Fluorine	4.440	50 × 50	Oxygen
22.853	400 × 400	Water	1.102	20 × 20	Fluorine	5.185	80 × 80	Oxygen
0.608	10 × 10	Nitrogen	2.351	40 × 40	Fluorine	6.219	100 × 100	Oxygen
1.218	20 × 20	Nitrogen	3.868	50 × 50	Fluorine	7.314	200 × 200	Oxygen
2.599	40 × 40	Nitrogen	4.517	80 × 80	Fluorine	3.771	325 × 325	Oxygen
4.276	50 × 50	Nitrogen	5.418	100 × 100	Fluorine	9.182	400 × 400	Oxygen
			6.372	200 × 200	Fluorine			

Screen bubble point may be increased by calendering screens which involves passing the screen through rollers, flattening the high points and forcing the wires closer together. The process increases the bubble point of a screen, however, it also increases fluid pressure drop and impedes wicking along the screen.

2.2 SCREEN FLOW - PRESSURE DROP

Considerable effort has been expended in obtaining accurate flow data for dutch twill and square weaves for using cryogenic and noncryogenic fluids. The work, performed in a Convair IRAD program, is presented in detail in References 2.4 and 2.5 and summarized in References 2.6 and 2.7. Results will be summarized here to the extent required to analyze and design capillary devices.

Screen flow is characterized by two flow regimes which are dependent upon screen Reynolds number. In the high Reynolds number inertial regime, the Euler number, $(2\,\Delta P_f g_c)/(\rho\, V_f^2)$ is a constant which can be used to predict screen pressure drop and in the viscous regime the Poiseuille number $(\Delta P_f g_c\, D_a^2)/(L\,\mu\, V_f)$ can be used in a similar manner.

For the square weave screens, a correlation, $Eu = [S/(1-S)]^2$ can be used in the inertial regime. This regime persists to velocities less than 0.1 fps so that it can be used for the full range of normally anticipated flow conditions for square weave screens. Table 2-4 gives geometric properties for several square weave screens. Several investigations have attempted to correlate dutch twill screen data with theoretical and semi-empirical models. These investigators, notably Armour and Cannon (Ref. 8) developed flow equations using bubble point diameter and other dubious geometric properties. Also, their flow setup was inherently less accurate than the one used at Convair, described in Reference 2.4. Convair data did not agree with either Armour and Cannon's model, or Tucker's model described in Reference 2-4. The Convair data did not conveniently collapse to a single equation for all screens; however, data for the many fluids run was self consistent for each screen tested. It was concluded that the manner of presentation which best suited the data was an equation of the form:

$$\Delta P_f = \frac{A_1\, L\, \mu\, V_f}{D_a^2\, g_c} + \frac{A_2\, L\, \rho\, V_f^2}{D_a\, g_c}$$

where A_1 and A_2 are empirical constants for a particular dutch twill screen.

The average capillary diameter, D_a, was obtained from mercury porosimeter testing described in the Appendix of Reference 2-4. Values of A_1, A_2, L and D_a for the nine screens tested are presented in Table 2-5. These screens should include any dutch twill screens which might be used for propellant control applications, thus no additional testing should be required in order to design a capillary device.

Table 2.4. Screen Geometry, Square Weave Screens

Mesh	(Microns) D_{BP}	Solidity S
400 × 400	38	0.64
325 × 325	44	0.44
200 × 200	74	0.66
150 × 150	104	0.63
100 × 100	140	0.698
80 × 80	180	0.686
50 × 50	280	0.700
40 × 40	440	0.640
20 × 20	860	0.538

Table 2-5. Screen Geometry, Flow and Wicking Data, Dutch Twill Screens

Screen Mesh	D_{BP} Bubble Pt. Diameter (Microns)	D_a Avg. Capillary Dia. (Microns)	L Thickness (in.)	Porosity (Meas.)	Dimensionless A_1	Dimensionless A_2	Dimensionless Wicking A_W	$A = \frac{A_1 L}{D_a^2 g_c}$ (sec^2/ft^2)	$B = \frac{A_2 L}{D_a}$ (sec^2/ft)
200 × 1400	13.4	22.8*	0.0058	0.256	190	18		509687	3.6
165 × 1400	18.6	28.3*	0.0060	0.301	150	16	580	270185	2.6
200 × 600	19.05	36.7*	0.0055	0.347	52	3	368	51053	0.3
165 × 800	22.7	48.5**	0.0065	0.310	43	135		28568	14.3
150 × 700	22.7	60.8**	0.0070	0.171	500	133		227642	12.0
80 × 700	29.7	139.3**	0.0098	0.416	1000	34	6230	121427	1.8
50 × 250	33.9	129.5**	0.0127	0.325	115	191		20938	14.7
30 × 250	48.5	112.2**	0.0265	0.276	130	12	1120	65795	2.2
20 × 250	52.8	155.3**	0.0280	0.325	150	20		41869	2.8

*Microporosimeter
**Macroporosimeter

2.3 PRESSURE DROP IN A CAPILLARY DEVICE

For propellant transfer applications it is necessary to consider pressure drops within the annular passages of a screen liner or channel reservoir configuration. Collector tube design for providing liquid flow to a vent device also must consider the pressure drop of a long capillary tube or channel and entrance and bend losses occurring within the system. A typical configuration of interest is shown in Figure 2-5.

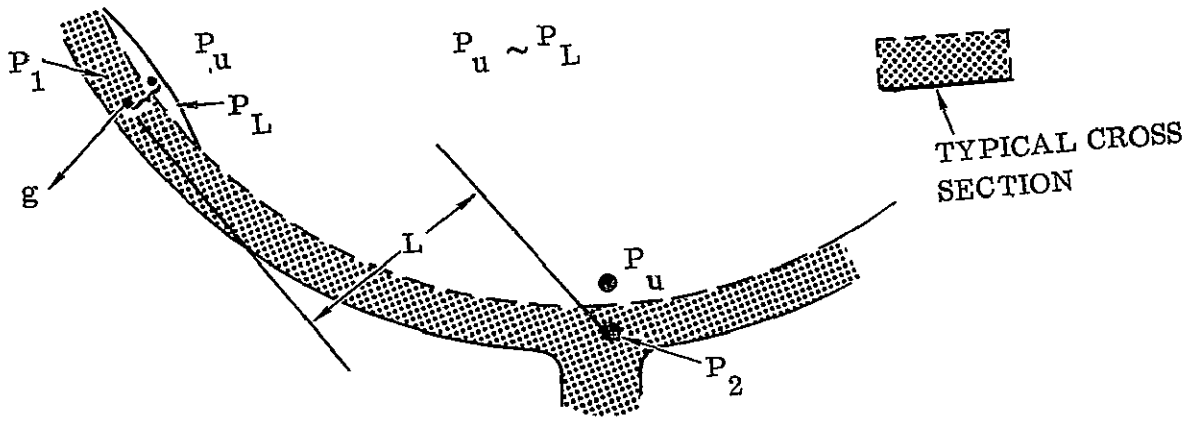


Figure 2-5. Total Orientation Device Draining

$P_L - P_1$ = screen pressure drop described in the previous paragraphs.

$$P_1 - P_2 = \Delta P_{\text{hydrostatic}} + \Delta P_{\text{channel or liner}}$$

where ΔP channel or liner is a function of channel geometry, friction in the channel, contractions and expansions or bending caused by system shape in supports and suction in the channel causing increased pressure drop due to mass addition.

Frictional pressure drop and losses due to bends and expansion and contraction losses can be evaluated using sources such as Reference 2-9 Chapter 7 for friction and Reference 2-10 for K factors so that

$$\Delta P_{fr} = \frac{fL}{D_h} \frac{\rho V^2}{2g} \quad \text{and} \quad \Sigma K \frac{\rho V^2}{2g} = \Delta P_b$$

Another factor of $\Delta P_{\text{channel}}$ is the effect of suction or introduction of fluid through a porous wall on increasing the pressure drop in the channel where the fluid is comingling and flowing. For channels this has been handled by several investigators including Acrivos, et al (Ref. 2-11) and Terrill (Ref. 2-12). Terrill examined the pressure losses in a porous annulus.

The point at which vapor breaks through the screen initially will depend on the direction of the acceleration and corresponding hydrostatic head. In general, if the acceleration is small, or the fluid is oriented opposite to the outlet by the acceration, the pressure difference across the screen will be greatest near the outlet. Thus vapor break through will generally occur near the outlet.

The surface tension pressure, $\Delta P_\sigma = \frac{4\sigma}{D_{BP}}$, must exceed the pressure drop $Pu-P_2$ to prevent vapor breakthrough.

$$Pu - P_2 = \Delta P_{fr} + \Delta P_b + \Delta P_{hydrostatic} + \Delta P_{suction} + \Delta P_{screen}$$

The surface area available for flow and screen weave determine the screen pressure drop. Increased surface tension pressure cannot generally be obtained without a corresponding increase in screen pressure drop. If the ΔP_{screen} is a large percentage of the total pressure drop care should be taken in increasing ΔP_σ to retard vapor breakthrough, since the increase in ΔP_{screen} may completely offset any increase in ΔP_σ. For a given mesh screen and working fluid ΔP_{screen} is completely dependent on screen velocity. Screen velocity can be held to a minimum if the surface area available for flow is maximized.

Channel flow area, length and hydraulic diameter are the principle variables in channel frictional pressure drop. Widening of the channels will reduce pressure drop; however, it will also increase system weight. Pressure drop due to bends and changes in area can be minimized by spacing support members and shaping obstructions in the flow channel in order to minimize area changes and abruptness of flow disturbances. The pressure drop increase due to suction depends upon the friction and momentum effects in the channel and across the screen.

The numerous variables affecting the total system pressure drop are indicative of the difficulty in establishing generalized optimization techniques. Parametric plots that will lead to the selection of an optimum capillary system design cannot be presented, even for a narrow requirement range. The structural requirements imposed upon a channel design (such as type and numbers of supports) can have an important effect upon system pressure losses. Thus it has been possible only to present a general discussion relative to this subject.

2.4 WICKING

Wicking is of interest because flow wicking through a screen can be used to replace liquid evaporated from that surface. This can assure that no liquid will be evaporated from the capillary device, as would occur in a propellant transfer or liquid collection application.

Wicking was examined in a manner similar to screen flow with the driving pressure equal to the surface tension pressure. Several models were postulated (Ref. 2-14), and computer programs developed for their numerical solution. Test results were obtained for a horizontal screen (Ref. 2-7) in order to simulate low gravity wicking. Results were in the form of Equation 2-1 however, because of the low pressure drop and flow rates, the inertial term was negligible. An equation of the form,

$$\Delta P = \frac{4\sigma}{D_{BP}} = \frac{A_w L_w}{g_c D_a^2} \mu V_w, \text{ represented the data where} \qquad (2\text{-}2)$$

L_w = distance along the screen from liquid vapor front.

The constant, A_w, for the four dutch twill screens tested was greater than A_1 by a factor which varied from 4 to 8.5, as shown in Table 2-5. Thus the wicking velocity along the screen is less than the velocity perpendicular to the screen for an equal pressure drop indicating the more restrictive nature of the path taken by the wicking fluid. Tests were conducted with flow perpendicular to the warp wires since this gives minimum wicking velocities which can be used for design purposes. One test was run for wicking rates parallel to the warp wires using 30 × 250 screen and Dow Corning 200 silicone oil. For this case the wicking rates are slightly higher with $A_w = 733$. Even though this is a less restrictive path than the other direction it may serve as the design value since L is usually longer in the direction of the warp wires due to the way screen mesh is fabricated.* Wicking is a property which is not desirable from a refilling standpoint. This is discussed in Section 2.7.

For screens not tested, order of magnitude wicking velocities may be obtained by multiplying A_1 by a factor 4 to 8.5 depending upon the mesh being considered. Relatively simple tests could be run to obtain A_w empirically for the screen of interest if more accurate confirmation is required.

In order to determine how much wicking flow will contribute to preventing vapor formation we can set $\phi \times V_w \times (L \times W) \times \rho_L \times \lambda = Q$ where L is the screen thickness, ϕ ϕ is the porosity and W is the width of screen perpendicular to flow. V_w is computed from Equation 2-2 where L_w is the distance from the incipient vapor to the main pool of liquid. λ is the heat of vaporization of the liquid.

Solving Equation 2-2 for V_w for each of the four screens tested indicates that the 30 × 250 screen has the highest wicking velocity. This indicates that the thicker screens such as 50 × 250, 20 × 250 and 30 × 250 present a less restrictive path in the direction of wicking flow than do the thinner screens. Tests on a 400 × 400 mesh square weave screen indicated no wicking, confirming the non wicking property of square weave screen.

*Screen cloth is normally made in widths of four feet and lengths of 30 feet with the four foot dimension parallel to the shute wires.

If wicking velocities in excess of dutch twill screen velocities are required, parallel screens or perforated plates closely spaced can be used. The volumetric flow rate of liquid between parallel plates was derived by Newman, Journal of Colloid Science, 1968, Volume 26 to be:

$$Q_w = \frac{2}{3} \frac{\Delta P\, B^3\, W\, g_c}{\mu L} = \frac{2}{3} B^2 \frac{\Delta P\, A_{flow}\, g_c}{\mu L}$$

where B is one half the distance between plates, W is the plate width or $2BW = A_F$ (Flow area). For horizontal or zero g wicking $\Delta P = \Delta P_\sigma$.

Expressing the wicking equation for screens in a similar manner we find

$$Q_{screen} = V_w A_F = \frac{\phi D_a^2\, \Delta P_\sigma\, g_c\, A_F}{A_w\, \mu L}$$

thus

$$\frac{Q_{plate}}{Q_{screen}} = \frac{\frac{2}{3} B^2 \Delta P_\sigma\, g_c}{\phi \frac{D_a^2}{A_w} \Delta P_\sigma\, g_c}$$

For the screen $\Delta P_\sigma = \sigma\left(\frac{2}{D_1} + \frac{2}{D_2}\right) = \frac{4\sigma}{D_{BP}}$ where D_1 and D_2 are orthogonal radii of curvature and for the parallel plates

$$\Delta P_\sigma = \sigma\left(\frac{1}{B_1} + \frac{1}{B_2}\right) = \frac{\sigma}{B} \quad \text{since one of the radii is very large.}$$

$$\frac{Q_{plate}}{Q_{screen}} = \frac{\frac{2}{3} B^2 \sigma/B}{\phi \frac{D_a^2}{A_w} 4\sigma/D_{BP}} = \frac{B/6}{\phi \frac{D_a^2}{A_w D_{BP}}}$$

Figure 2-6 illustrates that more flow can be realized utilizing plates than screens of an equivalent thickness (assuming the plates have negligible thickness. More significant is the fact that plate spacing can be increased without bound to achieve increased wicking flow while the physical limitations of dutch twill screen mesh severely bounds single screen wicking capability.

Single square weave screens do not wick, at least in the meshes commercially obtainable. This was evidenced by testing several square weave screen samples including 400 × 400 mesh screens.

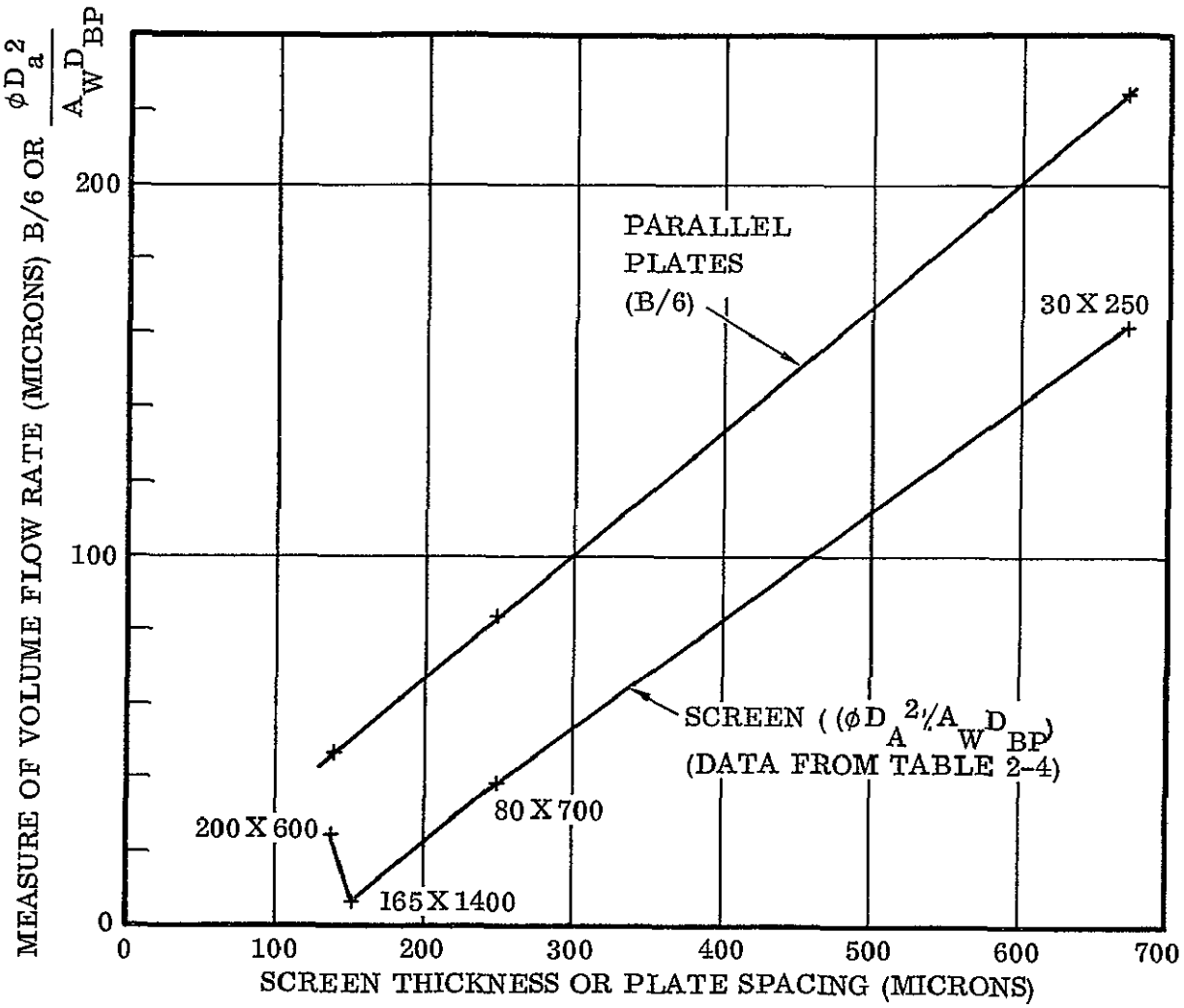


Figure 2-6. Comparison of Wicking Rates in Screen and Parallel Plates

2.5 PROPELLANT SETTLING AND SLOSHING

Design of passive propellant control systems is critically dependent upon proper consideration of the phenomenon of liquid propellant settling. Confidence in a flight-ready propellant control system will utilimately depend upon knowledge of the liquid motion under impulsively applied body forces and upon the design methods used to compensate for uncertainties. In the following paragraphs the settling problem is examined in detail, and analytical procedures to be used for obtaining design information are outlined.

Influence of Settling on Capillary System Design - An essential capillary system design concept is to provide a liquid retention system capable of furnishing liquid to the engine feed line for engine starts independent of orientation of the bulk of the liquid propellant. As thrust develops during this initial engine firing period, the bulk propellant begins to flow toward an equilibrium position at the aft end of the tank. For smooth, continuous operation, the propellant must be "settled" and be capable of refilling the capillary retention device as the liquid in the device is being depleted.

Before the settling thrust is applied, the propellant generally occupies a position as shown in Figure 2-7.

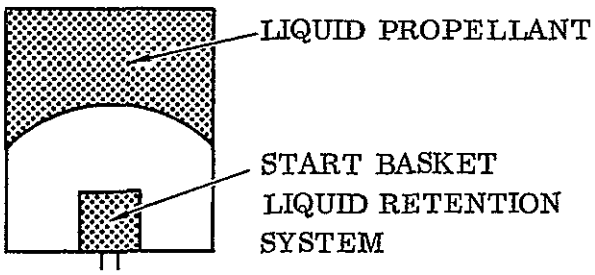


Figure 2-7. Typical Position Prior to Engine Restart.

As thrust is applied, the fluid near the tank walls moves aft. The curved interface may become unstable and form a jet of liquid. A high intensity of turbulence is created as the liquid impacts the tank bottom and the start basket, and a considerable quantity of vapor (in the form of tiny bubbles) can be entrained. In addition to the turbulence, large-amplitude surface motions are usually present which could alternately cover and uncover the start basket. Dissipation of the fluid kinetic energy ultimately will occur (by decay of the turbulence and viscous dissipation of the sloshing motions) until the surface motions are small and the trapped vapor can escape. Only then can the liquid be considered settled sufficiently for start basket refill.

Normally, the two methods available for an investigation such as the one needed for settling are: analytical (theoretical and empirical) and experimental. The marker and cell (MAC) method provides a third basic tool. Because the MAC method solves the complete Navier-Stokes equations of fluid motion (including viscous and nonlinear terms) and because its accuracy has been verified many times (References 2-4, 2-15, 2-16), it can be used as a pseudo-experimental tool.

The advantage of running "computer experiments" over actual laboratory experiments is that the "test" conditions can be regulated at will on the computer. Variable gravity levels, surface tension, slip or no-slip at tank walls, heat transfer, in- and outflow, all can be imposed on or removed from the computer simulation as desired. This very versatile tool, when combined with complementary analytical and experimental methods, provides an excellent technique for predicting the effects of settling on operation of the passive retention/expulsion system.

Several empirical investigations have been accomplished to evaluate settling. Most notably, Masica and Petrash (Ref. 2-17) ran a series of drop tower tests and correlated fluid velocities, before impingement on the aft bulkhead, based on the Bond number. Using the basic results of this study another drop tower correlation program was conducted at NASA LeRC to predict liquid accumulation rates in a Centaur scale model tank. This study by Salzman and Masica (Ref. 2-18) gives geysering regimes as a function of Weber number. The equations given in this report have been arranged into a short computer program which will compute screen sizes to resist impingement forces, settling velocities, collection velocities and settling time. A listing of this program is given in Ref. 2-4.. Results of this program were compared with results of the MAC model for settling in the S-IVB LH_2 tank shown in Figure 2-8.

An acceleration of 0.337 g's will be applied to the S-IVB vehicle in order to settle the propellants. According to both NASA correlations and the MAC model, fluid impinges on the aft bulkhead after 1.27 seconds. Discrepancies exist between the models in the collection and recirculation period following impingement. The NASA correlation predicts a fairly rapid collection period while the MAC model predicts violent recirculation and indicates that collection will take considerably longer. This indicates that the NASA correlations do not hold for the high Bond and Weber numbers occurring in the recirculation and collection period. Unless the Bond number is less than 66, the Weber number less than 200, and the tank similar in shape to a Centaur tank, the LeRC correlation should not be used for this period.

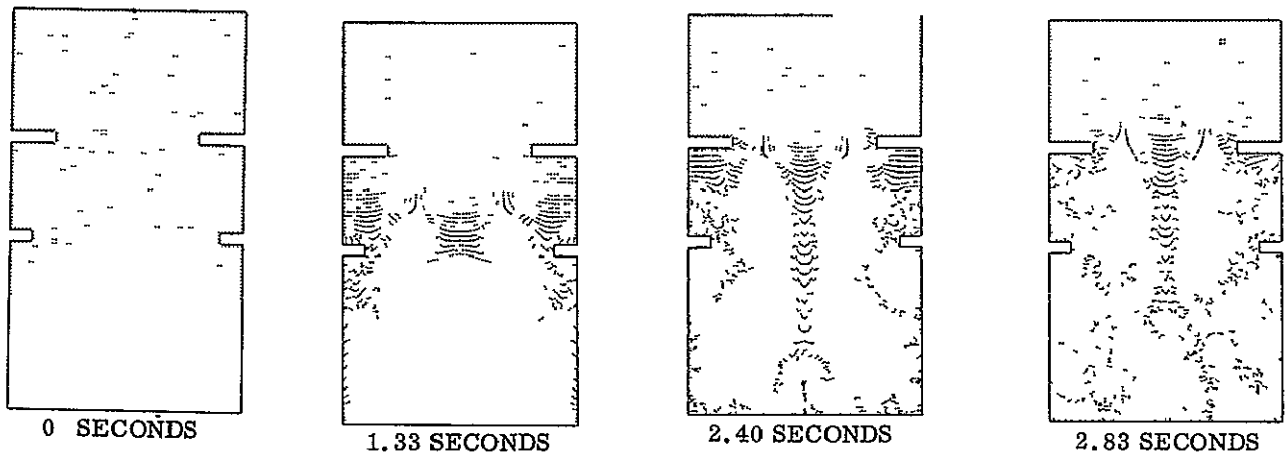
Motion of the liquid from its low-g stable configuration toward the aft end of the tank may be predicted by the MAC method and by the results of Reference 2-4 and 2-19. An expression for the time required for the center of mass of the liquid to move a distance L is approximated by

$$\Delta t = 1.5\ (L/g)^{1/2} \left[1 - \left(\frac{0.84}{Bo}\right)^{Bo/4.7}\right]^{-1}$$

where g is the vehicle acceleration and $Bo = \rho g R^2/\sigma$, the Bond number. This expression has been amply verified experimentally for the approximate range $2 < Bo < 2{,}000$ and by the MAC model for the single case mentioned, where $Bo \sim 10^6$.

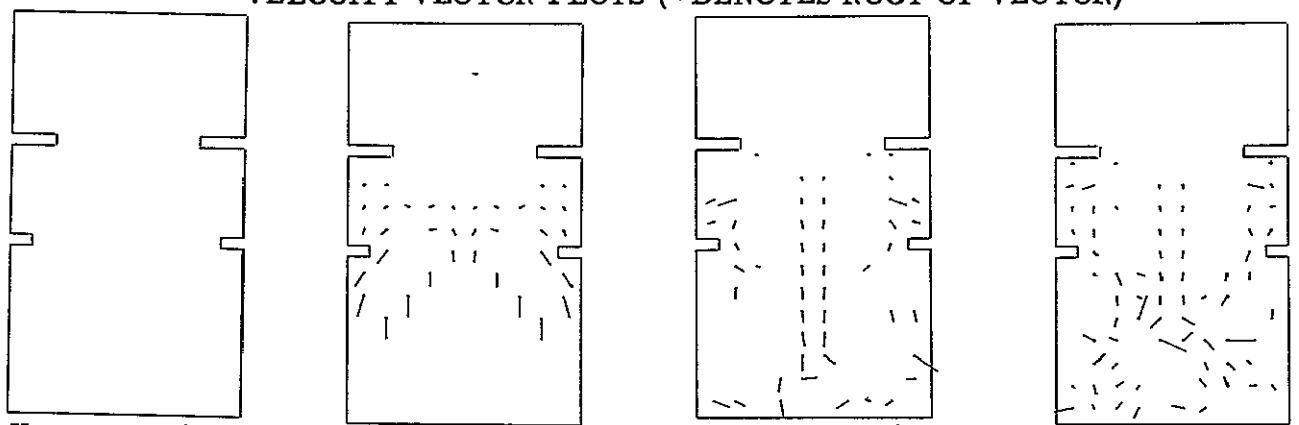
FLUID SIMULATION OF S-IVB LIQUID HYDROGEN TANK SETTLING
0.337 G'S, 60% FULL, R = 10.82 FT

FLUID CONFIGURATION PLOTS



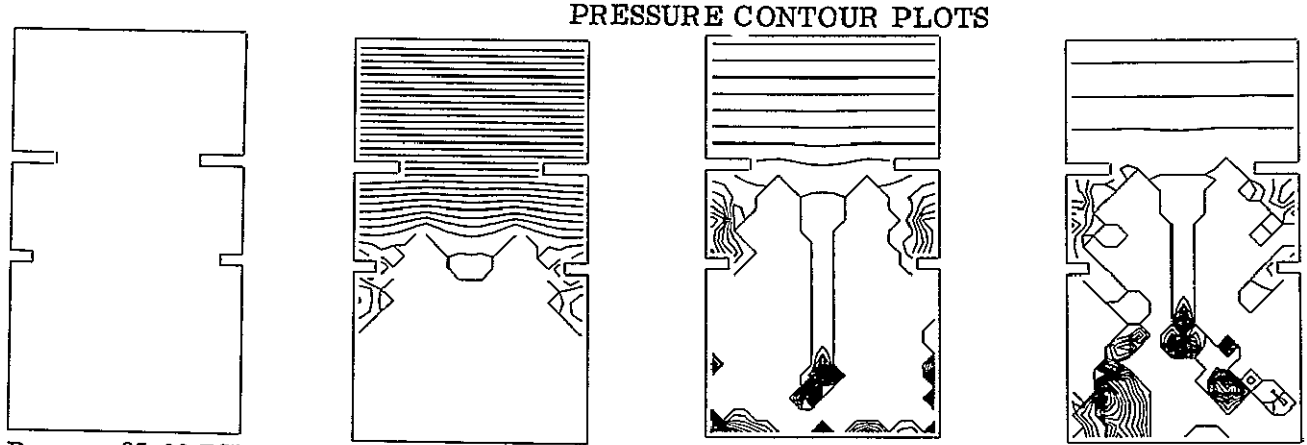
0 SECONDS | 1.33 SECONDS | 2.40 SECONDS | 2.83 SECONDS

VELOCITY VECTOR PLOTS (+DENOTES ROOT OF VECTOR)



V_{max} = 0 FT/SEC | V_{max} = 8.5 FT/SEC | V_{max} = 33.4 FT/SEC | V_{max} = 47.2 FT/SEC

PRESSURE CONTOUR PLOTS



P_{min} = 25.00 PSI
P_{max} = 25.00 PSI
ΔP = 0 PSI

P_{min} = 24.83 PSI
P_{max} = 25.01 PSI
ΔP = 0.006 PSI

P_{min} = 24.81 PSI
P_{max} = 25.24 PSI
ΔP = 0.015 PSI

P_{min} = 24.47 PSI
P_{max} = 25.35 PSI
ΔP = 0.030 PSI

Figure 2-8. MAC method simulation of S-IVB LH_2 tank settling.

The character of liquid motion changes completely when the advancing liquid strikes the tank bottom. Decay of turbulence can be treated theoretically by an analogy with laminar wave motion decay (Ref. 2-19) or with the similarity and self-preservation concepts of isotropic turbulence (Ref. 2-20). These theoretical models should be substantiated by experimental data for the particular cases under consideration.

Slosh wave decay rates may be predicted using the relationships of Reference 2-21. If an analytical investigation shows that axisymmetric slosh modes exist, the MAC method can be used to verify the results of Reference 2-21.

Bubble rise may be accurately predicted through use of a sophisticated numberical method which computes the interaction and dynamics of bubbles in a very general fluid field. Any gravity vector in a tank can be used, and the liquid can have pressure and temperature gradients as desired. Quiescent fluid is assumed; however, the wakes of adjacent rising bubbles are taken into consideration. Also considered is bubble agglomeration and wall interaction. Reference 2-4 gives a good account of this method embodied in the EVOLVE program.

Times required for all four of these processes may then be summed. Since it is conceivable that some overlap will occur, such a procedure is conservative. The resulting sum is the time required for complete settling.

If the time required for complete settling appears to be excessively long, methods may be investigated to avoid this problem. Corrective measures can take three basic forms (or combinations of all three):

1. Use the settling characteristics to advantage, i.e., momentum refill, etc.
2. Test the settling process details to determine if complete settling is really necessary for refill.
3. Use dual thrust level to reduce the settling time.

In the momentum refill approach it may be possible to baffle the flow so that it impinges directly on the capillary device. Efficient refilling by this procedure appears extremely difficult to accomplish.

In the partial settling approach, the fluid may have established a level above the bottom of the start basket screened area which will initiate the refilling process before the settled liquid completely covers the start basket.

In the dual thrust approach, a gentle initial thrust would allow a flow of fluid to the tank bottom at a relatively low velocity. Because of the low velocity, turbulence and sloshing will occur at lower intensity. When most of the liquid has collected aft, a stronger acceleration will dampen the sloshing and cause faster bubble rise as the turbulence decays.

A problem directly related to settling is the impact force on the start basket from the advancing liquid. These forces may be estimated both analytically and with the MAC method. Since pressure contours are a normal part of MAC output, such a prediction is a straight-forward application of the program.

As described, propellant settling is important only for restart devices. Propellant sloshing should be considered for both restart and propellant transfer capillary device applications. Sloshing is a problem only when slosh velocities become high enough to exceed the surface tension pressure of the screen. Specific configurations can be analyzed by order of magnitude calculations to indicate if potential sloshing problems exist. Problems of interest can be input on the MAC model to accurately determine velocities. These velocities can then be compared with surface tension pressure as shown in Figure 2-4 to determine if vapor will enter the capillary device and displace liquid.

2.6 SPILLING AND VAPOR INGESTION

When fluid retention capability of a capillary device breaks down, liquid or vapor can flow across the control surfaces of the device. It is essential to determine the quantity of liquid spilled or vapor ingested in order to adequately predict restart and draining behavior. There are several ways in which the retention capability of the screen can be exceeded. Application of high acceleration such as during restart, vaporization of liquid from the surface of a capillary device and flow losses in propellant flow can all cause spillage or vapor ingestion. The spillage and vapor ingestion of most interest is that occurring during propellant outflow since this will occur normally and must be accounted for in the capillary device design. The other causes of spillage should not occur if the capillary device design is adequate.

By making the top screen have a slightly higher micron rating than the side screens vapor will initially break at the top screen. If the pressure drop across the top screen exceeds the liquid head by greater than the surface tension pressure, vapor will be ingested at all points of the screen. If on the other hand the surface tension pressure is great enough, vapor can be prevented from penetrating the basket sides.

If the liquid head exceeds the pressure drop (HG)across the top screen, the pressure inside the basket will exceed the pressure outside and liquid will spill from the basket Surface tension will not appreciably aid in preventing spilling since the wetting liquid will spread over the outer surface of the screen with a large radius of curvature.

The ideal way to prevent spilling and vapor ingestion is to make the top screen HG greater or equal to the liquid head and use the surface tension pressure to prevent vapor ingestion. Since liquid head will be dropping as the basket is drained it is desirable to initially make HG essentially equal to the liquid head.

A computer program has been developed to predict spilling, vapor ingestion, refilling, vapor pullthrough and vapor motion. This has been correlated successfully with scale model S-IVC data. The program consists basically of the following analyses, which are described in more detail in Reference 2-14.

Vapor will break through the top screen initially when a restart occurs. The magnitude of the pressure drop is critical in determining the flow across the screen surfaces on the side of the capillary device. Looking at one case, the pressure drop $\Delta P_L = P_u - P_L$ at the top of the side screen, with no liquid collected outside the basket is,

$$\Delta P_L = HG - HT$$

if $\Delta P_L < 0$, liquid will spill from from the capillary device

if $\Delta P_L > 0$, and > HS (surface tension pressure head) vapor will be ingested into the capillary device

if $\Delta P_L > 0$, and < HS no flow will occur at this point.

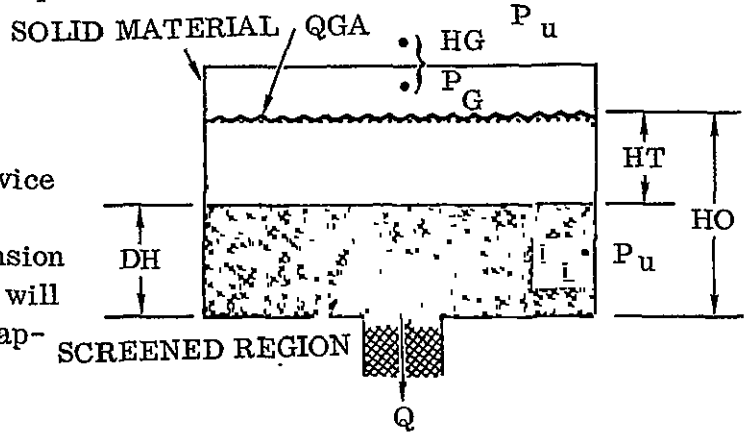
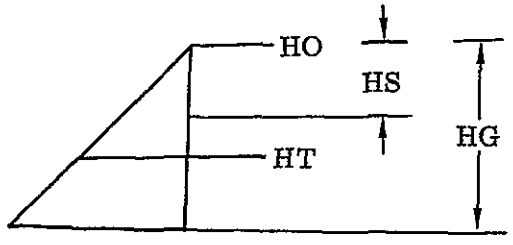


Figure 2-9. Fluid Configuration for Spilling and Vapor Analyses.

At the bottom of the screen $\Delta P_L = HG-HO$ and the same inspection of ΔP_L is made to determine the direction of the flow. For illustration, assume $\Delta P_L > 0$ and > HS at the top of the screen and $\Delta P_L < 0$ at the bottom of the screen. The vapor will be ingested over the top portion of the screen at a volume flow rate

$$\dot{Q}_V = \int_0^{HG-HS-HT} dQ_V \text{ , which as explained in Reference 2-22 yields}$$

$$\dot{Q}_V = \frac{2}{3} \times \sqrt{\frac{2g\,\rho_L}{CSV\,\rho_g}}\,(HG-HS-HT)^{3/2}$$



No flow will occur over a region HS wide.

