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STUDY OF LIQUID AND VAPOR FLOW INTO A CENTAUR CAPILLARY DEVICE

GENERAL DYNAMICS
Convair Division

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STUDY OF LIQUID AND VAPOR FLOW INTO A CENTAUR CAPILLARY DEVICE

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FOREWORD

This study was performed by General Dynamics Convair Division under NAS3-20092. Under a subcontract from November 1978 to May 1979, Science Applications, Inc. completed propellant management systems comparisons and prepared the written draft of this report. This final report summarizes the technical effort from March 1976 to September 1979. Convair program manager from March 1976 to August 1978 was M. H. Blatt. R. D. Bradshaw was program manager from August 1978 to September 1979. M. H. Blatt developed the refilling computer program, monitored the refilling tests, data reduction and modeling correlation, completed vapor inflow testing and data correlation and performed the propellant management system comparison. F. Merino developed the vapor inflow analysis. L. E. Siden designed the experimental apparatus for both the liquid and vapor flow tests, R. Spencer and D. Uhlken were test conductors. J. A. Risberg provided technical support in running vapor inflow tests, reducing data from both liquid and vapor inflow tests and correlating the data with analytical models. M. D. Walter developed capillary device and thermal subcooler weights. R. Makela determined propellant management system relative reliability. Chloe Bradshaw prepared the artwork and typed the final report.

All data are presented with the International System of Units as the primary system and English Units as the secondary units. The English system was used for the basic calculations.

SUMMARY

The study was concerned with three main areas (1) analytical and experimental investigation of refilling of start baskets with settled fluid, (2) analytical and experimental investigation of the retention capability of wetted screens when subjected to vapor flow and, (3) comparison of alternative propellant management systems for the Centaur D-1S vehicle.

In the refilling task, a computer program was written to include the effects of dynamic pressure, screen wicking, multiple screen barriers, standpipe (window) screens, variable vehicle mass for computing vehicle acceleration, calculation of tank outflow rate and vapor pullthrough height, options for wetting and spilling. An experimental apparatus was designed, fabricated and tested to provide data for correlation with the analytical model. The test program was conducted in normal gravity using a scale model capillary device and ethanol as the test fluid. The test program provided data that was successfully correlated with the analytical model. The model was then used to analyze Centaur D-1S LO_2 and LH_2 capillary devices for worst case mission conditions.

Analysis of vapor inflow across initially wetted screens was performed using bench tests to provide a semi-empirical model for the flow and pressure relationships applicable to the operation of a single screen window within a multiple screen capillary device. An extensive program of small scale bench tests was conducted using hexane, ethanol and Freon with transparent models simulating multiple screen/window configurations. The results obtained had lower repeatibility than was desired, creating greater variability in the semi-empirical model predictions than is generally desirable for capillary device design. The worst case semi-empirical model predictions were used, however, to verify that the Centaur D-1S passive thermal conditioning system would have a high probability of operating successfully. A description is given of the recommended experimental program to obtain repeatable data on vapor flow across wetted screen window configurations.

Propellant management system alternatives were compared for the Centaur D-1S vehicle. Ten system concepts were compared on the basis of payload weight penalty, hardware weight, relative reliability, electrical power consumption and mission profile flexibility. Subsystem comparisons were made between settling rockets and start baskets; pressure feed and thermal subcoolers for boost pump NPSP (net positive suction pressure); boost pumps, thermal subcoolers and pressure feed for turbopump NPSP; cooled and uncooled ducts; and dumping any coolant required overboard or pumping it back into the tank. Comparisons indicate that the baseline Centaur D-1S system is a prime

propellant management system candidate based on payload weight. Depending upon the relative importance of hardware weight, reliability, power consumption and flight profile flexibility, promising subsystem alternatives worthy of consideration are thermally subcooled boost pumps, pressure fed turbopumps and capillary devices.

1

INTRODUCTION

The objectives of this study were to determine the characteristics of liquid and vapor flow into a Centaur D-1S capillary device and to compare capillary devices with other propellant feed system alternatives.

The use of capillary devices for replacing the baseline hydrogen peroxide settling system on Centaur was examined in detail in Reference 1-1. The analysis indicated that passively cooled start baskets (using layers of fine mesh screen materials for wicking) coupled with thermal subcoolers (for replacing the main tank pressurization system) were promising for multiple burn missions. Subsequent work, reported in Reference 1-2, was conducted to study wicking configurations for passive cooling, and thermal subcoolers for replacing boost pumps. Experimental evaluation of the passive cooling configurations identified that closely spaced multiple layers of perforated plate and fine mesh screen material could satisfy all Centaur D-1S capillary device thermal conditioning requirements. Several important areas for investigation were identified as a result of the efforts undertaken in Reference 1-2. These areas were capillary device refilling with settled fluid and vapor flow across wetted screens. (Vapor must enter the capillary device to replace liquid evaporated by incident heat flux). A comparative evaluation of competing propellant management techniques for Centaur D-1S was identified as a useful method of determining the relative merits of promising subsystem alternatives.

The baseline vehicle configuration for this study was the Centaur D-1S. The Centaur D-1S, as defined in Reference 1-3, represented a minimum change D-1T configuration (Centaur formerly used with Titan), modified to be compatible with the Space Shuttle interface, operations and safety requirements. Approximately 95% of the existing Centaur components remain unchanged for the D-1S. Figure 1-1 summarizes significant modifications made to the existing D-1T to evolve the D-1S configuration.

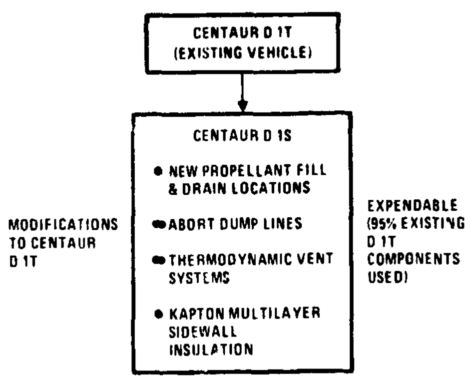


Figure 1-1. Evolution of the Existing Centaur D-1T to a Centaur Compatible with Space Shuttle

Mission profiles for the study were the planetary (1 burn), synchronous equatorial (2 burn) and low earth orbit (5 burn) flight profiles defined in References 1-1, 1-2, and 1-3 and documented in Tables 1-1, 1-2, and 1-3.

Table 1-1. Planetary Mission Profile

Event/ Time (min.)	Initial Mass, kg_m (lb_m)		Burn Time, sec	Propellant Burned, kg_m (lb_m)	Final Mass, kg_m (lb_m)	Initial Percent Full*	Initial Acceleration, g
Loading (T=0)	LO_2	11,554 (25,450)					
	LH_2	2,397 (5,279)					
MES1 (T=67)	Vehicle	22,434 (49,413)			8,888(19,578)		
	LO_2	11.488 (25,304)	441.4	11,302 (24,894)	186 (410)	96	0.61
	LH_2	2,344 (5,164)		2,243 (4,941)	101 (223)	95	

*Assumes 11,946 kg_m (26,313 lb_m), LO_2 2,478 kg_m (5,459 lb_m), LH_2 for full tank.

Main engine thrust = 13,620 kg_f (30,000 lb_f)
Maximum ACS thrust = 10.9 kg_f (24 lb_f)
Maximum ACS acceleration before last burn = 4.86×10^{-4} g's
Main engine flow rates, LO_2 = 25.6 kg/sec (56.4 lb/sec)
LH_2 = 5.1 kg/sec (11.2 lb/sec)

ISP = 443.82 sec
Payload = 6,567 kg_m (14,465 lb_m)
Dry weight = 2,015 kg_m (4,439 lb_m)
Burnout acceleration = 1.53 g's

Table 1-2. Synchronous Equatorial Mission Profile

Event/ Time (min.)	Initial Mass, kg_m (lb_m)		Burn Time, sec	Propellant Burned, kg_m (lb_m)	Final Mass, kg_m (lb_m)	Initial Percent Full*	Initial Acceleration, g
Loading (T = 0)	LO_2	11,554 (25,450)					
	LH_2	2,397 (5,279)					
MES1 (T=67)	Vehicle	21,541 (47,447)			12,100 (26,653)		
	LO_2	11,488 (25,304)	305.4	7,854 (17,299)	3,634 (8,005)	96	0.63
	LH_2	2,344 (5,164)		1,525 (3,360)	819 (1,804)	95	
MES2 (T=384)	Vehicle	12,162 (26,788)			7,956 (17,525)		
	LO_2	3,621 (7,975)	132.3	3,403 (7,496)	190 (419)	30.3	1.12
	LH_2	782 (1,723)		665 (1,465)	117 (258)	31.6	

*Assumes 11,946 kg_m (26,313 lb_m), LO_2 2,478 kg_m (5,459 lb_m), LH_2 for full tank.

Main engine thrust = 13,620 kg_f (30,000 lb_f)
Maximum ACS thrust = 10.9 kg_f (24 lb_f)
Max. ACS acceleration before last burn = 8.96×10^{-4} g's
Mixture ratio = 5.0
Main engine flow rates, LO_2 = 25.7 kg/sec (56.65 lb/sec)
LH_2 = 5.01 kg/sec (11.03 lb/sec)

ISP = 443.35 sec
Payload = 5,538 kg_m (12,199 lb_m)
Dry weight = 2,090 kg_m (4,604 lb_m)
Burnout acceleration = 1.71 g's

Table 1-3. Low Earth Orbit Mission Profile

Event/ Time (min.)	Initial Mass, kg_m (lb_m)		Burn Time, sec	Propellant Burned, kg_m (lb_m)	Final Mass kg_m (lb_m)	Initial Percent Full*	Initial Acceleration, g
Loading (T = 0)	LO_2	11,554 (25,450)					
	LH_2	2,397 (5,279)					
MES1 (T = 67)	Vehicle	19,090 (42,048)			16,363 (36,042)		
	LO_2	11,488 (25,304)	88.6	2,294 (5,052)	9,194 (20,252)	96	0.71
	LH_2	2,344 (5,164)		434 (955)	1,911 (4,209)	95	
MES2 (T = 118)	Vehicle	16,264 (35,824)			10,373 (22,849)		
	LO_2	9,155 (20,165)	191.32	4,955 (10,915)	4,200 (9,250)	77	0.84
	LH_2	1,885 (4,153)		935 (2,060)	950 (2,093)	76	
MES3 (T = 408)	Vehicle	10,246 (22,568)			6,536 (14,397)		
	LO_2	4,162 (9,167)	120.51	3,121 (6,875)	1,038 (2,286)	35	1.33
	LH_2	913 (2,010)		587 (1,294)	325 (716)	37	
MES4 (T = 459)	Vehicle	6,443 (14,192)			5,861 (12,910)		
	LO_2	998 (2,198)	18.90	489 (1,078)	509 (1,121)	8.4	2.11
	LH_2	295 (650)		93 (204)	207 (456)	11.9	
MES5 (T = 553)	Vehicle	5,765 (12,698)			5,433 (11,967)		
	LO_2	468 (1,031)	10.8	279 (614)	189 (417)	3.9	2.36
	LH_2	178 (393)		53 (116)	126 (277)	7.2	

*Assumes 11,946 kg_m (26,313 lb_m), LO_2, 2,478 kg_m (5,459 lb_m), LH_2 for full tank.

Main engine thrust = 13,620 kg_f (30,000 lb_f)
Maximum ACS thrust = 10.9 kg_f (24 lb_f)
Max. ACS acceleration before 5th burn = 1.89×10^{-3} g's
Mixture ratio = 5.298
Main engine flow rates, LO_2 = 25.9 kg/sec (57.05 lb/sec)
LH_2 = 4.89 kg/sec (10.77 lb/sec)

ISP = 443.8 sec
Payload = 2,842 kg_m (6,260 lb_m)
Dry weight = 2,225 kg_m (4,901 lb_m)
Burnout acceleration = 2.51 g's

2

CAPILLARY DEVICE REFILLING DURING ENGINE FIRING

Partial control capillary acquisition devices (start baskets) operate by retaining liquid over the tank outlet between main engine burns. The start basket provides liquid flow to the main engines for engine restart and for a sufficient period of time to settle the propellants and refill the capillary device in preparation for the next burn. A typical start basket is shown schematically in Figure 2-1.