Liquid flow will be

$$\dot{Q}_L = \frac{2}{3} X \sqrt{2g/(CSL)}\,(HO-HG)^{3/2}$$

where CSL and CSV are flow constant defined in the appendix in the INGASP listing.

Using triangle diagrams, such as shown above, the pressure drops and flow equations for all possible cases were considered and coded into the INGASP program. These cases included liquid level in the capillary device below the screened area and liquid present outside the capillary device due to collection, with consequent refilling calculations. Initially the program made calculations to determine motion of ingested bubbles based on drag between liquid and vapor flowing in the capillary device. This calculation is not present in the current listing because the change in velocity due to drag was found to be negligible for all cases run with that option included. The problem case is terminated when the liquid level in the start basket falls below the pullthrough height.

Pullthrough, as input in the listing, is determined from S-IVC data correlation; however, a pullthrough correlation which best suits the problem configuration being run can easily be substituted for this.

The program has been used for several cases under Contract NAS8-21465. An example analysis performed to maximize available liquid flow for the S-IVC LO_2 capillary device is illustrated in Figure 2-10. The curve shows the amount of liquid which can be transferred without refilling before the volume inside the capillary device reaches 5.00 ft^3. This can be directly translated into fluid quantity by multiplying the time by 5.88 ft^3/sec. The curve is influenced by spilling when the standpipe area is greater than 0.50 ft^2. The increased pressure drop below 0.2 ft^2 standpipe area would cause vapor ingestion which may not jeopardize restart but creates a possible problem of vapor entering the outlet. The standpipe area chosen for the S-IVC was thus chosen to be 0.50 ft^2. Tradeoffs between spilling, vapor ingestion and residual requirements are presented in Reference 2-22 for the S-IVC LO_2 and LH_2 tank start basket.

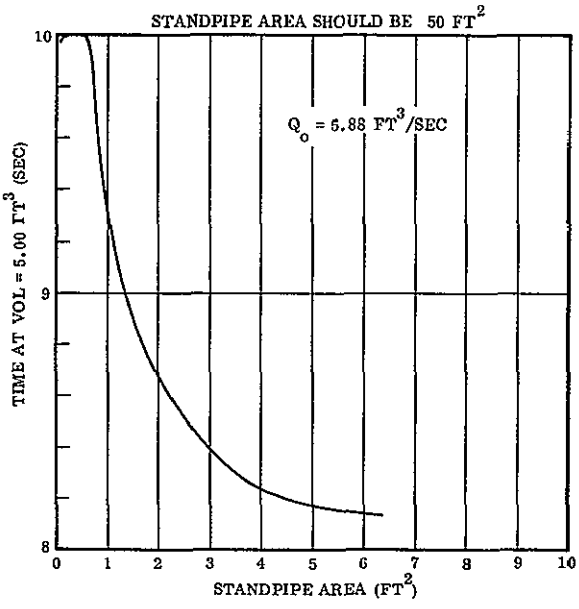


Figure 2-10. Standpipe Area Vs Available Engine Flow S-IVC 64 Ft^3 LOX Tank Start Basket

Several principles should be kept in mind to reduce spilling while not impairing refilling or residual minimization. First the pressure drop across the top of the capillary device should be high to reduce spilling and residuals; at least equivalent to the liquid head in the device. Secondly, side screen flow area should be large to promote refill and low residuals. Thirdly, the surface tension pressure of the side screen should be high to resist vapor ingestion and the surface tension pressure of the top screen should be relatively low to limit trapped vapor during filling.

Spilling from a propellant transfer device such as a screen liner can be predicted by using the basic equations previously illustrated. This type of analysis is useful for predicting propellant transfer residuals.

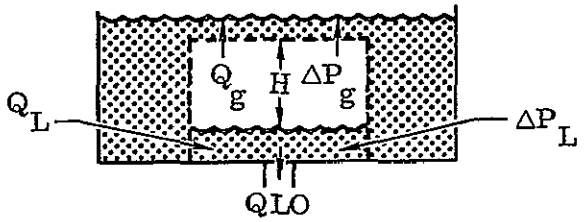
2.7 REFILLING WITH SETTLED FLUID

Refilling of a capillary restart device is essential to maintain continuous liquid flow and to provide a full device for a subsequent restart. The discussion in the settling section indicated that, generally, the liquid does not collect on the aft bulkhead without considerable turbulence and recirculation first occurring.

We can promote refilling passively by effective start basket design, and actively by introducing refill valves. Passive refilling is desirable from the standpoint of simplicity. However, for complete and quick refilling a refill valve has definite advantages particularly under severe restart duty cycle conditions where refill time is critical.

$$\Delta P_L + \Delta P_g + \Delta P_\sigma = \rho_L g H$$

$$\text{where } \Delta P_L = \frac{A_1 L \mu_L V_L}{D_a^2 g_c} + \frac{A_2 L \rho_L V_L^2}{D_a g_c}$$



$$\Delta P_g = \frac{A_1 L \mu_g}{D_a^2 g_c} V_g + \frac{A_2 L \rho_g V_g^2}{D_a g_c}$$

$$\Delta P_\sigma = 4\sigma / D_{BP} \qquad QLO = QG + QL$$

Figure 2-11. Refilling Configuration

Start basket refill depends upon the driving pressure, $\Delta P = \rho g H$, and the resistance to vapor removal such as screen pressure losses due to liquid flow into and vapor flow out of the basket. An additional and critical parameter is surface tension pressure, ΔP_σ, that must be overcome before vapor can penetrate the screen. Refill will commence shortly after liquid begins to collect at the aft end of the tank. Since driving pressure is proportional to the vapor head, refill rate will decrease as basket fill approaches completion.

The considerations expressed in Figure 2-11 are embodied in the refilling calculations of the INGASP. Final vapor head trapped is simply equal to $4\sigma/\rho_L g D_{BP}$.

The use of a screened standpipe at the top of the capillary device can be used to reduce the trapped vapor volume. This reduction in trapped vapor volume will require more time if the standpipe flow area is smaller than the screen flow area originally present at the top of the screen.

The considerations for effective refilling tend to promote spilling since low surface tension retention pressure is conducive to low trapped vapor head. Use of a standpipe with increased pressure losses may tend to promote vapor ingestion into the start basket because of the low pressures which would occur inside the capillary device.

Another approach to promote refilling is to replace the standpipe with a vent tube and solenoid-operated valve. The advantage of a vent tube is that refill can go to completion in a shorter time period, and surface tension effects will be eliminated. It will, of course, be necessary to trade off the passive approach of a screened standpipe

with the more complex alternative of a vent tube, which should guarantee refill for a broader range of conditions. Vent tube complexity can be minimized by installing the solenoid at the tank wall where critical components, including electrical leads, can be located external to the tank, in a less hostile environment. A poppet attached to a plunger will seat against the tube inlet to prevent flow. During restart the plunger will be actuated, unseating the poppet and permitting vapor expulsion. A sketch of the vent tube modification to the design is given below. This approach is applicable for severe refilling requirements where the added complexity of the solenoid valve cannot be avoided.

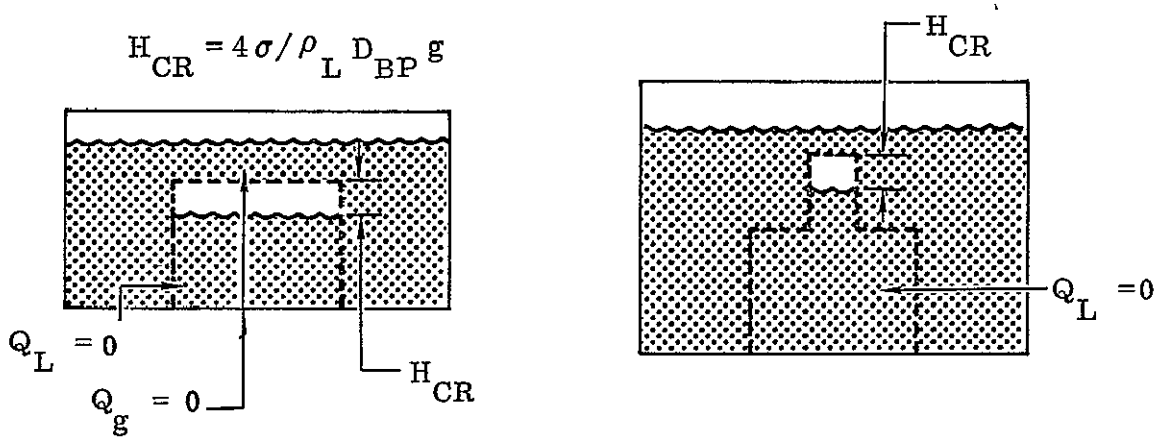


Figure 2-12. Use of a Standpipe to Reduce Trapped Vapor Volume.

It is to be noted from Figure 2-13 that if refill is not completed prior to engine shutdown, vapor becomes positioned over the tank outlet for subsequent starts. Pure liquid flow to the engine cannot be assured unless a second screened compartment is placed over the tank outlet.

The significant difficulty in predicting start basket refill is determining the liquid/vapor configuration external to the capillary device during the settling and collection period. This information may be obtained in a manner described in Section 2.5.

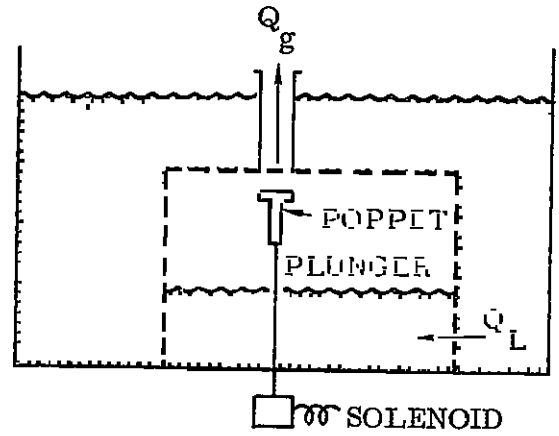


Figure 2-13. Use of a Refill Valve to Eliminate Trapped Vapor

2.8 TANK REFILLING

Ground Filling Methods. Ground filling of a tank containing a capillary device requires procedures for minimizing the possibility of trapping vapor within the device. This can occur if filling is too rapid as illustrated by Figure 2-14.

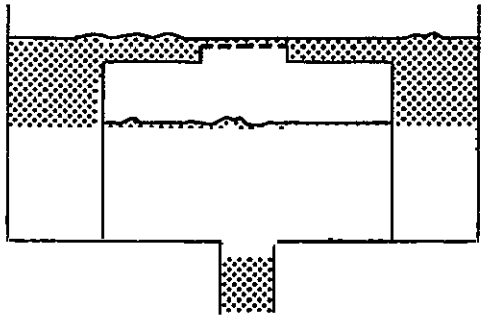


Figure 2-14. Capillary Device Filling.

Because of the high gas pressure drop across the top screen of the typical capillary device shown it will be easier to fill the tank region outside the capillary device than the capillary device itself. If the filling process occurs at too high a flow rate the top of the capillary device will be covered before the inside is filled, effectively trapping an undesirable quantity of vapor in the capillary device. If filling is performed intermittently at a preprogrammed rate and schedule, the level inside the capillary device will catch up to the liquid level outside the capillary device so that no vapor will be trapped.

Another means of providing a capillary device completely filled with liquid is the use of a fill valve, which can be solenoid operated at the top of the capillary device. This additional hardware may be useful in reducing complex filling requirements since, by leaving the valve open, filling can be accomplished at a high flow rate without trapping any vapor. Closing the valve then assures a capillary seal. The valve would also aid in refilling the capillary device during propellant settling and reorientation.

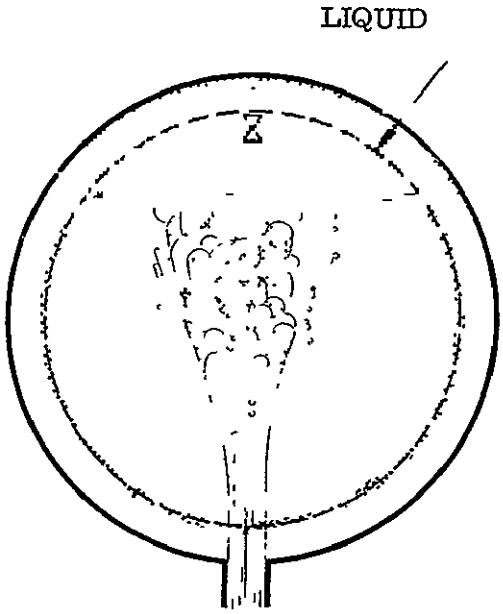


Figure 2-15. Possible Undesirable Fluid Orientation During Orbital Filling

Orbital Filling. Filling of a tank with a capillary device in orbit can cause significant amounts of vapor to be trapped inside the device if necessary precautions are not taken. For example, if the acceleration in the receiver tank is such that liquid will tend to be positioned at the forward end of the tank, then fluid introduced into the tank at low gravity levels will tend to migrate along the walls toward this end of the tank. In transit the fluid will tend to wet the capillary device and, if wetted completely, vapor will be trapped inside the capillary device. The use of fill valves as mentioned for ground filling might not provide much advantage because, as shown in Figure 2-15, the presence of liquid over the valve is a possibility. A possible operational method of filling a tank with a capillary device would obviously be to induce an acceleration so that filling procedures will be similar to those on the ground.

2.9 RESIDUALS

To obtain maximum volumetric efficiency in fluid transfer and restart it is necessary to minimize residuals by effective capillary device design. Residuals can be minimized by suppressing pullthrough and by designing the capillary device to retain liquid over the outlet during draining.

Pullthrough. The concept of vapor pullthrough or suction dip was discussed in Reference 2-14 with two equations culled from the literature presented. Referring to the flow diagram of Figure 2-16, when

$$h_c >> r_o, \quad \frac{Q^2}{gh_c^5} = 6.5 \tag{2-3}$$

and for

$$h_c \ll r_o, \quad \frac{Q^2}{r_o^2 gh_c^3} = 11.8 \tag{2-4}$$

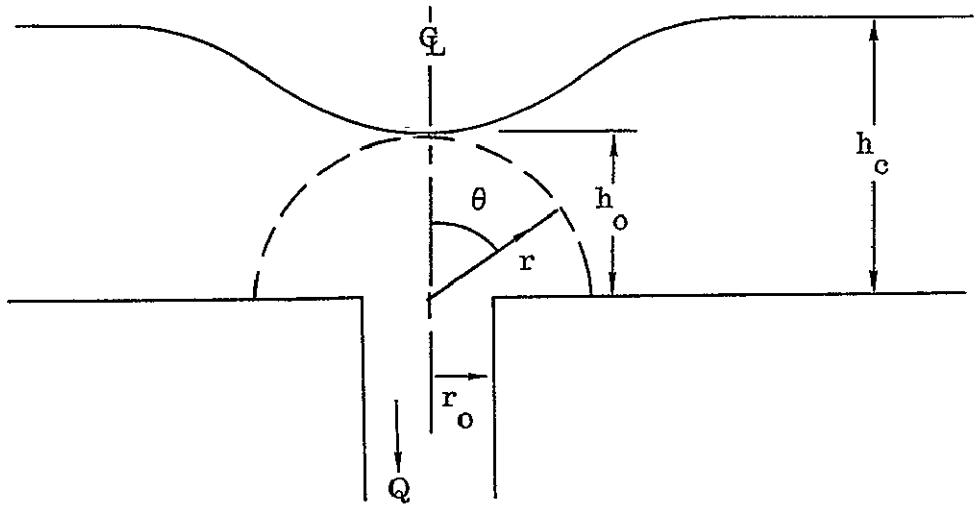


Figure 2-16. Suction Dip Model Terminology.

These two expressions are shown graphically in Figure 2-17. Tests were run to determine the pullthrough expression for $h_c \sim r_o$ by employing a scale model S-IVC tank which was pressurized up to 70 psi. Test results for water and pentane were used to obtain an empirical equation which is good for the entire range of h_c vs r_o. This expression, equivalent to Equation 2-3 for $h_c >> r_o$ and equivalent to Equation 2-4 for $h_c << r_o$ is $Q/(gh_c^{\alpha} r_o^{\beta}) = C$, where Q is the volume flow rate, g the gravity level, h_c is the height of the surface at the tank wall at inception of pullthrough and r_o is the outlet radius. α, β and C are empirical factors defined by, $\alpha = 3 + (h_c/r)^{1/10}$, $\alpha \leq 5$, $\beta = 2 - (h_c/r_o)^{1/10}$, $\beta \geq 0$, and $C = 11.8 - 2.65\,(h_c/r)^{1/10}$.

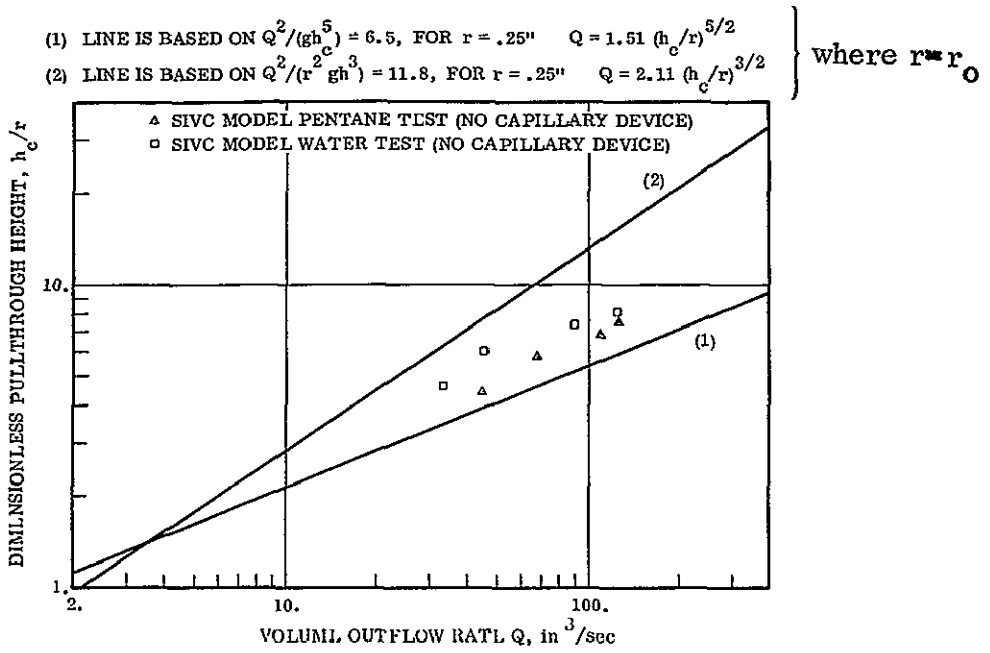


Figure 2-17. Vapor Pullthrough Correlations for S-IVC Scale Model Testing.

Interface Shape. For the case where $h_c \sim r_o$ an empirical equation was derived which represents S-IVC scale model outflow tests using both pentane and water. This expression is

$$y/h_c = (r/r_o)^{0.137} - 0.56 \qquad (2\text{-}5)$$

where h_c and r_o are as previously defined and y and r are coordinates of the interface.

For $h_c << r_o$, an equation which may be used to obtain the interface shape is

$$\frac{Q^2}{8g\pi^2 r^2 y} + y = h_c \qquad (2\text{-}6)$$

This is obtained from Equation 14, Reference 2-14.

Interface shape for $h_c >> r_o$ is not available, however this case does not normally occur in propellant tanks using capillary devices. A more conventional approach to pullthrough evaluation is shown in Figure 2-18 where data from several investigators is presented. Saad (Ref. 2-23) and Gluck (Ref. 2-24) data for flat bottomed cylindrical tank show some disagreement. There is a source of possible difference in consideration of the meniscus of the draining fluid on the tank wall. Easton and Catton indicate some theoretical agreement with the treatment of Gluck, Saad also examined flat bottom cylindrical tanks with offset outlets as shown. Saad's data for hemispherical tanks with center positioned outlets indicates that pullthrough will occur at lower

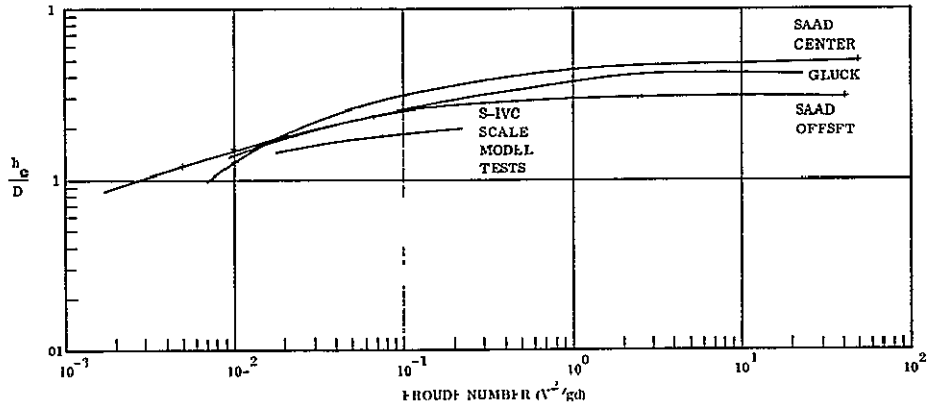


Figure 2-18. Pullthrough Correlation

levels than predicted for the cylindrical flat bottomed cases with similar volumes. This is because the hemispherical tank allows a greater depth at the center for the same volume of contained fluid in a container of a given radius.

These equations and correlations may be used to predict pullthrough when the outlet is unbaffled or unscreened.

Low gravity pullthrough empirical correlations are not currently available however Bernoulli's equation leads to an expression; for $h_c \ll r_o$,

$$\frac{\rho Q^2 R^2}{r_o^2 h_c^3 \sigma} = 23.6$$ as derived in Reference 2-25, where R is the tank radius

and $$\frac{\rho Q_c^2 R^2}{h_c^5 \sigma} = 13 \text{ for } h_c >> r_o.$$

Pullthrough Suppression. One obvious method of reducing residuals is to reduce pullthrough height. This can be accomplished as indicated by the previous equations by increasing drain radius, increasing g level during draining or decreasing outflow rate. Another approach which does not alter overall configuration and mission parameters is to suppress pullthrough by using screens or baffles strategically placed over the outlet. The use of baffles has been considered in Reference 2-25. Using screens to resist pullthrough is easily accomplished with a capillary device by placing a screen over the outlet of the tank. The presence of the screen has a twofold advantage in reducing pullthrough. The screen tends to smooth out the velocity gradients in the flow, effectively making a bigger outlet and the small pores of the screen tend to resist vapor penetration in a manner similar to a baffle. It is the smoothing of the flow pattern over the outlet which potentially gives the screens an advantage over baffles.

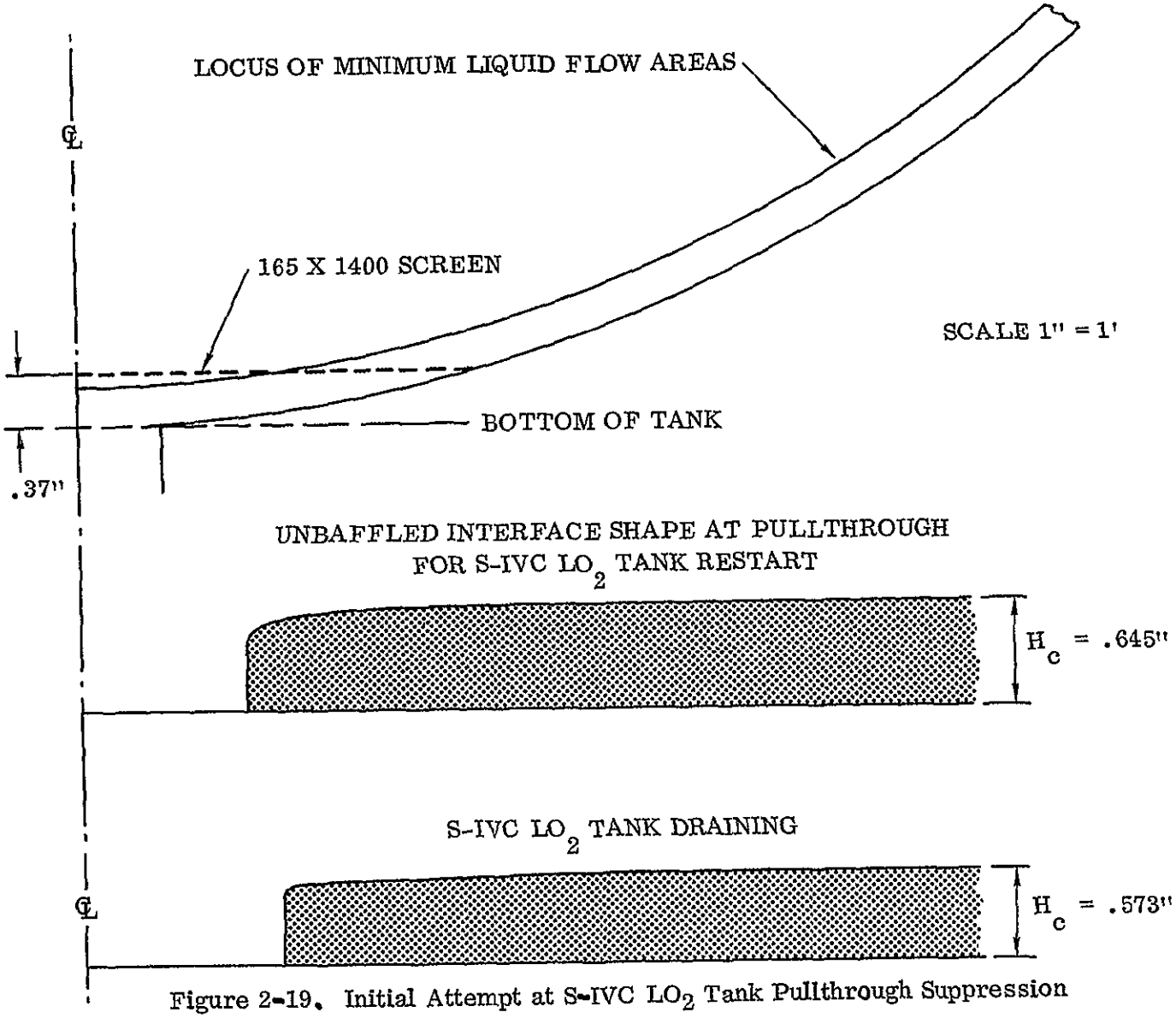


Figure 2-19. Initial Attempt at S-IVC LO_2 Tank Pullthrough Suppression

Screen sizing can be accomplished by considering the analytical and graphical procedures discussed in References 2-14 and 2-27.

The initial step in sizing screens is to determine the wetted flow area which must exist if the surface tension pressure drop is not to be exceeded by the liquid flowing from the tank. Maximum screen velocity can be found in Tables 2-2 and 2-3. In most cases a 400 mesh screen is likely to be optimum for reducing pullthrough height. Taking the velocity corresponding to the fluid being considered, determine the flow area from $A_f = Q/V_{MAX}$. Determine tank cross sectional area versus height and by subtracting A_f find the allowable unwetted area vs height. Plot this area vs height on a scale drawing of the tank outlet region.

Fluid interface shape during draining may be approximated using Equation 2-5 or 2-6. Actually interface shape will be somewhat flatter than predicted since the screen affects the interface shape during draining. Interface shape may then be plotted to scale and put on a template to superimpose on the tank drawing. Placing the interface shape template at different positions along the tank and on the tank drawing indicates the residual volume if the pullthrough screen were placed at this position. This procedure is illustrated in Figure 2-19. The height which gives minimum residual volume is then selecte

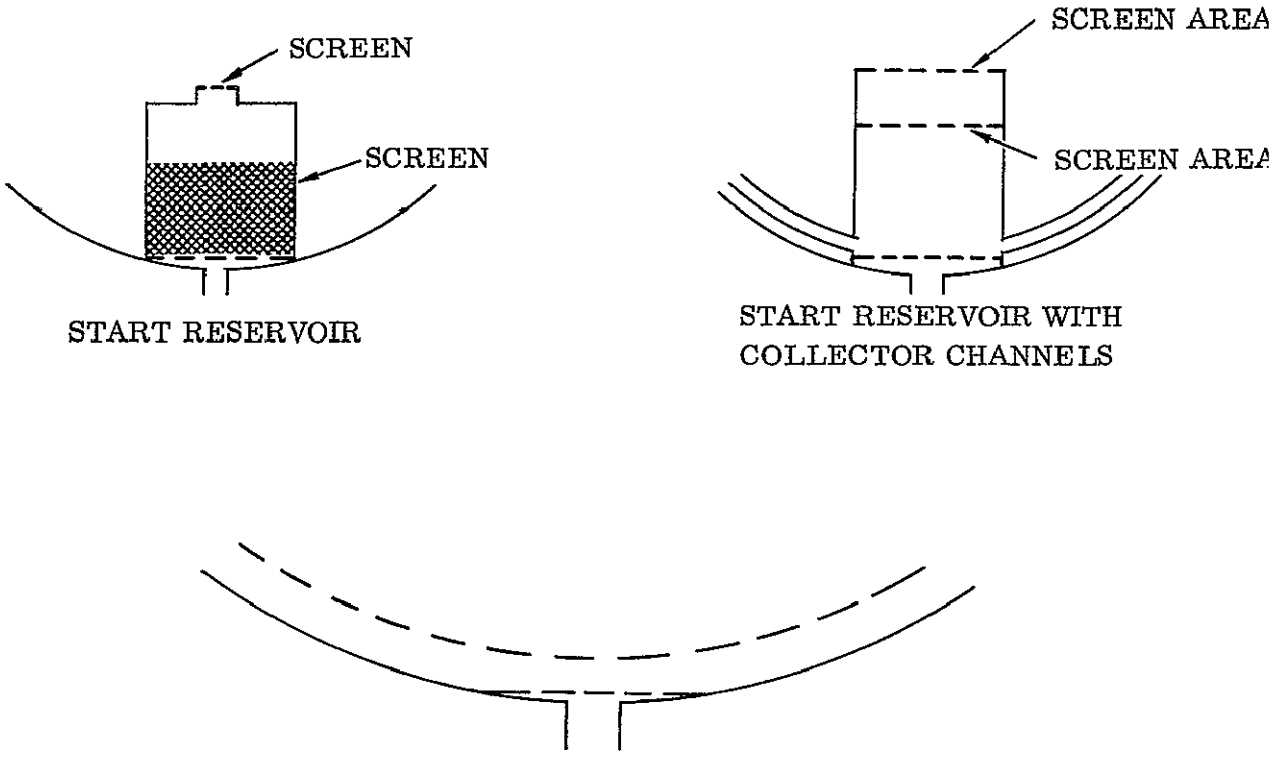
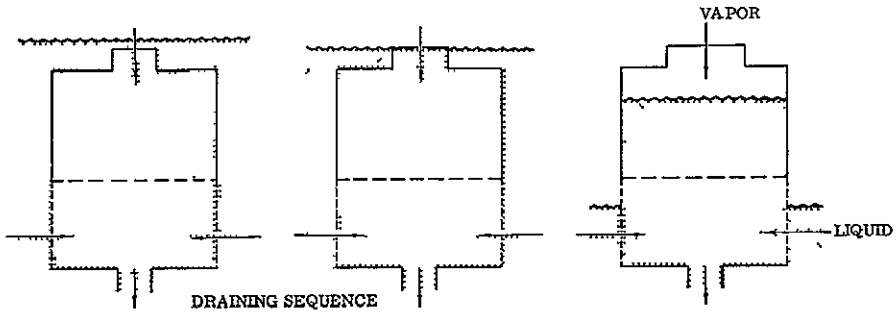


Figure 2-20. Typical Capillary Device Configurations.

The illustration shown was an initial attempt to minimize residuals before it was realized that a 200 × 600 screen was optimum for dutch twill screens for reducing residuals. Using a 200 × 600 or 400 × 400 screen would allow placement of the screei at progressively lower levels.

Residual Prediction With a Capillary Device. In order to design a capillary device for minimum residuals during draining it is necessary to drain as much fluid as possible from the tank before the capillary device over the outlet is drained. Several typical configurations shown below illustrate this principle.

The typical start reservoir configuration should employ a small top screen area to inhibit reservoir draining. The following sequence illustrates how to minimize residuals in a start basket configuration.



Initially, when the level is above the start basket, liquid flows through the standpipe and through the side screen. When the liquid level outside the basket drops to the top of the standpipe, no flow will occur directly from the basket if the pressure drop of the flowing liquid through the side screen does not exceed the surface tension of the top screen. Thus we want a screen with high surface tension retention pressure for the standpipe. As the level outside the tank falls, the area for liquid flow through the side screen decreases with a corresponding increase in pressure drop. When the flow pressure drop across the side screen exceeds the surface tension pressure of the top screen. vapor will flow across the standpipe.

It is important to minimize vapor flow across the side screen. If the screen mesh utilized for the side screen has too low a surface tension retention pressure vapor may break through this screen before the top screen. This will allow more vapor flow area with lower vapor pressure drop than is desirable for minimizing liquid flow directly from the start basket. One method of inhibiting vapor flow across the start basket side screen is to give it a screen with equal or greater surface tension pressure than the top screen. Making the upper portion of side of the start basket from solid sheet material is another way of inhibiting vapor flow. The height of the solid portion, in this case should exceed the difference between top screen and side screen surface tension pressure head. This is the best approach generally because it allows side screen selection based on velocity considerations rather than retention requirements.

Assuming the top and side screens are sized properly from a retention standpoint, vapor pressure drop through the top screen should be high to inhibit draining of the start basket. More flow will come from the tank than from the start basket and residuals will be held to a minimum. If pressure drop across the side screen could be minimized by utilizing coarser screens such as square weave screens draining would be more efficient. Unfortunately, surface tension retention pressure and screen wicking properties are important in reducing spilling and increasing surface tension stability of screens subjected to heating.

A computer program was developed to predict residuals in a capillary device based on flow, volume and screen properties of the tank-capillary device configuration. This program, for high Bond number draining, is applicable to most propellant transfer and restart residual problems. The technique embodied in DREGS 2 is discussed at the end of this section.

Considering a propellant transfer application using a channel reservoir configuration is depicted in Figure 2-21. The principles for minimizing residuals are influenced by the dual function of the top screen. The top screen is designed so that the vapor pressure drop across it will be low enough to prevent vapor from entering one of the channels during a vehicle disturbance which causes the main body of liquid to become disconnected from the capillary device. Because of this requirement it is necessary that the reservoir have less pressure drop than the screen channels. Since the flow area of the reservoir is small compared to the flow area of the channels the screen mesh across the reservoir must be less restrictive than the mesh applied to the channels. This would allow liquid inside the basket to partially drain before the channel. Several square weave screens placed at different heights in the reservoir would allow some liquid to remain over the outlet. When the main bulk of liquid recovers the channels the liquid flow through the reservoir will be stopped by the surface tension pressure of the screen just below the surface. These screens should also have higher bubble point diameters than the channel screens so that vapor will break through them if the channels become uncovered during subsequent adverse vehicle disturbances.

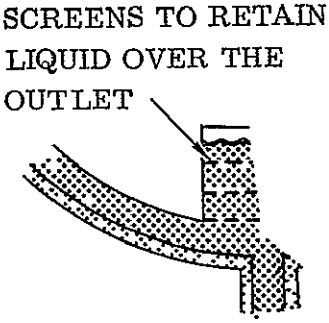


Figure 2-21. Intermediate Screen Placement in Propellant Transfer Capillary Device.

For a liner or channel reservoir propellant transfer reservoir system it is possible to have significant residuals if the propellant is not scavenged by settling it over the outlet during the final stage of draining. This final stage begins when no fluid remains outside the capillary device which can be transferred through the capillary device to the

outlet. At this point, if the acceleration on the tank is such as to position the propellants directly opposite the outlet, it is possible that vapor will be ingested through the capillary device into the outlet. This would result in one capillary device volume of residuals. Prevention of these residuals is best accomplished, if feasible, by scavenging the propellants with linear acceleration imparted during the final stages of draining.

The settled channel reservoir configuration is shown in Figure 2-22. Liquid will drain through the channel screens with no liquid being drained directly from the reservoir until reduction in channel flow area causes the channel pressure drop to exceed the surface tension pressure of the reservoir screen. Fluid will then drain more rapidly from the reservoir. Available flow area can usually be arranged so that the tank can be drained almost to the junction of the channel and reservoir before the reservoir screen surface tension is broken.

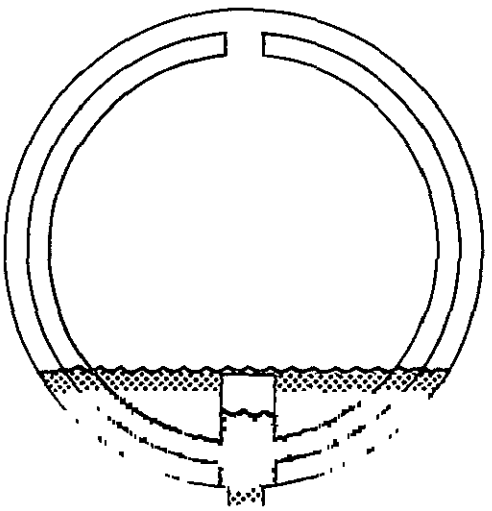
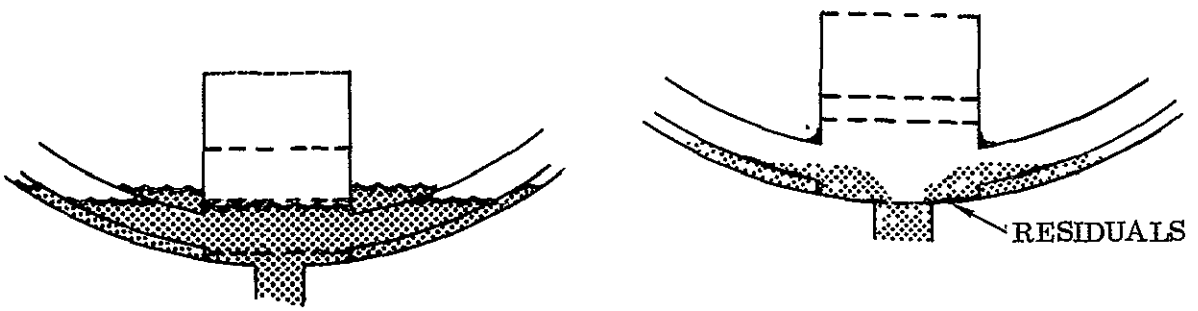
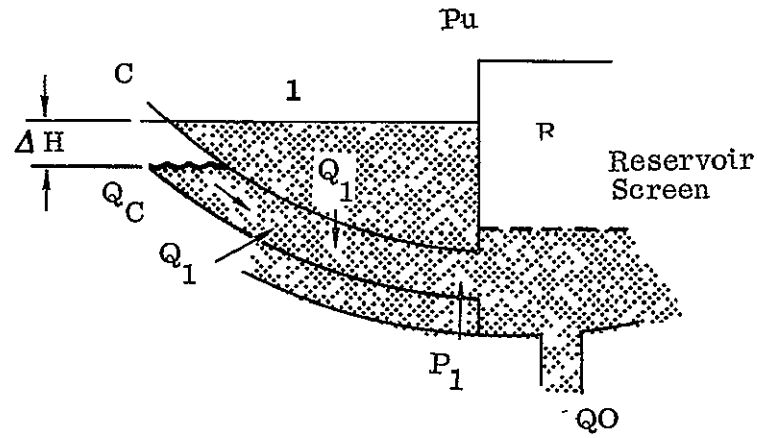


Figure 2-22. Settled Liquid Configuration

Once the liquid level inside the reservoir drops below the junction draining will proceed until pullthrough occurs at the screen over the outlet. Residuals will be somewhat greater than in a tank without a capillary device since small quantities of additional liquid may remain between the capillary device and the wall, and between the top of the collector channels and side of the reservoir. This liquid is not trapped by surface tension. The small head difference driving the flow across the screens in these two regions relative to the high outlet rate is what causes these additional residuals. The difference in levels can be determined by iteration as shown below.





$$Q_o = Q_c + Q_1$$

The pressure drop in the channel is small relative to the screen pressure drop, thus

$$Q_1 = f(\Delta H, A_s)$$

ΔH = f(VOL 1, VOL C, Q1, QC) where VOL 1 and VOL C are the fluid volume in the tank and channel respectively.

This may be solved iteratively for the liquid levels. When ΔH exceeds ΔP_σ of the reservoir screen, vapor breaks through the reservoir screens and the tank and reservoir drain simultaneously as indicated. Flow from the reservoir can then be included in the flow analysis

$Q_o = Q_C + Q_R + Q_1$ where Q_R is the volume flow from the reservoir

ΔH_{1-c} = f(VOL 1, VOL C, Q1, QC) where H_{1-c} is the difference in liquid level between 1 and C.

ΔH_{C-R} = f(VOL C, VOL R, QR, QC) where VOL R is the volume in R and ΔH_{C-R} is the difference in liquid level between C and R.

For the screen liner system, scavenging is necessary as indicated in previous paragraphs, to minimize residuals. The flow analysis during draining is similar to that discussed for a channel reservoir configuration. Relative liquid levels can be determined by iteration using the equations presented above.

DREGS Program. A computer program was written to predict residuals in capillary devices during draining. The program, a coding of the following flow analysis, is listed in Appendix B. The equations were formulated based on the following schematic and analysis.

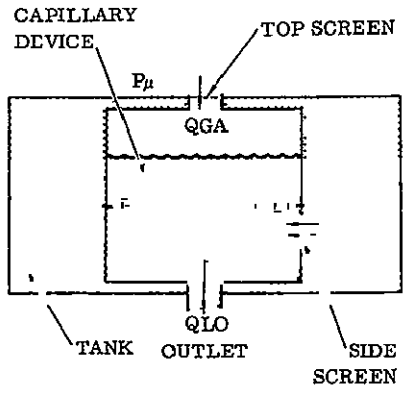
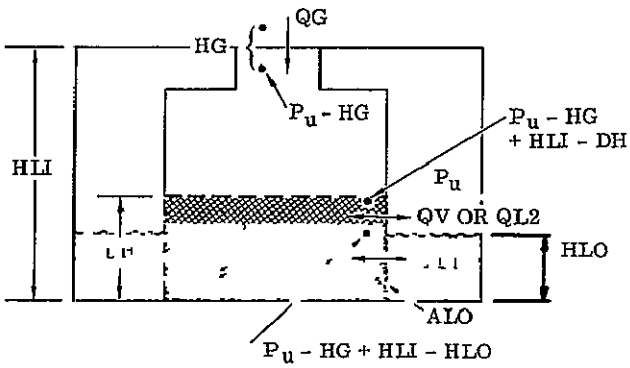


Figure 2-23. DREGS Model Terminology

The problem is trivial until the liquid level recedes to the top of the capillary device. At this point the liquid pressure drop through the side screen is evaluated to see if the surface tension pressure of the top screen is exceeded. If it is, vapor flow through the top screen is computed by equating pressure drop across the top screen to pressure drop across the side screen. A criteria which als must be satisfied is QGA + QL1 = QLO. These two equations are solved to obtain the flow rates and pressure drops.

The other initial possibility is that the surface tension pressure of the top screen is not exceeded by the liquid pressure drop through the side screen. The liquid volume outside the capillary device is then reduced until either the side or top screen pressure drop is exceeded. The calculation at this point relates the pressure drops and flow rates as indicated below.



The program calculates the flow rates and pressure drops in the system. This is done by iteration. The pressure drop across the top screen is calculated to determine the direction of the flow, i.e., if HG< HLI -HLO liquid would flow from the capillary device to the tank and if HG> HLI-HLO flow would occur into the capillary device. Flows are computed using the pressure drops referenced against the common ullage pressure. For example if HG< HLI-HLO flow across the top portion of the side screen would be from liquid to vapor, designated by QL2 and would be found by integrating the expression

$$QL2 = \frac{X}{2BL} \int_{HLO}^{DH} \left[-AL + (AL^2 + 4BL\,[HLI - HG])^{1/2} \right] dH$$

which is obtained by inverting the screen flow pressure drop equation. BL and AL are screen flow pressure drop constants, X is the width of the screen, and DH, HLI, HLO, and HG are head terms shown in the figure above.

Proceeding from these two initial states; for each time step the flow rates and relative volume changes are computed. New liquid levels are computed for the new time steps and calculations of flow rates are repeated. The general procedure is iteration to satisfy both pressure drop and volume conservation considerations. Computations are considered for all possible variations in liquid level. Pullthrough terminates each case when the liquid level inside the capillary device falls below the pullthrough height as computed by using the flow from the free surface inside the start basket or QLO-QL1-QL2.

A complete listing of the program in the appendix indicates the equations used to evaluate the liquid level cases not discussed in detail here.

2.10 VAPOR IMPINGEMENT

A problem encountered during periods of violent fluid motion, such as experienced during settling or high amplitude sloshing, is the passage of entrained vapor into the capillary device. Retardation of the entrance vapor has been discussed in Section 2.1. The exposition here will be concerned with means of controlling the motion of vapor once it has entered the capillary device.

The basic objective of the effort is to keep vapor from entering the outlet. This can be accomplished by directing the flow of vapor by means of screens and/or performated plates.

Vapor motion is controlled mainly by buoyancy and drag forces and the initial inertia of the vapor imparted by the pressure gradient across the capillary device which allowed the vapor to enter. In the presence of large buoyancy forces as would occur with large bubbles or in high gravity, the problem can be eliminated if the orientation of the acceleration tends to position liquid over the outlet. In general, however, bubble inertia will tend to be the dominant consideration if the vapor quantities are worthy of interest. In any case the solution to the prevention of vapor into the outlet can be accomplished in the same manner.

The hydrophilic properties of all screens with commonly used liquid propellants can be used to advantage in preventing the passage of vapor and deflecting vapor away to a "safe region" of the capillary device. If a refill valve is employed, vapor can then be expelled from the device. The application of a screen of this type is illustrated below.

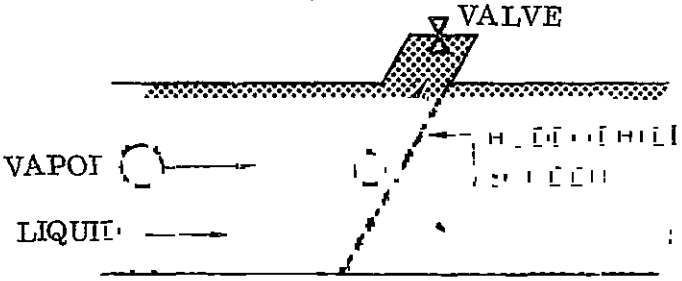


Figure 2-24. Use of a Hydrophilic Screen Deflector.

The screen deflects the vapor so that it is collected away from the liquid outlet. The motion of the vapor depends directly on the angle between the screen and impacting vapor. The bubble will be held up by the normal component of velocity and forced up by the tangential component and buoyancy forces (which are

are usually negligible for the small bubbles encountered with small micron rating screens).

Passage of the vapor through the screen is prevented if the vapor velocity does not cause the impingement forces to exceed the screen surface tension pressure. As vapor collects on the screen shown in Figure 2-24 it must be removed or else the liquid flow-area will be reduced below that required to maintain the liquid pressure drop below the surface tension pressure. If ΔP_L exceeds ΔP_σ the vapor will be contained in the liquid breaking through the screen. If the case of a valve is not practical as shown above, vapor breakthrough can be delayed with a series of parallel screens which deflect vapor, however it may be difficult to discharge this vapor from between the screens during refill.

If vapor impingement cannot be successfully controlled it may be necessary to alter the fluid reorientation during settling by revising the baffle configuration or, in the extreme case, the thrust level.

2.11 VENTING

Use of a capillary device with cryogenic fluids requires consideration of the vent cycle. A blowdown sequence normally associated with ullaging of the propellants will cause tank pressure to fall below liquid vapor pressure. The consequent bulk boiling could be appreciable and could cause large amounts of vapor to be generated and trapped within a capillary device. An analyses which should be performed to evaluate the seriousness of bulk boiling is illustrated in the following exposition.

Consider a capillary device of volume, V_1, immersed in liquid at temperature T_1 and corresponding vapor pressure P_1. Liquid contained within the device will be unaffected by blowdown until tank pressure becomes less than P_1. At this time boiling will commence, and the generated vapor will expell liquid from the device. The boiling process will cool the remaining fluid, with a corresponding reduction in liquid vapor pressure. It is emphasized that saturation properties of liquid and vapor are implicit in the equation development that follows because the physical process involves that of a saturated fluid. The First Law of Thermodynamics applicable to the conditions described above and in the sketch below is given as:

$$dE_L + dE_g = \delta Q - \delta W - h_L \delta m_{LO} \quad \text{where vapor only is vented} \qquad (2\text{-}7)$$

where

dE_L = change in liquid internal energy contained within fixed volume, Btu

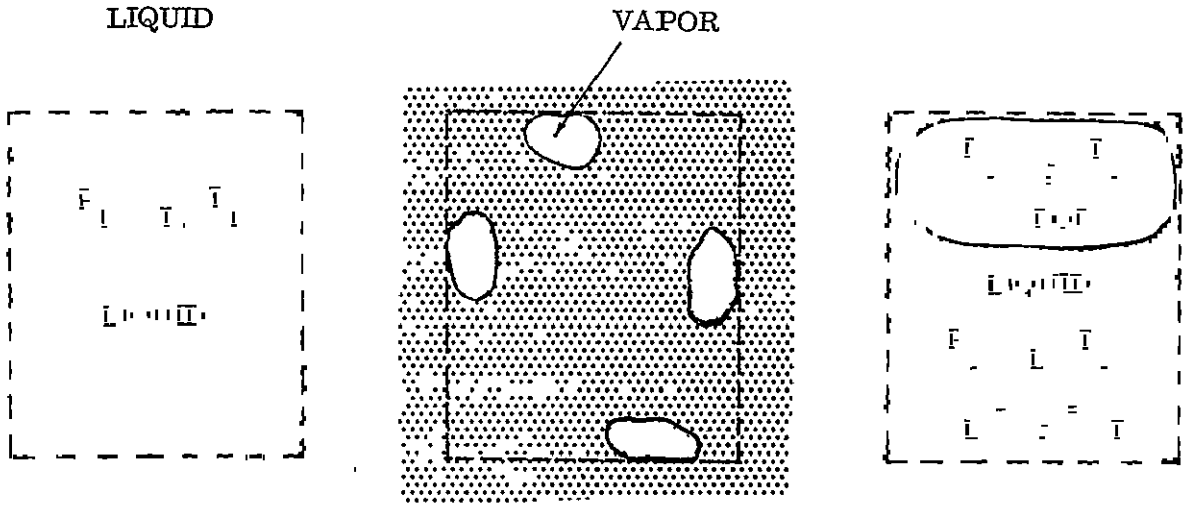
dE_g = change in vapor internal energy contained within fixed volume, Btu

δQ = heat transfer across boundaries (assumed zero)

δW = work done by fluid on surroundings (equals zero)

h_g = enthalpy of liquid flowing across boundaries, Btu/lb

δm_{LO} = mass of liquid flowing across boundaries, lb



INITIAL STATE INTERMEDIATE STATE FINAL STATE

Integrating Equation 2-7 (and recognizing that $\delta Q = \delta W = 0$) results in

$$(E_{L_2} - E_{L_1}) + (Eg_2 - Eg_1) = -\bar{h}_L\, m_{LO} \tag{2-8}$$

But, $E = mu$

where

u = specific internal energy of fluid, Btu/lb

m = fluid mass, lb

Therefore Eq. 2-8 becomes, $\left[(mu)_2 - (mu)_1\right]_L + \left[(mu)_2 - (mu)_1\right]_g = -\bar{h}_L\, m_{LO}$ (2-9)

where

$\bar{h}_L$ = average enthalpy of liquid crossing boundaries between the state 1 and state 2 conditions.

m_{LO} = mass of liquid expelled from fixed volume during the change from state 1 to state 2.

Add and subtract $(m_g u_{L_2})$, $u_{L_2}(m_{LO})$ and set $m_{g_1} = 0$ in Equation 2-9 and rearrange to obtain

$$m_{T_1}(u_2 - u_1)_L + m_{g_2} u_{E_2} = (-\bar{h}_L + u_{L_2}) m_{LO} \tag{2-10}$$

where

$u_{E_2} = (u_g - u_L)_2$ = internal energy of evaporation, Btu/lb.

If states 1 and 2 are specified along with the system volume, only m_{LO} and m_{g_2} remain unknown. However m_{g_2} can be determined explicitly using the following relations:

$$\left.\begin{aligned} m_T &= m_g + m_L \\ V_T &= V_g + V_L \\ m_g &= \rho_g V_g \\ m_L &= \rho_L V_L \end{aligned}\right\}$$

Simultaneous solution of these four equations provides

$$m_{g_2} = (V_T \rho_{L_2} - m_{T_2}) \left(\frac{\rho_{g_2}}{\rho_{L_2} - \rho_{g_2}}\right) \tag{2-11}$$

Substituting $m_{T_2} = m_{T_1} - m_{LO}$ and letting $\lambda = \dfrac{\rho_{g_2}}{\rho_{L_2} - \rho_{g_2}}$ results in

$$m_{g_2} = (V_T \rho_{L_2} - m_{T_1} + m_{LO}) \lambda \tag{2-12}$$

Cominging Equations 2-12 and 2-10 and rearranging terms gives

$$m_{LO} = \frac{m_{T_1}\left[\left(u_2 - u_1\right)_L - \lambda u_{E_2}\right] + V_T \rho_{L_2} \lambda u_{E_2}}{-(\bar{h}_L + \lambda u_{E_2} - u_{L_2})} \tag{2-13}$$

Now, it is of interest to determine the volume of liquid expelled normalized to the fixed system volume or

$\dfrac{V_{LO}}{V_T} = \dfrac{m_{LO}/\rho_{L_1}}{m_{T_1}/\rho_{L_1}} = \dfrac{m_{LO}}{m_{T_1}}$. Thus it is seen that Equation 2-13 should be divided by

m_{T_1}. This results in

$$\frac{V_{LO}}{V_T} = \frac{m_{LO}}{m_{T_1}} = \frac{1}{-(\bar{h}_L + \lambda u_{E_2} - u_{L_2})} \left\{ \left[\frac{}{(u_2 - u_1)_L - \lambda u_{E_2}} \right] + \frac{\rho_{L_2}}{\eta u_{E_2} \rho_{L_1}} \right\} \qquad (2\text{-}14)$$

But the bracketed term of equation 2-14 can be reduced to

$$(u_2 - u_1)_L - \lambda u_{E_2} (1 - \rho_{L_2}/\rho_{L_1}) \approx (u_2 - u_1)_L \quad \text{(because } \rho_{L_1} \approx \rho_{L_2})$$

Consequently equation 2-14 becomes

$$\frac{V_{LO}}{V_T} = \frac{(u_2 - u_1)_L}{-(\bar{h}_L + \lambda u_{E_2} - u_{L_2})} \qquad (2\text{-}15)$$

Equation 2-15 provides the normalized volume of liquid expelled from the fixed volume. The normalized volume of vapor remaining within the system can be accounted for in the following manner.

$$V_{g_2} + V_{L_2} = V_T, \qquad V_{L_2} = V_T - V_{LO}$$

therefore $V_{g_2} + (V_T - V_{LO}) = V_T$ or $V_{g_2} = V_{LO}$

Consequently

$$\frac{V_{g_2}}{V_T} = \frac{V_{LO}}{V_T}$$

The quantity of vapor generated within the capillary device can be approximated from the data of Figure 2-25. It is obvious, of course, that the dimensionless volume ratio cannot exceed 1.0 because at this point all liquid has been expelled and there is no capacity for further vapor generation. However, the volume ratio range from zero to one provides useful data.

In order to minimize large pressure reductions inherent with ullaging and blowdown a thermodynamic vent system may be used. This system, discussed in detail in References 2-28 and 2-29, can control pressure within a narrow band of less than one psi. This system also provides cooling capacity for preventing vapor formation due to incident heating. Thus for a tank containing a capillary device subjected to long orbital stay times and lockup periods the use of a thermodynamic vent system is essential.

NOTES:

1. Capillary device initially filled with liquid.
2. Liquid commences boiling at 25 psia.
3. Liquid only is expelled from control volume.
4. Liquid and vapor at saturation throughout blowdown.

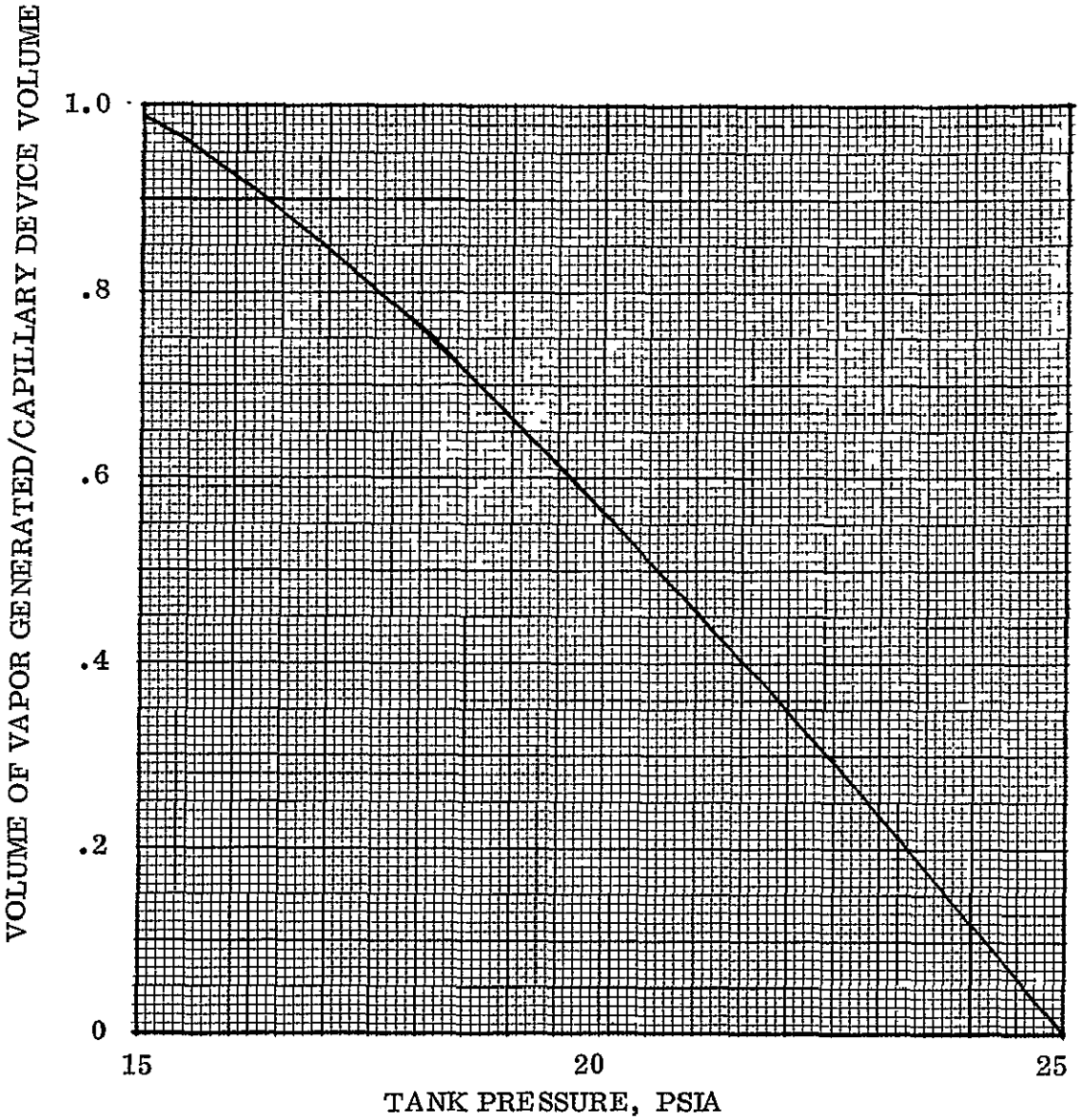


Figure 2-25. GH_2 Vapor Generated Within Capillary Device During Tank Venting Blowdown Sequence

For short lockup periods where venting will not be required it is possible to operate without a thermodynamic vent system if the quantity of vapor formed within the capillary device during this period is within acceptable limits.

Use of a thermodynamic vent system requires that liquid be supplied to the inlet of the throttle valve in order to assure sufficient cooling capacity for maintaining liquid in the capillary device. Providing all liquid to a vent system requires that a capillary collection system be designed either in the form of collector tubes or channels or as a portion of a liner type propellant transfer configuration. For a multiple restart mission channels or tubes will be difficult to refill and the compartment type propellant transfer concept is likely to appear more suitable for supplying liquid.

2.12 PROPELLANT TANK ULLAGE PRESSURE COLLAPSE

Another source of vapor generation within the start basket may occur following an engine shutdown. Should the propellant tank ullage at engine shutdown be substantially warmer than liquid temperature, a severe ullage pressure decay will result due to propellant mixing. If decay proceeds to below liquid vapor pressure, boiling may occur within the start basket.

Equations to evaluate tank pressure collapse may be developed from the First Law of Thermodynamics for a closed system as given below:

$$dE_L + dE_g = \delta Q - \delta W^{\circ} \qquad (2\text{-}16)$$

where dE_L = Change in liquid internal energy contained within system boundaries, Btu
dE_g = Change in vapor internal energy contained within system boundaries, Btu
δQ = Heat transfer across boundaries, Btu
δW = Work done by fluid on surroundings = 0

Integrating equation 2-16 results in

$$(E_{L_2} - E_{L_1}) + (E_{g_2} - E_{g_1}) = Q \qquad (2\text{-}17)$$

But, $E = mu$
where u = specific internal energy of fluid, Btu/lb
m = fluid mass , lb
Therefore (2-17) becomes

$$\left[(mu)_2 - (mu)_1\right]_L + \left[(mu)_2 - (mu)_1\right]_g = Q \qquad (2\text{-}18)$$

In general, the ullage will be superheated at engine shutdown (condition 1 of this analysis), whereas the liquid is saturated at a vapor pressure corresponding to its temperature. After propellant mixing has occurred, (condition 2) it is assumed that

both liquid and gas are saturated at the final tank pressure. For the purposes of clarification the subscript (sL) will represent saturated liquid, subscript (sg) will represent saturated vapor, and subscript (g) will represent superheated vapor. Thus equation 2-18 becomes

$$\left[(mu)_2 - (mu)_1 \right]_{sL} + \left[(mu)_{2sg} - (mu)_{1g} \right] = Q \qquad (2\text{-}19)$$

Adding and subtracting $(m_g u_{sg})_1$, $(m_{sg} u_{sL})_1$, and $(m_{sg} u_{sL})_2$ and rearranging terms, equation 2-19 becomes

$$\left[(m_{sL} + m_{sg}) u_{sL} \right]_2 - \left[(m_{sL} + m_g) u_{sL} \right]_1 + \left[m_{sg} (u_{sg} - u_{sL}) \right]_2 -$$

$$\left[m_g (u_{sg} - u_{sL}) \right]_1 - \left[m_g (u_g - u_{sg}) \right]_1 = Q \qquad (2\text{-}20)$$

Recognizing that $m_T = (m_{sL} + m_{sg})_2 = (m_{sL} + m_g)_1$ and $(u_{sg} - u_{sL}) = u_{Ev}$ (internal energy of evaporation, equation 2-20 is simplified to

$$m_T (u_2 - u_1)_{sL} + (m_{sg} u_{Ev})_2 - m_{g_1} \left[u_{Ev} + (u_g - u_{sg}) \right]_1 = Q \qquad (2\text{-}21)$$

Since $m_{sg_2} = (V_T \rho_{sL_2} - m_T)_2 \left(\frac{\rho_{sg}}{\rho_{sL} - \rho_{sg}} \right)_2$ from equation 2-11, equation 2-21 can be re-written as

$$m_T (u_2 - u_1)_{sL} + (V_T \rho_{sL} - m_T)_2 \left(\frac{\rho_{sg}}{\rho_{sL} - \rho_{sg}} \right)_2 u_{Ev_2} - m_{g_1} \left[u_{Ev} + (u_g - u_{sg}) \right]_1 = Q \qquad (2\text{-}22)$$

Inspection of equation 2-22 reveals that the only unknowns are fluid properties after mixing has occurred (condition 2) and Q, the heat transferred to propellants during mixing. The PRISM program computes Q on the basis of stored energy in the tank walls as defined by tank wall temperatures. The fluid properties can be determined as a function of saturation pressure. Consequently the PRISM program is able to solve equation 2-22 for a final tank pressure. If one assumes that propellant mixing occurs without quenching the tank walls, Q = 0 and a minimum final ullage pressure results. When wall quenching is accounted for, an upper limit final ullage pressure is computed. The PRISM Program is described in detail in Reference 2-31).

Pressurization system design should minimize the possibility of ullage collapse during engine start up by use of low temperature pressurant gas.

2.13 BUBBLE DYNAMICS

An application where the motion of liquid vapor interfaces is of importance is the determination of bubble motion within a capillary device and bubble growth or collapse due to heat transfer effects.

Heat transfer to the propellant is defined by the liquid level, its orientation, and energy transport mechanisms at the tank wall. The latter necessitates a specification of boiling parameters, e.g. number of sites, radius of each site, and frequency of production at each site.

The propellant moments of inertia and the liquid location are determined by the spatial distribution of voids, heat transfer and void generation, surface orientation, and pressure transient of the tank contents. Additional requirements for void distribution specification are generated by propellant venting and outflow problems, e.g. vapor entrainment.

An investigation and computer program development has been undertaken to provide the prediction and pre-design definition of the previously mentioned variables. The resulting computer program (EVOLVE) describes the temporal and spatial evolution of a bubble society. The phenomenological considerations which are embodied in the program are:

1. Bubble generation with time and spatial dependent radii and frequencies.

2. Kinematics and energetics of a single bubble moving in temperature and inertial acceleration fields in three dimensions.

3. Time and spatial dependent temperature and inertial acceleration fields.

4. The effect of wake behind a bubble on following bubbles.

5. Bubble agglomeration (collision absorption).

6. Slip or no-slip interaction with tank walls.

7. Interaction of a single bubble with porous walls (screens).

8. Vaporization (2 ways).

    a. Nucleate boiling as mentioned.

    b. "Bulk" boiling due to change in state of liquid (pressure decay) - this vapor generation is divided between the liquid-ullage interface and the existing bubble population in proportion to relative surface areas.

9. Liquid energy conservation, outflow, and level determination.

10. Convective heat transfer to liquid phase which is dependent on liquid level.

The program is designed to consider populations of up to 1,000 bubbles, three dimensional transport, bubble generation from up to 100 sites at varying radii and frequencies, time dependent surface orientation (not necessarily normal to inertial acceleration vector), and time dependent ullage pressure history. Analytical treatments of the above phenomena which are incorporated in the program are described in references 2.4 and 2.5 with a listing of the program given in reference 2.30.

3

THERMAL CONTROL SYSTEMS DESIGN AND ANALYSIS

The basic purpose of the thermal control systems is to prevent vapor formation within the liquid containment systems and associated feed lines. In order to provide some design conservatism and since it would be extremely difficult to determine the total amount of vapor generated over a complete mission it is recommended that the system be designed to eliminate all vapor formation, even though in actual operation a small amount may be tolerated.

In the case of a perfectly mixed tank fluid (no superheated gas) at constant pressure with no direct contact of the collected liquid with warm tank walls no adverse vaporization would occur. However, under actual conditions basket supports are required, tank mixing is not complete, and the tank pressure does change.

The basic design approach is to use normally vented fluid to cool potential hot spots, and to provide mechanical tank fluid mixing to minimize the magnitude of these hot spots or temperature gradients. Cooling must also be accomplished to the extent necessary to prevent anticipated tank pressure decay cycles from causing evaporation within the collection device. Initially the elimination of vaporization was investigated with the idea of reducing temperature differences between the collected fluid and any contact surfaces to below the incipient boiling point. However, based on Convair test results (Ref. 3-1) the incipient point was found to be likely to occur at extremely low ΔT for normal spacecraft surfaces. The design criteria thus recommended is to provide cooling as necessary to maintain all surfaces in direct contact with the collected fluid at a temperature no greater than its saturation temperature, thereby eliminating the possibility of local boiling. Typical thermal control elements and corresponding thermodynamic states are illustrated in Figures 3-1 and 3-2. System operation is discussed below.

As shown in Figures 3-1 and 3-2 liquid is collected from the main storage tank, throttled to a lower pressure and temperature and used to cool the main collection system surface, supports and feed lines as necessary to maintain the collected fluid below its saturation temperature. Supplemental heat exchange is then accomplished with the bulk tank fluid in order to insure that superheated vapor exits the system for maximum overall energy removal. Significant variations in the thermodynamic conditions at states 4, 5 and 6 can occur due to variations in heat transfer caused by changes in external heating or vehicle orientation and the difference in heat transfer coefficients between gas and liquid, either or both of which may be in contact with the cooling system. Thus it is not feasible to assure cooling throughout the flow path

together with a 100% gas exit condition without supplemental heat exchange. The heat exchanger operating between states 6 and 7 is designed such that the outlet (state 7) is always close to the bulk fluid temperature, which is the heat source, over the full range of possible inlet (state 6) conditions.

The basic system of Figure 3-1 shows a flow control device downstream of the final heat exchanger with subsequent discharge to space. An alternate system, where applicable, is to use the discharge from one system to cool another. A typical situation is where both H_2 and O_2 tanks are present and thus the hydrogen may be used to cool the O_2 system. In this case the main flow control would be downstream of the O_2 heat exchanger and the state path would correspond to 8' and 9 of Figure 3-2.

Reference to the fluid state diagram shows that in order to provide any reasonable amount of cooling the vent or cooling fluid must be supplied as a liquid. The basic cooling system design thus incorporates liquid collection channels to provide such liquid. This device is a low flow, low pressure drop surface tension system designed to operate continuously. In this application some vapor formation is allowed within the device resulting in an increase of the initial quality of the cooling fluid with a corresponding loss in cooling capacity. This must be accounted for in the overall design.

The throttling device can be either a fixed restriction or a regulator controlling downstream pressure at state 3. The choice depends on whether a constant or variable cooling flow is desired. This is discussed further in Section 3.1 and the final choice depends on an evaluation of overall heat balances for a particular application.

The thermal control configuration for cooling the main collection system surface is based on a combination of mixing to prevent vaporization and vent fluid cooling. The final determination of the optimum ratio of cooling to mixing is primarily dependent on the location and configuration of the collection device and the availability of cooling fluid. For a liquid collection surface located within the bulk tank fluid the only sources of adverse vaporization are convection heat transfer from a superheated gas and a reduction in pressure or saturation temperature below that of the collected fluid. The existence of superheated gas can be minimized by proper mixing, and analysis has show that only a small amount of cooling is required to prevent evaporation from tank pressur changes that are normally expected. Cooling requirements are thus a maximum in area where good fluid mixing is difficult such as where a collector surface is close to a tank wall. For cases where liquid collection devices are employed which are always in contact with some bulk liquid in the tank, evaporation at the screen surface could be allowed. This assumes the use of a wetting screen such that wicking is sufficient to keep up with any evaporation. In any case, where supports exist between the collection device and the tank walls or the collected liquid is in direct contact with externally heate surfaces, such as the tank or feed line, active cooling of these surfaces would be requir

The detailed placement of the cooling coils and whether they are external or internal to the tank involves detailed design analysis and depends on the particular vehicle and collection configurations involved. This is further discussed in the following sections. A typical overall cooling configuration is shown in Figure 4-9 for a start basket feed system. Figure 4-12 shows a typical LO_2 collection device configuration

which uses hydrogen from the Figure 4-9 system for cooling. In all cases the amount of cooling fluid available is assumed to be limited to the vent flow required to maintain a constant tank pressure under the minimum predicted external tank heating conditions. This prevents a potential drop in tank pressure below the desired minimum. For the case where hydrogen is used to cool an oxygen system the available LO_2 tank cooling is of course limited by hydrogen tank heating. Overall heat balances and the effects on system design are discussed further in Section 3.1.

A summary of the tasks involved in a complete analysis and design of a thermal control system and how these tasks fit in with the overall collection system design is presented in Table 3-1. The performance of these tasks is detailed in the following sections.

3.1 PRELIMINARY DESIGN ANALYSIS

In order to define system feasibility, type(s) of thermal control systems required and a general flow configuration a preliminary design analysis is performed, as described in this section.

Initially the locations and magnitudes, including expected ranges, of all sources of fluid heating are determined. Typical sources of heating which must be accounted for are:

1. Tank wall heating from the external environment; usually of a fairly uniform nature coming from radiation through a protective insulation. Significant variations of heating around the tank should be defined.

2. Local tank wall heating through external insulation penetrations. It is important that internal collection device supports not be located in conjunction with such external penetrations in order to prevent direct conduction of heat from the vehicle external surface to the contained fluid. If this condition must exist, then special cooling provisions need to be provided at these locations.