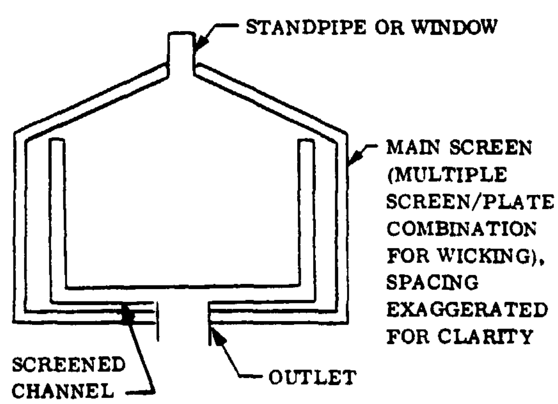


Figure 2-1. Schematic of Typical Start Basket Configuration

Due to vehicle drag the initial position of propellant in the tank will be at the forward end of the tank. Engine thrust, which builds up during the start sequence to the steady state thrust level, will settle the propellant to the aft bulkhead. Refilling of the capillary device must be accomplished in the subsequent high-g period coincident with settling and main engine steady state operation. Refilling can be accomplished during this period because the retention capability of the screen is sized for much lower acceleration levels (e.g., 1×10^{-3} g's) than occur during main engine firing (e.g. 1 to 3 g's). For refilling to be successful, liquid must enter the capillary device in sufficient quantity to sustain engine firing without vapor pullthrough and refill the capillary in preparation for the next engine start.

The process of refilling is a basic element in start basket operation. Analysis of refilling is required to assure that the start basket functions successfully during restart. An analysis was performed in Reference 2-1 for the LO_2 and LH_2 start baskets using conservative assumptions. Only hydrostatic pressure was assumed as the driving pressure. (No refilling augmentation due to liquid velocity impinging on the screen was used.) Refilling was assumed to start after settling was complete. Screen wetting was assumed to exist during the entire refilling period.

Refilling was computed based on pressure differences between the inside and the outside of the capillary device. Equations were formulated, as described in Reference 2-1, for capillary device geometry, and flow/pressure drop. Capillary device volumes were divided into shapes that permitted close form integration of the flow into each volume segment as a function of screen open area.

In the present contract the analysis of refilling was broadened to include the effects of dynamic pressure, screen wicking, multiple screen barriers, window (standpipe) screens that can be different mesh than the main screens, and time dependent liquid settling (collection). The analysis also included the effects of vehicle mass on the vehicle acceleration as the propellant tanks are being drained. Outflow from the tank was included either as an input or as a calculated value based on feed system pressures. Other analysis features are: calculation of vapor pullthrough height in the basket based on tank outflow rate (and channel geometry), an option for including a standpipe screen in the calculations, options for maintaining the standpipe in either a dry or wetted condition, an option for simulating liquid spilling from the capillary device at initiation of tank outflow (from the start basket), and an option for selecting the type of multiple screen barrier to be used for the main screen in the screen wicking calculations.

Because of the complexity of the analysis a closed form solution did not appear to be feasible. A finite difference solution was constructed using the basic screen flow equations and the continuity equation. The screen flow equations are the heart of the computer program developed for analyzing capillary device refilling.

An experimental program was conducted in normal gravity using a scale model capillary device and ethanol as the test fluid. The test program, while limited in scope due to the uniform gravity conditions during both retention and refilling, provided data that was used to successfully correlate the analytical model. The model was then used to predict Centaur D-1S start basket refilling.

The following sections describe the refilling analysis computer program, the normal gravity non-cryogenic testing and the test data correlation. Documentation of the computer program is presented in Appendix A.

2.1 REFILLING ANALYSIS

An analysis of capillary device refilling with settled fluid was performed as a tool for design and analysis of capillary acquisition device (start basket) sizing. A computer program was written to incorporate all significant analysis elements. Computer program documentation is presented in Appendix A. Input requirements are fluid and screen properties, start basket and tank geometry vs height above the bottom of the tank, liquid collection vs time, screen impingement velocities, vehicle mass properties, tank pressure and outlet geometry.

A flow chart of the computer program is shown in Figure 2-2. The heart of the program is the flow equations governing vapor or liquid flow into or out of the start basket. The program elements determine the boundary conditions for calculating start basket fluid flows based on liquid level, system pressure and screen configuration and surface area. Continuity is satisfied by summing the flows into and out of the capillary device and adjusting the pressure difference between the inside and outside of the basket until the flows balance. This iterative solution is achieved for time step increments until either

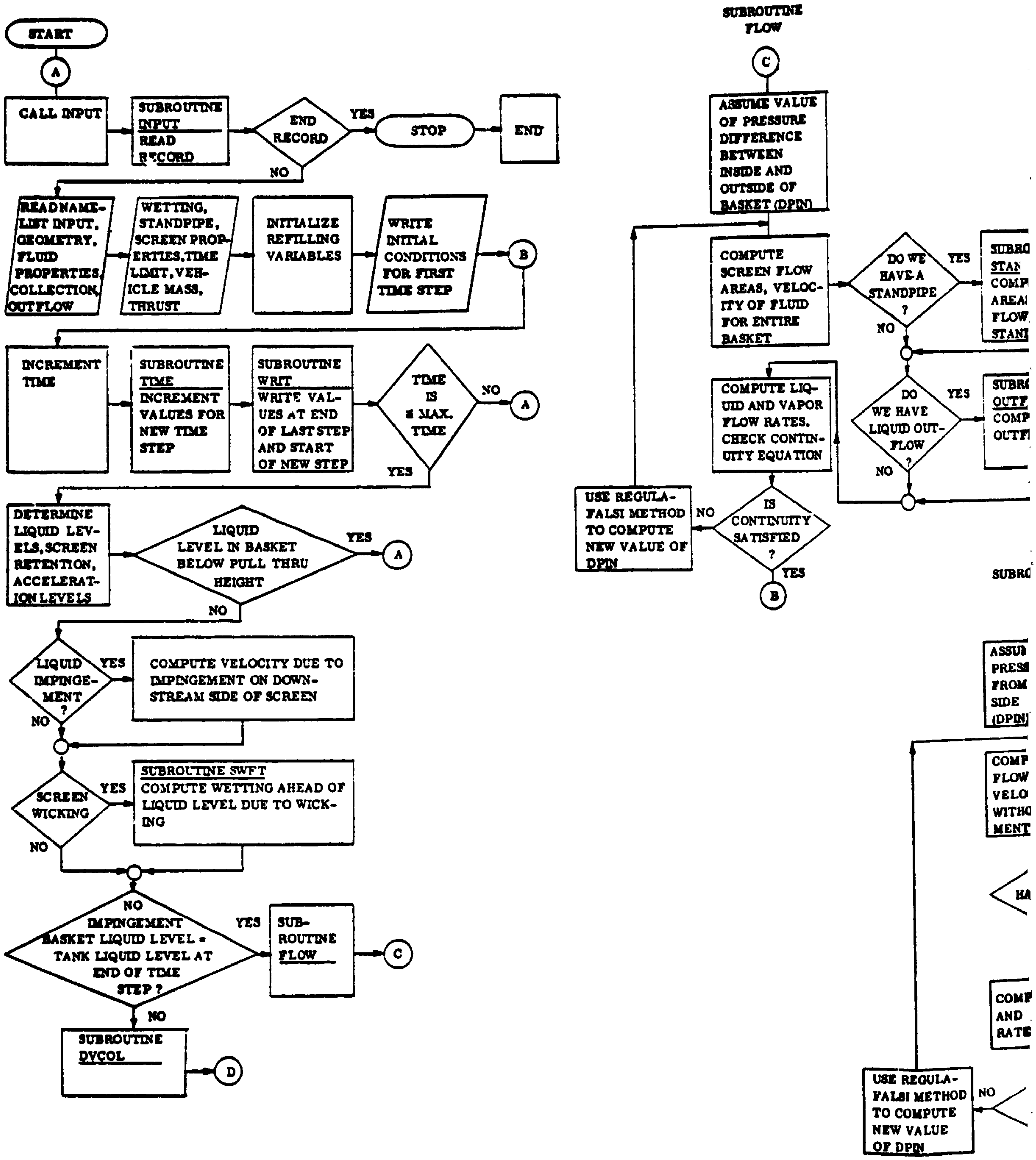
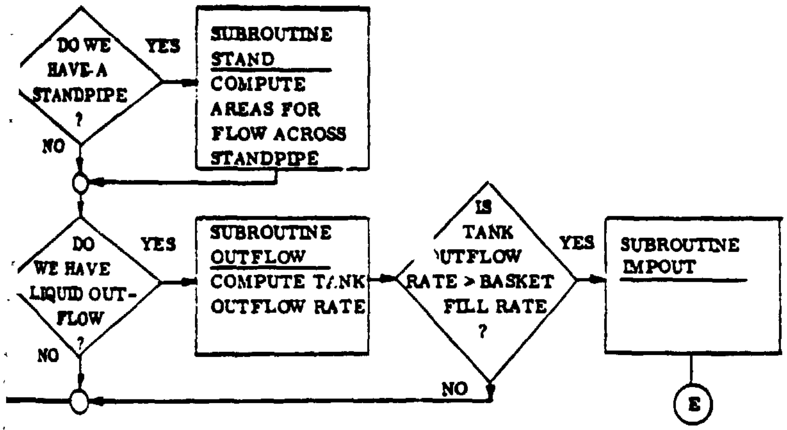
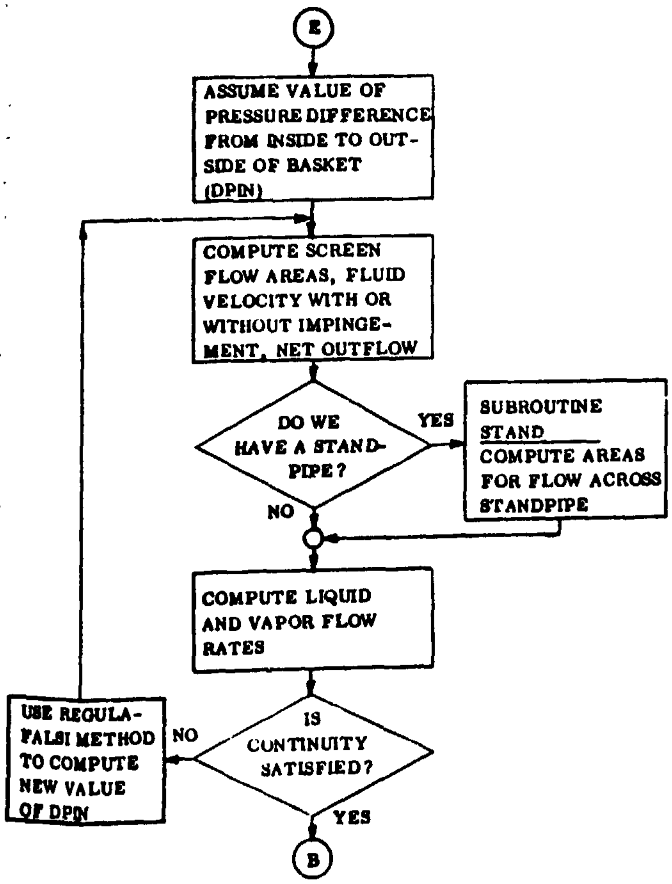


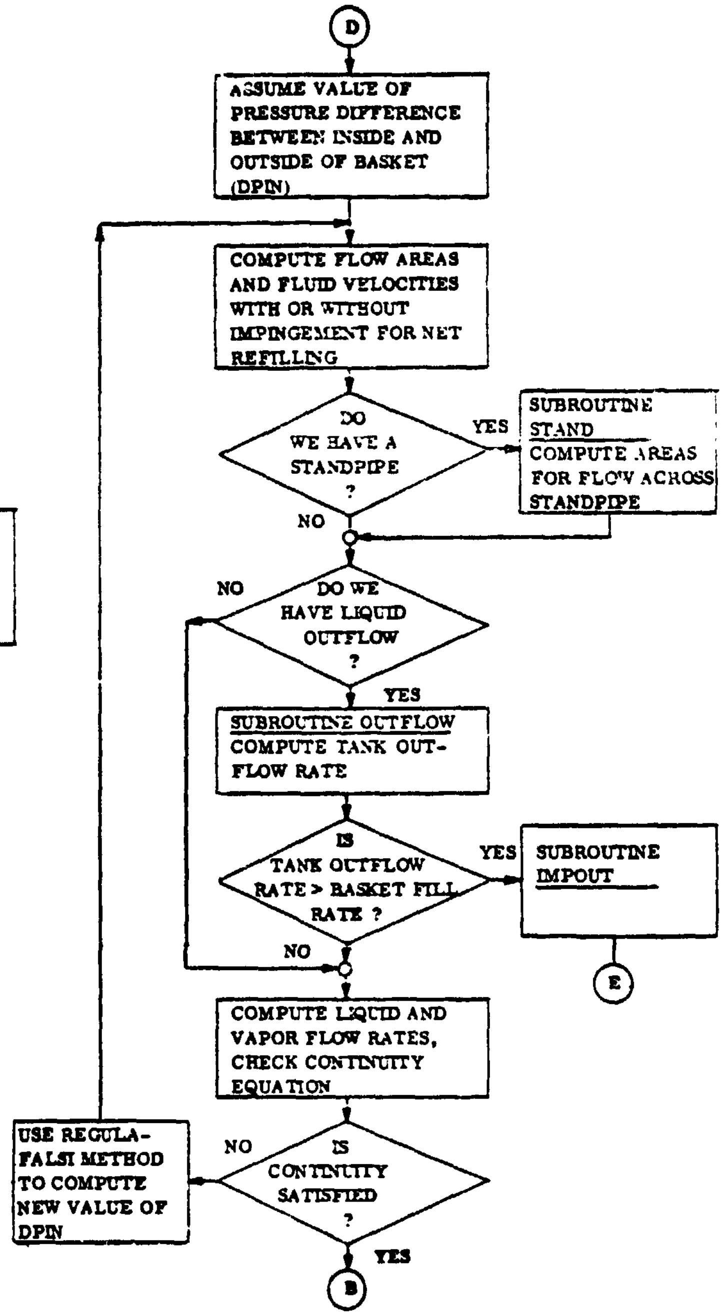
Figure 2-2. REFILL - Program Flowchart



SUBROUTINE IMPOUT



SUBROUTINE DVCOL



NOTE

Subroutines IMPOUT and DVCOL have similar flow charts, the difference between the subroutines is in the area and velocity calculations. (For IMPOUT, DPIN is opposite in sign to that used in FLOW or DVCOL). DIAGNOS subroutine call statements are now shown in order to avoid excess complexity.

the total burn time or the pullthrough height is reached.