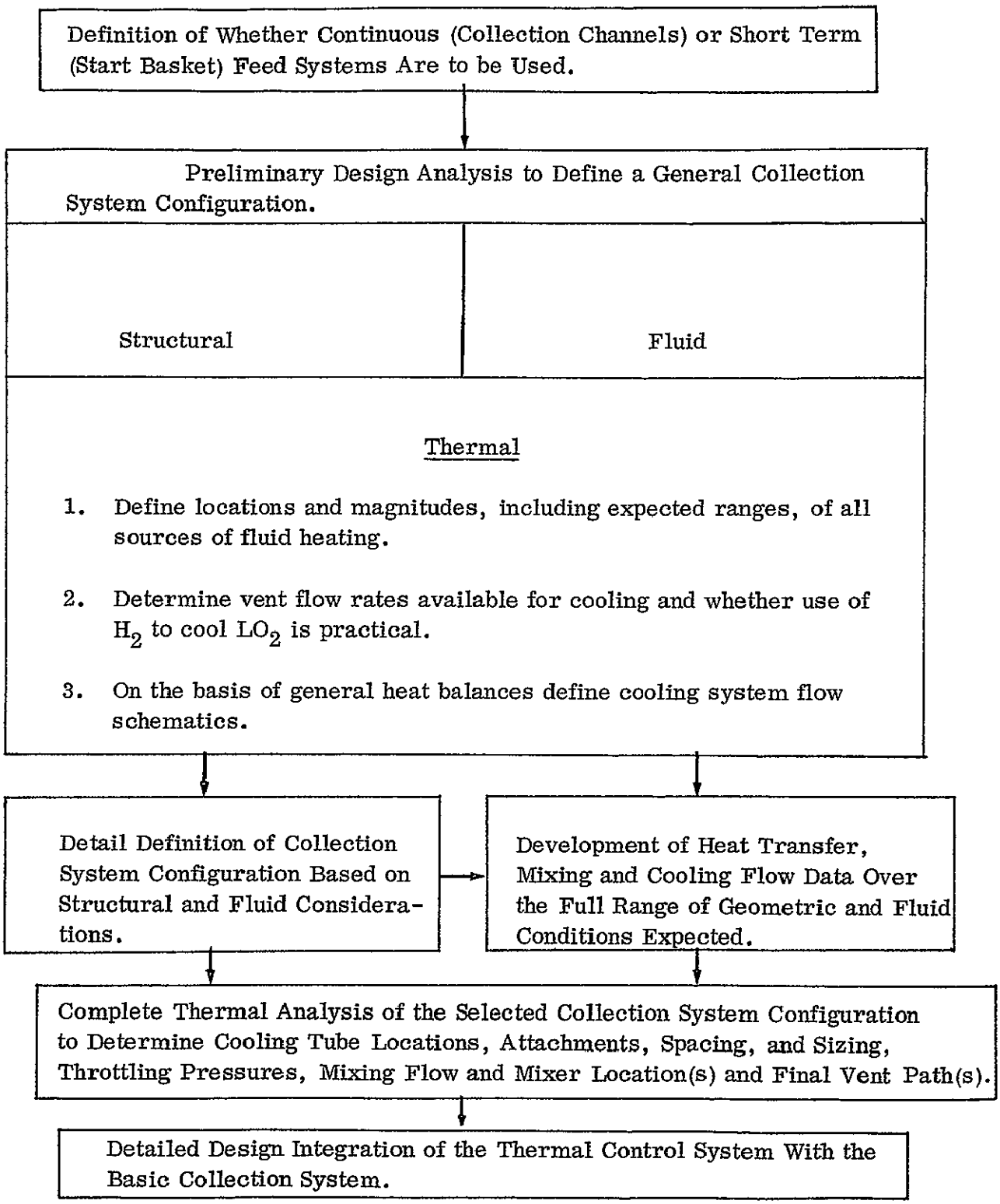
3. Heating from an adjacent propellant such as O_2 heating H_2.

4. Radiation and wall and fluid conduction from the hot end of a fluid line, such as the feed line, which is connected directly into the collected fluid.

5. Heat from internal or external auxiliary power such as an electric motor operating a fluid mixing device.

Potential variations in the above heating rates throughout a mission are primarily due to changes in vehicle orientation and location with respect to the sun and/or other bodies in space. Changes or degradations in the surface emissivities of the vehicle and its insulation can also occur, thus changing the various heat loads. It is also important that any cooling, such as of an H_2 tank by radiation to space, be accounted for, since the net tank heating is required to determine the vent requirements.

Table 3-1. Thermal Control Systems Design and Analysis Tasks



The above data are needed in order to determine realistic locations of the collection devices and the availability of cooling fluid. As mentioned previously the amount of cooling fluid is limited to the vent flow required to maintain a minimum tank pressure under minimum external heating conditions. In this regard, when designing the thermal control system, potential variations in analytical predictions must be considered as well as normal environmental variations. Figure 3-2 of Ref. 3-4 presents vent flow versus energy input data for hydrogen at 25 psi. The applicable equation is presented below.

$$\dot{m}_v = \left.\frac{\dot{Q} + \dot{P}}{h_2 + e\lambda/(1-e) - h_L}\right]_{P_T = \text{Constant}} \tag{3-1}$$

where

$\dot{m}_v$ is the vent flow rate

h_2 is the exit enthalpy

h_L is the tank liquid enthalpy

e is the vapor density/liquid density ratio

λ is the heat of vaporization

$\dot{Q}$ is the heat input rate

$\dot{P}$ is any power input

For a cryogenic fuel-oxidizer system the next step is to determine, based on the heating data obtained, overall energy balances to ascertain if LO_2 (oxidizer) cooling with H_2 (fuel) is practical and to define an overall flow schematic. The two major constraints which must be met in defining the flow configuration are:

1. The availability of cooling fluid, which is limited to the minimum vent requirement.

2. The requirement to maintain all collected fluid at a temperature below saturation.

Purely on the basis of an overall heat balance it is obvious that prevention of vapor formation within a collection device by using the venting fluid is feasible since it is theoretically possible to prevent any heat from entering the tank at constant pressure by a proper balance of vent flow to external heating. Practically, however, difficulty arises in the distribution of the vent cooling to all parts of the tank in proportion to the heat entering. Variations in heat transfer to the tank and cooling fluid and problems in accurate prediction of heat transfer coefficients within the tank fluid due to unknowns such as the fluid state, mixing and acceleration levels add to this difficulty.

Definition of the basic flow configuration includes a determination of the minimum and maximum energy conditions at the state points illustrated in Figures 3-1 and 3-2 as well as flow rates and flow control requirements. Determination of state points and flow rates are based on the energy data and design constraints described above. Definition of flow control requirements is discussed below.

A primary consideration is whether the cooling flow should be constant or variable. In either case it must be continuous in order to prevent vapor formation at any time during the mission. Figures 3-3 and 3-4 illustrate typical variable and constant flow systems respectively. The system shown in Figure 3-4 has a bulk heat exchanger in series with the collection device cooling system. Overall tank pressure control and collection device cooling are accomplished with this single system. In order to provide a continuous flow over the full range of possible heating conditions a modulating or continuous flow regulator would be required at the vent outlet of the bulk exchanger. Also, since the flow rate is now a variable, the throttling device as shown in Figure 3-1 would likely need to be a pressure regulator in order to control the cooling fluid temperature within reasonable limits.

The system shown in Figure 5-2 of Reference 3-4 utilizes a bulk exchanger vent system operating independent of the start basket cooling system to provide final tank pressure control through on-off regulation. The cooling system flow and inlet throttling device can thus be fixed and any difference in vent flow required to control the tank pressure is made up by the bulk unit. This further provides a constant vent flow for cooling of the oxygen tank.

In either case a bypass control system will likely be required for a system using H_2 for O_2 tank cooling, in order to allow for potential variations in the net O_2 tank heating. In this system a continuous hydrogen cooling flow is used at a rate corresponding to that required to cool the LO_2 start basket and maintain a constant LO_2 tank pressure under minimum net tank heating conditions. A by-pass flow control valve is incorporated to divert the remaining H_2 flow from the H_2 tank to either provide additional LO_2 tank cooling or be vented directly overboard. This control is maintained as a function of LO_2 tank pressure, i.e., when the LO_2 tank pressure reaches an upper limit the total hydrogen flow available is used for cooling and the tank pressure will drop until the lower tank pressure limit is reached at which time the minimum cooling flow is used with the remainder bypassing the LO_2 tank. This assumes that the total hydrogen cooling heat sink available is somewhat in excess of the maximum net LO_2 tank heating which can occur, which is of course the primary factor in determining the desirability of using hydrogen to cool a LO_2 tank.

Development of the detailed analytical data required to perform a final thermal control system analysis and design is discussed in the following section.

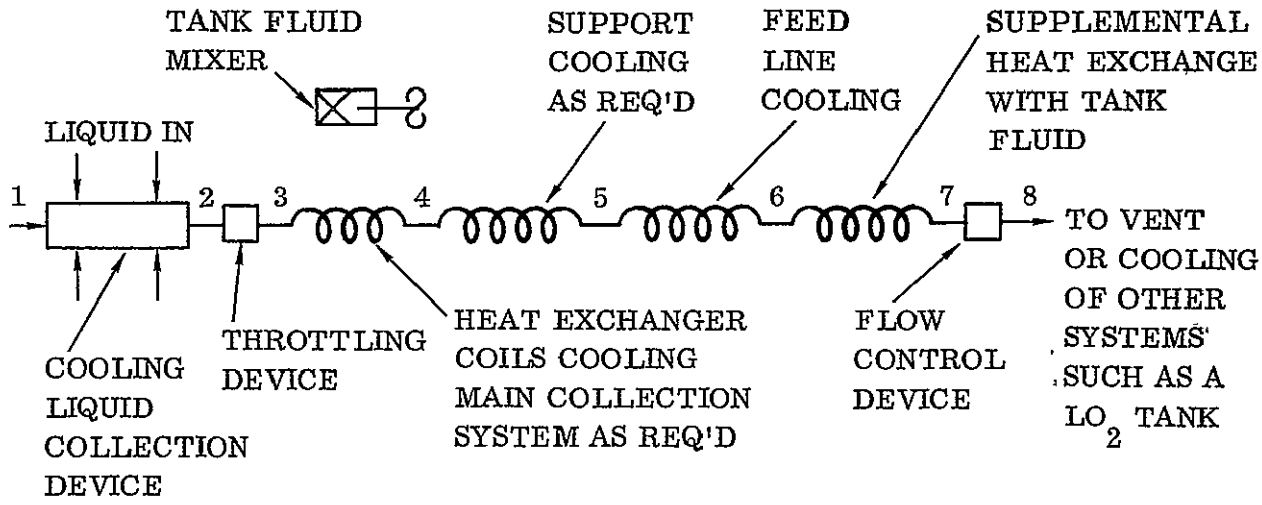


Figure 3-1. Typical Thermal Control Elements

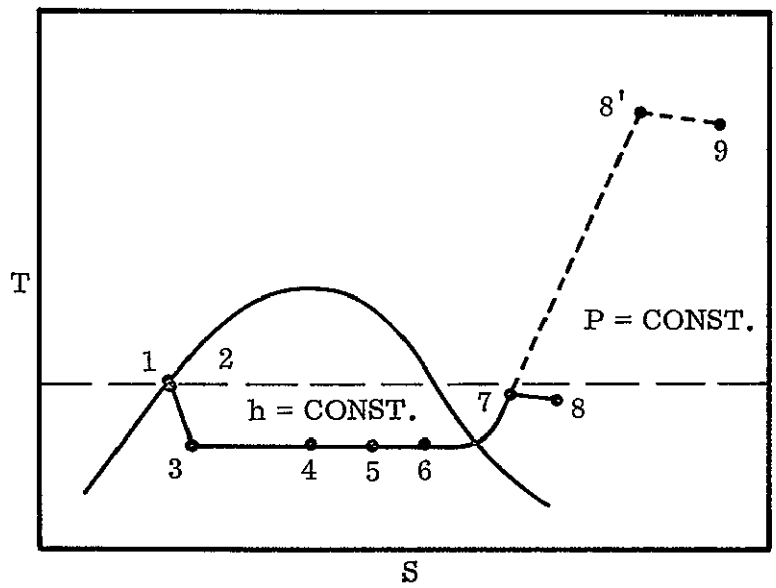


Figure 3-2. Typical Thermal Control State Flow Path

3.2 DEVELOPMENT OF DETAILED ANALYTICAL DATA

The development of applicable mixing, heat transfer and flow data is discussed in this section. Such data should be generated over the full range of expected geometric and fluid conditions, as defined by the preliminary design analysis. An overall flow chart is presented in Table 3-1, showing the relationship of this thermal analysis task to other collection system definition tasks. It is seen that configuration details which depend solely on structural and fluid dynamic considerations will be used as a guide for thermal data development. As an example, screen mesh, material and mounting information are needed in order to determine an expected range of collection surface heat conductances.

Details are presented in the following paragraphs.

3.2.1 MIXING. The basic purpose of mixing the tank fluids is to minimize thermal gradients at the collection device surfaces such that vapor will not be generated within the capillary device in these areas. Mixing also effects the magnitude of the heat transfer coefficients and thus the heat transfer at a surface being actively cooled.

In order to determine heat transfer coefficients and approximate temperature gradients throughout a fluid tank, velocities and mixer induced flow rates must be determined as a function of distance from the mixer. Potential variables which effect mixer operation and over which data should be generated are vehicle acceleration and the state of the fluid being mixed. Also, in order to make final design trade-offs, the above data should be determined as a function of mixer power, size, weight and efficiency. Jet mixing using an axial flow constant speed pump is the primary mixing method considered. With an axial flow pump the volume flow rate is essentially independent of the fluid phase being pumped.

Mixing analyses performed in the present study are based on data generated by the Fort Worth division of General Dynamics under Contract NAS8-20330 (Reference 3-3). Minimum mixing velocities required to provide an essentially homogeneous liquid are based on penetrating the warm layer of liquid at a vapor/liquid interface. This assures low temperature gradients in the capillary device area as well as sufficient mixing to assure adequate tank pressure control. The time to accomplish such mixing must also be considered in order to compare intermittent and continuous mixing schemes. The applicable equations are presented below.

$$(V_o\ D_o)_i = \frac{1}{2}\left\{\frac{\beta\ \Delta T_{max}\ Z_i^3\ a\ P}{\left[1-\left(\frac{V_{max}}{V'_{max}}\right)^2\right]_{(P+1)(P+3)}}\right\}^{1/2} \qquad (3\text{-}1)$$

$$\dot{V}_Z = .456 \frac{\dot{V}_o \, Z}{D_o} \qquad (3\text{-}2)$$

$$A_Z = \pi \, \delta^2 \qquad (3\text{-}3)$$

$$\dot{V}_Z = A_Z \, V_{e_Z} \qquad (3\text{-}4)$$

$$\delta = b \, Z \qquad (3\text{-}5)$$

$$\theta_m = \frac{N_p \, D_t^2}{.456 \, V_o \, D_o} \qquad (3\text{-}6)$$

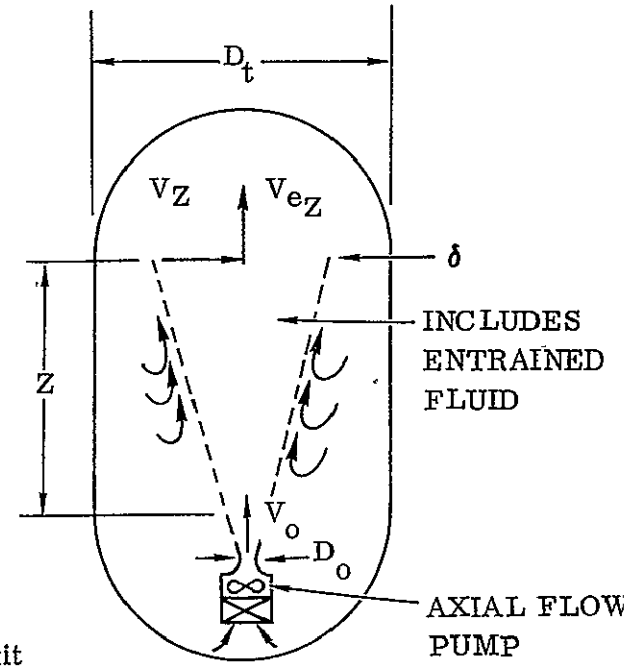


Figure 3-3. Geometric Mixing Parameters

where

V_o = velocity at mixer exit

D_o = diameter of mixer exit

$(V_o D_o)_i$ = velocity-diameter product required to penetrate warm liquid layer at vapor/liquid interface

β = coefficient of volumetric expansion for the liquid

ΔT_{max} = maximum temperature difference between bulk liquid and liquid/vapor interface usually assumed to be 1°F

Z = distance from mixer to liquid/vapor interface

a = local acceleration

P = exponential constant usually taken as 1.0

V_{max} = maximum centerline velocity with a temperature gradient

V'_{max} = maximum centerline velocity without a temperature gradient

V_{max}/V'_{max} is taken to be 0.9

$\dot{V}_Z$ = volume flow rate at the distance Z from the mixer. Includes entrained flow.

$\dot{V}_o$ = volume flow at mixer exit

A_Z = total flow area at the distance Z from the mixer

δ = radius of flow at distance Z from the mixer

b = proportionality factor determining the spreading rate of flow from the mixer taken to be 0.25 for the present case

θ_m = bulk mixing time

N_p = dimensionless mixing time constant approximating 6.0 for present conditions

D_t = tank diameter

The geometric significance of the major variables is illustrated in Figure 3-3. Figure 3-3 indicates conditions as a general function of distance, Z, from the pump outlet. Specific conditions associated with the liquid vapor interface are designated by the subscript i. $(V_o D_o)_i$ is the velocity diameter product at the jet exit which is required to penetrate the warm liquid layer at the vapor/liquid interface. θ_m is the time from pump actuation required to obtain complete mixing.

Combining Equations 3-1 through 3-5 the velocity required to mix at the vapor/liquid interface $(V_Z)_i$ is determined below.

$$(V_Z)_i = \frac{.057}{b^2} \left\{ \frac{\beta \, \Delta T_{max}{}^{P}}{\left[1-\left(\frac{V_{max}}{V'_{max}}\right)\right]^{2}{}^{(p+1)(P+3)}} \right\}^{1/2} a^{1/2} \, Z_i^{1/2} \qquad (3\text{-}7)$$

Based on the general definitions of the above terms, typical interface velocities required for hydrogen mixing are illustrated in Figure 3-5 of Reference 3.4. The data are presented as a function of interface distance and vehicle acceleration level.

A further combination of Equations 3-2 through 3-5 results in fluid velocity as a function of mixer size and flow rate and distance from the mixer, as presented below.

$$V_Z, \; f_{ps} = .465 \, \frac{(\dot{V}_o / D_o, \; \text{cfm/in.})}{(Z, \; \text{ft})} \qquad (3\text{-}8)$$

This allows a determination of velocities and thus heat transfer coefficients at various points in the tank as a function of distance and mixer properties. Typical data are plotted in Figure 3-7 of Reference 3-4 for hydrogen.

When considering intermittent mixer operation the mixing time, as determined by Equation 3-6, is an important parameter. In most applications intermittent mixer operation minimizes total power requirements. However, fairly rapid response is required in order to prevent an adverse amount of temperature stratification buildup during non-operating periods. It is anticipated that in most applications more than one mixer will be required in order to provide a reasonably uniform fluid mixing. In this case, alternate operation of the mixers may be optimum and should be considered. Also temperature sensing devices could be provided to determine when mixer operations

are required. Anticipated liquid/vapor orientations as well as collection device locations will be important factors in determining mixer locations and operating cycles. Such trade-offs must be made for each individual design case using the overall data presented above.

3.2.2 HEAT TRANSFER. This section is concerned with heat transfer to the collected fluid and the thermal control cooling fluid. As discussed in Section 3.1 the two major constraints in defining a suitable thermal control system are the availability of cooling fluid and the requirement to contain all collected fluid at a temperature below saturation.

The basic heat transfer processes affecting the design of such a system and for which data must be generated are heat transfer between the bulk tank fluid and the collection device and/or cooling tubes, heat conduction at the collection device and cooling tubes and heat transfer between the cooling tubes and the cooling fluid.

In general, data for both continuous and point attachment of cooling tubes must be obtained. The applicable equations, derived from the data of Reference 3.5 are presented below. In each case maximum temperatures on the cooled structure, temperatures at attachment points and total heat transfer to the cooling fluid are required. The use of continuous versus point attachment cooling will depend on the particular collection device and tank geometry under consideration as well as the available cooling capacity.

For continuous cooling attachment the equations presented below are used. Geometric representation of the major variables is found in Figure 3-4.

$$\frac{T_X - T_H}{T_C - T_H} = \frac{\cosh\left[N\,(a/2)\left(1 - \frac{x}{a/2}\right)\right]}{\cosh N\,a/2} \tag{3-2}$$

$$T_{(a/2)} = T_H - \frac{\left(T_H - T_C\right)}{\cosh N\,a/2} \tag{3-3}$$

$$\frac{\dot{Q}}{A_b(T_H - T_C)} = \frac{K_w\, t_e\, N \tanh N\,a/2}{a/2} \tag{3-4}$$

$$\frac{T_H - T_C}{T_H - T_M} = \cosh N\,a/2 \tag{3-5}$$

where:

$N = \sqrt{\bar{h}_f/(K_w t_e)}$

$K_w t_e$ = effective conductivity - conduction thickness of the structure to which the cooling coils are attached.

A_b = total surface area of basket

T_c = coolant temperature

a/2 = half the distance between the coils

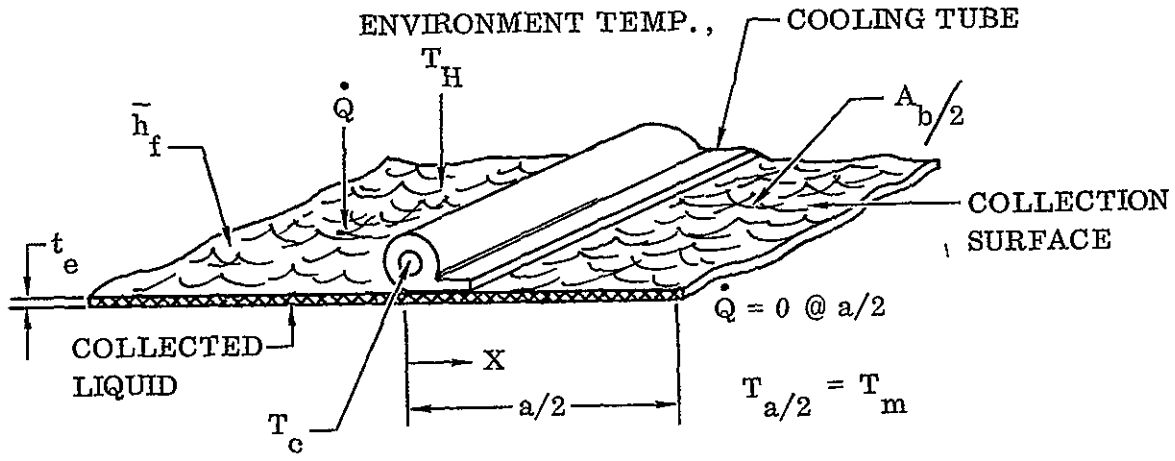


Figure 3-4. Continuous Cooling Configuration

These equations are for steady-state heat transfer where the collected fluid is completely cooled by surrounding coils. In this case the steady-state or equilibrium condition is when there is no net heat transfer out of or into the collected liquid. Therefore, as illustrated in Equations 3-2 through 3-5 and Figure 3-4, only heat transfer from the bulk tank fluid or external environment is included. The equations are generally applicable to feed line cooling and start basket cases where complete surface cooling is to be accomplished. It is further assumed that the heat transfer coefficients between the cooling fluid and the tube surface are high in relation to those external to the collection device. This is normally the case since cooling flow heat transfer is generally by boiling and/or highly turbulent forced convection flow, while the external heat transfer is through a high performance insulation, by natural convection or by only slightly turbulent forced flow such as produced by a mixer.

The temperature at the tube attach point may thus reasonably be taken as the cooling fluid temperature. Heat transfer coefficient data are presented in later discussions in this section. The conductivity of the structure to be cooled is an important parameter, as illustrated by Equation 3-2 thru 3-5. In the case of a solid structure such as a feed line the evaluation of this parameter is straightforward. For screen surfaces, the task is more difficult and equivalent or effective values must be determined. In the present analyses an effective conductivity-conduction thickness, $K_w t_e$, was used. This is based on the actual material conductivity and an equivalent structure thickness equal to the total structure solid volume divided by the structure surface area. Surface supports and stiffeners are included.

From Equation 3-4 data on heat transfer as a function of collection device or feed line surface area, environment and cooling fluid temperature difference, heat transfer coefficient and tube spacing can be generated. This data will be used in the overall tradeoffs to determine final tube spacings and required cooling fluid temperatures. Typical data generated for the S-IVB start basket are presented in Figure 3-18 of Reference 3-4. Feedline data are presented in Figure 3-24 of this same reference

Corresponding data on maximum surface temperatures obtained from Equation 3-5 will also be required. Such typical information is presented in Figure 3-19 of Reference 3-4.

The next type of heat transfer to be considered is that occurring at a point or local support area where no direct cooling of the support itself is involved. A typical application is where liquid collection channels are used to supply the cooling fluid as discussed in Section 3.0. In this case some heat transfer to the collected fluid can be allowed, but the magnitude must be known and accounted for in any overall heat balances. The applicable equation is presented below with definitions of terms found in Figure 3-5.

$$Q_o = (T_n - \zeta)\, 2\pi\, k_w\, \delta\, \epsilon\, r_s\, \frac{K_1(\epsilon r_s)}{K_o(\epsilon r_s)} \qquad (3\text{-}6)$$

where:

$\dot{Q}_o$ = heat transfer at each support assuming the support path between the wall and channel does not restrict the heat flow.

δ = tank wall thickness

$\epsilon = \sqrt{(h_{f_1} + h_{f_2})/k_w\, \delta}$

h_{f_1} = heat transfer coefficient external to the tank wall.

h_{f_2} = heat transfer coefficient between the wall and tank fluid.

r_s = the radius of the channel support at the tank wall.

ζ = wall temperature at an infinite distance from the support = $(h_{f_1} T_{g_1} + h_{f_2} T_{g_2})/(h_{f_1} + h_{f_2})$.

T_{g_1} = temperature external to the insulation.

T_{g_2} = tank fluid temperature.

T_n = temperature at the support, taken to be the same as the tank fluid or collector temperature.

k_w = wall thermal conductivity.

K_1 = first order modified Bessel function.

K_o = zero order modified Bessel function.

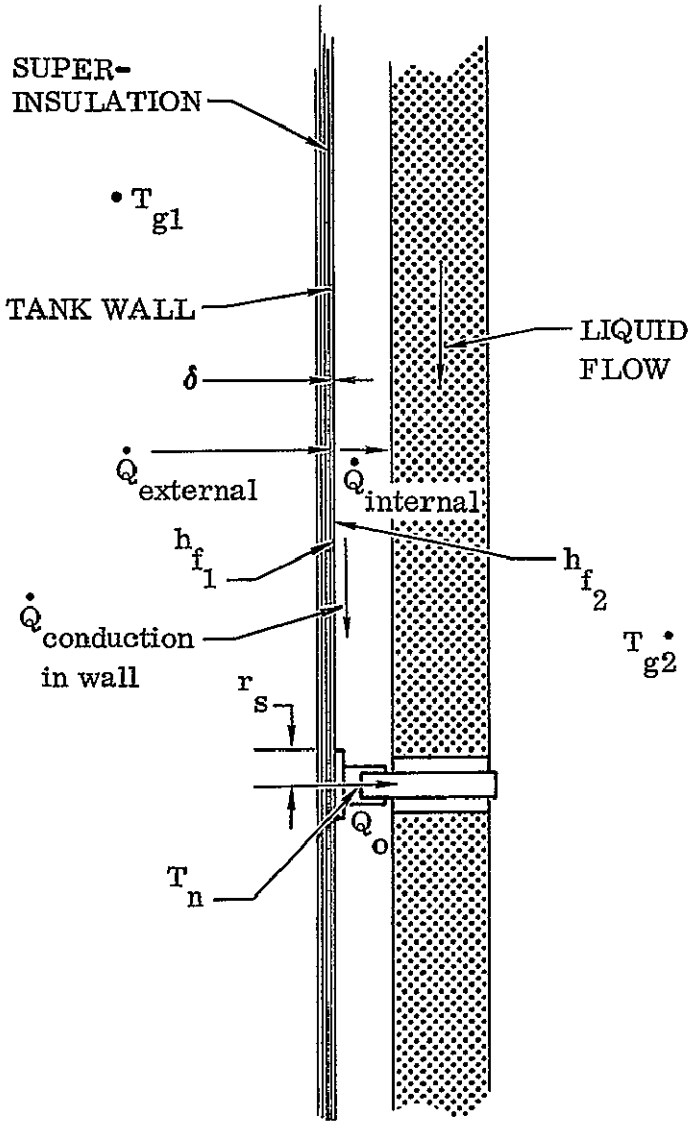


Figure 3-5. Collection Tube Support Heat Transfer

For cases where cooling is accomplished by tubes attached at discrete points rather than continuously the following equations apply. A representation of the nomenclature is found in Figure 3-6.

This type of configuration is useful in limiting cooling of a capillary device region to prevent overcooling with consequent loss of cooling capacity or to eliminate possible freezing due to overcooling as in a LO_2 capillary device cooled by LH_2 boiloff.

$$\dot{Q}_{n_1} = (\zeta - T_n)\, 2\pi k_w \delta_w \epsilon r_s \frac{K_1(\epsilon r_s)}{K_o(\epsilon r_s)} \quad (3\text{-}7$$

$$\dot{Q}_{n_2} = 2L(T_n - T_v)\sqrt{k_{tw}\, \delta_{tw}\, h_{f_1}} + h_{f_i} A_i \quad (3\text{-}8$$

where $\dot{Q}_{n_1}$ = heat transfer rate to the attachment point from the tank fluid taking account of conduction in the tank wall.

$$\zeta = \frac{h_{f_1} T_{g_1} + h_{f_2} T_{g_2}}{h_{f_1} + h_{f_2}}$$

$$\epsilon = \sqrt{(h_{f_1} + h_{f_2})/k_w \delta_w}$$

$\dot{Q}_{n_2}$ = heat transfer rate from the attachment to the cooling fluid

L = tube circumference

A_i = tube area in intimate contact with the tube support

T_v = cooling fluid temperature

h_{f_i} = cooling tube internal heat transfer coefficient

Otherwise the terms are defined the same as for Equation 3-6 with the subscript t here referring to the cooling tube.

Assuming that $Q_{n_1} = Q_{n_2}$ and solving for T_n in Equation 3-8 results in

$$T_n = T_v + \frac{\dot{Q}_n}{2L\sqrt{k_{tw}\,\delta_{tw}\,h_{f_i} + h_{f_i}\,A_i}} \tag{3-9}$$

Substituting into Equation 3-7 and solving for $\dot{Q}_n$,

$$\dot{Q}_{n_1} = \frac{\zeta - T_v}{\dfrac{K_o(\epsilon r_s)}{2\pi k_w \delta_w \epsilon r_s K_1(\epsilon r_s)} + \dfrac{1}{2L\sqrt{k_{tw}\,\delta_{tw}\,h_{f_i} + h_{f_i}\,A_i}}} \tag{3-10}$$

Further, from Equation 3-7 the tank wall temperature (Tr) as a function of radial distance from the support is,

$$T_r = \zeta - \frac{\dot{Q}_n K_o(\epsilon r)}{2\pi k_w \delta_w \epsilon r_s K_1(\epsilon r_s)} \tag{3-11}$$

where $\dot{Q}_n$ is determined from Equation 3-10.

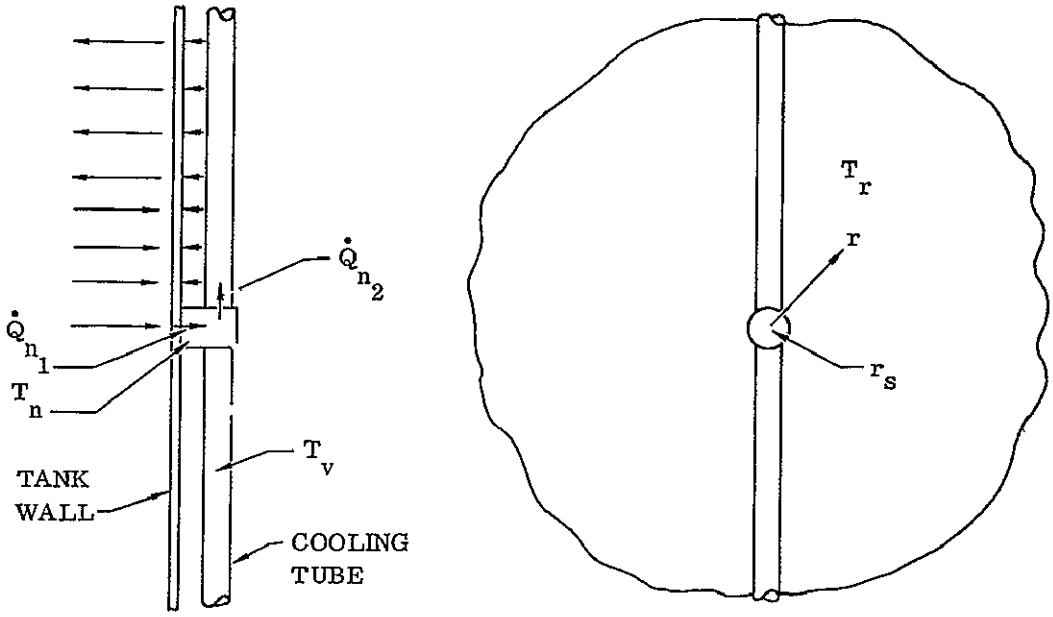


Figure 3-6. Local Cooling Tube Attachment Configuration

In this case, heat transfer coefficients inside the cooling tube and conduction along the tube are taken into account. This is important in the present case because of the small amount of cooling surface which is actually in direct contact with the surface to be cooled and thus the attachment temperature cannot generally be assumed to be equal to the cooling fluid temperature. Also, heat transfer from the collected fluid as well as external heat transfer is accounted for; since typical applications of point cooling do not completely enclose the collected fluid. Heat transfer to surfaces other than those being cooled directly must therefore be removed by the cooling fluid by way of heat transfer from the collected fluid.

From Equation 3-10, heat transfer to the cooling fluid per attachment point can be determined as a function of heat transfer coefficients, temperatures and wall and attachment physical characteristics to be expected. Wall temperatures as a function of radial distance from the cooling point are determined from Equation 3-11. From this data cooling attachment spacing and contact areas can be determined which satisfy the basic temperature and heat transfer constraints as discussed previously.

A major parameter in all of the above heat transfer equations is the fluid to surface heat transfer coefficients. In general, data on boiling, gas and liquid forced convection in tubes, gas and liquid forced convection over large surfaces, gas and liquid natural convection and condensing heat transfer must be determined. Equations used in the present program are illustrated below.

Cooling tube, cold side heat transfer to an initially boiling fluid is computed by considering the process to consist of three phases (x indicates quality - % vapor):

1. Nucleate boiling, $0 \leqq x \leqq 0.90$.

2. Fully developed turbulent flow at constant temperature (saturation) $0.90 < x \leqq 1.0$.

3. Fully developed turbulent gas flow with increasing temperature $T > T_{SAT}$.

Phase 1 calculations are made using the Kutateladze correlations as reported in Reference 3-6.

Turbulent gas flow heat transfer is calculated from Reynold Analogy (Ref. 3-7) where,

$$\bar{h}_{f_i} = \frac{f}{2} \rho V_e C_{p_f} = \frac{f}{2} \frac{\dot{m}}{A} C_{p_f} \tag{3-12}$$

For bulk fluid heat transfer the following equations from Reference 3-8 were used.

Forced Convection, Laminar Flow $Re_x \leqq 5 \times 10^5$

$$\bar{h}_f = .664 \, (Pr)^{1/3} (Re_X)^{1/2} \left(\frac{K}{X}\right) \tag{3-13}$$

Natural Convection, Laminar Flow $Gr_X < 10^9$

$$\bar{h}_f = \frac{.677 \, Pr^{1/2} (Gr_X)^{1/4}}{(.952 + Pr)^{1/4}} \left(\frac{K}{X}\right) \tag{3-14}$$

Condensation, Laminar Flow

$$\bar{h}_f = \left(\frac{4}{3}\right) (N_{SH})^{1/4} \left(\frac{K}{X}\right) \tag{3-15}$$

where:

$\bar{h}_f$ = average film heat transfer coefficient

X = length from start of temperature boundary layer at a flat plate

$Re_X = (\rho V_X)/\mu$

$$Gr_X = \frac{g \beta \Delta T X^3 \rho^2}{\mu^2}$$

$$P_r = \frac{C_p \mu}{K}$$

$$N_{SH} = \frac{g \rho_L^2 \lambda X^3}{4 \mu_L K_L (T_s - T_w)} = \text{Sherwood Number}$$

ΔT = temperature difference between bulk fluid and heated or heating surface

T_s = saturation temperature

T_w = wall temperature

Typical parametric data generated for the S-IVC design application are presented in Figures 3-10 through 3-17 of Reference 3-4. It is seen that, in general, condensing heat transfer represents the maximum to be expected for a given temperature difference between the bulk tank fluid and the collection or cooling surface. It is noted, however, that such heat transfer can never raise the surface above the saturation temperature since condensation goes to zero as the saturation temperature is approached. The main consideration of condensing heat transfer is in determining the maximum heat transfer to be expected into the cooling fluid. From comparisons of Equations 3-13 and 3-15 allowable mixing velocities can be determined such that condensing heat transfer is still the limiting case. If velocities must be greater, then resulting higher heat transfer rates must be taken into account in defining final overall heat balances.

Heat transfer from superheated vapor is the only bulk fluid heat transfer which can cause vaporization of the collected fluid. Therefore, cooling requirements for maintaining surface temperatures below saturation must be predicated on this limiting condition. Tank areas where significant amounts of superheat can exist must therefore be defined and corresponding cooling requirements established.

3.2.3 COOLING FLOW DATA. In order to define a complete thermal control system, cooling flow pressure drop and thermodynamic fluid properties data must be obtained. This allows a final sizing of the cooling coils in conjunction with the various heat transfer design requirements. Development of such data is discussed in this section.

Two phase flow pressure drop calculations are made using the methods and data presented in Reference 3-6. From Reference 3-6 the two phase flow pressure drop (ΔP_{TPF}) is taken as

$$\Delta P_{TPF} = \Delta P_V (\Phi_{vtt})^2 \qquad (3\text{-}16)$$

where,

ΔP_V = single component frictional pressure drop assuming only the vapor faction is flowing.

Φ_{vtt} = function obtained experimentally.