The pressure loss equations are separately delineated for each of six regions for fluid flow (without liquid impingement). The six regions (for net refilling) are: an unwetted region where vapor flows out of the basket into vapor, a wetted region where vapor flows out of the basket into vapor, a region where the liquid level outside the basket covers the screen and vapor flows into the liquid, a region where no flow occurs across the screen barrier, a region where liquid enters the basket flowing into vapor and a region where liquid enters the basket flowing into liquid. Figure 2-3 depicts these regions. All six regions will not exist simultaneously. The delineation presented in Figure 2-3 illustrates the entire range of possible conditions.

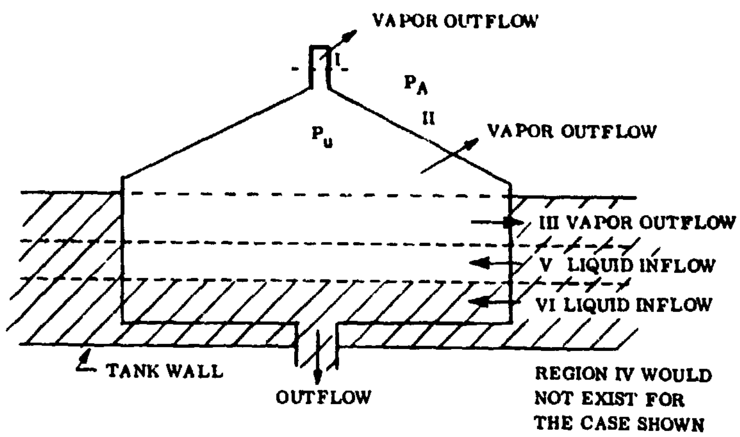


Figure 2-3. Schematic of Capillary Device Refilling Flow Regimes

$$DPIN = P_u - P_A \tag{2-1}$$

$$DPS = 2.72\,\sigma/D_{BP}, \text{ wetted screen retention pressure} \tag{2-2}$$

where

DPIN = pressure differential between vapor inside the basket and tank ullage

DPS = pressure difference that can be sustained by surface tension

σ = liquid surface tension

D_{BP} = screen bubble point

For the equations presented in the following paragraph

P_o = pressure in liquid outside the basket

P_i = pressure in liquid inside the basket

A&B are viscous and inertial constants for vapor flow across the screen

Y&Z are viscous and inertial constants for liquid flow across the screen

Liquid flow across the screen is computed from the following equation

$$\Delta P_L = YV + ZV^2 \tag{2-3}$$

where V is the liquid velocity through the screen.

Vapor flow across the screen is computed from

$$\Delta P_V = AV + BV^2 \tag{2-4}$$

where V is the vapor velocity across the screen.

Substituting the pressure relationships for each region and solving Equations 2-3 and 2-4 by using the quadratic formula yields the following expressions used in Subroutine FLOW.

For Region I with unwetted screen and vapor flow into va... .

$$VV = \frac{-A + \sqrt{A^2 + 4B\ (DPIN)}}{2B} \tag{2-5}$$

For Region II with wetted screen and vapor flow into vapor

$$VVW = \frac{-A + \sqrt{A^2 + 4B\ (DPIN-DPS)}}{2B} \tag{2-6}$$

For Region III with liquid outside the basket and vapor flow into liquid

$$VVL = \frac{-A + \sqrt{A^2 + 2B\ (DPIN-DPS)}}{2B} \tag{2-7}$$

For Region IV no flow occurs.

For Region V liquid flow into vapor occurs

$$VL = \frac{-Y + \sqrt{Y^2 + 2Z\ (P_o - P_i - DPIN)}}{2Z} \tag{2-8}$$

For Region VI with liquid flow into liquid

$$VT = \frac{-Y + \sqrt{Y^2 + 4Z\ (P_o - P_i - DPIN)}}{2Z} \tag{2-9}$$

The outflow velocity from the start basket is computed in subroutine OUTFLOW from the following equation

$$V\emptyset UT = \sqrt{64.4\,DPF/(KC * CC * \rho_L)} \qquad (2\text{-}10)$$

where

DPF is the pressure difference across the outlet (average during the time step). DPF is a function of DPIN

KC is the contraction loss coefficient for the outlet

CC is a correction factor for a rounded entrance

ρ_L is the liquid density

The continuity equation evaluated using flow velocities and areas

$$VV\ (AV) + VVW\ (AVW) + VVL\ (AVL) + V\emptyset UT\ (A\emptyset UT) - VL\ (AL)$$
$$- VT\ (AT) = 0 \qquad (2\text{-}11)$$

An iterative solution is performed by varying DPIN until Equation 2-11 is satisfied.

Screen impingement is included in the liquid refilling flow in Regions V and VI as applicable based on the dynamic pressure aiding refilling using the expression

$$V\emptyset = \frac{-FKA + \sqrt{(FKA)^2 + 4\,\rho_L V_j^2\,(FBK + \rho_L K)}}{2\,(FBK + \rho_L K)} \qquad (2\text{-}12)$$

for the velocity of the emergent jet incident on a screen

F is a constant used to determine the pressure drop through the screen (empirically found to be equal to 2)

K is a proportionality constant equal to the emergent jet liquid area/impinging jet liquid area (empirically found to be equal to 4)

V_j is the velocity of the impinging jet

A, B and ρ_L are as previously defined.

Equation 2-12 was obtained from Reference 2-2.

Sample runs were made with the REFILL computer program to test program capability. Program runs were made in order to design an experimental refilling apparatus. Several of the program capabilities described in Figure 2-2 such as subroutine STAND, variable acceleration capability and spilling options were added based on model correlation requirements described in Section 2-4.

2.2 REFILLING EXPERIMENT PREPARATION

An experimental apparatus and normal gravity test procedure was developed with the following objectives: simulate actual conditions for refilling as much as possible considering the nonvariant ambient acceleration, simulate actual settling and collection, (with realistic screen impingement), run cases where both net refilling and net draining of the start basket occurs, run with tank outflow at both zero and nonzero values, and simulate realistic standpipe and channel flow operation.

2.2.1 TEST MODEL AND EXPERIMENTAL APPARATUS. A complete set of design drawings are shown in Figures 2-4 through 2-6. Figure 2-4 is a general arrangement of the refilling apparatus. Figure 2-5 details the multiple screen layer start basket. Figure 2-6 shows the screened standpipe assembly and manufacturing details.

The basic configuration shown in Figure 2-5 consists of a start basket with multiple screen barriers for thermal conditioning and a screened window on top of the basket to allow vapor penetration during thermal conditioning and vapor removal during refilling. Fine mesh screened channels within the basket were designed to provide liquid outflow from within the start basket and will be maintained full of liquid during testing. The channel screen was 325 × 2300 mesh. The start basket screen was multiple barriers of 200 × 600 screen. Two of the basket walls were made of Lexan to allow backlighting, visual observation, and photographs to be employed. The top screen window on the basket (view M-M) was either 200 × 600 or 50 × 250 mesh screen. With 50 × 250 mesh screen, 23.45 cm (4.9 in) of liquid head could be retained in the basket when it is completely wetted, (similarly 12.45 cm (4.9 in) of vapor will be trapped in the completely wetted basket during refilling). With 200 × 600 screen the basket could hold its own head of liquid or vapor. A single layer removable standpipe of 50 × 250 screen (View Q) was used for some of the runs. The start basket outer envelope was a square prism, 16.5 cm high × 45.72 cm wide (6.5 in × 18 in wide). Channels were 22 cm (8.5 in) long × 15.2 cm (6 in) wide and 0.95 cm (3/8 in) thick. The outlet tube was 5.08 cm (2 in) in diameter.

A square tank was fabricated with front and back sides of Lexan sheet to serve as the outer tank. Within this tank a movable cover over the basket controlled the collection rate of liquid. This cover consisted of a square cross section box with an open framework on top. The cover has front and back sides constructed of Lexan. The cover keeps liquid between the tank wall and the cover until the cover is lifted. Lifting the cover allows liquid collection around the basket. Splashing of liquid against the screen was controlled by deploying a fence for some of the runs to cause liquid spilling over the fence when the cover was removed. The cover was lifted at different rates to simulate different collection times. A piston/stop arrangement was used to control cover motion. This approach was selected because the collection rate is controllable and the geometry can be made to simulate the wall flow that would occur during an actual axisymmetric reorientation case.

A plumbing schematic of the capillary device refilling apparatus is shown in Figure 2-7. A schematic showing instrumentation is presented in Figure 2-8.

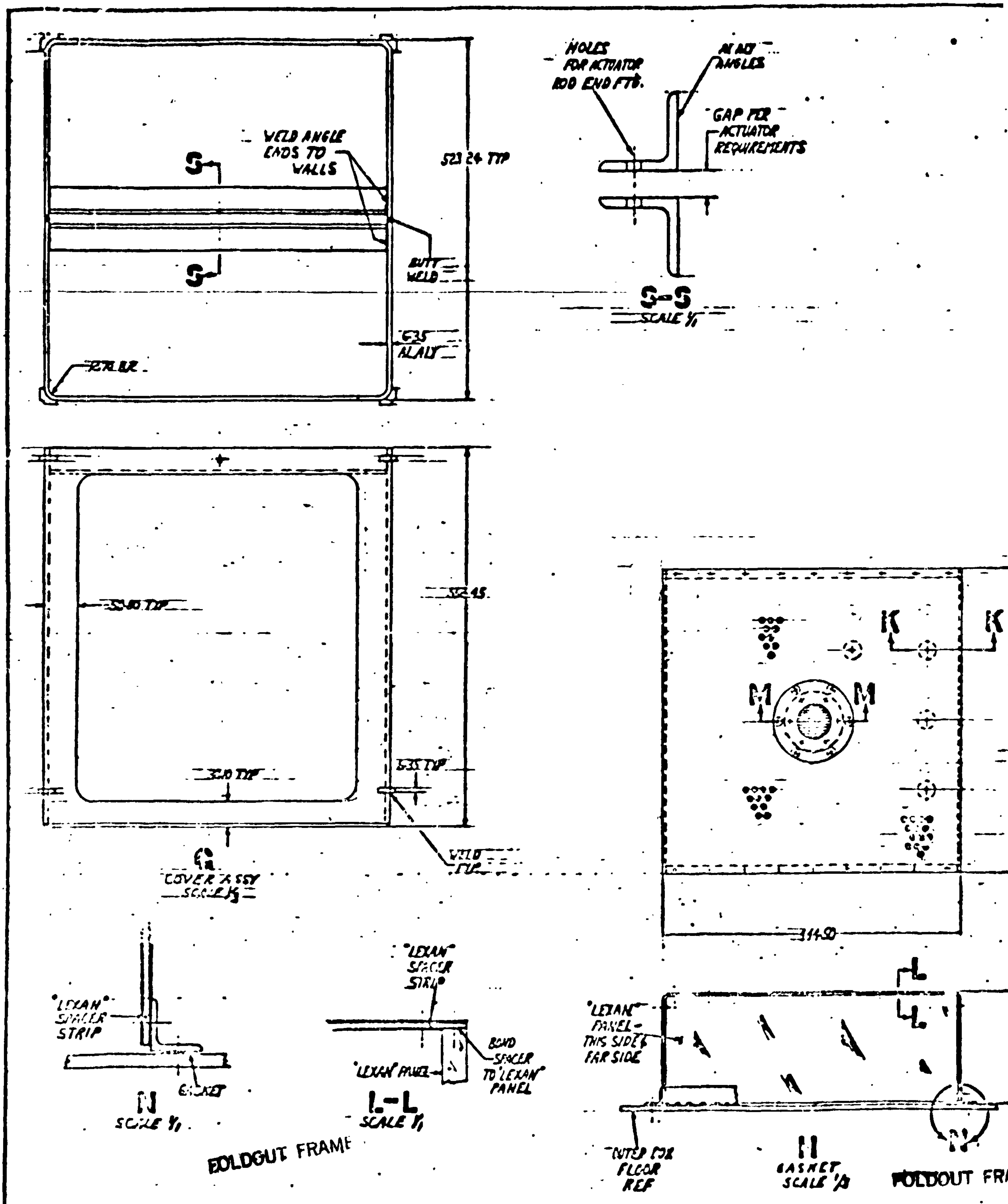
2.2.2 TEST VARIABLES AND INSTRUMENTATION. Ethanol was used as the test fluid because of its good wettability, low toxicity and low vapor pressure at room temperature. The properties of ethanol allowed reasonable start basket heights and flow rates to be used.

Surface geometry was recorded photographically on 16 mm color movie film. A scale with 0.1 mm divisions was mounted on the start basket Lexan surface. Liquid level inside and outside the basket was measured using General Dynamics Convair fabricated parallel plate capacitance probes. Variable reluctance type pressure transducers were used to measure the pressure difference across both the start basket and channel. Flow rate out of the basket was measured with a turbine flow meter in the outlet line. Temperatures were measured with chromel/constantan thermocouples. The temperatures measured were T_1, the temperature at the start basket ΔP transducer; T_2, the temperature at the channel ΔP transducer; T_3, the temperature at the top of the start basket outer screen; T_4, the temperature in the outflow line; T_5, the fluid temperature in the outer annulus; and T_6, the supply tank temperature.

Analog recordings were obtained for each run. Data channels recorded were outer chamber liquid level, start basket liquid level, start basket pressure drop, channel pressure drop, channel outflow rate, and the six selected temperatures. All quantitative data was obtained from the analog recordings. The motion picture runs were used for qualitative observations and for assistance in determining boundary conditions such as settling flow pattern and screen wetting during refill.

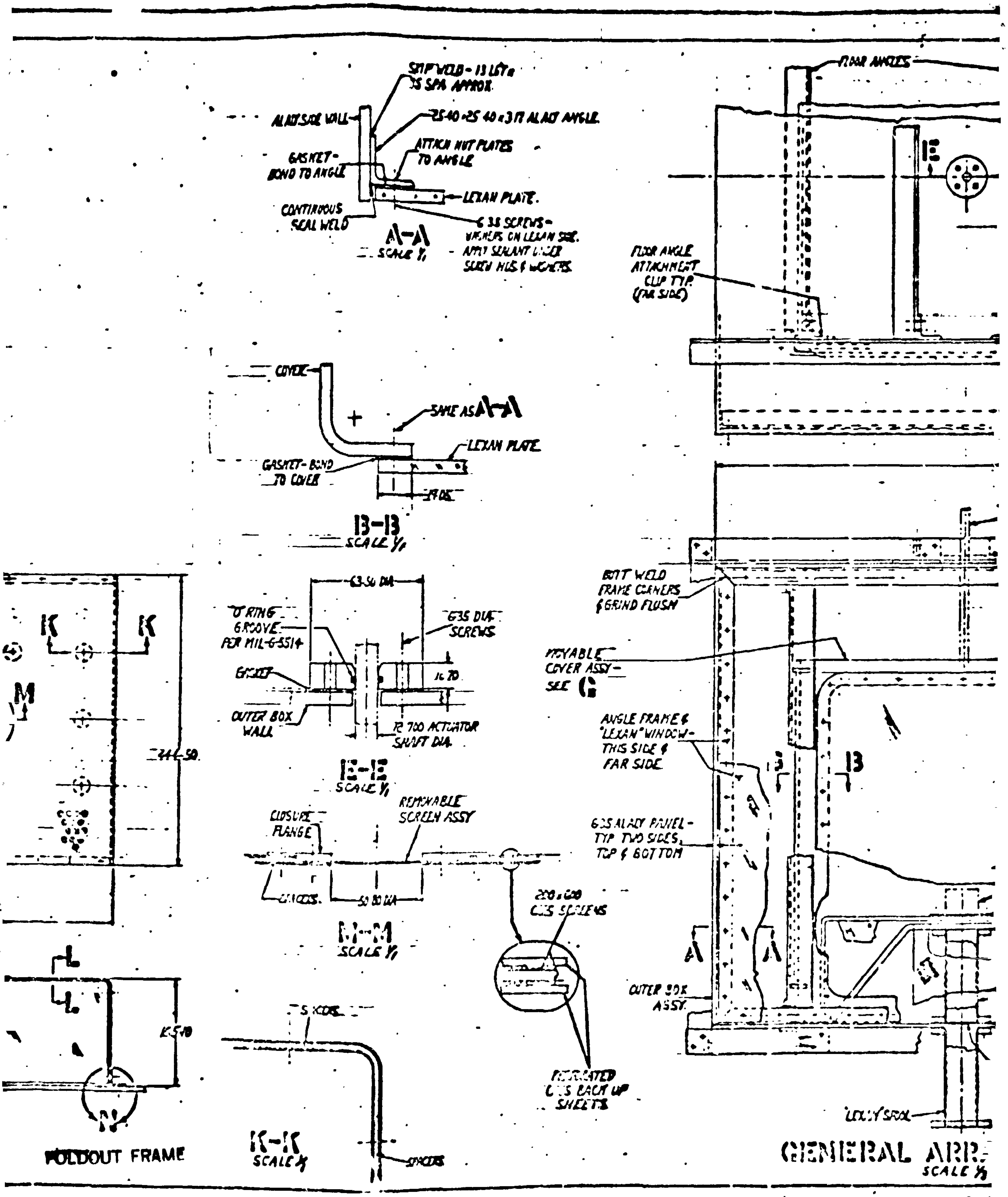
Test variables were outflow rate, top screen (standpipe) configuration, initial start basket wetting, liquid collection rate and refilling geometry.

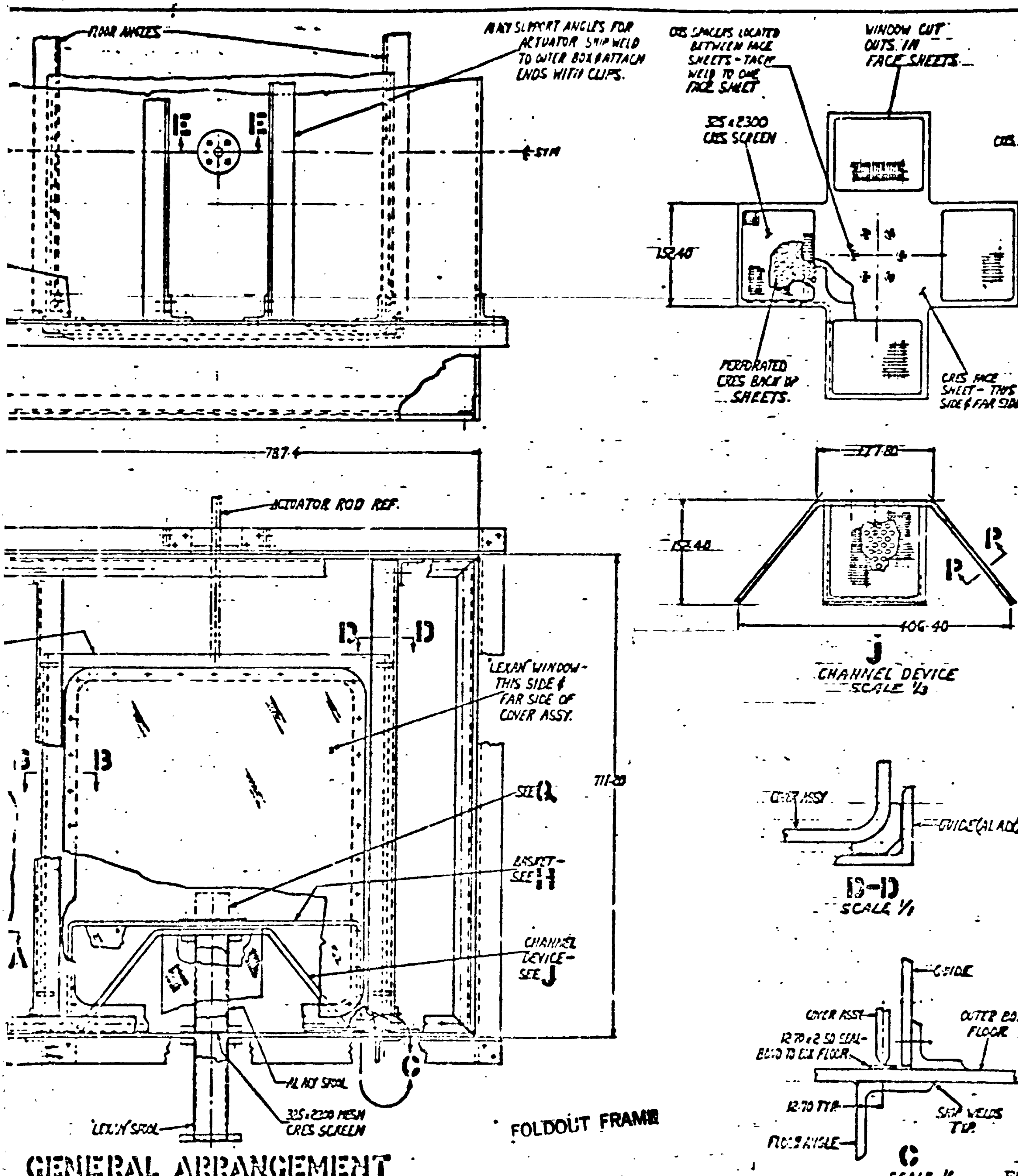
After assembly of the start basket, bubble point testing was conducted preparatory to completing test set up assembly. Leakage occurring at the curved scarfed Lexan spacers between the 200 × 600 screen layers was sealed with fast curing epoxy. Shown in Figures 2-9 and 2-10 is the assembled test apparatus. The start basket shown does not have a standpipe. Figure 2-10 shows the outlet region under the test model.