Substituting for ΔP_v where,

$$\Delta P_v = \frac{fL}{D} \rho_v \frac{V_v^2}{2g} \tag{3-17}$$

and since $\dot{m}_v = \rho_v A V_v$

and

$$\dot{m}_v = X_{avg} \dot{m}_T$$

$$\Delta P_{TPF} = \frac{fL}{D} \frac{\rho_v X_{avg}^2 \dot{m}_T^2}{2g_c \rho_v^2 A^2} \tag{3-18}$$

where X is the quality, $\dot{m}_v$ is the vapor mass flow rate, V_V is the vapor velocity. Substituting $A = \pi D^2/4$ into Equation 3-19 and simplifying.

$$\Delta P_{TPF} = \frac{fL}{D^5}\left(\frac{16}{\pi^2 2g_c}\right)\left(\frac{1}{\rho_v}\right) X_{avg}^2 \dot{m}_T^2 \left(\Phi_{vtt}\right)^2 \tag{3-19}$$

Putting Equation 3-20 in a convenient parametric form results in

$$\frac{\Delta P_{TPF},\ PSI}{\left[L,\ in./(D,\ in)^5\right]\left(\dot{m}_T,\ lb/Hr\right)^2} = \frac{4.2 \times 10^{-9}\left(X_{avg}\right)^2\left(\Phi_{vtt}\right)^2}{\left(\rho_v,\ lb/ft^3\right)} \tag{3-20}$$

Data obtained from the above equation for hydrogen are plotted in Figure 3-20 of Ref. 3- as a function of vent pressure for several exit qualities. The average quality is an arithmetic average of inlet and outlet quality. Values of Φ_{vtt} are found from data presented in Reference 3-6.

In order to determine the quality at various points in the cooling system as a function of energy absorbed, enthalpy values are presented in Figure 3-7 for H_2 for various vent pressures. These data are used in the detailed heat balances and cooling system analyses described in the following section.

3.3 DEFINITION OF DETAILED THERMAL CONTROL CONFIGURATION

Using the analytical methods and parametric data generated in the previous analyses a detailed thermal control configuration will be defined. This section presents a step by step procedure for such a design definition. Under this task the following information will be obtained:

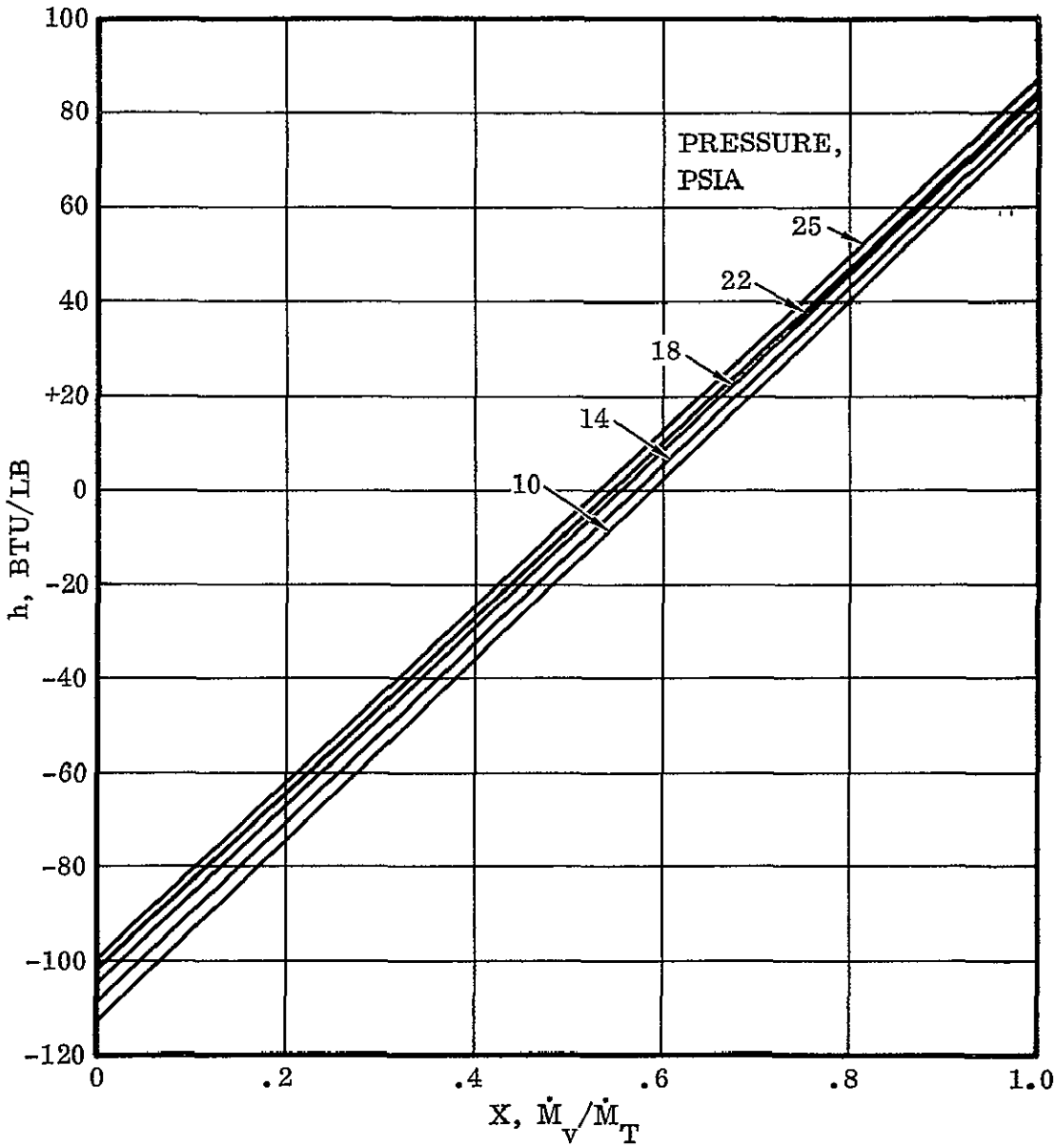


Figure 3-7. Hydrogen Enthalpy Vs Quality

1. Cooling tube locations. The major choices are between locations inside and outside the tank and whether or not local cooling of supports is required.

2. Types of cooling tube attachments, such as continuous versus point.

3. Spacing of cooling tubes and/or cooling tube attachment points.

4. Cooling tube sizing as to lengths and diameters.

5. Throttling pressures or cooling fluid temperatures and pressures.

6. Mixer locations within the bulk tank fluid.

7. Mixer sizing as to flow rates and velocities.

8. Complete flow paths including by-pass flow requirements and the resolution of parallel versus series flow for certain cooling areas.

It is noted that prior to performing the detailed configuration analysis outlined below general system flow schematics and fluid cooling requirements, as illustrated by Figures 3-1 and 3-2 and discussed in Section 3.1, have been defined. Furthermore, all potential heat sources have been determined as well as a detailed collection device configuration based on structural and fluid dynamic considerations.

The first step is to determine the likely cooling tube locations and what type of mixing would be desirable. The main considerations are whether start basket or collection channel systems are involved and whether the collected fluid is in direct contact with a potentially warm wall or the bulk tank fluid. The detailed analysis outlined below is divided into that to be performed on compact capillary devices and collection channels with cooling coils located either inside the tank or outside the tank. Feed line cooling is also considered.

Compact Capillary Device - Internal Cooling Coils

A typical configuration to be analyzed is shown in Figure 4-2. The step by step analysis is presented below.

1. Determine the maximum heat transfer which can exist between any superheated gas and the basket surface. This is a combination of the maximum heat transfer coefficient and superheated gas temperature which can be expected. For the present case this is estimated from a consideration of wall to fluid heat transfer and fluid mixing which can reasonably be accomplished. Mixing and heat transfer data discussed in Sections 3.2.1 and 3.2.2 respectively are used. As an example, for the configuration of Figure 4-2 it is estimated that the critical area will be between the common bulkhead and the start basket surface since mixing would be

somewhat difficult in this area unless a mixer were to be employed primarily for mixing only in this local area.

It is noted that for the internally located coils continuously attached cooling coils surrounding the basket would be the first configuration to be considered. Equations 3-4 and 3-5 would therefore apply to the heat transfer analyses. This allows direct cooling protection of the collected fluid with only nominal reliance on mixing to minimize temperature stratification.

2. Assume a value for cooling fluid temperature or throttling pressure and calculate a value for $(T_H - T_C)/(T_H - T_m)$ where T_m is the maximum allowable temperature at the start basket, taken as the saturation temperature at the minimum tank pressure expected. T_H is of course the maximum superheated gas temperature determined in step 1 above.

3. From Equation 3-5 find the tube spacing required to meet the above conditions.

4. Steps 1 thru 3 are then repeated for each basket surface and an overall tube spacing determined.

5. For the spacing determined above calculate the total heat transfer which may occur between the tank fluid and the cooling fluid under maximum heat transfer conditions. In general this will be for condensing heat transfer as defined by Equation 3-15, however, this will need to be verified for each particular case by comparisons with data obtained from Equations 3-13 and 3-14.

6. Determine the required cooling flow rate from a fluid energy balance. The primary limitation is that the cooling fluid exit the basket cooling area with no greater energy than that corresponding to saturated liquid at the cooling fluid pressure. Allowance must also be made for any energy pickups in the cooling liquid collection device and any additional cooling requirements such as that of a feed line. Fluid energy data as a function of saturation pressure and quality is discussed in Section 3.2.3.

7. Check that the cooling flow required above is not greater than the vent rate required to control the tank pressure to the minimum allowable value under minimum external tank heating conditions. If the required cooling flow is higher than the minimum vent rate the cooling temperature or throttling pressure must be increased and steps 2 thru 7 repeated. If the cooling flow is significantly less than the minimum vent rate the cooling temperature or throttling pressure should be decreased and steps 2 through 7 repeated. It is recommended that some margin of safety be provided such that the final cooling flow is somewhat less than the minimum vent flow. There is, of course, a limitation on the range of throttling pressures which can be allowed. The lower limit is controlled by minimum back pressures which present potential fluid freezing problems. The upper limit is controlled by the tank supply pressure and reasonable throttling pressure control tolerances.

8. If the required cooling flow cannot be brought to a value lower than the minimum vent rate based on the initial conditions determined in step 1 then increased mixing must be postulated and steps 1 thru 7 and possibly 8 repeated.

9. If the above analysis does not result in a satisfactory solution to the problem then use of cooling tubes attached at discrete points rather than continuously and cooling only the support points at locations external to the tank must be considered. In the latter case, good fluid mixing must be accomplished to ensure minimum temperature gradients at the basket surfaces where direct cooling is not accomplished. Discrete point cooling is described by Equations 3-7 thru 3-11.

10. The tube size is now estimated and the overall pressure drop calculated. The methods of Section 3.2.3 are used. An iteration on tube size is made until pressure drop requirements are met. In order to minimize pressure drop parallel flow arrangements can be considered. In the case of two phase flow, however, a significant distribution problem can exist. As an example, for saturated liquid hydrogen throttling from 25 psia to 16 psia the vapor to liquid volume ratio was found to be 1.89. This would result in the potential of starving certain cooling passages with all gas and thus providing insufficient cooling in these areas. Therefore a series flow arrangement is generally recommended where two phase fluid is involved. Each case must of course be analyzed individually.

Feed Line Cooling

A typical feed line cooling application is illustrated in Figure 3-23 of Ref. 3-4. In general, Equations 3-4 and 3-5 are applicable to the analysis and the procedure is basically as described for the start basket case. In the feed line case external heat transfer is likely through some type of high performance insulation. The main consideration here which requires design ingenuity is the cooling of the areas at the end of the line which see direct heat conduction from hot engine surfaces. Also, areas such as an exposed elbow which receive direct radiation from such hot surfaces must be adequately protected. The screen shown in Figure 3-23 of Ref. 3-4 is utilized to isolate the liquid from the engine with the area at the screen and slightly downstream cooled sufficiently to prevent vaporization in the line upstream of the screen.

Compact Start Basket-External Cooling Coils

Again the analytical procedure is basically the same as described for the internal start basket case, except that cooling at the wall, where the collected liquid is located, is now a specific requirement. Trade-offs still exist between temperature control of basket surfaces internal to the tank directly by cooling or by significant mixing and indirect cooling. A typical configuration with external cooling only is shown in Figure 4-12.

Collector Channel Cooling - (Large Surface Area Cooling)

The main difference between this type of capillary device and those previously discussed is that wicking takes place such that evaporation at the channel surface may not cause vapor generation within the channel.

The actual contribution of wicking to the prevention of internal channel vapor generation must be evaluated for each individual case; i.e., the rate of wicking must be such as to keep the channel surface covered with liquid over the range of bulk fluid to channel heat transfer rates to be expected. Wicking data required for such an evaluation are presented in Section 2.4. One factor is that areas significantly removed from the bulk liquid source wick at a fairly low rate and thus mixing will also likely be required in order to minimize temperature gradients at the channel surfaces. Therefore, local cooling of the channel supports is a likely cooling method. A trade-off exists between cooling at the supports internal to the tank and cooling external to the tank. Where a significant number of supports are distributed throughout the tank and cooling capacity is limited external cooling is generally recommended. It is harder to control the total heat load to cooling tubes located in the tank where various fluid conditions can exist than it is for those external to the tank where a uniform high performance (low heat leak) insulation is employed. Also, due to the widely distributed cooling areas, it may be desirable to use a number of individual fixed flow throttling devices and corresponding cooling loops. These cooling loops would be located and designed to minimize the total cooling tube routing lengths in order to minimize total extraneous heat transfer to the cooling fluid. Each system requirement must be analyzed on an individual basis. The main limitation is on the minimum reasonable size of the restriction. This restricts individual flow rate to a certain minimum and in conjunction with the total vent limitation thus limits the number of restrictions or cooling loops. A typical system is illustrated in Figure 5-49 of Reference 3-4.

General Design Considerations

It is noted that where a fluid such as hydrogen is used to cool another fluid such as oxygen certain special design considerations are involved. As an example, when determining cooling tube spacing and attachment conditions the temperature of the coolin fluid will generally be changing from point to point, since the hydrogen cooling fluid will likely be in gaseous form. The design procedure is basically as described previously except a point by point analysis will need to be made and a uniform tube attachment spacing may not be optimum. Another consideration is the potential freezing of the oxygen by the cold hydrogen. Any proposed cooling system design must be analyzed for this possibility and adjusted as necessary to prevent any LO_2 freezing. Also, external cooling would be desirable where possible in order to minimize any potential hazards associated with possible mixing of the hydrogen and oxygen fluids. Use of the design philosophies and analytical procedures outlined in this design manual, plus free reference to the analyses described in Reference 3-4 should result in the generation of optimum thermal control systems for any particular application.

Following the system definitions as described throughout the present section, it is further recommended that a thermal network be set-up for the final system configuration, especially where indirect cooling is involved, to verify satisfactory temperature control under transient tank pressure changes. A typical analysis is described in Section 3.1.8 of Reference 3-4. This analysis showed that where potential tank pressure change rates are low only a small amount of cooling is required to maintain internal tank surfaces below saturation assuming complete mixing is accomplished.

4

STRUCTURAL AND MANUFACTURING CONSIDERATIONS

The success of capillary propellant retention devices is related to structural design and manufacturing. Design of the device, in many ways, is uniquely dependent upon mission requirements and will utilize special procedures in many areas. The purpose of this section is to outline design approaches, identify the problem areas, outline solutions, and make recommendations for future activities. The areas considered are:

Loads
Materials
Screen Attachments
Heat Exchanger Attachments
Configurations for Minimum Weight and Area
Design Approach
Screen Clogging

Loads:

Fluid impingement, pressure gradients due to flow, vibration, acceleration, and deflections between support points are factors affecting loading conditions. The restraints imposed by fluid dynamics and vehicle tank geometry generally dictate the use of flat surfaces and large radius profiles which in turn require an extensive stiffener system. Back up support systems may be required for screen elements used in high load areas. Flat surfaces should be avoided. A change in the screen absolute micron rating when exposed to major loads is a possible problem area which can be minimized by proper spacing of screen attachments and supports.

Material:

Applicable structural materials include honeycomb, waffle, monocoque, and skin stringer frame materials. These can be further expanded with the use of diffusion bonding (using filaments) coupled with several material combinations within a single assembly. The use of a skin stringer frame, for example, using 2219 aluminum alloy may be applicable in several cases due to simplicity and versatility. Compatibility with the propellant, strength characteristics, fabricability, repairability and thermal conductivity are factors that should be considered when selecting a material. Problems associated with sealing and venting closed compartments may be encountered with closed cell type structures such as honeycombs.

Screen Attachments:

The preservation of the reservoir absolute micron rating during fabrication, assembly and under various load environments affect attachment methods. Butt welding, mechanical fasteners, brazing, soldering, and seam welding are some possible approaches. Seam welding using back up strips appears attractive due to simplicity. A shift in micron rating at the attachment zones may be encountered with some fastening techniques.

Heat Exchanger Attachments:

Heat transfer path, structural integrity, relation to the overall structural system, repairability and inspection are the prime factors influencing heat exchanger attachments. Methods involving brazing, soldering, mechanical, and welding are available. A tube equipped with a web which in turn is seam welded to the supporting structure or screen appears promising . Problems relating to base material property changes, heat transfer path, and inspection may be encountered for some applications using mechanical, brazing and soldering.

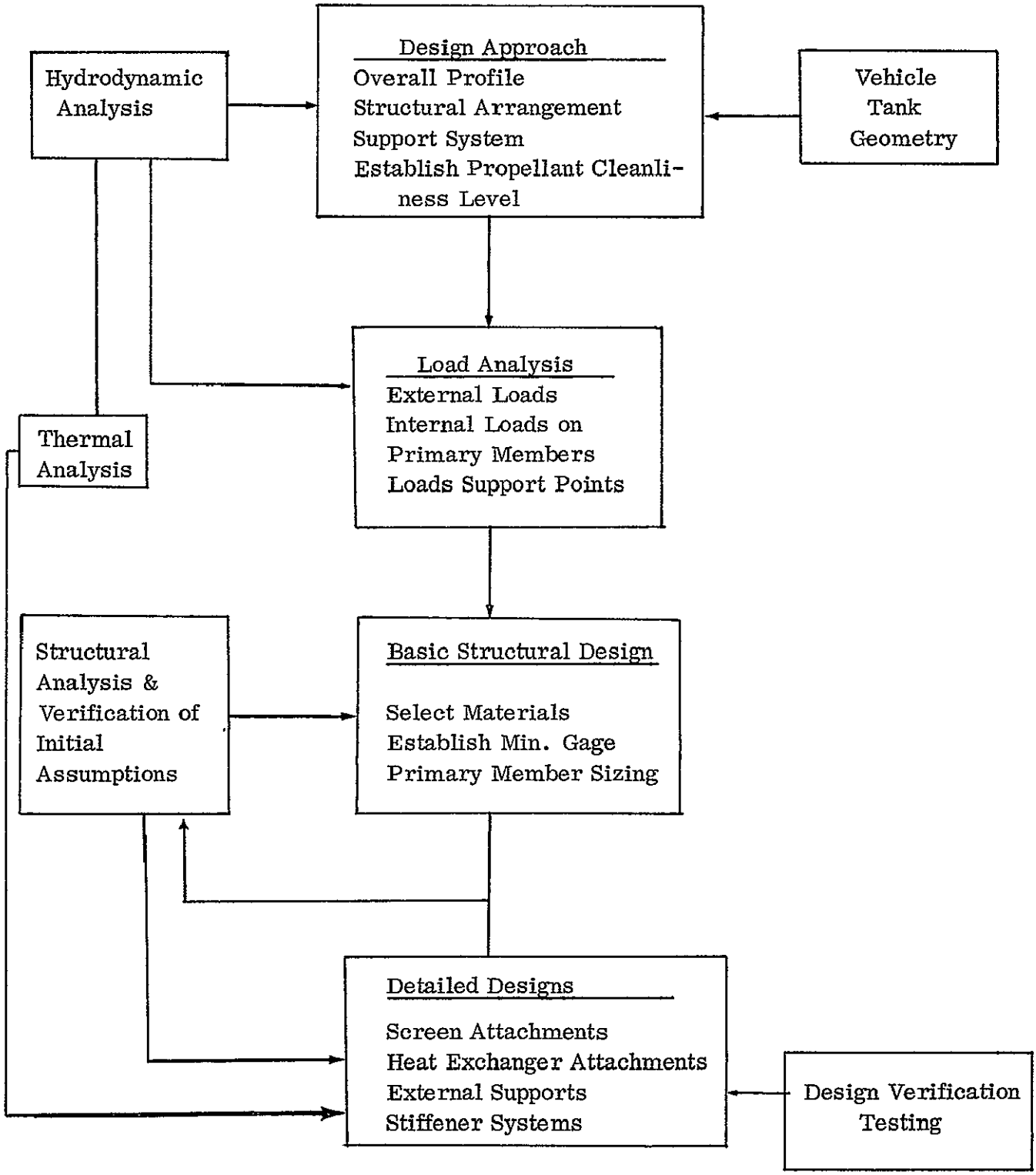
Configurations for Minimum Weight:

Surface areas and weights are basically controlled by the degree of restraint imposed by the vehicle tank profiles and the fluid dynamics. For example an appreciable difference of weight per unit volume exists when comparing a cylindrical type reservoir with an annulus type unit. However, hydrodynamics may dictate use of an annulus rather than a lower weight cylindrical configuration. Some additional influences are expected from the internal structural arrangement and material selection. The avoidance of flat surfaces and the use of profiles which offer stability when exposed to loads is recommended.

Design Approach:

The type of structural approach and component arrangement influences the weights, check out, inspection, cleaning and fabrication. The ability to check out is especially important when considering a unit which is assembled inside a vehicle tank. Where possible use symmetrical structural members, provide access to blind compartments, avoid varying surfaces and arrange the components such that simple fabrication and inspection procedures can be used. Combinations may develop where the optimum structural configuration is incompatible with performance parameters. This latter combination of events can frequently be solved by reviewing the specifications of the conflicting areas, adjusting those items which are not detrimental to performance and revising the design to meet the adjustments.

Table 4-1. Design Activity Flow Chart



Screen Clogging:

Particle collection on screened surfaces may influence the hydraulic performance and impose burdens upon other systems. A typical example for the latter is a gas liquid interface screen installed in a feed duct. Filling and draining operations thru screen assemblies should be avoided in those cases where a potential for high particle population release into other circuits is present. Requirements for standard cleaning procedures should be compared with the reservoir micron rating, and the designs, including the specifications, adjusted until the related areas are compatible.

Design:

A complete design of a capillary device will require trade offs between hydrodynamic analysis, thermal analysis, structural analysis, verification testing, and component details. A diagram showing the flow of events is shown in Table 4-1. A typical design program is initiated by using inputs from the fluid and thermal analysis, and vehicle tank areas to establish an approach. This first level of activity outlines the overall profiles, structural arrangements, basic support systems and establishes the level of propellant cleanliness. The second phase identifies the external loads, internal forces on primary structural members, and reactions at the support points by using outputs from the design approach and hydrodynamic sections. The basic structural layout consisting of primary member sizing, material selection and the selection of minimum gages is performed in phase three using load analysis data and inputs from a structural analysis section. A feed back of activities occurs between the outputs of phase three and the structural analysis section for verification of initial design assumptions. The final phase of the program consists of detailed component designs involving screen attachments, heat exchangers, external supports and stiffener systems. The detailed design level is supported by the structural and thermal analysis and design verification testing.

4.1 STRUCTURAL, FABRICATION & MFG. CONSIDERATIONS (Propellant Retention Devices)

Loads:

Propellant retention devices are subject to external and internal loading conditions due to fluid impingement; fluid flow pressure gradients; static heads; vibrational modes, and deflections between interfaces. Attention must also be given to combinations of the above and the affects upon the capillary screen micron rating which in turn influence the hydraulic characteristics of the system.

Under a zero gravity environment, the propellant mass (outside the reservoir) may be remotely located from the screen assembly and in the presence of an acceleration field, the mass may move aft impinging upon the capillary device structure which in turn causes external loads. The direction of these dynamic forces can be normal or

oblique to the surfaces depending upon capillary device shapes and the propellant slosh modes. Since the loads are applied externally, the structural analysis must consider general and local instabilities including factors for sudden force application. The influence of external loading varies between configurations and in some cases can be minimized with relatively small changes to the basic configuration. A cylindrical assembly with a flat diaphragm type forward head for example is more forgiving on the cylindrical portion than on the flat section. If the diaphragm is replaced with a spherical or elliptical bulkhead, the loads on the ring at the perimeter are reduced and the general stability improved (usually without a weight penalty). Some cases, however, cannot be readily changed such as rectangular shaped collector channels (Figure 4-1) and annulus type assemblies with large surface radii and flat sections (see Figure 4-2). Frequently the type of surfaces for these latter configurations are controlled by the hydraulic requirements and therefore a system of stiffeners or waffle types must be employed to resist the external loads within reasonable deflection limits.

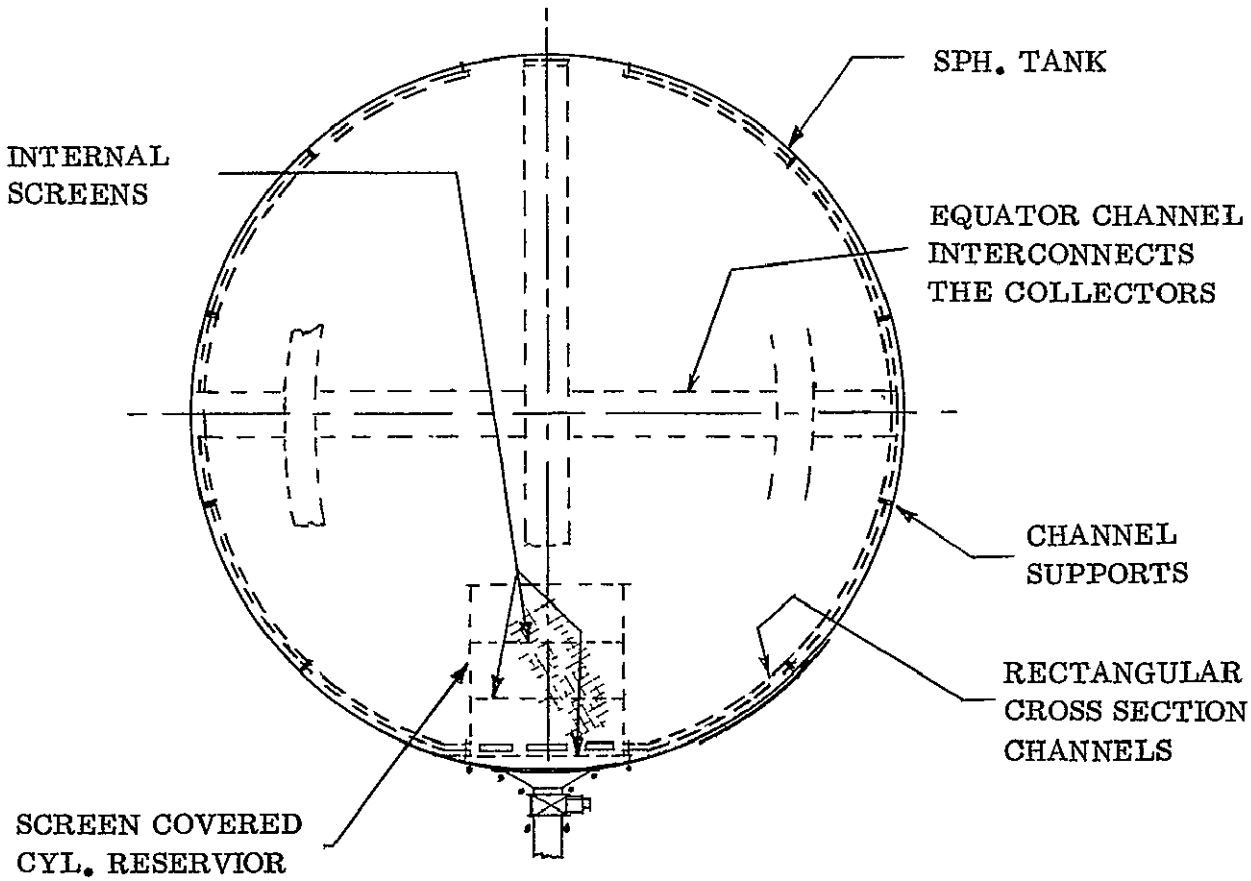


Figure 4-1. Channel Type Collector System

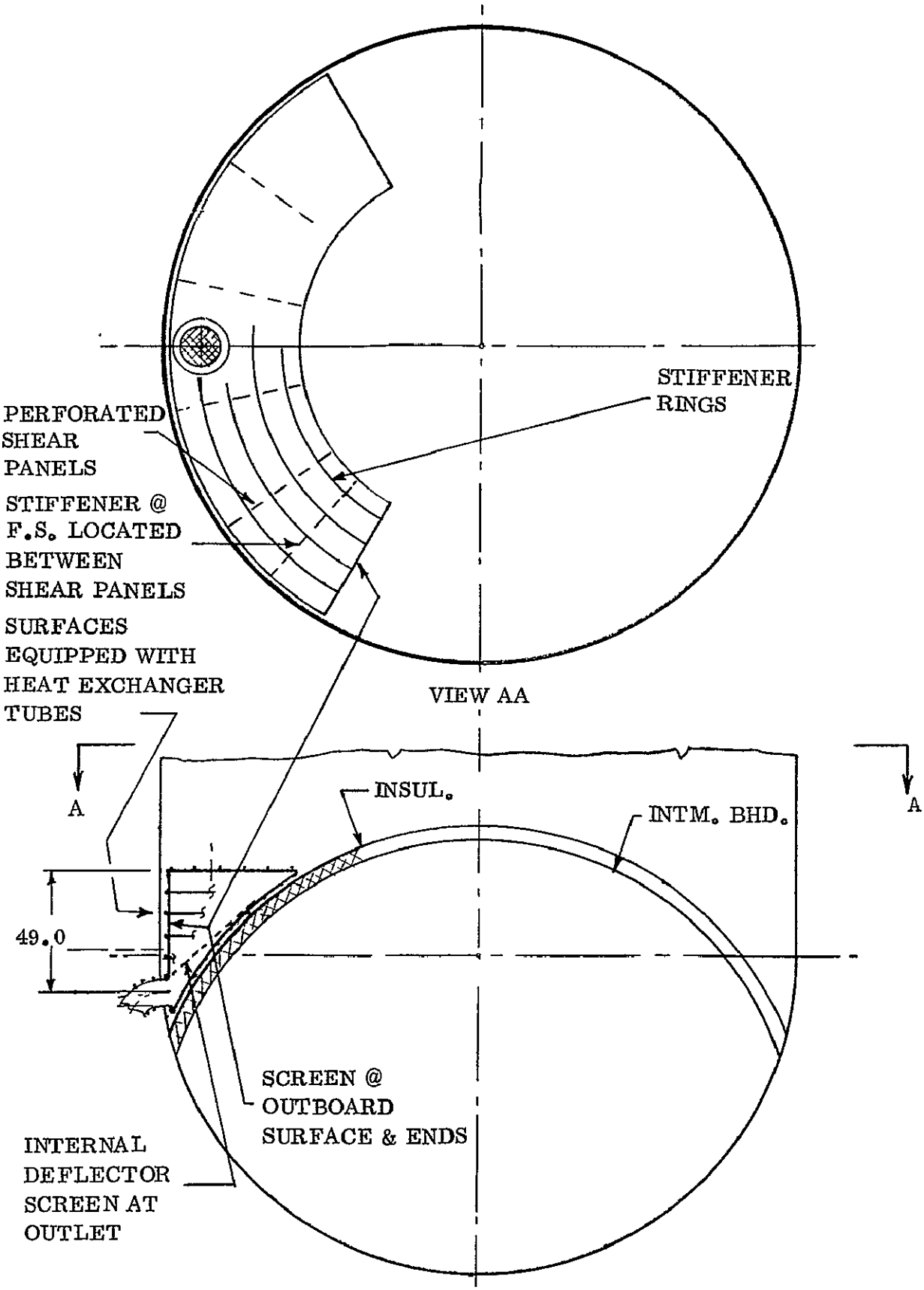


Figure 4-2. Annulus Type Reservoir

The load analysis must also include the contributions of pressure gradients across the screens during flow periods which in turn can be additive to the above impingement conditions. The magnitude of these pressure drops are outlined in the fluid analysis section of this report.

For some arrangements, a large portion of the capillary device surface area is equipped with capillary screens which are exposed to the loading behavior previously outlined. For flat surfaces, high interval stresses can develop causing a displacement between the warp and shute directions which in turn may alter the absolute micron rating. If the wire cloth is cylindrical or spherical shaped, buckling may occur causing a change in fluid retention qualities, therefore the unsupported area of a screen element should be limited or a continuous back up method employed. The use of a perforated sheet metal back up skin or a support mesh appears attractive when considering a minimum number of attachment joints (see Figures 4-3 and 4-4). For most applications the structural contribution of the screen is negligible. For cases involving large diaphragms, deflection of the back up members may be sufficiently large to affect the wire cloth, therefore special attention is required in the attachment details to allow the screen to deflect with the perforated member without degradation of the micron rating (see Figure 4-5). Future investigations are recommended to determine the sensitivity of the screen micron rating to loads.

During outflow or tanking operations, static heads can develop which may load the screen members externally or internally. These conditions must be included in the overall load analysis.

In many cases the hydraulic parameters and the storage tank configurations require reservoir surfaces which have flat or large radius profiles. These surfaces are sensitive to certain vibrational modes and must be considered in the load histories. The use of stiffener networks, the reduction of ring spacings, a change in minimum gage or some combination of these can be employed.

When external loads are applied to a capillary device, the resultant forces are reacted thru the supports which in turn are attached to the tank wall. Deflections occur at the interfaces due to tank wall breathing (pressurization and temperature gradients) and load reactions. These are locally applied loads which can produce internal stresses on the reservoir assembly above those expected from normal loading. An annulus unit for example has several support interfaces which must accommodate the external loads while compensating for radial deflections, tangential movements, and misalignments (see Figure 4-6). Special attention must also be given to propellant outlets to avoid the distribution of major loads thru sealed connections.