FOLDOUT FRAME

FOLDOUT FRAME


ALALY SIDE WALL
CONTINUOUS SEAL WELD
GASKET-BOND TO ANGLE
ATTACH NUT PLATES TO ANGLE
LEXAN PLATE.
A-A
SCALE 1/1
COVER
SAME AS A-A
LEXAN PLATE
GASKET-BOND TO COVER
B-B
SCALE 1/1
63.50 DIA
O RING GROOVE PER MIL-G-5514
6.35 DIA SCREWS
GASKET
OUTER BOX WALL
12.700 ACTUATOR SHAFT DIA.
E-E
SCALE 1/1
CLOSURE FLANGE
REMOVABLE SCREEN ASSY
50.80 DIA
M-M
SCALE 1/1
CRES SCREENS
PERFORATED CRES BACK UP SHEETS
FOLDOUT FRAME
K-K
SCALE 1/1
SPACERS
FLOOR ANGLES
FLOOR ANGLE ATTACHMENT CLIP TYP. (FAR SIDE)
BUTT WELD FRAME CORNERS & GRIND FLUSH
MOVABLE COVER ASSY SEE G
ANGLE FRAME & "LEXAN" WINDOW-THIS SIDE & FAR SIDE
6.35 ALALY PANEL-TYP. TWO SIDES, TOP & BOTTOM
OUTER BOX ASSY.
GENERAL ARR
SCALE 1/2



GENERAL ARRANGEMENT
SCALE 1/3

FOLDOUT FRAME

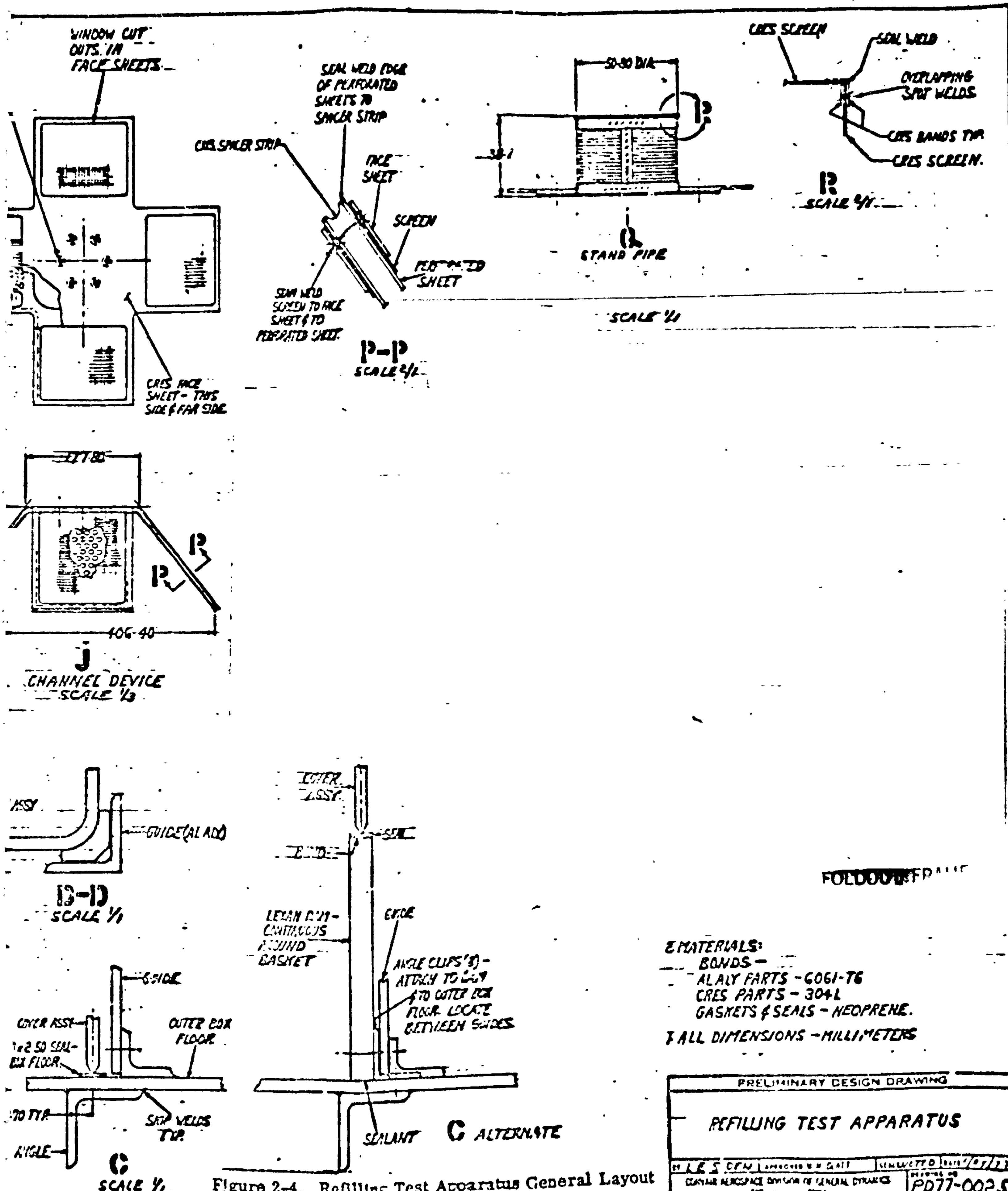
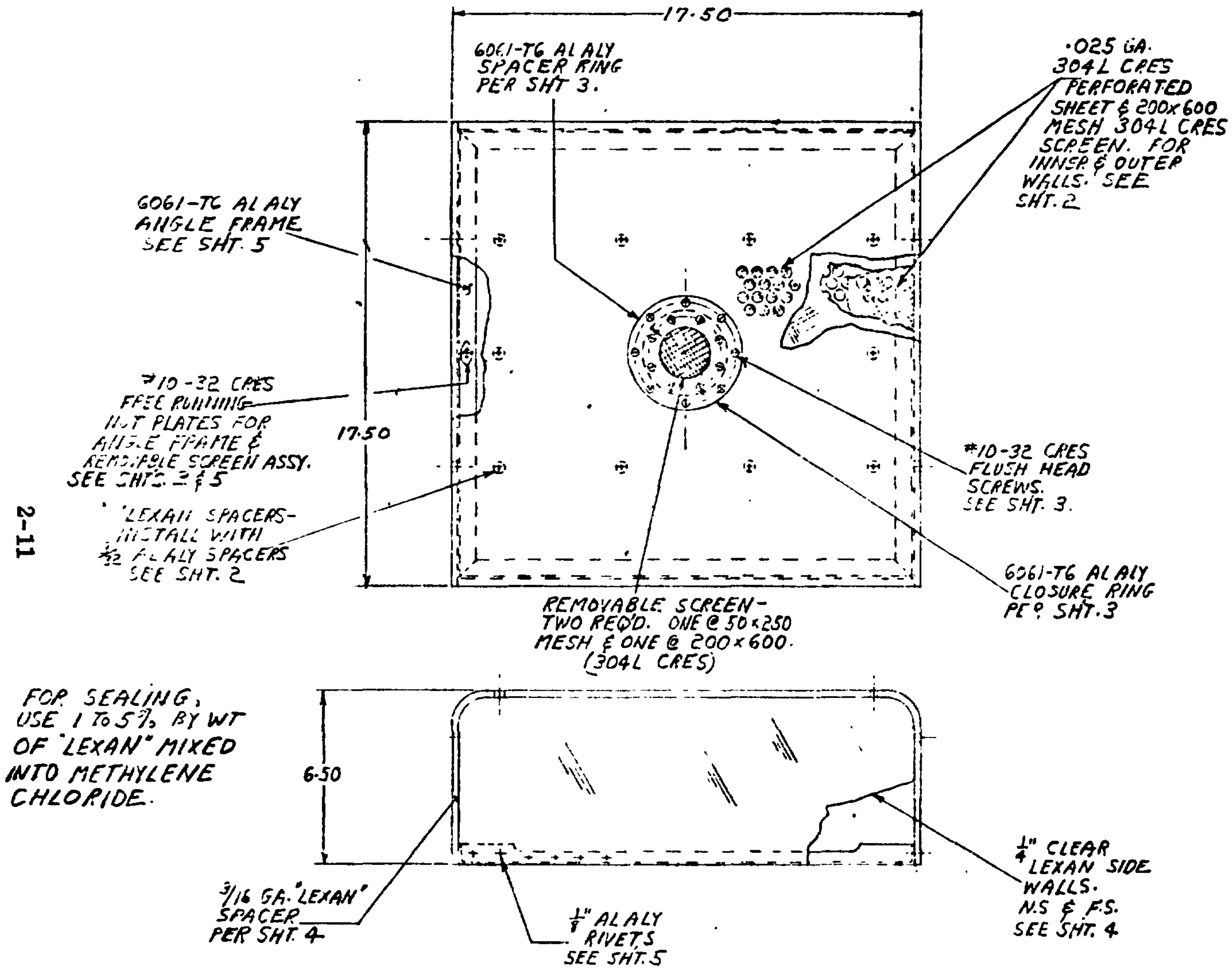


Figure 2-4. Refilling Test Apparatus General Layout



BILL OF MATERIAL

ITEM	MATL.	QUAN.
.025 GA. x 30 x 20 PERFORATED SHEET. 3/32 DIA. HOLES ON 1/2" CENTERS - STAGGERED PATTERN	304L CRES	2
200 x 600 MESH SCREEN. 30 x 20	304L CRES	2
50 x 250 MESH SCREEN 6 x 6	304L CRES	1
3/16 x 30 x 20 SHEET.	LEXAN	1
1/4 x 18 x 7 SHEET	CLEAR LEXAN	2
3/4 x 3/4 x 1/8 x 72 LGT. ANGLE	6061-T6 AL ALY	1
4.5 x 4.5 x 3/16 PLATE	6061-T6 AL ALY	1
4.5 x 4.5 x 5/16 PLATE	6061-T6 AL ALY	1
#10-32 FREE RUNNING NUT PLATES	CRES	36
1/8" UNIVERSAL HEAD RIVETS	AL ALY	100
3/32 UNIVERSAL HEAD RIVETS	AL ALY	24
3/32 FLUSH HEAD RIVETS	AL ALY	200
METHYLENE CHLORIDE SOLVENT		1/2 PINT
#10-32 BRAZIER HEAD SCREWS	CRES	16

Figure 2-5. Inner Basket Assembly/Refilling Test Apparatus (Sheet 1 of 5)

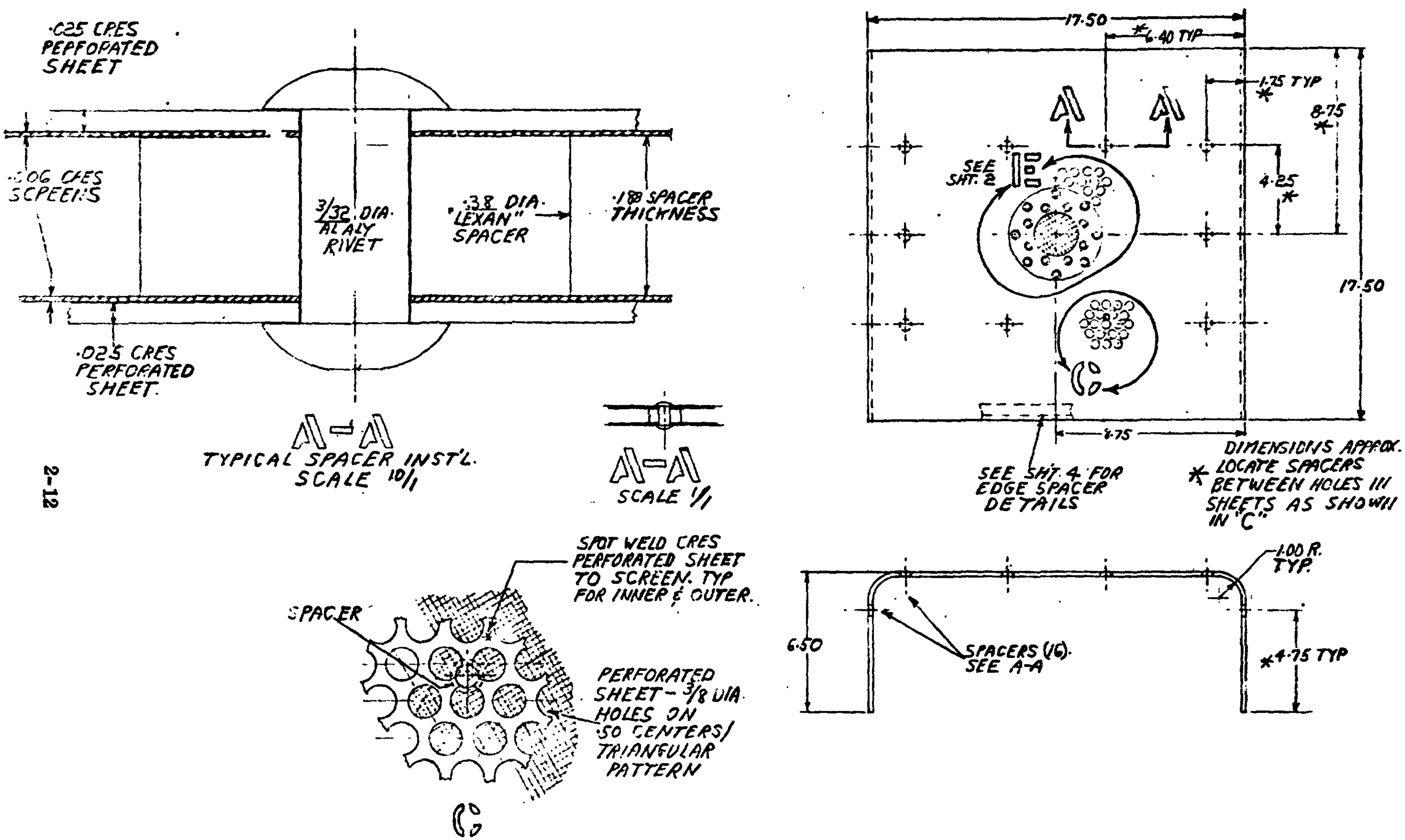


Figure 2-5. Inner Basket Assembly/Refilling Test Apparatus (Sheet 2 of 5)