Some systems (such as the S-IVC annulus fuel unit) are equipped with heat exchanger collector tubes which originate near the reservoir and route to the forward end of the tank (see Figure 4-7). A typical assembly is a perforated tube covered with capillary screen, and incorporating fittings for mounting to the tank wall. The sections between

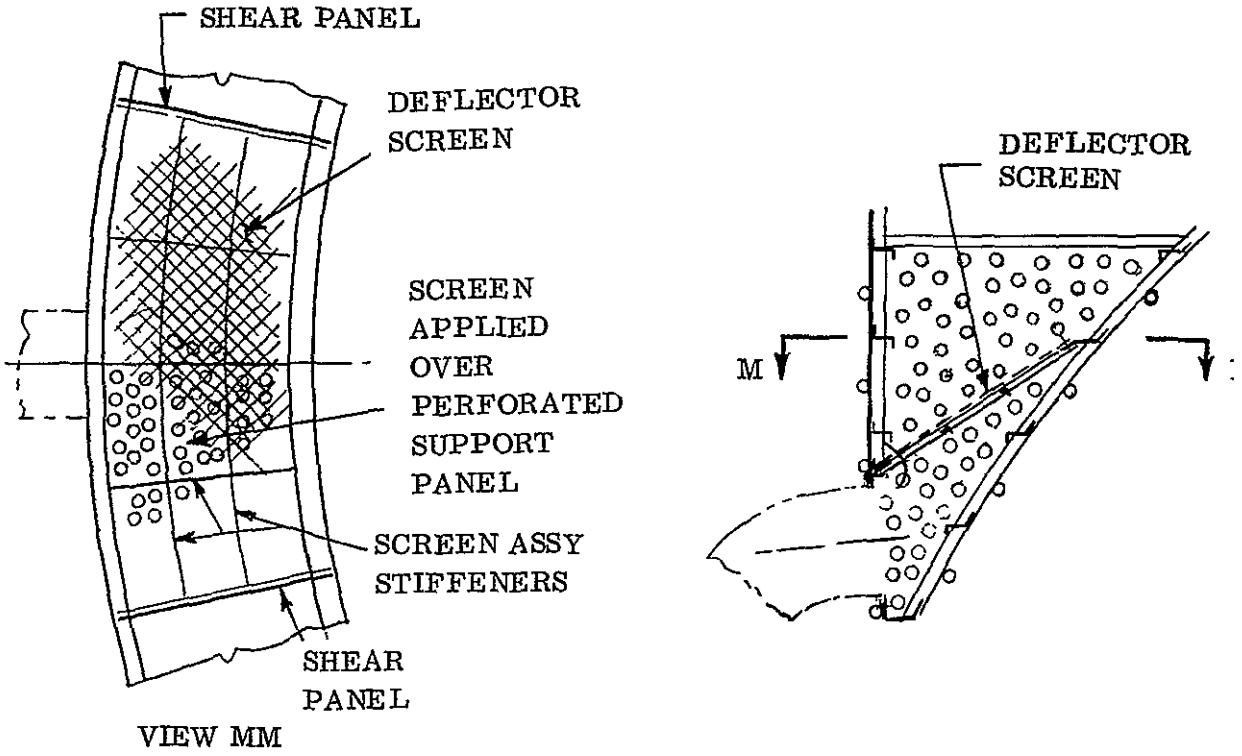


Figure 4-3. Screen Support Arrangement

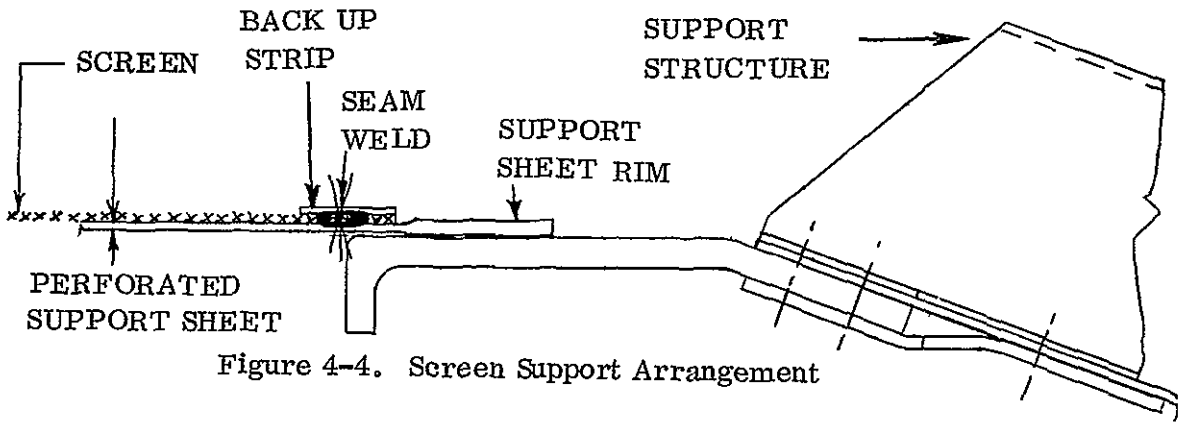


Figure 4-4. Screen Support Arrangement

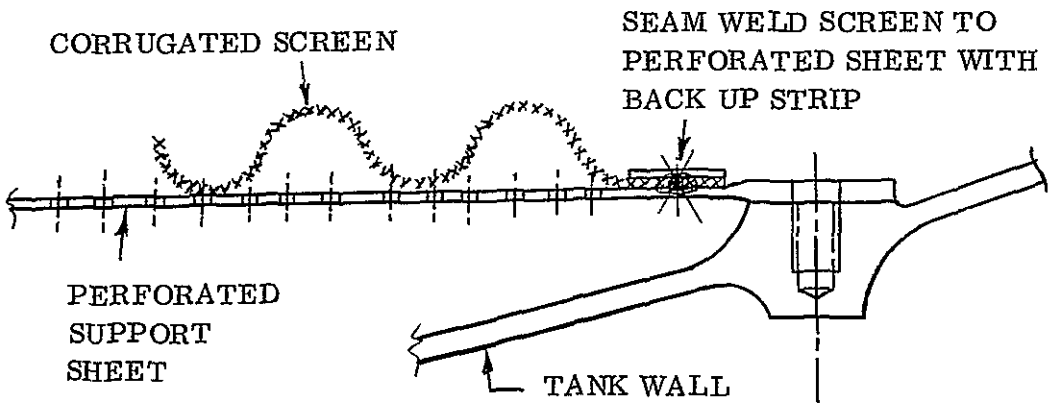


Figure 4-5. Screen Support Arrangement

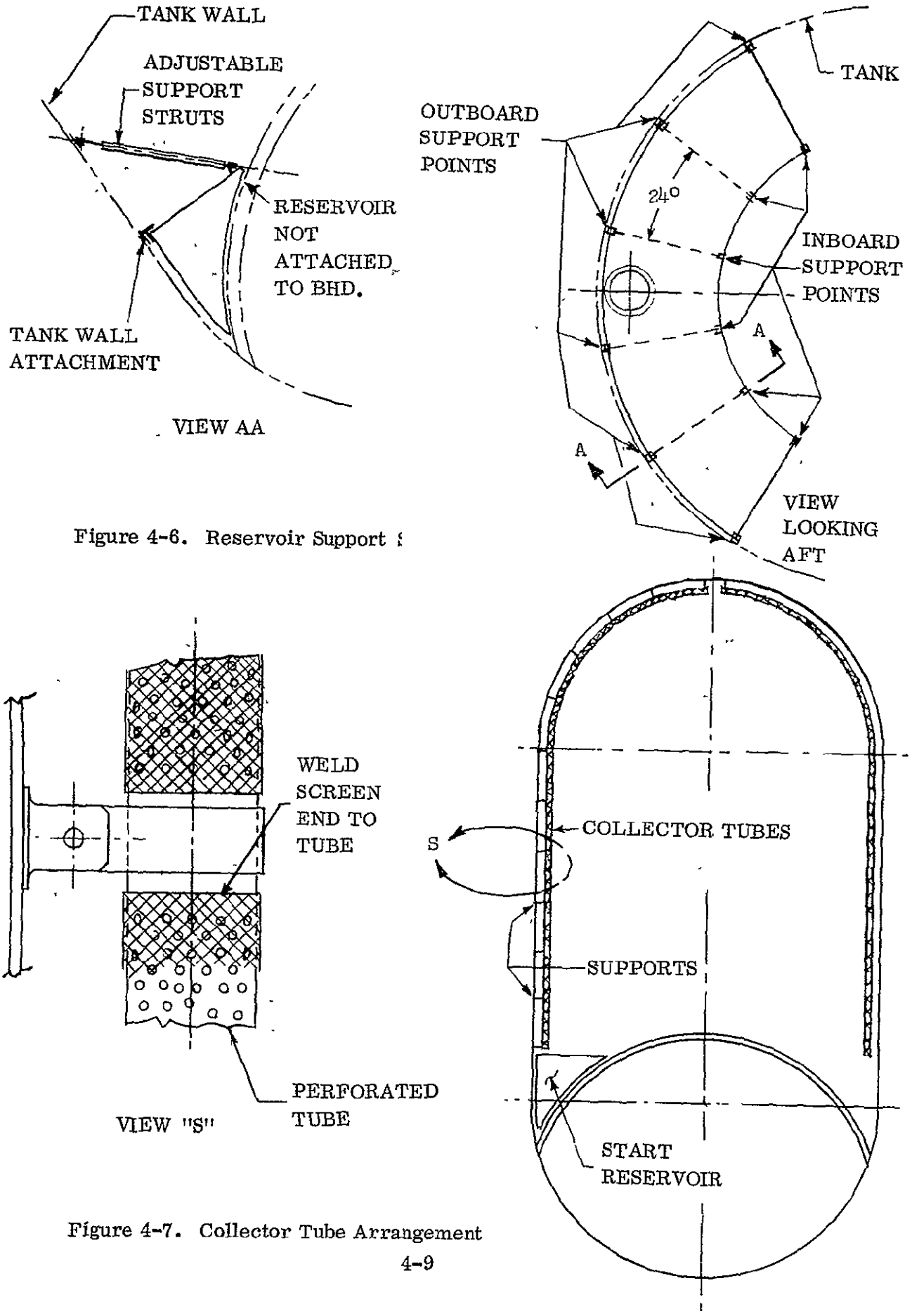


Figure 4-6. Reservoir Support

Figure 4-7. Collector Tube Arrangement

supports are basically simply supported beams subject to vibrational modes, accelerations and propellant slosh. A complete design analysis should include detailed trade-offs reflecting tube diameter, wall gages, and span.

For preliminary reservoir designs, a minimum gage can be selected, a simplified structural analysis conducted (hard calculations), and the results of the stress data used to re-estimate any gages outside the basic requirements. For some cases the minimum gage for skin type panels may be found sufficient or can be made adequate with a modest adjustment of the stiffener pattern. However for large flat surfaces (found in annulus reservoirs) excessive deflections may be experienced when sizing the members for strength, therefore it may be required to base the designs upon limited deflections. The amount of deflection depends upon the type of surface and the influence upon the overall structural make-up. Allowable deflections for surfaces equipped with screens, heat exchanger tubes or both should be less than for plain surfaces.

Materials:

Compatibility with the propellant, strength characteristics, fabricability, repairability, thermal conductivity, and configuration (honeycomb, waffle, monocoque, skin stiffener, etc.) should be considered when selecting a material. Compatibility with the propellant (especially in LOX applications) is a prime item since some materials support ignition with a relatively low energy input. The strength characteristics should also be considered since appreciable reduction in toughness at cryogenic temperatures is inherent in some materials. Can the material be fabricated within the present "state of the art" or are special developments required? Repairing of screen surface is a consideration particularly important for designs involving large surfaces. Installations such as complete tank liners can be sensitive even to normal shop practices and material quality control, therefore the ability to make local repairs without removing the total assembly appears advantageous.

Some propellant retention assemblies require non metals for low conductive supports and pressure seals. A trade-off analysis shown in Reference 4-1 compared teflon and 321 CRES support struts. Heat path lengths, structural capability and general complexity were considered. Plastics such as "teflon," "Kel F" or "Mylar" are usually required for seals at outlets, access openings and at removable baffle or gore sections.

Several frame material configurations are available such as honeycomb, waffle, and skin stringer. Variations for each of the above can also be generated using composites involving filaments. A detailed analysis may also show that an optimum design

requires a combination of the above such as waffle plus honeycomb. The skin stringer frame combination (using 2219 aluminum alloy) is an attractive approach due to the simplicity and adaptability to current manufacturing techniques. Trade off studies involving other combinations should be part of a complete design analysis.

Screen Attachments:

Capillary screens are metal cloth members consisting of fine wires woven into a variety of patterns. The ability of the screen to act as a gas liquid interface depends upon the openings between the wires and the type of weave. If the thread elements are displaced from their initial position, the micron rating of the screen can be changed. It therefore appears that standard fabricating procedures used for sheet metal will require revisions when using wire cloth. Off the shelf components in the form of filters, diaphragms, liners, etc., are commercially available but these items generally involve small surface areas and are packaged such that the total unit can be economically replaced in event of damage. Small units are also more adaptable to special shop practices when compared to surface areas of 220 inch diameter tanks such as shown in Figure 4-8. Large reservoirs having complex shapes (such as annulus types) coupled with a heat exchanger system and internal baffles will require many parts which in turn complicate the handling operations (see Figures 4-9 and 4-10). A completed unit can fail the final bubble test due to a small flaw in a wire mesh or an inadequate seal between the basic frame work and a screen element. It is important to design attachment methods which are reliable and easily re-worked in event local damage or deficiencies occurs.

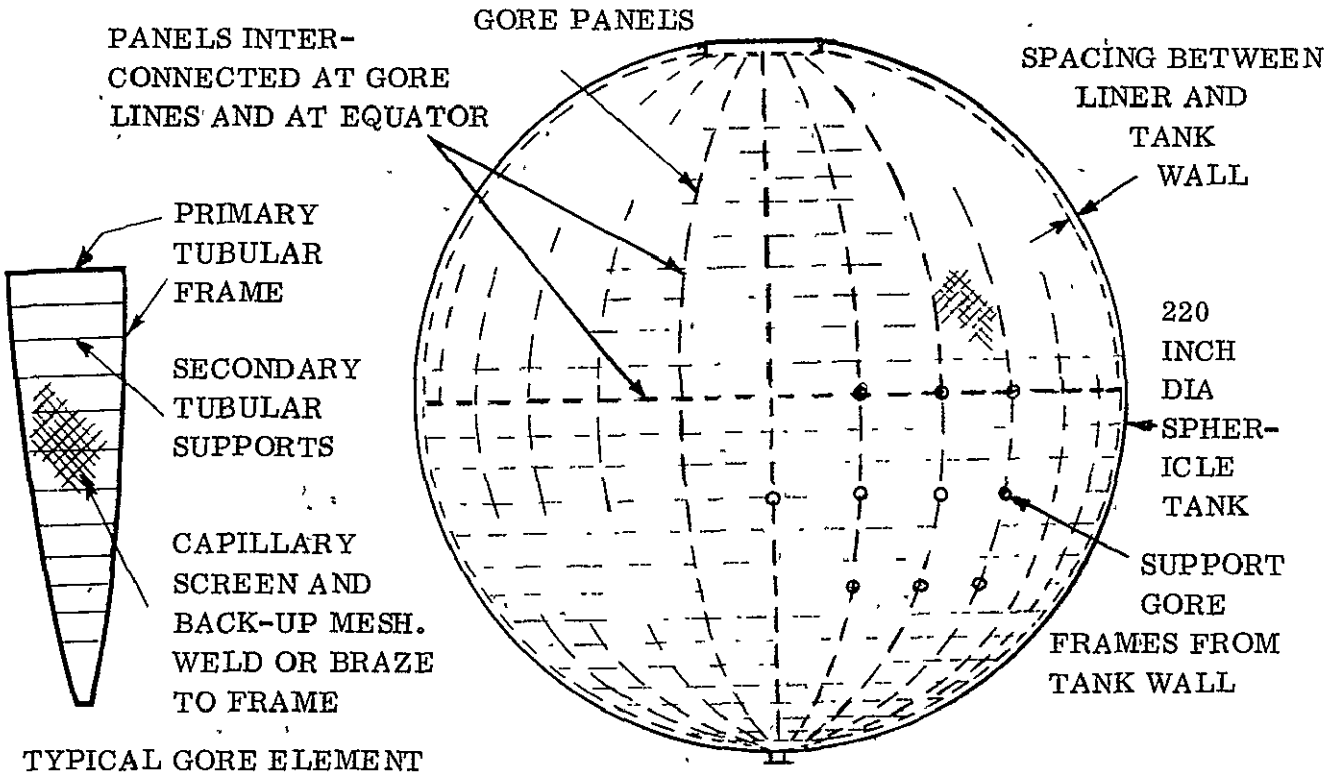


Figure 4-8. Full Liner Concept

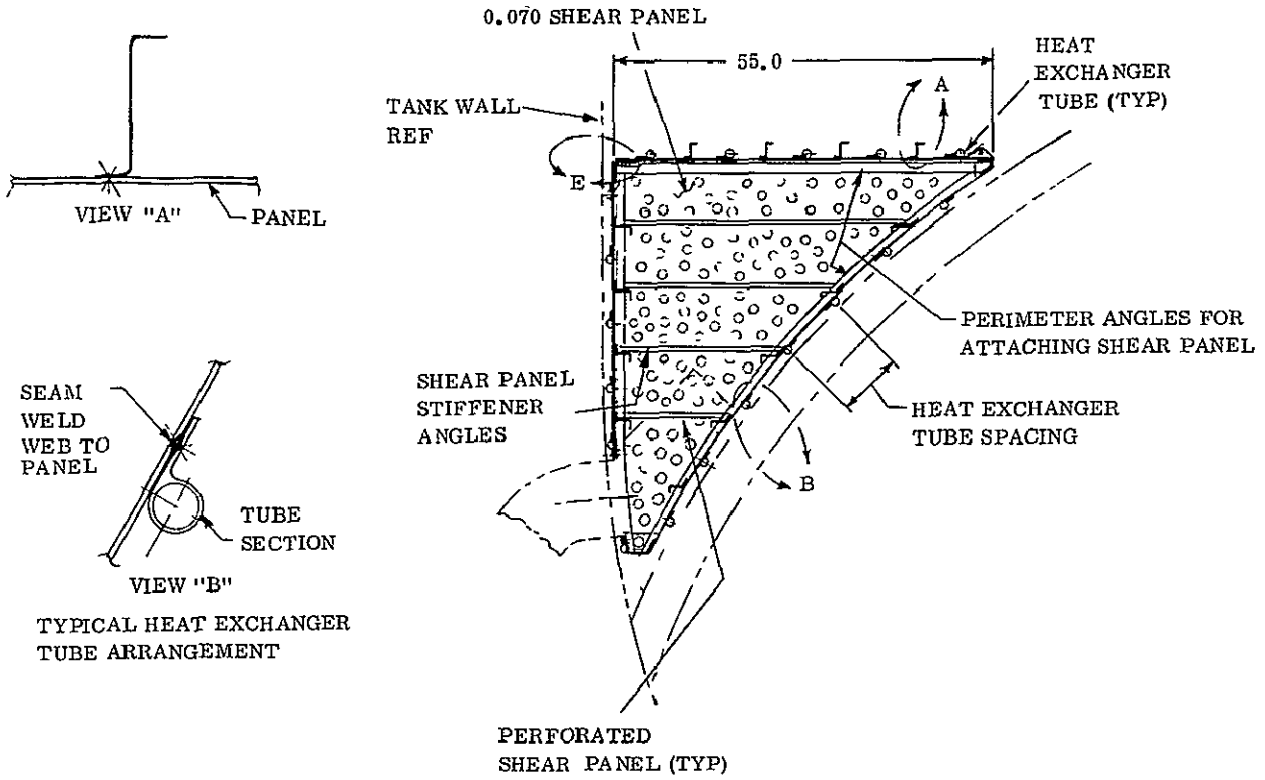


Figure 4-9. Annulus Reservoir Structural Arrangement

Available methods for attaching screens to the structural frame work involving butt welding, seam welding, mechanical fastening, braze, and soldering are available. Due to weight, many screen selections will involve aluminum and small gages which will eliminate the butt weld approach shown as an alternate. Attachment method in Figure 4-10 is not recommended due to the alignment problems, warpage, and the tendency for material "fall thru" during welding operations. Butt welding could be employed however for heavy gages using nickel and CRES. The advantage of this approach is at the inspection level where any attachment leaks during the bubble test are readily located. A reduction in faying surfaces is also realized but this is a relatively minor percentage of the total area.

The seam welding approach shown at view KK of Figure 4-10 is one attractive method of joining screens. GD/C has successfully seam welded aluminum screen with no back-up strips. Contacts with vendors, however, indicate that back-up strips are preferred since the wire mesh threads sometimes adhere to the welding wheel. Many designs may require heat exchanger coils to be located on or at the seam perimeters. For heat exchanger coils having attachment webs, these webs can be conveniently used as coil supports and as the back-up strip for the screen attachment.

Warpage, wicking, cleaning of fluxes from the screens, and holding the wire cloth elements in position during attachment are problems associated with brazing. Local repairs are also difficult without disturbing adjacent areas.

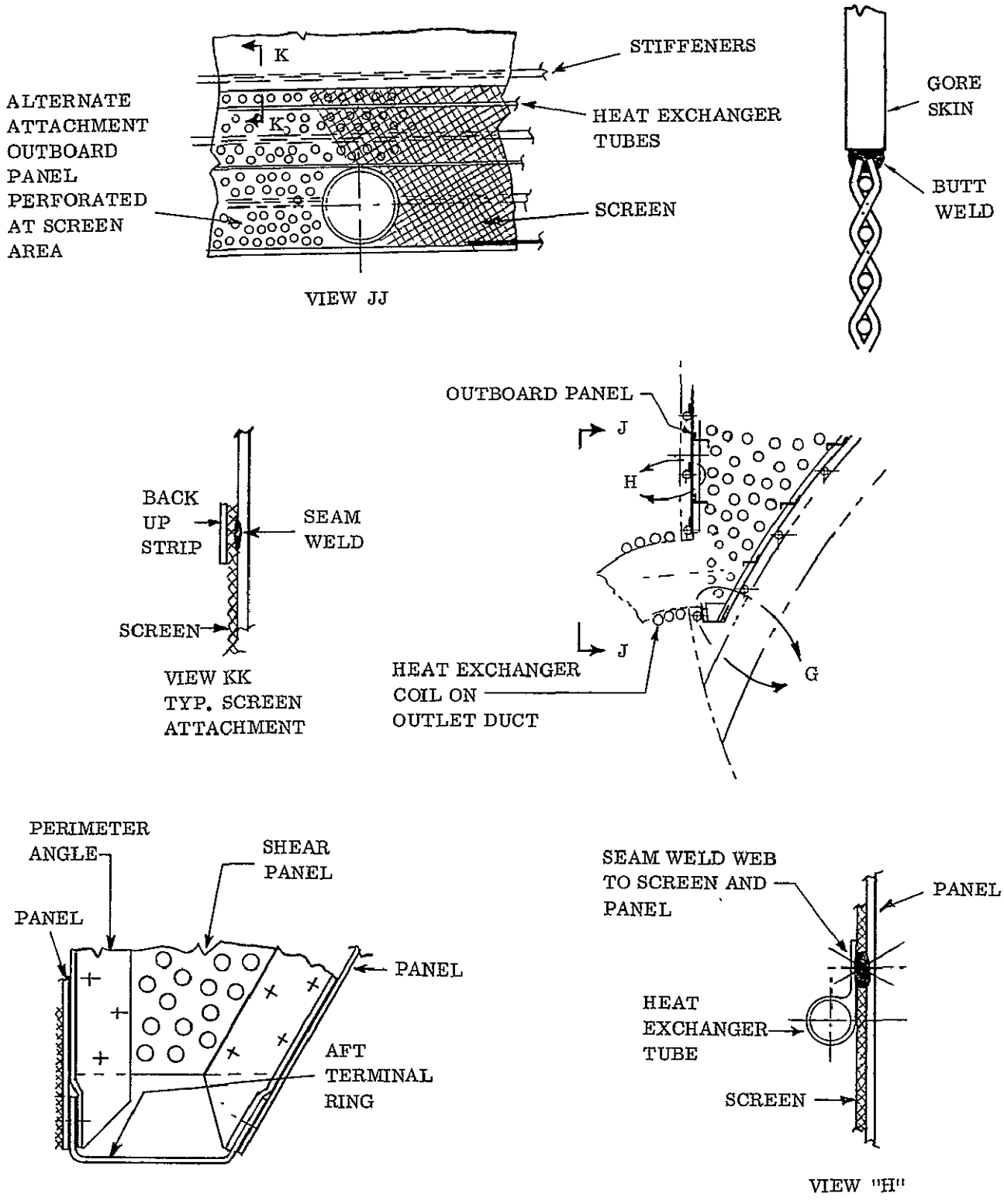


Figure 4-10. Annulus Reservoir Structural Arrangement

Low temperature attachments (450°F) using solder (50% lead + 50% indium) were investigated. A connection of this type is made by gold plating the overlapping surfaces on the screen and the supporting structure prior to the solder application. The method is not readily adaptable to positive temperature control of the base material. If a gun or torch is used, the operator (unknowingly) may over heat some areas which could affect the base materials. The process is also complex and costly due to the local plating of the joining surfaces.

Mechanical type connections should be limited to dissimilar metal applications, non-structural type attachments (retaining screens against support members) or for access openings that involve the interface of rings or flanges which in turn are welded to the screen. The method shown in Figure 41 of Reference 4-2 uses rivets equipped with teflon washers or strips and a channel shaped back-up member for distributing loads. The teflon member prevents coining of the screen and provides coverage of local mesh deformations adjacent to the holes. When dissimilar metals are involved (CRES screen attached to an aluminum frame) it is possible to delete mechanical connections by using a transition joint which is currently manufactured by the Dupont Corporation. The two materials are joined by a process (similar to the diffusion bonding) using a thin layer of interface material. Recent tests at GD/C using this couple for oxidizer feed duct applications have shown promising results. For capillary device applications, the couple furnished as strips may be used with one side welded to the support structure and the opposite side seam welded to the screen. A second method uses dissimilar metal frames (fabricated from the couple strips) which are welded to the screen elements and the frame screens assembly in turn welded to the supporting structure. Detailed design trade offs should include studies of dissimilar metal applications and the behavior of seam welded attachments when applied to complex shapes.

Heat Exchanger Attachments:

Past investigations revealed the need for heat exchanger circuits on reservoir surfaces, tank walls, at support areas, and on feed ducts (see Figures 4-11 and 4-12). The attachments for heat exchanger tubes vary from continuous to intermittent and include cases where the structural support pins are part of the flow path (see Figure 4-13). In Reference 4-1, a series of heat exchanger attachments involving brazing, soldering, mechanical fasteners, integral types (using structural members as tubes) and welding were presented. One method which appears promising uses an aluminum extrusion consisting of a tube attached to a web which in turn is seam welded to the structure or screen. An alternate construction would replace the special extrusion with an assembly consisting of a web brazed to a tube. The design provides a positive conduction path, adequate support, adaptability to standard inspection procedures, and can be applied without strength changes to the base material beyond the weld zones. Contributions to discontinuity stresses (tank wall applications) are considered negligible due to the small sectional area of the tube web combinations, and low yield point of the material. The web sections can also serve as back-up strips for

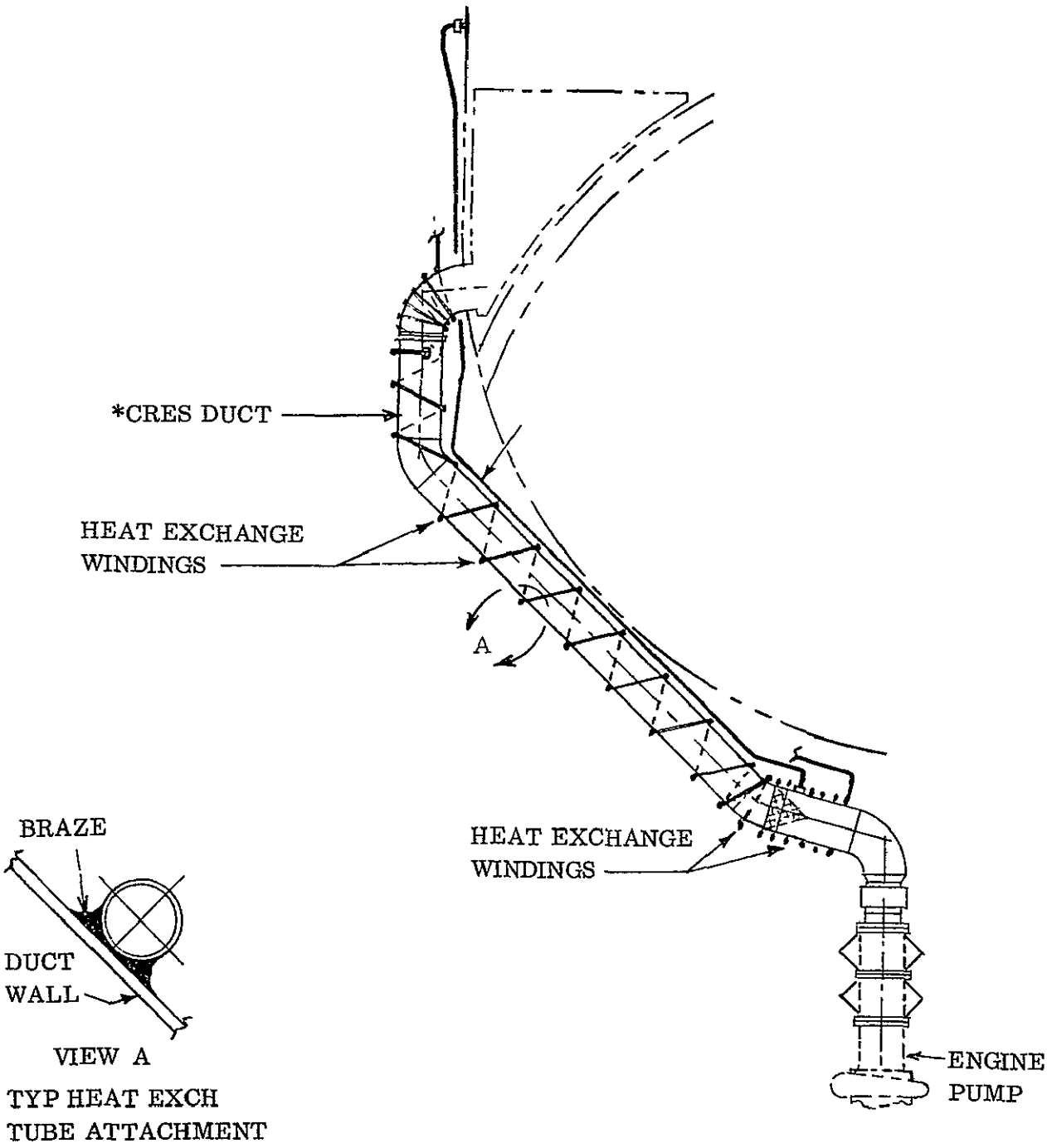


Figure 4-11. Feed Duct Accessories

capillary screen attachments. Stresses from thermal gradients are not considered a problem due to the small temperature differences between the fluid in the tubes and the support structure.

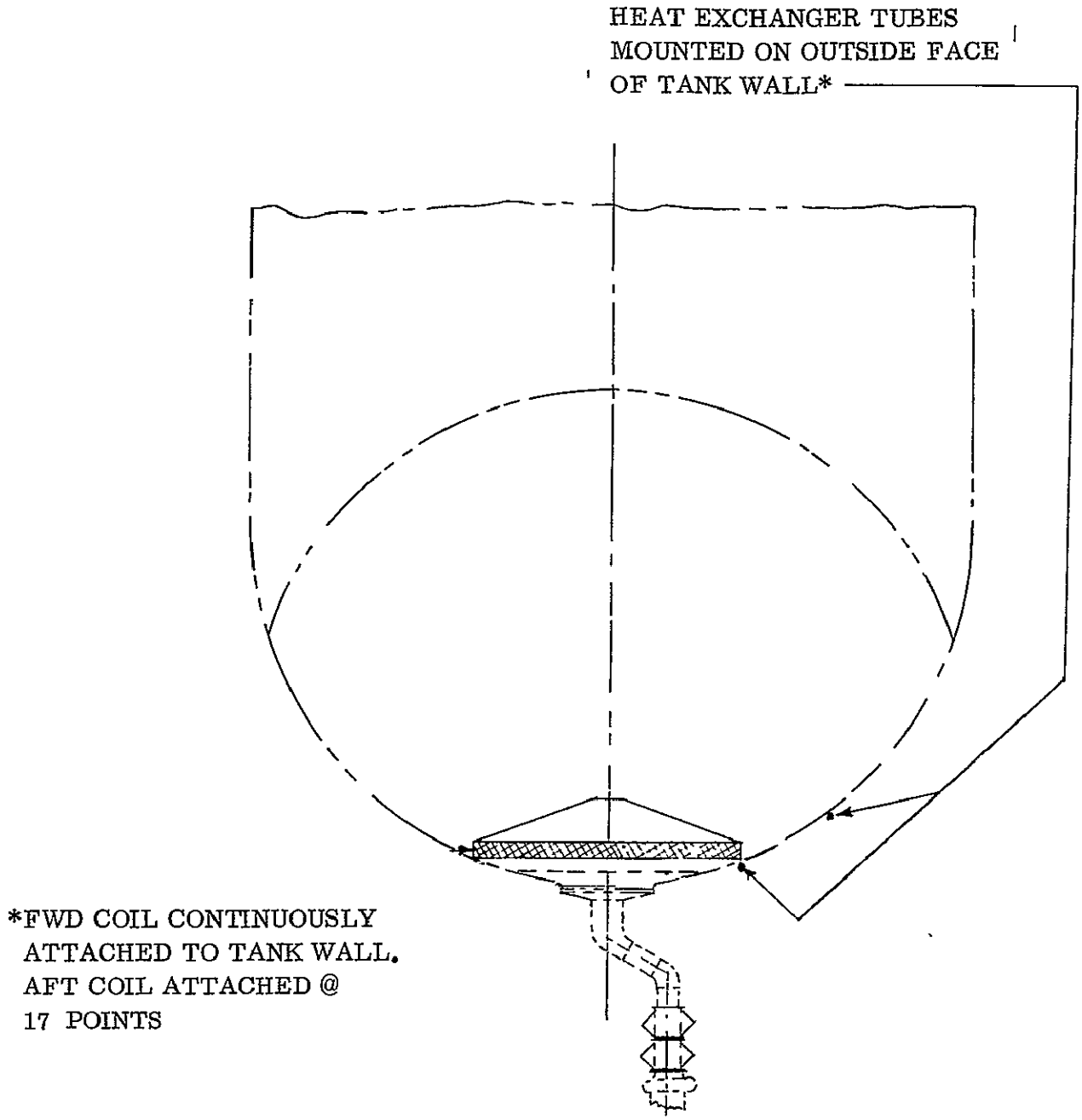


Figure 4-12. Oxidizer Tank Reservoir

Repairability is an important factor since the tubes become an integral part of the tank walls or reservoir structure. Should a tube become damaged during fabrication, the total assembly can be salvaged by locally repairing the tube. Scrapping a near completed assembly can be costly. Several repair techniques are available. For example, assume that an area in a tube web section is buckled (reducing the flow path), torn, or punctured. Repair is possible by locally severing the tube from the web, removing the damaged section, the cut tube ends formed away from the support structure (using a standard bend radius tool) to provide tool clearances, and a new jumper tube section welded in place using a portable orbit arc process. If loss of the conductive path at the repair area is critical, the jumper section can incorporate a web section

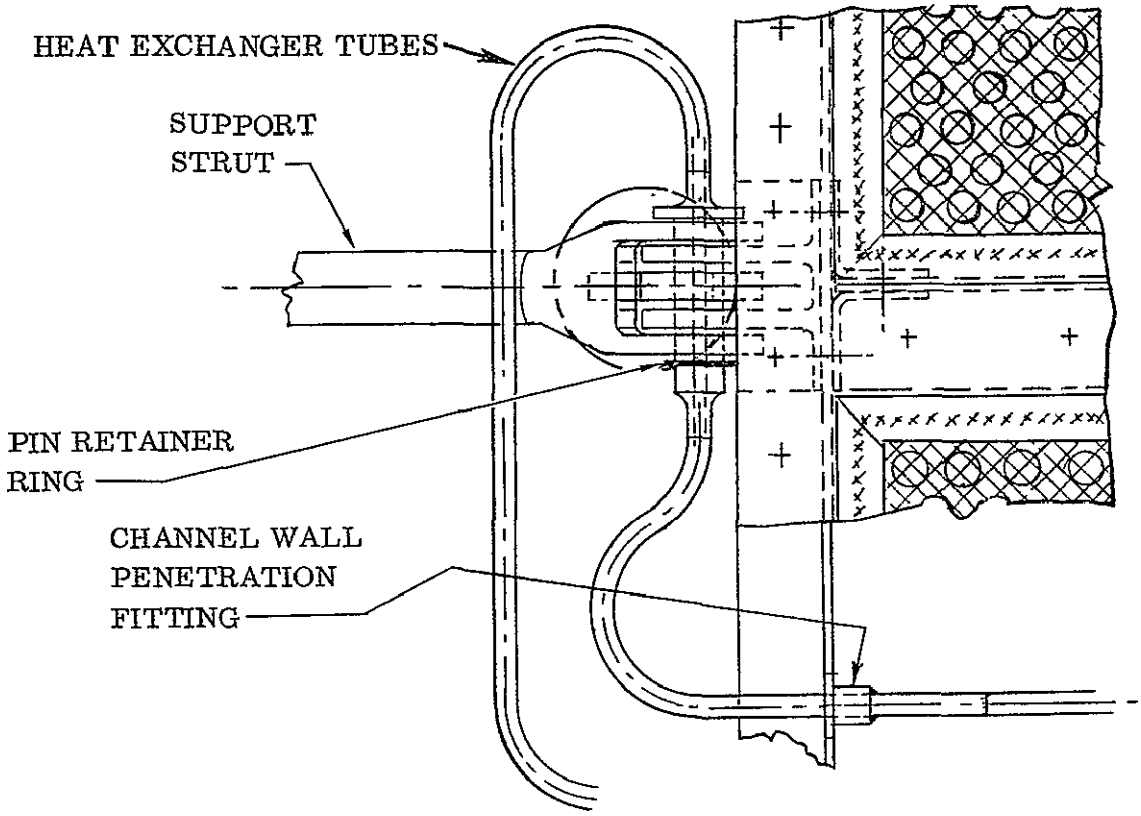


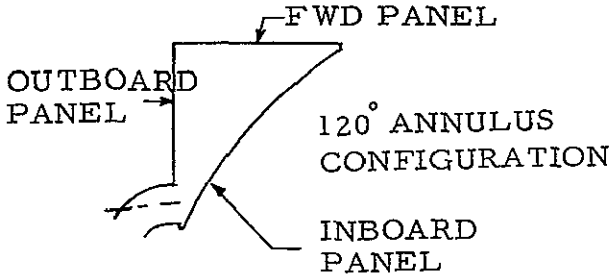
Figure 4-13. Collector Support Heat Exchanger

which is fillet welded to the original web member. Usually the heat transfer path areas exceed the requirements which would delete the need for heat path replacement.

4.2 CONFIGURATIONS FOR MINIMUM WEIGHT AND AREA

Minimum weight and surface area are basically controlled by the fluid mechanics and the vehicle tank parameters. A typical example is shown in Reference 4-1 where a series of fuel reservoir configurations involving cylinders, complete annulus, sections of an annulus, and complete bulkheads were outlined for the S-IVC tankage system. The effort included a detailed weight analysis (similar to that shown in Figure 4-14) and the data plotted against reservoir volumes. The results show an appreciable change of weight per unit volume between basic configurations. A 400 ft^3 unit for example weighs 300 lbs for a cylindrical profile compared to 600 lbs for an annulus type. This weight difference is related to structural arrangements, surface area and the type of surface exposed to fluid impingement. The basic geometry in turn is influenced by the hydraulic requirements and the vehicle tank restraints.