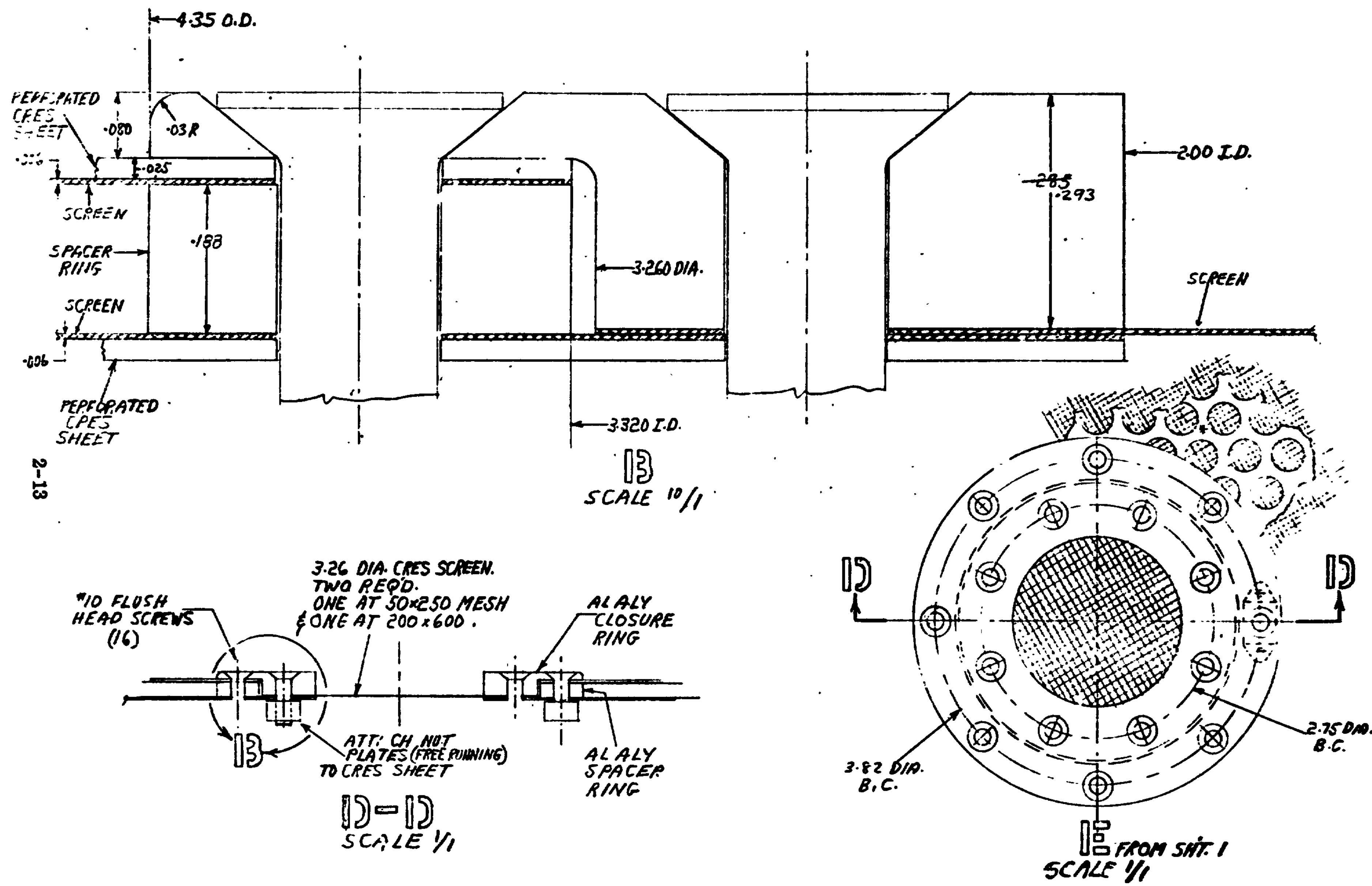


Figure 2-5. Inner Basket Assembly/Refilling Test Apparatus (Sheet 3 of 5)

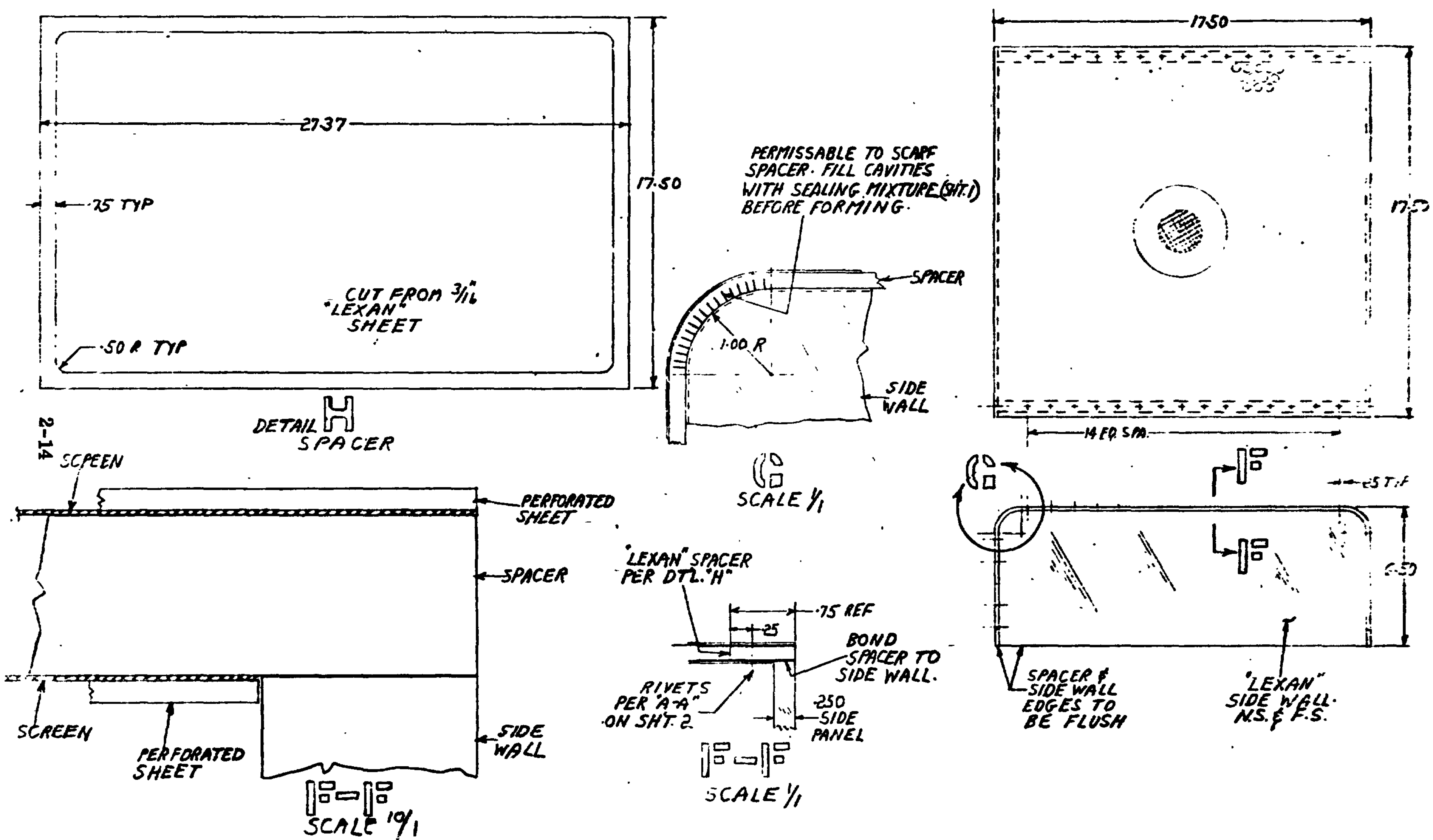


Figure 2-5. Inner Basket Assembly/Refilling Test Apparatus (Sheet 4 of 5)

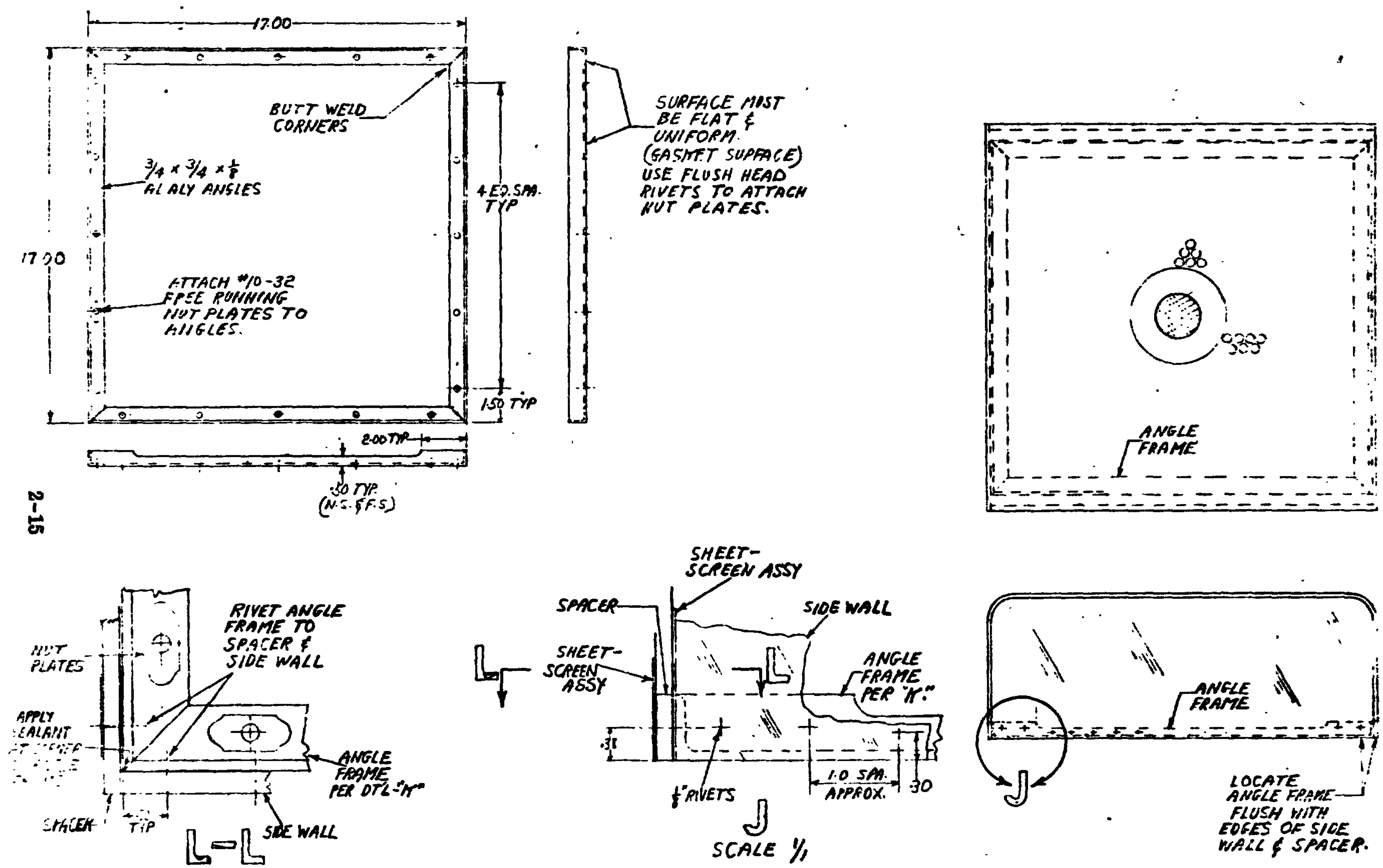


Figure 2-5. Inner Basket Assembly/Refilling Test Apparatus (Sheet 5 of 5)

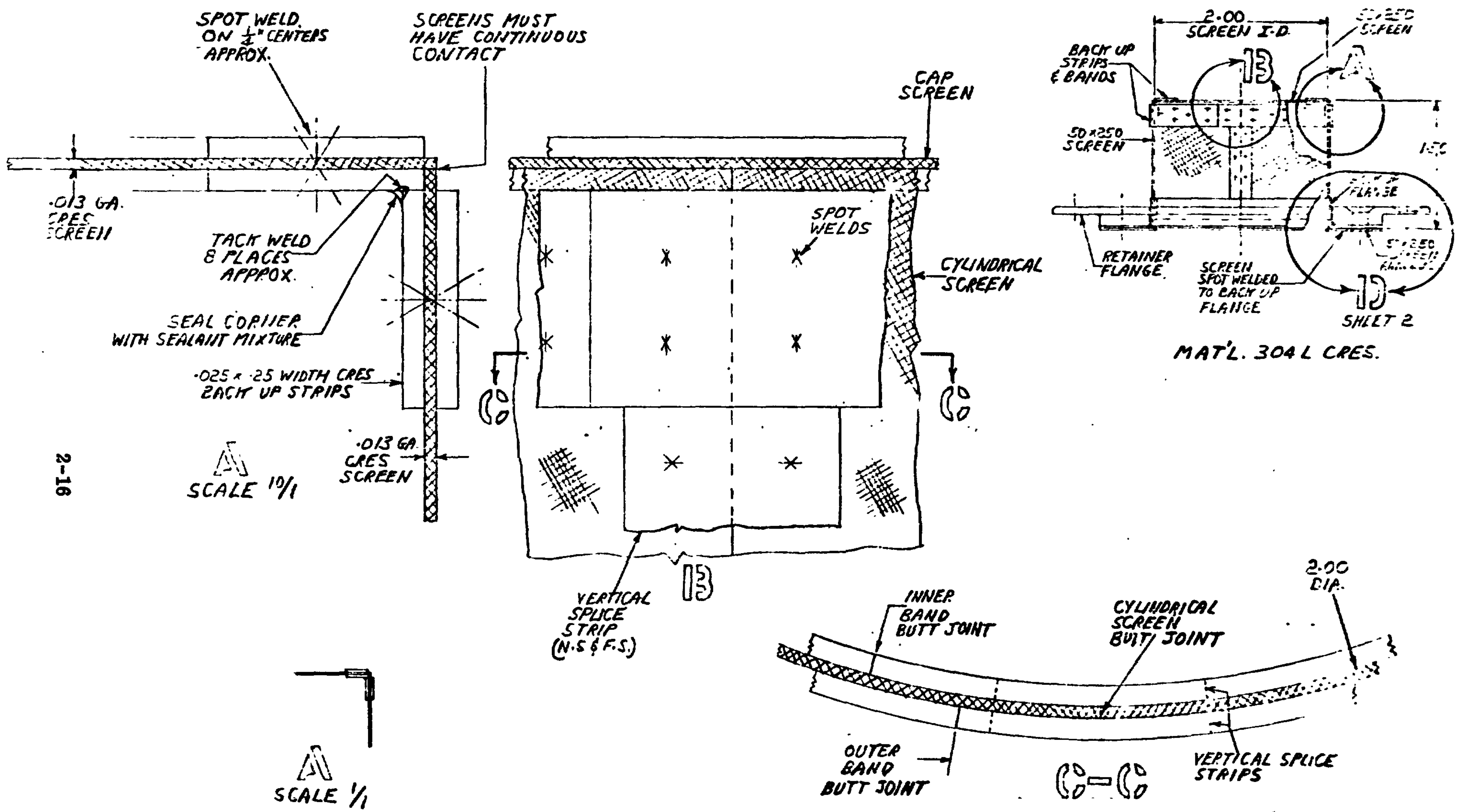


Figure 2-6. Standpipe Assembly/Refilling Test Apparatus (Sheet 1 of 2)

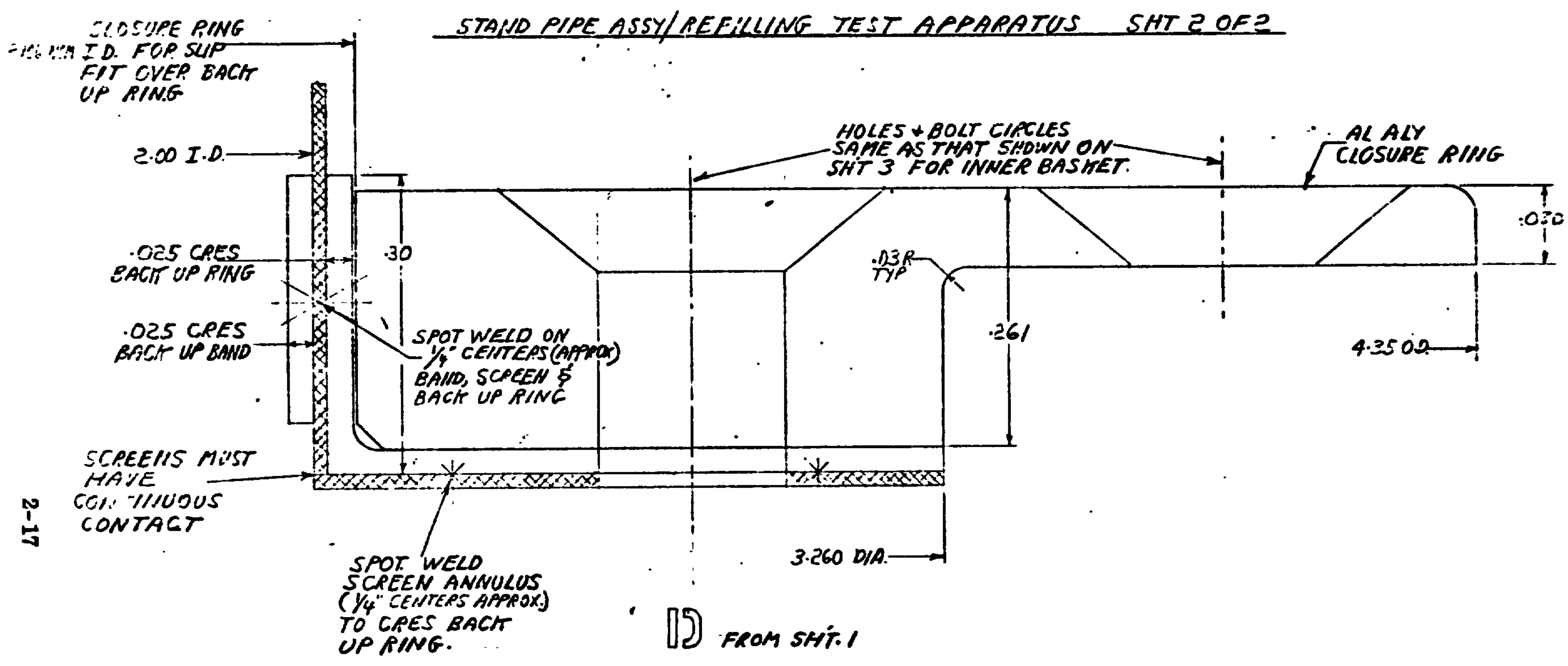


Figure 2-6. Standpipe Assembly/Refilling Test Apparatus (Sheet 2 of 2)