Configurations involving symmetrical surfaces (such as cylinders or spheres) are more acceptable to simple structural elements than that experienced for an annulus section. The load paths and the external supports for the annulus become complex. Due to the severe vehicle tank restraints coupled with hydraulic requirements, the surfaces of the annulus consist of flat and large radius profiles which are sensitive



200 FT^3 VOL.

MAT'L. AL ALY

* 4 24# FOR SERIES CIRCUIT USING 1/2 O.D. X .030 TUBES

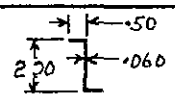
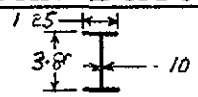
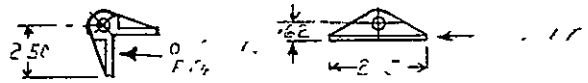
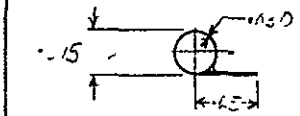
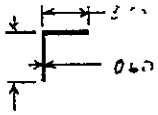
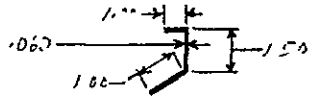
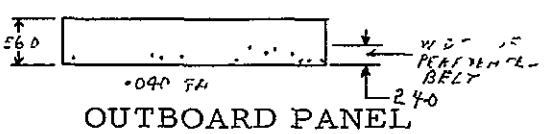
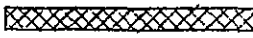
ITEM	WT. LBS	REMARKS
 FWD PANEL STIFFENER RINGS	14.94	4-120° RING SECTIONS 830" LGT. TOTAL
 FWD. PANEL	46.00	
 FWD PANEL ACCESS OPENING	2.00	RING REINF. PANEL DOUBLERS & COVER RING
 FWD PANEL RADIAL STIFFENERS	17.30	5 @ 55" LGT EA.
 SUPPORT FITTINGS @ FWD PANEL	1.20	6 EA. REQUIRED
 FWD PANEL HEAT EXCHANGER	4.18*	830" LGT TOTAL
 LOCATED @ OUTB'D. CORNER FWD CORNER RING	9.78	272" LGT 1 REQ'D
 LOCATED @ INBOARD CORNER FWD CORNER RING	3.30	157" LGT. 1 REQUIRED
 OUTBOARD PANEL	51.00	272" LGT. 1 REQUIRED
 OUTBOARD PANEL SCREEN	2.40	.053 #/FT^2

Figure 4-14. Weight Estimate/Fuel Start Basket

to pressure. To resist the external forces a system of bulkheads interconnected with stringers, skins, and a matrix of stiffeners are required which increase the weight penalties.

If the tank geometry restraints are relaxed such as shown for the S-IVC oxidizer application (Figure 4-12), the reservoir is more receptive to symmetrical elements such as cylinders, spherical sections, cones, and elliptical bulkheads. In most cases the fluid mechanics control the reservoir height and diameter such that a complete spherical or elliptical surface cannot be used, therefore combinations of cones, small sections of spheres, and cylinders must be employed. An exception is shown in Figure 4-8 for the oxidizer tank which uses a complete spherical liner.

Severe limits from both the hydrodynamic analysis and the vehicle tank profiles can be applied to some cases (with small external loads) without large weight penalties since minimum material gages are usually involved. In such arrangements, the weight is more directly related to the surface area. Typical examples are the channel type collectors used for the oxidizer tanker as discussed in Ref. 4-1 thru 4-3.

Design Approach:

It was previously stated that the general configuration of a reservoir is usually dictated by fluid dynamics and the vehicle tank requirements. Within the basic profile, however, the type of structural approach and component arrangement can have major influences upon weights, check out, inspection, cleaning, and fabrication. Should the unit be designed to permit complete assembly and check out prior to installation inside a finished tank or shall the reservoir be installed as a permanent fixture during vehicle tank construction? The former question may require tank access openings larger than feasible, in which case the reservoir would have to be fabricated into two or more sections that are interconnected inside the tank. The capillary device is thus exposed to considerable activity which increases the possibility of screen damage. A complete unit cleaned and checked out on the bench prior to installation is attractive, however, many cases arise where the reservoir size does not permit this (especially for liners and annulus types. A compromise is therefore the use of subassemblies. The disadvantages of interconnecting the sections inside tanks can be partially offset by including design features which simplify the installation operations.

The arrangement of components (such as rings, stiffeners, heat exchanger coils, etc. and the method of interconnecting influences fabrication. For example, if tubes are attached to a cylinder, a continuous spiral type pattern may be more difficult (depending upon shop capability) than applying a series of tube rings with jumpers. Interconnections between components should provide self alignment features including access for tooling.

The design should also reflect methods which are receptive to easy and positive inspections. Any internal baffling or blind compartments should be removable or equipped with access openings in event inspections are required after assembly.

A wire mesh cloth is a continuous series of faying surfaces which are difficult to clean especially for LOX applications. The problem is further amplified when considering the attachment areas which have overlapping surfaces between supports, screens, and back-up strips. Access to all reservoir compartments is a cleaning aid and can usually be provided without degrading the design. Little can be done, however, for the inherent faying surfaces of the screen, therefore cleaning and passivating procedures should reflect above average surveillance. Some past GD/C designs for oxidizer service used the following guides which may provide partial solutions to the above problems:

1. Choose a wire material that exhibits the highest compatibility with the propellant.

2. Avoid thin gages. Use the maximum permissible wire diameter.

3. Avoid mesh sizes smaller than what is required.

4. Avoid faying surfaces in the structural frame work providing there are no penalties to the design.

Screen Clogging:

Specifications for propellant cleanliness levels limit the size and population of particles in the fluid. If the hydrodynamic data dictates a screen which has pore sizes less than what is permitted by the specifications, the screen becomes a filter. This filtering action causes pressure drop changes across the wire cloth which can impair the function of the capillary device. Adjustments must therefore be made in the propellant cleanliness specifications, the hydrodynamic requirements, the overall designs, or a combination of these. If a set of conditions exist where the screen micron rating or the propellant cleaning requirements cannot be relaxed, configuration changes should be considered which would provide a surplus screen area. The areas selected should be verified with tests involving pressure drop vs. time.

Particle collections on capillary device screen surfaces affect the operations of other systems. Some arrangements require filling and draining thru the screened surfaces which may amplify the problems. For example, assume that a gas liquid interface screen is installed in an engine inlet duct. Since the screen surface area is limited (due to the duct restraints) the change in pressure drop thru the screen can become appreciable which in turn can alter the engine inlet conditions. If fill and drain operations are conducted thru the screen, particles collected during the filling operations are suddenly released thru the engine systems. Should a capillary

reservoir be installed in the tank (upstream of the screen) with filling and draining thru the reservoir, a high population of particles can be released from the reservoir surfaces during out flow which would augment the gas liquid interface screen problems. For large surface areas located inside storage tanks, the sensitivity to pressure gradients may be reduced, however, the basic function of the assembly can be impaired if excessive particle build up is allowed. If filling and draining is done outside the reservoir and several outflows conducted, the particle population collected on the screens may become intolerable. Each design analysis should therefore include investigations relating to propellant cleaning specifications, affects of particle retention upon the hydraulic characteristics of a reservoir, and special problems associated with screens located inside engine feed ducts.

5

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APPENDIX A

OUTFLOW COMPUTER PROGRAM LISTING

INGASP

This program predicts spilling, vapor ingestion pullthrough and refilling of a capillary propellant control device during restart under high Bond number conditions. Liquid levels inside and outside the capillary device as a function of time, outflow rate, liquid reorientation, gravity level and capillary device and tank geometry are computed. Results of a Convair IRAD program which developed screen flow and pullthrough correlations are used as the basis of the computer model. A modified Regula-Falsi technique is used to numerically solve the resulting equations.

Inputs to the program are given in the input section of the program with the format statements. All variables are defined in the comment cards with the exception of CSL which is a liquid pressure drop constant, CSV, which is a vapor pressure drop constant, KO which is the number of entries in the flow rate vs time table, QOO a factor to multiply the steady state flow rate QOX by to obtain QO and TI the time corresponding to QOO.

Outputs statements are dispersed throughout the program and are underlined for convenience.

A sample input is shown after the Fortran listing. The way the cards are arranged, if more than one case is to be input, the card containing the input flags need only be input once if all the tables lengths do not change from case to case.

```
      PROGRAM INGASP(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     THIS PROGRAM CALCULATES THE LIQUID  SPILLAGE AND VAPOR INGESTION IN A
C     START BASKET WITH CONTINUOUS LIQUID OUTFLOW
C     ACS=START BASKET AREA AT THE POINT OF VAPOR INGESTION(FOR LIQUID VELOCITY)
C     AG=STANDPIPE SCREEN TOTAL AREA,FT**2
C     ALO=SIDE SCREEN TOTAL AREA,FT**2
C     BUOY=BUOYANCY FORCE ON A BUBBLE OF SIZE DB
C     CD=BUBBLE DRAG COEFFICIENT
C     DA=TOP   SCREEN AVERAGE CAPILLARY DIAMETER MICRONS
C     DA1 SATISFIES PO=DA1+DA2*RE
C     DA2 SATISFIES PO=DA1+DA2*RE
C     DB=SIDE   SCREEN CAPILLARY DIAMETER IN MICRONS
C     DB1 SATISFIES PO=DB1+DB2*RE
C     DB2 SATISFIES PO=DB1+DB2*RE
C     DBP=ABSOLUTE MICRON RATING OF SIDE SCREEN
C     DELCD=TOLERANCE ON THE CD ITERATION FOR BUBBLE MOTION
C     DELFT= TOLERANCE ON THE DISTANCE ITERATION FOR CALCULATING INGESTION TIME
C     DELTAC=VAPOR SCREEN LOSS COEFFICIENT TOLERANCE
C     DELTAQ=VOLUME FLOW RATE TOLERANCE,FT**3/SEC
C     DH=DISTANCE BETWEEN THE TOP AND BOTTOM OF THE SIDE SCREEN FT
C     DHPULL=DISTANCE BETWEEN BOTTOM OF START BASKET AND CENTER LINE OF OUTLET
C     DP=DELTA P ,PRESSURE DROP  PSF
C     DRAG=DRAG FORCE ON A BUBBLE CAUSING IT TO BE SWEPT ALONG WITH THE LIQUID
C     USDI=BUBBLE VELOCITY FUNCTION
C     DTIME=TIME INTERVAL,SEC
C     FT=BUBBLE DISTANCE FUNCTION
C     GR=ACCELERATION/NORMAL GRAVITY
C     HAREA=DISTANCE ABOVE THE BOTTOM OF THE START BASKET
C     HBELOW=DISTANCE ABOVE BOTTOM OF START BASKET TO TOP OF ENGINE FEED LINE
C     HO=DISTANCE FROM LIQUID LEVEL TO BOTTOM OF SIDE SCREEN FT
C     HOF=FINAL HEIGHT BEFORE PULLTHROUGH OCCURS
C     HOT(I)=LIQUID LEVEL IN START BASKET ABOVE BOTTOM OF FEED LINE
C     HPULL=PULLTHROUGH HEIGHT WITH A SCREEN BAFFLE OVER THE OUTLET
C     HPULL=0. WHEN NO SCREEN BAFFLE IS PRESENT
C     HS=SURFACE TENSION PRESSURE HEAD
C     HSTART=DISTANCE FROM BOTTOM OF START BASKET SCREEN TO BOTTOM OF TANK
C     HT=DISTANCE FROM LIQUID LEVEL TO TOP OF SIDE SCREEN FT
C     HTAN(I)=HEIGHT OF LIQUID IN TANK AT VTANK(I)  (FT)
C     HVOL=START BASKET HEIGHT BELOW SCREENED AREA WHERE NO FLOW CAN OCCUR
C     IT=NUMBER OF ENTRIES IN START BASKET VOLUME VS HEIGHT TABLE
C     ITER=FLAG FOR EXIT FROM BUBBLE DRAG COEFFICIENT CALCULATIONS
C     N=NUMBER OF CASES
C     NI=NUMBER OF ENTRIES IN CROSS SECTIONAL AREA TABLE VS HEIGHT
C     NO=NUMBER OF ENTRIES IN REFILL VOLUME VS TIME TABLE
C     MO=NUMBER OF ENTRIES IN TANK VOLUME VS HEIGHT TABLE
C     QL1=SPILL RATE OF LIQUID INTO VAPOR (CFS)
C     QL2=SPILL RATE OF LIQUID INTO LIQUID (CFS)
C     QHT=VAPOR INGESTION RATE THRU OPEN SCREEN WHEN HT IS NEGATIVE (CFS)
C     QGA=INITIAL GUESS AT VAPOR FLOW  THRU STANDPIPE FT**3/SEC
C     QLIN=REFILLING RATE (CFS)
C     QO=INSTANTANEOUS ENGINE FLOW RATE FT**3/SEC
C     QOX=STEADY STATE ENGINE FLOW RATE FT**3/SEC
C     RE=REYNOLDS NUMBER
C     RHOG=VAPOR DENSITY,LB/FT**3
```

```
CCCCC      RHOL=LIQUID DENSITY,LB/FT**3
CCCCC      RO=RADIUS OF THE FEEDLINE
CCCCC      S=FLUID SURFACE TENSION LB/FT
CCCCC      S1=DISTANCE BETWEEN INGESTION POINT AT SCREEN AND FEEDLINE TOP
CCCCC      T=TIME FOR BUBBLE TO MOVE TO FEEDLINE TOP
CCCCC      TANKVOL(I)=VOLUME IN TANK AT TREFILL(I)  (FT**3)
CCCCC      THA=THICKNESS OF TOP SCREEN
CCCCC      THB=THICKNESS   OF SIDE SCREEN
CCCCC      TIME=INITIAL TIME,SEC
CCCCC      TFINAL=FINAL TIME SEC
CCCCC      TREFILL(I)=REFILLING TIME CORRESPONDING TO TANKVOL(I)   (SEC)
CCCCC      VIG=VAPOR VISCOSITY LB/FTSEC
CCCCC      VIL=LIQUID VISCOSITY LB/FT SEC
CCCCC      VLIQ=AVERAGE LIQUID VELOCITY AT THE POINT OF START BASKET VAPOR INGESTION
CCCCC      VOL=INITIAL LIQUID VOLUME IN THE START BASKET CUBIC FEET
C          VOLRES=RESIDUAL VOLUME IN BASKET,FT**3
C          VOLU(I)=START BASKET VOLUME FT**3
CCCCC      VTANK(I)=TANK VOLUME AT HTAN(I) (FT**3)
CCCCC      VOLTAN=VOLUME IN TANK AT TIME (FT**3)
CC         X=WIDTH OF SIDE SCREEN,FT
C          XQ=MULTIPLIER NEEDED TO OBTAIN QO FROM QOX
           COMMON HO,VOL,HOT(20),VOLU(20),IT,NO,MO,TANKVOL(20),TIME,VOLTAN,
          CHTAN(20),VTANK(20),HTANK,TREFILL(20),HSTART,KO,
          CHARE(20),ACSS(20),HAREA,ACS,NI,DVTANK,QO,QOO(20),TI(20),QOX
           K=0
C*****INPUT*****************************************************************
      11 FORMAT(6I10)
      10 READ(5,1)RHOL,VIL,RHOG,VIG,S,GR,QGA,QOX
           READ(5,11)N,NI,IT,NO,MO,KO
           READ(5,1)DB,DB1,DB2,DA,DA1,DA2,DBP
           READ(5,1)TIME,DTIME,TFINAL,DELTAQ,DELCD,DELFT,DELTAC,DHPULL
           READ(5,1)VOL,DH,ALO,X,AG,HBELOW,HVOL,HSTART
           READ(5,1)PO,HPULL,THA,THB,CSL,CSV
           READ(5,7)(HARE(IJ),IJ=1,NI)
           READ(5,7)(ACSS(IJ),IJ=1,NI)
           READ(5,7)(HOT(IJ),IJ=1,IT)
           READ(5,7)(VOLU(IJ),IJ=1,IT)
           READ(5,7)(TANKVOL(I),I=1,NO)
           READ(5,7)(TREFILL(I),I=1,NO)
           READ(5,7)(HTAN(I),I=1,MO)
           READ(5,7)(VTANK(I),I=1,MO)
           READ(5,7)(TI(K),K=1,KO)
           READ(5,7)(QOO(K),K=1,KO)
      1 FORMAT(8E10.6)
      7 FORMAT(11F7.3)
C*****************************************************************************
C*****INITIAL VALUES*********************************************************
           APHIA=DA1*5.08E4*THA/DA
           APHIB=DB1*5.08E4*THB/DB
           BSUBSA=DA2*APHIA/DA1
           BSUBSB=DB2*APHIB/DB1
           IF(DELTAQ.GT.QOX/100.)DELTAQ=QOX/100.
           IF(DELTAC.GT.DELTAQ)DELTAC=DELTAQ
           DTIME1=DTIME
```

```
      WRITE(6,15)
      WRITE(6,15)
      WRITE(6,15)
      WRITE(6,25)
   25 FORMAT(*          INITIAL CONDITIONS*)
      WRITE(6,15)
      WRITE(6,15)
      WRITE(6,3)GR,VOL,DH,DA,DB,AG,ALO,QGA
    3 FORMAT(* INPUT,GR=*E10.3,* VOL=*E10.3,* DH=*E10.3,* DA=*
     CE10.3,*  DB=*E10.3,* AG=*E10.3,* ALO =*E10.3,* QGA=*E10.3)
      WRITE(6,4)X,DELTAC,DELTAQ,QOX
    4 FORMAT(*X= *E14.7,* DELTAC = *E14.7,* DELTAQ = *E14.7,*QOX=*E14.7)
      DVTANK=0.
   15 FORMAT(*     *)
      WRITE(6,15)
      WRITE(6,15)
      WRITE(6,15)
C*****************************************************************
C*****NEW TIME STEP**********************   ************************
   49 A1=0.
      ENN=1.
      CALL FLOW
      QGA=QO
      QGA=11.
      IF(QGA.EQ.0.)GO TO 520
      CALL VOLUME
      CALL REFILL
      CALL VOLTANK
      WRITE(6,15)
      WRITE(6,15)
      WRITE(6,15)
      WRITE(6,20)
   20 FORMAT(*              CONDITIONS AT THE START OF THE TIME STEP     *)
      WRITE(6,15)
      WRITE(6,21)TIME
   21 FORMAT(* INITIAL TIME IS*E14.7*SECONDS                 *)
      WRITE(6,18)VOLTAN,DVTANK
   18 FORMAT(* VOLTAN=*E14.7,* DVTANK=*E14.7)
      WRITE(6,16)HO
   16 FORMAT( *   HO = *E14.7*FT*)
      HO=HO-HVOL
      WRITE(6,17)HO
   17 FORMAT( *HO=HO-HVOL= *E14.7*FT*)
      HT=HO-DH
      HOB=HO
      HO=HO-HTANK
      WRITE(6,22)HO
   22 FORMAT(* HO=HO-HTANK-HVOL=*E14.7*FT*)
      HS=.3048E+6*S/(DBP*RHOL*GR)**4.
      ASSIGN 411 TO NIPPY
      WRITE(6,15)
      WRITE(6,15)
C*****ITERATION LOOP FOR EACH TIME STEP**    ***************************
```

```
   50 QHT=0.
      QV=0.
      QL1=0.
      QL2=0.
      QLIN=0.
      QLIN1=0.
      QLIN2=0.
      IF(HT.LT.0.)GO TO 699
C*****HT IS POSITIVE  **********************************************
      IF(HTANK.GE.DH)HT=HO
      REG=RHOG*QGA*DA/(VIG*AG*.3048E6)
      REG=ABS(REG)
      CSG=APHIA/REG+BSUBSA
      DPG=CSG*RHOG*QGA**2/(64.4*AG**2)
      IF(QGA.LT.0.)DPG=-DPG
      HG=DPG/(RHOL*GR)
      HGP=HG-HS
      IF(HO.LE.0.)GO TO 370
      IF(HGP-HO)100,200,200
  100 IF(HGP-HT)300,300,119
  119 IF(HO.LE.HG)GO TO 125
  120 AL1=(HO-HG)*ALO/DH
      QL1=2.*X*SQRT(64.4*GR)*(HO-HG)**1.5/(3.*SQRT(CSL))
      REL=RHOL*QL1*DB/(VIL*AL1*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)122,122,121
  121 CSL=ABS(CSL+CSLA)/2.
      GO TO 120
  122 IF(HTANK.EQ.0.)GO TO 125
      AL2=ALO*HTANK/DH
      IF(HTANK.GT.DH)AL2=ALO
      QL2 =AL2    *SQRT(64.4*GR*(HO-HG)/CSL)
      REL=RHOL*QL2*DB/(VIL*AL2*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)125,125,123
  123 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 122
  125 AV=(HGP-HT)*ALO/DH
      QV=2.*X*SQRT(2.*GR*32.2*RHOL)*(HGP-HT)**1.5/(3.*SQRT(CSV*RHOG))
      REV=RHOG*QV*DB/(VIG*AV*.3048E6)
      CSVA=APHIB/REV+BSUBSB
      DELTAV=CSVA-CSV
      IF(ABS(DELTAV)-DELTAC)170,170,150
  150 CSV=ABS(CSVA-DELTAV/2.)
      GO TO 125
  170 CSV=CSVA-DELTAV/2.
      HAREA=HO+HTANK-HGP
      CALL INGEST
      ASSIGN 960 TO MAZ
      GO TO 909
  960 CONTINUE
      GO TO 400
  200 IF(HTANK.GE.DH)GO TO 285
```

```
      QV=2.*X*SQRT(64.4*GR*RHOL)*((HGP-HT)**1.5-(HGP-HO)**1.5)/(3.*SQRT(
     CCSV*RHOG))
      AV=(HO-HT)*ALO/DH
      REV=RHOG*QV*DB/(VIG*AV*.3048E6)
      CSVA=APHIB/REV+BSUBSB
      DELTAV=CSVA-CSV
      IF(ABS(DELTAV) -DELTAC)280,280,250
  250 CSV=ABS(CSVA-DELTAV/2.)
      GO TO 200
  280 CONTINUE
      HAREA=HTANK
      CALL INGEST
      ASSIGN 961 TO MAZ
      GO TO 909
  961 CONTINUE
  285 IF(HTANK.EQ.0.)GO TO 400
      AL3=ALO*HTANK/DH
      IF(HTANK.GT.DH)AL3=ALO
      QLIN=AL3    *SQRT(64.4*GR*(HG-HO)/CSL)
      REL=RHOL*QLIN*DB/(VIL*AL3*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)400,400,282
  282 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 285
  300 IF(HG-HT)310,310,340
  310 IF(HO.EQ.HT)GO TO 330
      AL1=(HO-HT)*ALO/DH
  315 QL1=2.*X*SQRT(1.*64.4*GR)*((HO-HG)**1.5-(HT-HG)**1.5)/(3.*SQRT(CSL
     C))
      REL=RHOL*QL1*DB/(VIL*AL1*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)330,330,320
  320 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 315
  330 IF(HTANK.EQ.0.)GO TO 321
      AL2=ALO*HTANK/DH
      IF(HTANK.GT.DH)AL2=ALO
      QL2 =AL2    *SQRT(64.4*GR*(HO-HG)/CSL)
      REL=RHOL*QL2*DB/(VIL*AL2*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)321,321,322
  322 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 330
  321 QV=0.
      GO TO 400
  340 AL1=ALO*(HO-HG)/DH
      QV=0.
      IF(HO-HG)400,400,345
  345 QL1=2.*X*SQRT(1.*64.4*GR)*(HO-HG)**1.5/(3.*SQRT(CSL))
      REL=RHOL*QL1*DB/(VIL*AL1*.3048E6)
      CSLA=APHIB/REL+BSUBSB
```

```
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)361,361,360
  360 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 345
  361 IF(HTANK.EQ.0.)GO TO 400
      AL2=ALO*HTANK/DH
      IF(HTANK.GT.DH)AL2=ALO
      QL2 =AL2*   SQRT(64.4*GR*(HO-HG)/CSL)
      REL=RHOL*QL2*DB/(VIL*AL2*.3048E6)
      CSLA=APHID/REL+BSUBSB
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)400,400,363
  363 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 361
  370 IF(HTANK.EQ.0..A.HG.GT.0.)GO TO 400
      IF(HG.LT.0.)GO TO 380
      QLIN=ALO   *SQRT(64.4*GR*(HG-HO)/CSL)
      REL=RHOL*QLIN*DB/(VIL*ALO*.3048E6)
      CSLA=APHIE/REL+BSUBSB
      GO TO 381
  380 IF(HO.LT.HG)QL1=ALO*SQRT(64.4*GR*(HO-HG)/CSL)
      REL=RHOL*QL1*DB/(VIL*ALO*.3048E6)
  381 CONTINUE
      DELTAL=CSLA-CSL
      IF(ABS(DELTAL)-DELTAC)400,400,372
  372 CSL=ABS(CSLA-DELTAL/2.)
      GO TO 370
C*************************************************************************
C****** NEGATIVE HT  ****************************************************
  699 REG=RHOG*QGA*DA/(VIG*AG*.3048E6)
      REG=ABS(REG)
      CSG=APHIA/REG+BSUBSA
      DPG=CSG*RHOG*QGA**2/(64.4*AG**2)
      IF(QGA.LT.0.)DPG=-DPG
      HG=DPG/(RHOL*GR)
      HGP=HG-HS
      AHT=-HT*X
      ALO=DH*X
      IF(AHT.GT.ALO)AHT=ALO
      HAREA=HO+HTANK
  701 IF(HTANK.GE.DH)GO TO 702
      IF(HTANK.GT.HOB)AHT=(DH-HTANK)*ALO/DH
      DPG=ABS(DPG)
      QHT=SQRT(DPG*AHT**2*64.4/(CSG*RHOG))
      IF(QGA.LT.0.)QHT=-QHT
      REG=RHOG*QHT*DB/(VIG*AHT*.3048E6)
      CSGA=APHIB/REG+BSUBSB
      CSG=ABS(CSG+CSGA)/2.
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 703
      GO TO 701
  703 CONTINUE
      IF(HGP-HO)750,900,950
  750 IF(HGP)760,760,800
```

```
760 AV=0.
    QV=0.
    GO TO 963
800 AV=ALO*HGP/DH
    HAREA=HO+HTANK-HGP
    GO TO 801
702 IF(HTANK.EQ.0.)GO TO 400
    IF(HTANK.LE.HOB)GO TO 703
    IF(HG.LT.0.)GO TO 731
710 QLIN1=2.*X    /3.*SQRT(64.4*GR/CSL)*((HG-HO)**1.5-(HG)**1.5)
    IF(HOB.LE.0.)GO TO 712
    IF(HTANK.GT.DH)QLIN1=2.*X    /3.*SQRT(64.4*GR/CSL)*((HG-HO)**1.5-(H
   CTANK-DH+HG)**1.5)
    ALIN1=-HO*ALO/DH
    IF(HTANK.GT.DH)ALIN1=(DH-HOB)*ALO/DH
    RELIN1=RHOL*QLIN1*DB/(VIL*ALIN1*.3048E6)
    CSLA=APHIB/REL+BSUBSB
    DELTAL=CSLA-CSL
    IF(ABS(DELTAL)-DELTAC)720,720,711
711 CSL=ABS(CSLA-DELTAL/2.)
    GO TO 710
712 ALIN=HTANK*ALO/DH
    IF(HTANK.GT.DH)ALIN=ALO
    QLIN=ALIN    *SQRT(64.4*GR*(HG+HTANK)/CSL)
    REL=RHOL*QLIN*DB/(VIL*ALIN*.3048E6)
    CSLA=APHIB/REL+BSUBSB
    IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 400
    CSL=ABS(CSL+CSLA)/2.
    GO TO 712
720 ALIN2=(HO+HTANK)*ALO/DH
721 QLIN2=ALIN2    *SQRT(64.4*GR*(HG-HO)/CSL)
    RELIN2=RHOL*QLIN2*DB/(VIL*ALIN2*.3048E6)
    CSLA=APHIB/REL+BSUBSB
    DELTAL=CSLA-CSL
    IF(ABS(DELTAL)-DELTAC)730,730,722
722 CSL=ABS(CSLA-DELTAL/2.)
    GO TO 721
730 QLIN=QLIN1+QLIN2
    GO TO 400
731 IF(HTANK.GT.DH)GO TO 780
    IF(HO.GE.HG)GO TO 732
    IF(HO.LT.HG)GO TO 735
732 AV=-HO*X
    IF(HG+HS.GT.0.)GO TO 734
733 IF(HO.LT.HG+HS)GO TO 739
    QV=-X*2./3.*SQRT(64.4*RHOL*GR/(CSG*RHOG))*((-HG-HS)**1.5-(-HG-HS+H
   CO)**1.5)
    AV=HO*X
    GO TO 740
739 AV=-(HG+HS)*X
    QV=-X*2./3.*SQRT(64.4*RHOL*GR/(CSG*RHOG))*  (-HG-HS)**1.5
740 CONTINUE
    REV=RHOG*QV*DB/(VIG*AV*.3048E6)
    REV=ABS(REV)
```

```
      CSGA=APHIB/REV+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 734
      CSG=(CSGA+CSG)/2.
      GO TO 733
  734 QL1=X*SQRT(64.4*GR*(-HG+HO)/CSL) *HOB
      AL1=HOB*X
      REL=RHOL*QL1  *DB/(VIL*AL1  *.3048E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 400
      CSL=(CSLA+CSL)/2.
      GO TO 734
  735 IF(HG+HS.GT.0.)GO TO 737
       AV=-(HG+HS)*X
  736 QV=-X*2./3.*SQRT(64.4*RHOL*GR/(CSG*RHOG))* (-HG-HS)**1.5
      REV=RHOG*QV*DB/(VIG*AV*.3048E6)
      REV=ABS(REV)
      CSGA=APHIB/REV+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 737
      CSG=(CSGA+CSG)/2.
      GO TO 736
  737 QLIN1=X*2./3.*SQRT(64.4*GR/CSL)*((HG-HO)**1.5)
      ALIN1=(HG-HO)*X
      REL=RHOL*QLIN2*DB/(VIL*ALIN2*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 738
      CSL=(CSLA+CSL)/2.
      GO TO 737
  738 QLIN2=X*SQRT(64.4*GR*(HG-HO)/CSL)*HOB
      ALIN2=HOB*X
      REL=RHOL*QLIN2*DB/(VIL*ALIN2*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      QLIN=QLIN1+QLIN2
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 400
      CSL=(CSLA+CSL)/2.
      GO TO 738
  780 IF(HO.GE.HG)GO TO 782
      IF(HO.LT.HG)GO TO 786
  782 AV=(DH-HOB)*X
      IF(HG+HS.GT.0.)GO TO 785
  783 IF(HO.LT.(HG+HS))GO TO 790
      QV=-X*2./3.*SQRT(64.4*RHOL*GR/(CSG*RHOG))*((-HG-HS+DH-HTANK)**1.5-
     C(-HG-HS-HO)**1.5)
      GO TO 791
  790 AV=(-HG-HS+DH-HTANK)*X
      QV=-X*2./3.*SQRT(64.4*RHOL*GR/(CSG*RHOG))* (-HG-HS+DH-HTANK)**1.5
  791 CONTINUE
      REV=RHOG*QV*DB/(VIG*AV*.3048E6)
      REV=ABS(REV)
      CSGA=APHIB/REV+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 784
      CSG=(CSGA+CSG)/2.
      GO TO 785
  785 CONTINUE
  784 QL1=X*SQRT(64.4*GR*(-HG+HO)/CSL) *HOB
      AL1=HOB*X
```

```
      REL=RHOL*QL1   *DB/(VIL*AL1   *.3048E6)
      CSLA=APHIL/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 400
      CSL=(CSLA+CSL)/2.
      GO TO 784
  786 IF(HG+HS.GT.0.)GO TO 788
      AV=(-HG-HS+DH-HTANK)*X
  787 QV=-X*2./3.*SQRT(64.4*RHOL*GR/(CSG*RHOG))* (-HG-HS+DH-HTANK)**1.5
      REV=RHOG*QV*DB/(VIG*AV*.3048E6)
      REV=ABS(REV)
      CSGA=APHIB/REV+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 788
      CSG=(CSGA+CSG)/2.
      GO TO 787
  788 QLIN1=X*2./3.*SQRT(64.4*GR/CSL)*((HG-HO)**1.5)
      ALIN1=(HG-HO)*X
      REL=RHOL*QLIN1*DB/(VIL*ALIN1*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 789
      CSL=(CSLA+CSL)/2.
      GO TO 788
  789 QLIN2=X*SQRT(64.4*GR*(HG-HO)/CSL)*HOB
      ALIN2=HOB*X
      REL=RHOL*QLIN1*DB/(VIL*ALIN1*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      QLIN=QLIN1+QLIN2
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 400
      CSL=(CSLA+CSL)/2.
      GO TO 789
  801 QV=2.*X*SQRT(64.4*RHOL*GR)*HGP**1.5/(3.*SQRT(CSG*RHOG))
      REG=RHOG*QV*DB/(VIG*AV*.3048E6)
      CSGA=APHIB/REG+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 802
      CSG=ABS(CSG+CSGA)/2.
      GO TO 801
  802 ASSIGN 963 TO MAZ
      GO TO 909
  963 CONTINUE
      AL=ALO*(HO-HG)/DH
      IF(HG-HO)803,951,951
  803 QL1=2.*X*SQRT(2.*32.2*GR)*(HO-HG)**1.5/(3.*SQRT(CSL))
      REL=RHOL*DB*QL1/(VIL*AL*.3046E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 804
      CSL=ABS(CSL+CSLA)/2.
      GO TO 803
  804 IF(HTANK.EQ.0.)GO TO 1000
      AL2=ALO*HTANK/DH
      IF(HTANK.GT.DH)AL2=ALO
      QL2  =AL2    *SQRT(64.4*GR*(HO-HG)/CSL)
      REL=RHOL*DB*QL2/(VIL*AL2*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 1000
      CSL=ABS(CSL+CSLA)/2.
      GO TO 804
```

```
  900 AV=ALO*HGP/DH
      HAREA=HTANK
  901 QV=2.*X*SQRT(64.4*GR*RHOL)*HGP**1.5/(3.*SQRT(CSG*RHOG))
      REG=RHOG*QV*DB/(VIG*AV*.3048E6)
      CSGA=APHIB/REG+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 902
      CSG=ABS(CSG+CSGA)/2.
      GO TO 901
  902 ASSIGN 964 TO MAZ
      GO TO 909
  964 CONTINUE
      IF(HTANK.EQ.0.)GO TO 1000
      AL3=HTANK*ALO/DH
      IF(HTANK.GT.DH)AL3=ALO
      QLIN=AL3*   SQRT(64.4*GR*(HG-HO)/CSL)
      REL=RHOL*QLIN*DB/(VIL*AL3*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      REL=RHOL*QLIN*DB/(VIL*AL3*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 1000
      CSL=ABS(CSL+CSLA)/2.
      GO TO 902
  950 AV=ALO*HO/DH
      HAREA=HTANK
  952 QV=2.*X*SQRT(64.4*GR*RHOL)*(HGP**1.5-(HGP-HO)**1.5)/(3.*SQRT(CSG*R
     CHOG))
      REG=RHOG*QV*DB/(VIG*AV*.3048E6)
      CSGA=APHIB/REG+BSUBSB
      IF(ABS(CSGA-CSG).LE.DELTAC)GO TO 951
      CSG=ABS(CSG+CSGA)/2.
      GO TO 952
  951 ASSIGN 965 TO MAZ
      GO TO 909
  965 CONTINUE
      IF(HTANK.EQ.0.)GO TO 1000
      AL3=HTANK*ALO/DH
      IF(HTANK.GT.DH)AL3=ALO
      QLIN=AL3   *SQRT(64.4*GR*(HG-HO)/CSL)
      REL=RHOL*QLIN*DB/(VIL*AL3*.3048E6)
      CSLA=APHIB/REL+BSUBSB
      IF(ABS(CSLA-CSL).LE.DELTAC)GO TO 1000
      CSL=ABS(CSL+CSLA)/2.
      GO TO 951
 1000 WRITE(6,1001)
 1001 FORMAT(*    HT IS NEGATIVE  *)
      QV=QV+QHT
      GO TO 400
C*************************************************************************
C*************************************************************************
C*************************************************************************
C***** VAPOR MOTION  *****************************************************
```

```
  909 S2=HAREA-HBELOW
      IF(S2.LE.0.)S2=0.
      S3=HAREA-HBELOW+2.*RO
      IF(S3.LE.0.)HAREA=HBELOW-2.*RO
      CALL INGEST
      S4=ACS/X
      S1=SQRT(S4**2+S2**2)
      VVAP=QV/AV
      T=S1/VVAP
  930 WRITE(6,931)S1,T
  931 FORMAT(* VAPOR IS INGESTED AT *F6.4* FT FROM TOP OF ENGINE FEEDLIN
     CE INLET INGESTION TIME IS*E14.7*SEC*)
  932 GO TO MAZ
C*****************************************************************
C ************** CONVERGENCE*****************************************
  400 QG=QO+QL1+QL2-QV-QLIN
      WRITE(6,401)QGA,QG
      WRITE(6,403)QO,QL1,QL2,QLIN,QV
  401 FORMAT(10X,*QGA=*E14.7*CFS*,10X,*QG=*E14.7*CFS*)
  403 FORMAT(*QO=*E14.7*CFS*,4X,*QL1=*E14.7*CFS*,4X,*QL2=*E14.7*CFS*,4X,
     C*QLIN=*E14.7*CFS*,4X,*QV=*E14.7*CFS*)
      DQA=QG-QGA
      IF(ABS(DQA)-DELTAQ)450,450,410
  410 A1=A1+1.
      IF(A1.EQ.1.)GO TO 402
      IF(A1.GE.25.)GO TO 480
      QG2=QG
      QGA2=QGA
      GO TO NIPPY
  411 CONTINUE
      IF(A1.GT.5..A.QG1.EQ.QG2)GO TO 419
      GO TO 412
  419 TIPPY=1.
      DELQGA=ABS(QGA1-QGA2)
  420 IF(QGA2.LT.QG2)GO TO 421
      QGA=QGA2-DELQGA
      BIPPY=1.
      GO TO 423
  421 BIPPY=2.
      QGA=QGA2+DELQGA
  423 ASSIGN 422 TO NIPPY
      IF(TIPPY.EQ.1000.)GO TO 430
      QGA3=QGA1
      QG3=QG1
      QG1=QG2
      QGA1=QGA2
      GO TO 50
  422 IF(BIPPY.EQ.1..A.QGA2.LT.QG2)GO TO 425
      IF(BIPPY.EQ.2..A.QGA2.GT.QG2)GO TO 426
      GO TO 420
  425 CONTINUE
      TIPPY=TIPPY*10.
      DELQGA=DELQGA/10.
```

```
      QGA2=QGA1
      QG2=QG1
      QGA1=QGA3
      QG1=QG3
      GO TO 420
  426 TIPPY=TIPPY*10.
      DELQGA=DELQGA/10.
      QGA2=QGA1
      QG2=QG1
      QGA1=QGA3
      QG1=QG3
      GO TO 421
  430 QG=QGA
      QLIN=QO-QG
      WRITE(6,431)QG,QO,QLIN
  431 FORMAT(*QG=*E14.7,*QO=*E14.7,*QLIN=*E14.7,* TIPPY=1000.*)
      DELQGA=DELQGA*10000.
      A1=6.
      ASSIGN 1422 TO NIPPY
 1420 IF(QGA2.LT.QG2)GO TO 1421
      QGA=QGA2+DELQGA
      BIPPY=1.
      GO TO 1423
 1421 BIPPY=2.
      QGA=QGA2-DELQGA
 1423 QGA3=QGA1
      QG3=QG1
      QGA1=QGA2
      QG1=QG2
      GO TO 50
 1422 IF(BIPPY.EQ.1..A.QGA2.LT.QG2)GO TO 1425
      IF(BIPPY.EQ.2..A.QGA2.GT.QG2)GO TO 1426
      GO TO 1420
 1425 CONTINUE
      TIPPY=TIPPY*10.
      DELQGA=DELQGA/10.
      QGA2=QGA1
      QG2=QG1
      QGA1=QGA3
      QG1=QG3
      GO TO 1420
 1426 TIPPY=TIPPY*10.
      DELQGA=DELQGA/10.
      QGA2=QGA1
      QG2=QG1
      QGA1=QGA3
      QG1=QG3
      GO TO 1421
  412 CONTINUE
      SLOPE=(QG2-QG1)/(QGA2-QGA1)
      QGA=(QG1-SLOPE*QGA1)/(SLOPE-1.)*(-1.0)
      IF(QLIN.EQ.0..A.QGA.LE.0.)QGA=0.1
      QGA1=QGA2
      QG1=QG2
      GO TO 50
```

```
  402 QG1=QG
      QGA1=QGA
      QGA=16.94
      IF(QGA1.EQ.16.94)QGA=25.0
      GO TO 50
  480 IF(A1.EQ.25.)GO TO 482
      IF(QG.GE.0..A.A1.EQ.26.)GO TO 490
      IF(QG.LT.0..A.A1.EQ.26.)GO TO 1490
      IF(QGA.LT.0..A.QGA.GT.QG)GO TO 1490
      IF(QGA.GT.0..A.QG.GT.QGA) GO TO 490
      QGB=QGA
      QGA=QGAR
      IF(ENN.GE.100.)GO TO 1500
      ENN=ENN*10.
      IF(QGB.LE.0.)GO TO 1490
      GO TO 490
  482 QGA=0.01
      GO TO 50
 1490 QGAR=QGA
      QGA=QGA-QO/ENN
      GO TO 50
  490 QGAR=QGA
      QGA=QGA+QO/ENN
      GO TO 50
 1500 QTOTAL=QV+QLIN-QL1-QL2
      QST=QO-QGA
      QRAT=QST/QTOTAL
      QV=QV*QRAT
      QLIN=QLIN*QRAT
      QL1=QL1*QRAT
      QL2=QL2*QRAT
      GO TO 450
C*********************************************************************
C*****VOLUME CHANGE*****************************************************
  450 VOLT=VOL
      VOL=VOL-(QO+QL1+QL2-QLIN)*DTIME
      DVTAN1=(QL1+QL2-QLIN)*DTIME
      DVTANK=DVTANK+DVTAN1
      CALL VOLUME
      H1=HO-DH
      TIME3=TIME+DTIME
      WRITE(6,501)QL1,QL2,QLIN
  501 FORMAT(*LIQUID SPILL INTO VAPOR=*E14.7*CFS*,4X,*LIQUID SPILL INTO
     CLIQUID=*E14.7*CFS*,4X,*REFILLING RATE=*E14.7*CFS*)
      WRITE(6,502)QV,QGA
  502 FORMAT(*  INGESTION RATE =*E14.7*CFS*,4X,*  STANDPIPE RATE = *E14.
     C7*CFS*)
      WRITE(6,15)
      WRITE(6,19)
   19 FORMAT(*          CONDITIONS AT THE END OF THE TIME STEP          *)
      WRITE(6,500)TIME3,VOL,HO,H1,HS
  500 FORMAT(* TIME=*E12.5*SEC*,5X,*LIQUID VOLUME IN BASKET=*E12.5*FT3*,
     C5X,*HO=*E12.5*FT*,5X,*HT=*E12.5*FT*,5X,*HS=*E12.5*FT*)
      WRITE(6,23) RHOG,VIG , RHOL, VIL, HG, REG, HGP
```

```
   23 FORMAT(*RHOG=*F10.4,*VIG=*F10.4,*RHOL=* F10.4, *VIL=*F10.4,
     C*HG=*F10.4, *REG=* F10.4, *HGP=* F10.4 )
C*****************************************************************
C***** PULLTHROUGH   *******************************************
      HOX=1.0
  503 ALPHA=3.0+(HOX/RO)**.10
      BETA=2.0-(HOX/RO)**.1
      CONE=11.8-2.65*(HOX/RO)**.1
      HOY=(QO**2/(GR*32.2*CONE*RO**BETA))**(1.0/ALPHA)
      HOF=HOY
      DHO=HOY-HOX
      IF(ABS(DHO).LT.DELCO)GO TO 510
      HOX=(HOY+HOX)/2.
      GO TO 503
  510 CONTINUE
      IF(HPULL.NE.0.)HOF=HPULL
      HOF=HOF+DHPULL
      IF(HO-HOF)600,525,520
C*****************************************************************
C*****TIME CHANGE*************************************************
  520 IF(TIME-TFINAL)521,700,700
  521 TIME=TIME+DTIME
      GO TO 49
  600 WRITE(6,601)HO,HOF
  601 FORMAT(* PULLTHROUGH OCCURS SINCE HO=*E12.5*    WHICH IS LESS THAN
     C *E12.5*,THE HEIGHT AT PULLTHROUGH*)
      DEH=HOF-HO
      IF(DEH.GT.DELTAC)GO TO 602
      TIME2=TIME+DTIME
      GO TO 605
  602 DTIME=DTIME/10.
      ADT1=DTIME/DTIME1
      IF(ADT1.LT..01)GO TO 603
      VOL=VOLT
      DVTANK=DVTANK-DVTAN1
      GO TO 49
  603 TIME2=TIME+DTIME*10.
  605 WRITE(6,604)TIME,TIME2
  604 FORMAT(* PULLTHROUGH OCCURS BETWEEN*E14.7*SEC**,AND*E14.7*SEC*)
      GO TO 700
  525 WRITE(6,526)
  526 FORMAT(*  PULL THROUGH IS IMMINENT   HOF=HO    *)
      GO TO 700
C*****************************************************************
  700 CONTINUE
      K=K+1
      IF(K.LT.N) GO TO 10
      STOP
      END
      SUBROUTINE REFILL
      COMMON HO,VOL,HOT(20),VOLU(20),IT,NO,MO,TANKVOL(20),TIME,VOLTAN,
     CHTAN(20),VTANK(20),HTANK,TREFILL(20),HSTART,KO,
     CHARC(20),ACSS(20),HAREA,ACS,NI,DVTANK,QO,QOO(20),TI(20),QOX
```

```
      DO 2 I=2,NO
      IK=I-1
      IF(TREFILL(I).LT.TIME)GO TO 2
      VOLTAN=TANKVOL(IK)+(TANKVOL(I)-TANKVOL(IK))*(TIME-TREFILL(IK))/(TR
     CEFILL(I)-TREFILL(IK))
      VOLTAN=VOLTAN+DVTANK
      GO TO 3
    2 CONTINUE
    3 CONTINUE
      RETURN
      END
      SUBROUTINE VOLUME
      COMMON HO,VOL,HOT(20),VOLU(20),IT,NO,MO,TANKVOL(20),TIME,VOLTAN,
     CHTAN(20),VTANK(20),HTANK,TREFILL(20),HSTART,KO,
     CHARE(20),ACSS(20),HAREA,ACS,NI,DVTANK,QO,QOO(20),TI(20),QOX
      DO 900 IJ=1,IT
      IK=IJ+1
      IF(VOLU(IT).LT.VOL)GO TO 6
      BB=VOLU(IK)-VOL
      IF(BB.LT.0.)GO TO 900
      HO=HOT(IJ)+(HOT(IK)-HOT(IJ))*(VOL-VOLU(IJ))/(VOLU(IK)-VOLU(IJ))
      GO TO 901
  900 CONTINUE
    6 HO=HOT(IT)
  901 CONTINUE
      RETURN
      END
      SUBROUTINE VOLTANK
      COMMON HO,VOL,HOT(20),VOLU(20),IT,NO,MO,TANKVOL(20),TIME,VOLTAN,
     CHTAN(20),VTANK(20),HTANK,TREFILL(20),HSTART,KO,
     CHARE(20),ACSS(20),HAREA,ACS,NI,DVTANK,QO,QOO(20),TI(20),QOX
      DO 2 I=2,MO
      IK=I-1
      IF(VOLTAN.GT.VTANK(MO))GO TO 6
      IF(VTANK(I).LT.VOLTAN)GO TO 2
      HTANN=HTAN(IK)+(HTAN(I)-HTAN(IK))*(VOLTAN -VTANK(IK))/(VTANK(I)-VT
     CANK(IK))
      IF(HTANN-HSTART)4,4,5
    4 HTANK=0.
      GO TO 3
    5 HTANK=HTANN-HSTART
      GO TO 3
    2 CONTINUE
    6 HTANN=HTAN(MO)
    3 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INGEST
      COMMON HO,VOL,HOT(20),VOLU(20),IT,NO,MO,TANKVOL(20),TIME,VOLTAN,
     CHTAN(20),VTANK(20),HTANK,TREFILL(20),HSTART,KO,
     CHARE(20),ACSS(20),HAREA,ACS,NI,DVTANK,QO,QOO(20),TI(20),QOX
      DO 2 IJ=2,NI
      IK=IJ-1
      IF(HAREA.GT.HARE(NI))GO TO 6
      IF(HARE(IJ).LT.HAREA)GO TO 2
      ACS=ACSS(IK)+(HAREA-HARE(IK))/(HARE(IJ)-HARE(IK))*(ACSS(IJ)-ACSS(I
     CK))
      GO TO 3
    2 CONTINUE
    6 ACS=ACSS(NI)
    3 CONTINUE
      RETURN
      END
      SUBROUTINE FLOW
      COMMON HO,VOL,HOT(20),VOLU(20),IT,NO,MO,TANKVOL(20),TIME,VOLTAN,
     CHTAN(20),VTANK(20),HTANK,TREFILL(20),HSTART,KO,
     CHARE(20),ACSS(20),HAREA,ACS,NI,DVTANK,QO,QOO(20),TI(20),QOX
      DO 2 K=2,KO
      KI=K-1
      IF(TI(K).LT.TIME) GO TO 2
      XQ=QOO(KI)+(QOO(K)-QOO(KI))*(TIME-TI(KI))/(TI(K)-TI(KI))
      QO=QOX*XQ
      GO TO 3
    2 CONTINUE
    3 CONTINUE
      RETURN
      END
R
        1          10           8           6          10           2
     4.26       8.E-6        0.14      0.8E-6   1.126E-4       0.337        17.3        17.3
     22.8         190.         18.        13.4        36.7        52.          3.       19.05
       0.           1.0        15.         0.1         0.1        0.1         0.1        0.29
     200.           2.0        41.        20.5        1.42       0.75       0.001         1.0
    0.458           0.       .0055       .0058         20.        20.
       0.    .458    .906   1.166   1.584    2.00   2.416   2.833    3.25   4.083
    8.72   15.17   22.03   26.27   32.87   39.12   45.87   53.03   59.82   75.79
       0.   0.458   0.874   1.291   2.125   2.958   3.798    4.4
       0.    5.36   17.86   30.36   55.36   85.36  155.36  200.
       0.     10.     50.    100.    640.  6298.
       0.      1.      2.      3.      10.     30.
       0.    .416    .833    1.00    1.67    2.50    3.34    4.16    5.40   20.74
       0.    5.46    26.4    30.1    55.0    97.0   181.0   262.5    640.   6298.
       0.     30.
     1.0      1.0
>
```

APPENDIX B

OUTFLOW COMPUTER PROGRAM LISTING

DREGS2

This program predicts liquid levels and volumes in a draining tank containing a capillary device. The equations for screen flow and vapor pullthrough are taken from Convair test data correlations, however these correlations may easily be modified to suit the condition of the problem being run. The program is limited to the high Bond number case. The iterative technique employed uses a modified Regula-Falsi convergence procedure.

All input variables are given in 8 consecutive cards in the initial portion of the program. These variables are defined in the comment cards. Input flags are given 4 cards before this group of inputs. The input flags are; N, the number of cases input, NI, the number of tank volume vs height entries and NO, the number of capillary device height vs volume entries. With the flag card placed as shown, the flag card need only be input in front of the initial case.

Output statements are underlined in the Fortran listing for a sample output.

```
      PROGRAM DREGS2 (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON HLO,HLI,VOLO,VOLI,HLOT(11),HLIT(11),VOLOT(11),VOLIT(11),NI,
     CNO,IT,QGA,QGAT,QLO,QGA1,QGA2
C     A1=VISCOUS CONSTANT OF SIDE SCREEN
CC    A2=INERTIAL CONSTANT SIDE SCREEN
CC    ALO=SIDE SCREEN FLOW AREA
CC    B1=VISCOUS CONSTANT TOP SCREEN
CC    B2=INERTIAL CONSTANT TOP SCREEN
CC    DA=AVERAGE CAPILLARY DIAMETER OF SIDE SCREEN MICRONS
CC    DB=AVERAGE CAPILLARY DIAMETER OF TOP SCREEN MICRONS
CC    DBP=BUBBLE POINT SIDE SCREEN MICRONS
CC    DBPB=BUBBLE POINT TOP SCREEN MICRONS
CC    DELTAQ=ITERATION TOLERANCE ON DELTAQ
CC    DH=HEIGHT  OF SIDE SCREEN FLOW AREA
CC    DHPULL=DISTANCE BETWEEN BOTTOM OF CAPILLARY DEVICE AND OUTLET CENTERLINE
CC    DTIME=TIME STEP INTERVAL   SECONDS
CC    GR=GRAVITY LEVEL (G)
CC    HBELOW=DISTANCE ABOVE BOTTOM OF START BASKET TO TOP OF ENGINE FEED LINE
CC    HLI=LIQUID LEVEL IN CAPILLARY DEVICE ABOVE BOTTOM OF START BASKET
CC    HLO= LIQUID LEVEL IN TANK ABOVE BOTTOM OF START BASKET
CC    HLOOK=SUBROUTINE TO LOOK UP HEIGHT VS VOLUME INSIDE CAPILLARY DEVICE
CC    HVOL=START BASKET HEIGHT BELOW SCREENED AREA WHERE NO FLOW CAN OCCUR
CC    QLO=OUTLET FLOW RATE FT**3/SEC
CC    REDO=RESTART FLAG-IF EQUAL TO 1, LIQUID LEVEL INSIDE CAPILLARY DEVICE IS
CC    INITIALLY BELOW THE TOP OF THE CAPILLARY DEVICE
CC    RHOG=VAPOR  DENSITY LB/FT**3
CC    RHOL=LIQUID DENSITY LB/FT**3
CC    S=SURFACE TENSION LB/FT
CC    THA=THICKNESS OF SIDE SCREEN FEET
CC    THB=TOP SCREEN THICKNESS FEET
CC    TIME =INITIAL TIME SECONDS
CC    TIMEF=FINAL TIME SECONDS
CC    VIG=VAPOR VISCOSITY LB/SEC*FT
CC    VIL=LIQUID VISCOSITY LB/SEC*FT
CC    VOLI=VOLUME INSIDE THE CAPILLARY DEVICE  FT**3
CC    VOLIN=SUBROUTINE TO LOOK UP VOLUME VS HEIGHT INSIDE CAPILLARY DEVICE
CC    VOLIT=VOLUME IN CAPILLARY DEVICE AS A FUNCTION OF HEIGHT
CC    VOLO=TANK VOLUME OUTSIDE THE CAPILLARY DEVICE  FT**3
CC    VOLOT=VOLUME IN TANK AS A FUNCTION OF HEIGHT
C     VOLOUT=SUBROUTINE TO LOOK UP VOLUME VS HEIGHT OUTSIDE CAPILLARY DEVICE
      NUM=0
      READ(5,11)N,NI,NO
    2 NUM=NUM+1
      WRITE(6,99)
      WRITE(6,99)
      WRITE(6,99)
   99 FORMAT(*                              *)
      READ(5,1)RHOL,VIL,RHOG,VIG,S,GR,QLO,DHPULL
      READ(5,1)DA,A1,A2,DBP,DB,B1,B2,DBPB
      READ(5,1)TIME,DTIME,TIMEF,DELTAQ,ALO,DH,HPULL,REDO
      READ(5,1)THA,THB,VOLO,VOLI,AG,RO,HVOL,HBELOW
      READ(5,7)(HLOT(I),I=1,NI)
      READ(5,7)(VOLOT(I),I=1,NI)
      READ(5,7)(HLIT(I),I=1,NO)
```

```
      READ(5,7)(VOLIT(I),I=1,NO)
      WRITE(6,35)AG,ALO,GR,RHOL,QLO
   35 FORMAT(*AG=*E12.5,*  ALO=*E12.5,* GR=*E12.5,* RHOL=*E12.5,* QLO=*E1
     C2.5)
   31 FORMAT(*HG=*E12.5,*HLO=*E12.5,*HLI=*E12.5,*QGA=*E12.5,*QGAT=*E12.5
     C,*QL1=*E12.5,  *QL2=*E12.5,*QV=*E12.5)
    1 FORMAT(8E10.3)
    7 FORMAT(11E7.3)
   11 FORMAT(8I10)
      DB=DB/.3048E6
      DA=DA/.3048E6
      DBP=DBP/.3048E6
      DBPB=DBPB/.3048E6
      QGA=QLO
      QL1=0.
      QL2=0.
      QV=0.
      AL=A1*THA*VIL/(DA**2*32.2*RHOL*GR)
      AV=B1*THB*VIG/(DB**2*32.2*RHOL*GR)
      AX =A1*THA*VIG/(DA**2*32.2*RHOL*GR)
      BL=A2*THA*RHOL/(DA*32.2*RHOL*GR)
      BV=B2*THB*RHOG/(DB*32.2*RHOL*GR)
      BX =A2*THA*RHOG/(DA*32.2*RHOL*GR)
      X=ALO/DH
      CALL VOLIN
      CALL VOLOUT
      VOLI1=VOLI
      VOLO1=VOLO
      DTIME1=DTIME
      VFL=QLO/ALO
      HFL1=AL*VFL+BL*VFL**2
      HS=4.*S/(DBP*GR*RHOL)
      HSB=HS*DBP/DBPB
      IF(HFL1+HLO-HLI.GT.HSB)GO TO 90
      VFL=-AL/(2.*BL)+SQRT(AL**2/(4.*BL**2)+HS)
      AL1=QLO/VFL
      HLO=AL1/X
      IF(REDO.EQ.1.0)GO TO 90
      IF(HS.LT.HSB-HLI+HLO)GO TO 20
      GO TO 21
   20 CONTINUE
      VFL=-AL/(2.*BL)+SQRT(AL**2/(4.*BL**2)+HSB)
      AL1=QLO/VFL
      IF(AL1.GT.ALO)AL1=ALO
      HLO=AL1/X
   21 CONTINUE
      VOL1=VOLO
      CALL HLOOK
      DTIM=(VOL1-VOLO)/QLO
      TIME = TIME+DTIM
      WRITE(6,30)VOLO,VOLI,HLO,HLI,TIME,AL1
   30 FORMAT(* VOLO=*F8.5,*  VOLI=*F8.5,* HLO=*F8.5,* HLI=*F8.5,* TIME=*F
     C8.5,* AL2=*F8.5)
      GO TO 90
```

```
 90 IT=0
    QGA1=0.
    QGA2=0.
    QGA=QLO
    WRITE(6,99)
    IF(HLO.LT.DH.A.HLI.GT.DH)GO TO 1000
    IF(HLI.LT.DH.A.HLO.GT.DH)GO TO 2000
    IF(HLI.LT.DH.A.HLO.LT.DH) GO TO 4000
100 VG=QGA/AG
    HG=AV*VG+BV*VG**2
    IF(HLO-HLI+HG)101,102,103
101 QL1=(AL/(2.*BL)-SQRT(AL**2/(4.*BL**2)+(HLI-HLO-HG)))*ALO
    GO TO 104
102 QL1=0.
    GO TO 104
103 QL1=(-AL/BL+SQRT(AL**2/(BL**2)+4.*(HLO-HLI+HG)))/2.*ALO
104 CONTINUE
    QGAT=QLO-QL1
    WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
    IF(ABS(QGAT-QGA).LE.DELTAQ)GO TO 3000
    CALL CONV
    IF(EPP.EQ.1.)GO TO 3000
    GO TO 100
1000 AL1=HLO*ALO/DH
1001 VG=QGA/AG
    HG=AV*VG+BV*VG**2
    DPL=HG+HLO-HLI
    IF(DPL)1002,1003,1004
1002 QL1=-AL1/(2.*BL)*(-AL+SQRT(AL**2-4.*BL*DPL))
    QV=0.
    QL2=          X/(12.*BL**2)*((AL**2+4.*BL*(HLI-HG-DH))**1.5-(AL
   C**2+4.*BL*(HLI-HG-HLO))**1.5)+X*AL/(2.*BL)*(DH-HLO)
    QGAT=QLO-QL1-QL2
    WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
    IF(ABS(QGAT-QGA).LE.DELTAQ)GO TO 3000
    CALL CONV
    IF(EPP.EQ.1.)GO TO 3000
    GO TO 1001
1003 IF(HG-HS.LE.HLI-HLO)GO TO 3000
    QV=          X/(12.*BX**2)*((AX**2+4.*BX*(HG-HS-HLI+DH))**1.5-
   C(AX**2+4.*BX*(HG-HS-HLI+HLO))**1.5)-X*AX/(2.*BX)*(DH-HLO)
    QL1=0.
    QL2=0.
    QGAT=QLO-QV
    WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
    IF(ABS(QGAT-QGA).LE.DELTAQ)GO TO 3000
    CALL CONV
    GO TO 1001
1004 QL1=AL1/(2.*BL)*(-AL+SQRT(AL**2+4.*BL*DPL))
    QL2=0.
    IF(HG-HS.LE.HLI-HLO)GO TO 1005
    QV=          X/(12.*BX**2)*((AX**2+4.*BX*(HG-HS-HLI+DH))**1.5-
   C(AX**2+4.*BX*(HG-HS-HLI+HLO))**1.5)-X*AX/(2.*BX)*(DH-HLO)
```

```
      GO TO 1006
1005  QV=0.
1006  CONTINUE
      QGAT=QLO-QL1-QV
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LT.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 1001
2000  VG=QGA/AG
      HG=AV*VG+BV*VG**2
      AL1=HLI*ALO/DH
      QV=0.
      QL1=AL1*(-AL/BL+SQRT(AL**2/BL**2+4.*(HLO-HLI+AV*VG+BV*VG**2)/BL))/
     C2.
      QL2=                  X/(12.*BL**2)*((AL**2+4.*BL*(HLO-HLI+HG))**1.5-(
     CAL**2+4.*BL*(HLO-DH+HG))**1.5)-X*AL/(2.*BL)*(DH-HLI)
      QGAT=QLO-QL1-QL2
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LE.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 2000
4000  IF(HLO.GT.HLI)AV1=(DH-HLO)*ALO/DH
      IF(HLO.LE.HLI)AV1=(DH-HLI)*ALO/DH
      AG=AV1+AG
      VG=QGA/AG
      HG=AV*VG+AV*VG**2
      IF(HLO-HLI)4100,4200,4300
4100  DPL=HG+HLO-HLI
      IF(DPL)4102,4103,4104
4102  QL1=-AL1/2./BL*(-AL+SQRT(AL**2-4.*BL*DPL))
      QV=0.
      QL2=                 -X/(12.*BL**2)*((AL**2+4.*BL*(HLI-HG-HLO))**1.5)
     C+X*AL/(2.*BL)*(HLI-HG-HLO)
      QGAT=QLO-QL1-QL2
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LE.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 4000
4103  IF(HG-HS.LE.HLI-HLO)GO TO 3000
      QV=                  X/(12.*BX**2)*(AX**2+4.*BX*(HG-HS-HLI+HLO))**1.5
     C-X*AX/(2.*BX)*(HG-HS-HLI+HLO)
      QL1=0.
      QL2=0.
      QGAT=QLO-QV
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LE.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 4000
4104  QL1=AL1/2./BL*(-AL+SQRT(AL**2+4.*BL*DPL))
      QL2=0.
```

```
      QV=              X/(12.*BX**2)*((AX**2+4.*BX*(HG-HS))**1.5-(AX**2+4.
     C*BX*(HG-HS-HLI+HLO))**1.5)-X*AX/(2.*BX)*(HLI-HLO)
      GO TO 4106
 4105 QV=0.
 4106 CONTINUE
      QGAT=QLO-QL1-QV
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LT.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 4000
 4200 QL1=(ALO-AV1)/(2.*BL)*(-AL+SQRT(AL**2+4.*BL*HG))
      QL2=0.
      QV=0.
      QGAT=QLO-QL1
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LT.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 4000
 4300 QL1=HLI*ALO/(DH*BL*2.)*(-AL+SQRT(AL**2+4.*BL*(HLO-HLI+HG)))
      QV=0.
      QL2=                X/(12.*BL**2)*((AL**2+4.*BL*(HLO-HLI+HG))**1.5-(
     CAL**2+4.*BL*(    HG))**1.5)-X*AL/(2.*BL)*(HLO-HLI)
      QGAT=QLO-QL1-QL2
      WRITE(6,31)HG,HLO,HLI,QGA,QGAT,QL1,QL2,QV
      IF(ABS(QGAT-QGA).LT.DELTAQ)GO TO 3000
      CALL CONV
      IF(EPP.EQ.1.)GO TO 3000
      GO TO 4000
 3000 TIME=TIME+DTIME
      WRITE(6,3001)QLO,QGA ,QL1,QL2,QV,TIME
 3001 FORMAT(*QLO=*E14.7,* QGA=*E14.7,* QL1=*E14.7,* QL2=*E14.7,* QV=*E1
     C4.7,* TIME=*F9.3)
      VOLI1=VOLI
      VOLO1=VOLO
      VOLO=VOLO-(QL1+QL2)*DTIME
      VOLI=VOLI-(QLO-QL1-QL2)*DTIME
      CALL VOLIN
      CALL VOLOUT
      IF(VOLO.LT.VOLOT(1))GO TO 602
      WRITE(6,3002)VOLO,VOLI,HLO,HLI
 3002 FORMAT(* VOLO=*E14.7,* VOLI=*E14.7,* HLO=*E14.7,* HLI=*E14.7)
      QO=QLO-QL1-QL2
      QL1=0.
      QL2=0.
      QV =0.
      HOX=1.0
  503 ALPHA=3.0+(HOX/RO)**.10
      BETA=2.0-(HOX/RO)**.1
      CONE=11.8-2.65*(HOX/RO)**.1
      HOY=(QO**2/(GR*32.2*CONE*RO**BETA))**(1.0/ALPHA)
```

```
      HOF=HOY
      DHO=HOY-HOX
      IF(ABS(DHO).LE.DELTAW)GO TO 510
      HOX=(HOY+HOX)/2.
      GO TO 503
  510 IF(HPULL.NE.0.)HOF=HPULL
      HOF=HOF+DHPULL
      IF(HLI.LE.HOF)GO TO 590
      IF(TIME.LE.TIMEF)GO TO 90
  590 IF(ABS(HLI-HOF).LT.DELTAW)GO TO 600
      TIME=TIME-DTIME
      DTIME=DTIME/10.
      IF(DTIME.LT.DTIME1/100.)GO TO 600
      VOLI=VOLI1
      VOLO=VOLO1
      CALL VOLIN
      CALL VOLOUT
      WRITE(6,3002)VOLO,VOLI,HLO,HLI
      GO TO 90
  600 WRITE(6,601)HLI,HOF
  601 FORMAT(* PULLTHROUGH OCCURS SINCE HLI=*E13.6,*  WHICH IS LESS THAN
     C *E12.5*,THE HEIGHT AT PULLTHROUGH*)
      GO TO 650
  602 VOLO=VOLOT(1)
      DELTEE=(VOLO1-VOLOT(1))/QLO
      TIME=TIME+DELTEE-DTIME
      VOLI=VOLI1-(QLO-QL1-QL2)*DELTEE
      VOLI1=VOLI
      CALL VOLIN
      HLO=HLOT(1)
      WRITE(6,3002)VOLO,VOLI,HLO,HLI
      HLI=HOF
      DO 603 I=2,NI
      K=I-1
      IF(HLIT(I).LT.HLI)GO TO 603
      VOLI=VOLIT(K)+(VOLIT(I)-VOLIT(K))*(HLI-HLIT(K))/(HLIT(I)-HLIT(K))
      GO TO 634
  603 CONTINUE
  634 CONTINUE
      TIME=TIME-(VOLI-VOLI1)/QLO
      WRITE(6,3004)TIME
 3004 FORMAT(* TIME=*E12.5*SECONDS*)
      WRITE(6,3002)VOLO,VOLI,HLO,HLI
      GO TO 2
  650 CONTINUE
      IF(NUM.LT.N)GO TO 2
      STOP
      END
      SUBROUTINE VOLIN
      COMMON HLO,HLI,VOLO,VOLI,HLOT(11),HLIT(11),VOLOT(11),VOLIT(11),NI,
     CNO,IT,QGA,QGAT,QLO,QGA1,QGA2
```

```
      DO200 I=2,NI
      K=I-1
      IF(VOLI.GT.VOLIT(NI))GO TO 210
      IF(VOLIT(I).LT.VOLI)GO TO 200
      HLI=HLIT(K)+(HLIT(I)-HLIT(K))*(VOLI-VOLIT(K))/(VOLIT(I)-VOLIT(K))
      GO TO 220
  200 CONTINUE
  210 HLI=HLIT(NI)
  220 CONTINUE
      RETURN
      END
      SUBROUTINE VOLOUT
      COMMON HLO,HLI,VOLO,VOLI,HLOT(11),HLIT(11),VOLOT(11),VOLIT(11),NI,
     CNO,IT,QGA,QGAT,QLO,QGA1,QGA2
      DO300 I=2,NO
      K=I-1
      IF(VOLO.GT.VOLOT(NO))GO TO 310
      IF(VOLOT(I) .LT.VOLO)GO TO 300
      HLO=HLOT(K)+(HLOT(I)-HLOT(K))*(VOLO-VOLOT(K))/(VOLOT(I)-VOLOT(K))
      GO TO 320
  300 CONTINUE
  310 HLO=HLOT(NO)
  320 CONTINUE
      RETURN
      END
      SUBROUTINE CONV
      COMMON HLO,HLI,VOLO,VOLI,HLOT(11),HLIT(11),VOLOT(11),VOLIT(11),NI,
     CNO,IT,QGA,QGAT,QLO,QGA1,QGA2
      IF(IT.EQ.0)GO TO 500
      EPP=0.
      IF(IT.GE.25.)GO TO 520
      ENN=1.
      QGA2=QGA1
      QGAT2=QGAT1
      QGA1=QGA
      QGAT1=QGAT
      SLOPE=(QGAT2-QGAT1)/(QGA2-QGA1)
      QGA=(QGAT1-SLOPE*QGA1)/(1.-SLOPE)
      IF(QGA.LE.0.)QGA=QLO/10000.
      IF(QGA.EQ.QGA1)QGA=QGA/100.
      GO TO  550
  520 IF(IT.EQ.25.)GO TO 530
      IF(QGAT.GE.0..A.IT.EQ.26.)GO TO 545
      IF(QGAT.LT.0..A.IT.EQ.26.)GO TO 540
      IF(QGA .LT.0..A.QGA.GT.QGAT)GO TO 540
      IF(QGA .GT.0..A.QGAT.GT.QGA) GO TO 545
      QGB=QGA
      QGA=QGAR
      IF(ENN.GE.100.)GO TO 546
      ENN=ENN*10.
      IF(QGB.LT.0.)GO TO 540
      GO TO 545
  546 QTOTAL=QV+QL1+QL2
      QSR=QLO-QGA
      QRAT=QSR/QTOTAL
```

```
      QV=QV*QRAT
      QL1=QL1*QRAT
      QL2=QL2*QRAT
      EPP=1.
      GO TO 550
  530 QGA=0.01
      GO TO 550
  540 QGAR=QGA
      QGA=QGA-QLO/ENN
      GO TO 550
  545 QGAR=QGA
      QGA=QGA+QLO/ENN
      GO TO 550
  500 QGA1=QGA
      QGAT1=QGAT
      QGA=(QGAT+QGA)/2.
      IF(QGA.LE.0.)QGA=QLO/10000.
  550 IT=IT+1
      RETURN
      END
      SUBROUTINE HLOOK
      COMMON HLO,HLI,VOLO,VOLI,HLOT(11),HLIT(11),VOLOT(11),VOLIT(11),NI,
     CNO,IT,QGA,QGAT,QLO,QGA1,QGA2
      DO 400 I=2,NO
      K=I-1
      IF(HLO.GT.HLOT(NO))GO TO 410
      IF(HLOT(I).LT.HLO)GO TO 400
      VOLO=VOLOT(K)+(VOLOT(I)-VOLOT(K))*(HLO-HLOT(K))/(HLOT(I)-HLOT(K))
      GO TO 420
  400 CONTINUE
  410 VOLO=VOLOT(NO)
  420 CONTINUE
      RETURN
      END
```

R

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    4.26      8.E-6      0.14   0.8E-6  1.126E-4   0.482   17.3   0.29
    22.8      190.        18.     13.4      36.7     52.     3.   19.05
     0.        5.        100.    0.025     10.25     0.50   0.46    0.
  .0055     .0058        640.     200.      0.70    0.458  0.001   0.75
  0.   0.67   1.50   2.34   3.16   4.40   4.41   4.42
30.1    55.    87.   171.  252.5   640.   641.   642.
  0.  0.458  0.874  1.291  2.125  2.958  3.798  4.400
  0.   5.36  17.86  30.36  55.36  85.36 155.36   200.
    4.26      8.E-6      0.14   0.8E-6  1.126E-4   0.482   17.3   0.29
    22.8      190.        18.     13.4      36.7     52.     3.   19.05
     0.        5.        100.      0.4      20.5      1.0   0.46    0.
  .0055     .0058        640.     200.      0.70    0.458  0.001   0.75
  0.   0.67   1.50   2.34   3.16   4.40   4.41   4.42
30.1    55.    87.   171.  252.5   640.   641.   642.
  0.  0.458  0.874  1.291  2.125  2.958  3.798  4.400
  0.   5.36  17.86  30.36  55.36  85.36 155.36   200.
    4.26      8.E-6      0.14   0.8E-6  1.126E-4   0.482   17.3   0.29
    22.8      190.        18.     13.4      36.7     52.     3.   19.05
     0.        5.        100.      0.4       41.      2.0   0.46    0.
  .0055     .0058        640.     200.      0.70    0.458  0.001   0.75
  0.   0.67   1.50   2.34   3.16   4.40   4.41   4.42
30.1    55.    87.   171.  252.5   640.   641.   642.
  0.  0.458  0.874  1.291  2.125  2.958  3.798  4.400
  0.   5.36  17.86  30.36  55.36  85.36 155.36   200.
    4.26      8.E-6      0.14   0.8E-6  1.126E-4   0.482   17.3   0.29
    22.8      190.        18.     13.4      36.7     52.     3.   19.05
     0.        5.        100.      0.4      82.0      4.0   0.46    0.
  .0055     .0058        640.     200.      0.70    0.458  0.001   0.75
  0.   0.67   1.50   2.34   3.16   4.40   4.41   4.42
30.1    55.    87.   171.  252.5   640.   641.   642.
  0.  0.458  0.874  1.291  2.125  2.958  3.798  4.400
  0.   5.36  17.86  30.36  55.36  85.36 155.36   200.
```