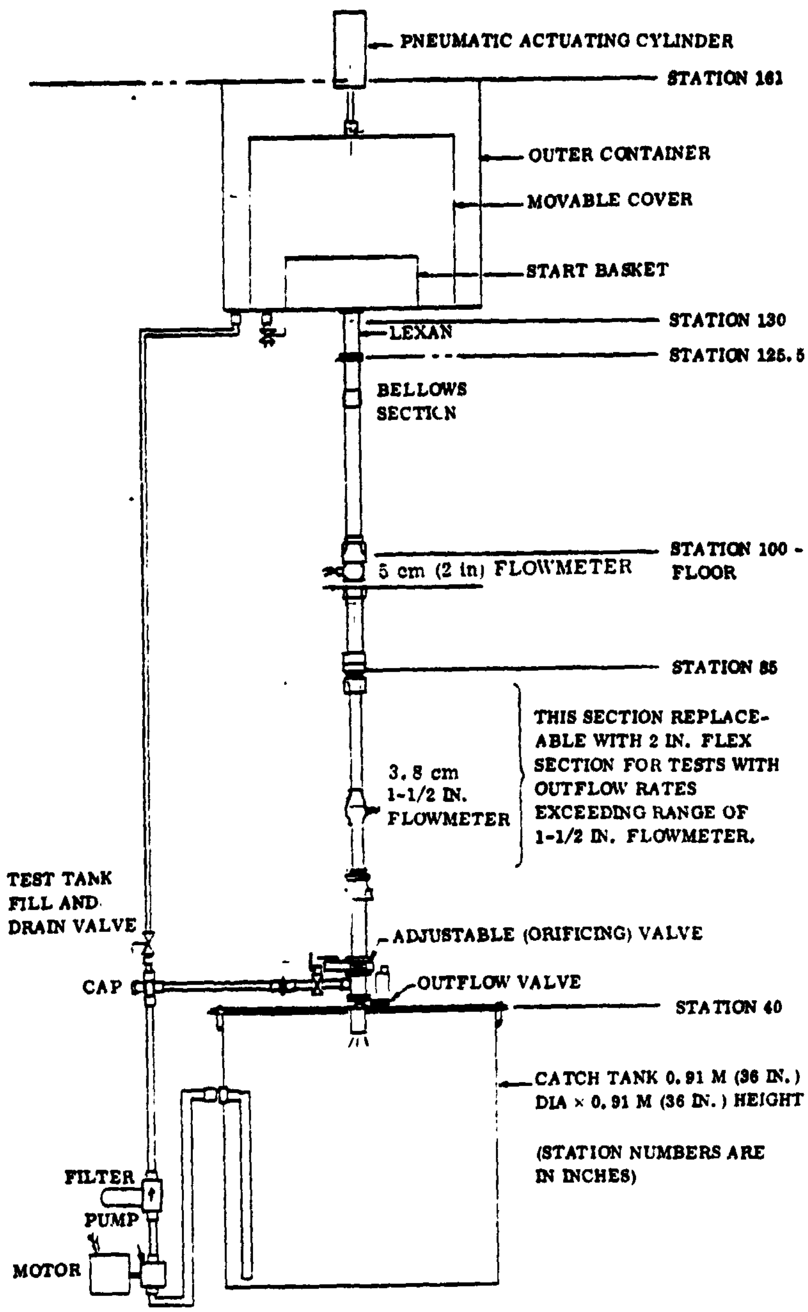


Figure 2-7. Capillary Device Refilling Apparatus Plumbing Schematic

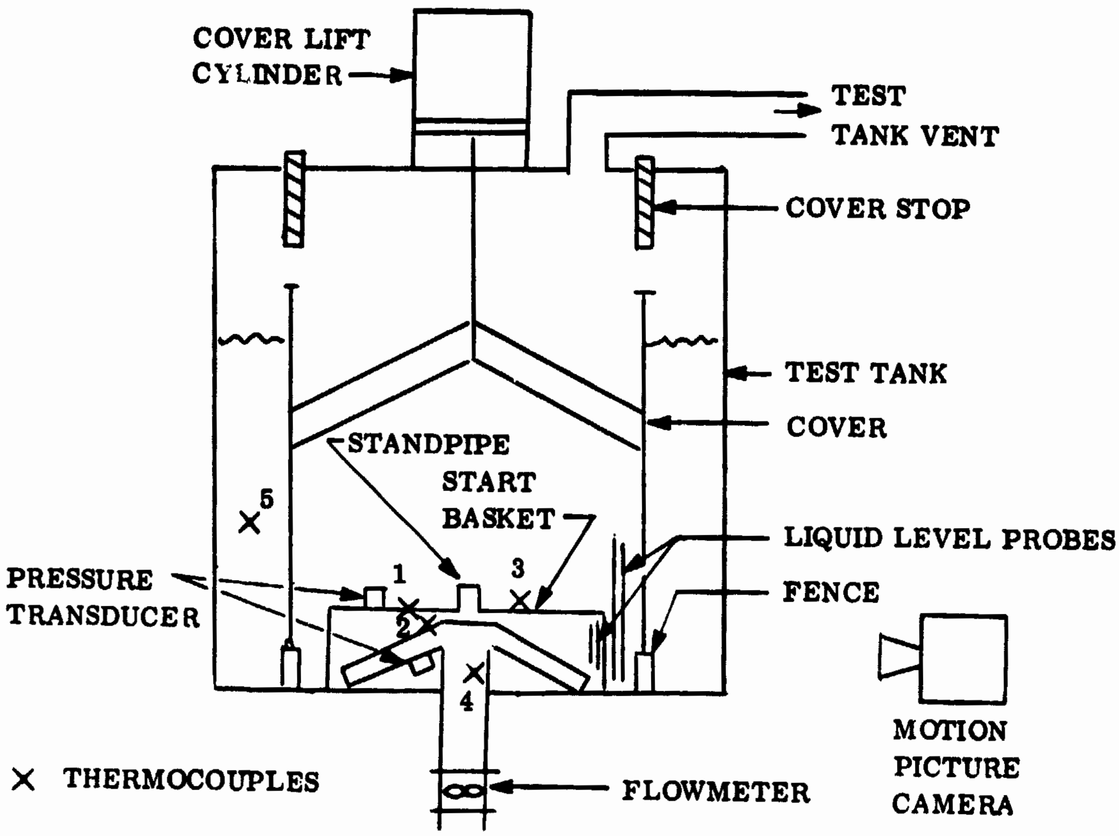


Figure 2-8. Schematic Showing Test Apparatus Instrumentation

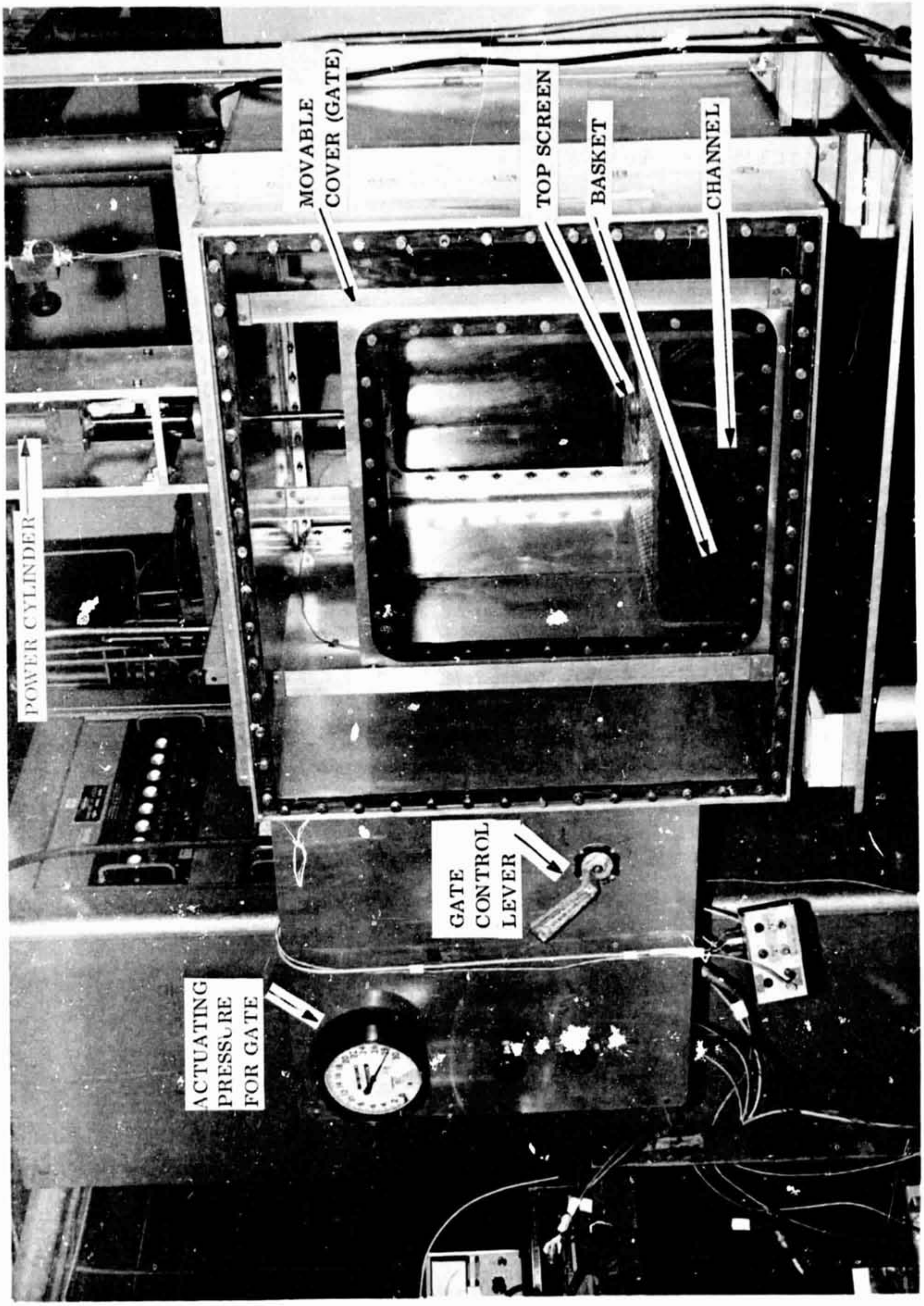


Figure 2-9. Refilling Test Model

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

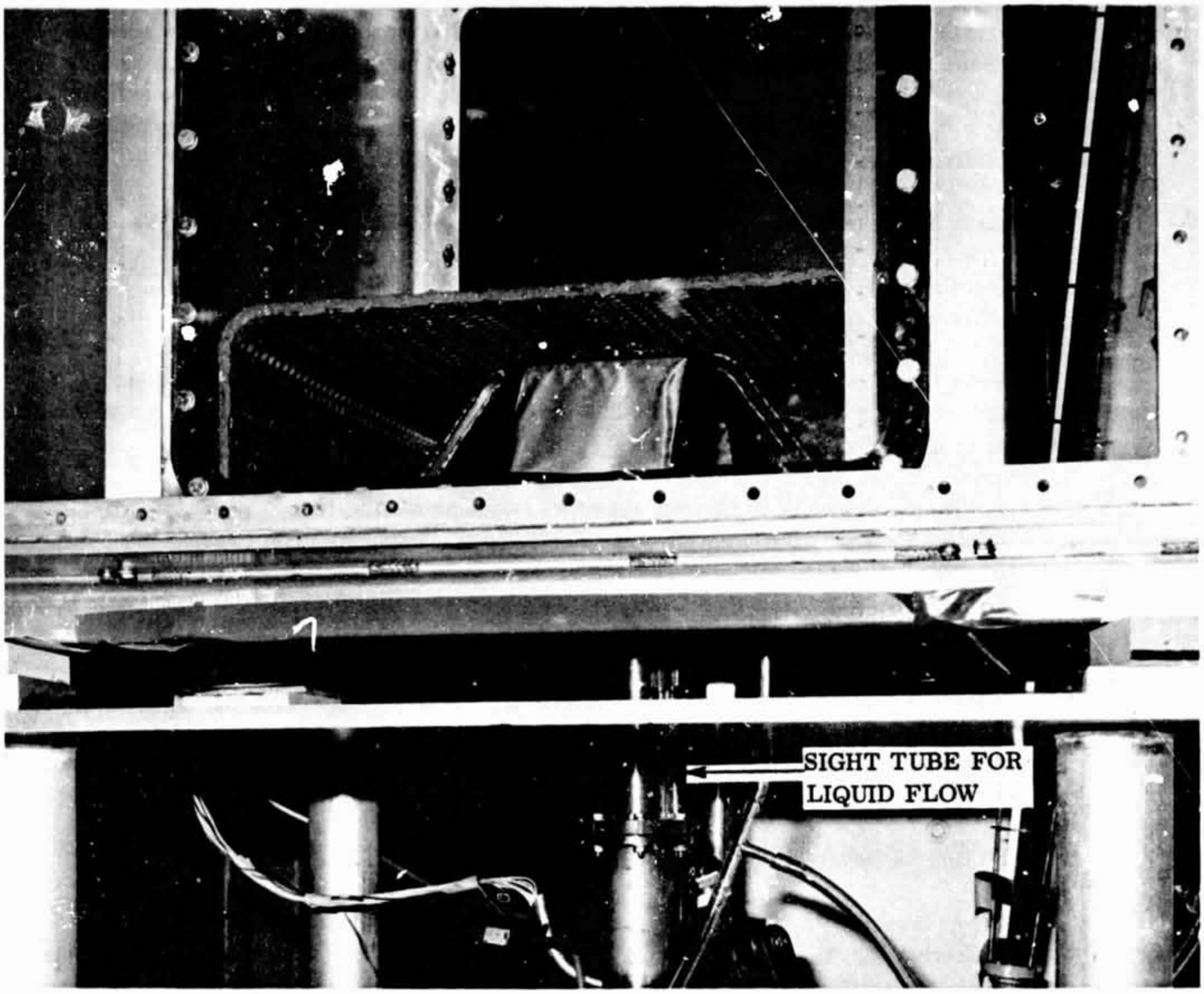


Figure 2-10. Lower Portion of Refilling Test Model

2.3 REFILLING TESTS

A series of runs were made with the test configuration shown in Figures 2-9 and 2-10 in order to check out instrumentation, valves, and apparatus controls. After checkout a series of twenty nine runs were made with data taken as described in Section 2.2.2. Results were obtained over a wide spectrum of refilling times ranging from no refilling, with the 200 × 600 mesh screens, to rapid refilling with the 50 × 250 mesh standpipe and initially dry screens.

The matrix of test runs is presented in Table 2-1 showing the screens tested, the outflow rate, initial wetting condition, liquid collection rate, start basket initial liquid level at start of collection and start of outflow. Runs recorded on motion picture film are noted with an "M."

For the start basket top screen, three configurations were used; 50 × 250 mesh and 200 × 600 mesh flat screens and a 50 × 250 mesh standpipe 3.81 cm (1.5 in) high and 5.08 cm (2 in) in diameter.

The majority of runs were made with the start basket screen wet. Several runs were made with the basket initially empty and no outflow (Runs No. 10,11,19,23 and 24) with the screen therefore initially dry. Other runs were made with dry top screens. In these runs the basket was filled to a low level and the liquid level between the basket and the cover was initially equal to the liquid level in the basket.

Zero time for each run was at the timing mark on the analog recording just preceding the lifting of the cover to allow liquid to collect over the basket. Timing marks were made at one second intervals. Liquid levels and flow rates are approximately linear between the time values shown in Table 2-1.

A typical test sequence occurred as follows

1. Dry top screen with GN_2 purge and drain residual liquid from test tank in preparation for start basket filling.

2. Fill basket and inner annulus to desired level with ethanol.

3. Drain inner annulus (between start basket and cover) as required.

4. Fill outer annulus (cover is down) to desired level.

5. Open outflow valve (if flow is desired) and drain start basket.

6. When start basket is at desired level, lift cover (cover lift time is as desired) to collect liquid over the start basket.

Table 2-1. Refilling Test Data

Run No.	Basket Top Screen	Initial Top Screen Wetting	Time, sec.	Start Basket Internal Liquid Level, cm (in)		Start Basket External Liquid Level, cm (in)		Flow Channel, ΔP, kN/m² (in H_2O)		Start Basket, ΔP, kN/m² (in H_2O)		Flow Rate, cm³/sec (GPM)		Start Basket Top Temp., K (F)
1	200×600	Wet	0	15.2	(6.0)	0	(9.0)	1.0	(4.0)	2.0	(8.0)	807	(13.8)	-
			19	15.2	(6.0)	22.4	(8.8)	1.0	(4.0)	0.19	(0.75)	807	(13.8)	-
			20	15.2	(6.0)	22.4	(8.8)	0.62	(2.5)	0.19	(0.75)	454	(7.2)	-
			30	15.2	(6.0)	21.1	(8.3)	0.62	(2.5)	0.19	(0.75)	454	(7.2)	-
			31	15.2	(6.0)	21.1	(8.3)	1.0	(4.0)	0.19	(0.75)	719	(11.4)	-
			105	15.2	(6.0)	3.0	(1.2)	1.0	(4.0)	1.37	(5.5)	719	(11.4)	-
2	200×600	Wet	0	14.2	(5.6)	0.5	(0.2)	0.62	(2.5)	2.0	(8.0)	473	(7.5)	-
			21	8.1	(3.2)	0.5	(0.2)	1.5	(6.0)	2.0	(8.0)	568	(9.0)	-
3	200×600	Wet	0	13.5	(5.3)	1.0	(0.4)	0	(0)	0.17	(0.7)	454	(7.2)	-
			31	4.6	(1.8)	1.3	(0.5)	0.6	(2.4)	0.17	(0.7)	492	(7.8)	-
4	50×250	Wet	0	9.4	(3.7)	2.3	(0.9)	1.74	(7.0)	1.0	(4.0)	624	(9.9)	-
			13	5.6	(2.2)	2.0	(0.8)	3.23	(13.0)	0.9	(3.5)	662	(10.5)	-
5	50×250	Wet	0	10.9	(4.3)	1.0	(0.4)	1.24	(5.0)	0.75	(3.0)	568	(9.0)	-
			37	2.8	(1.1)	1.3	(0.5)	6.22	(25.0)	0.6	(2.5)	492	(7.8)	-
			42	3.6	(1.4)	22.6	(8.9)	5.47	(2[illegible].0)	-0.5	(-2.0)	492	(7.8)	-
			89	4.3	(1.7)	17.8	(7.0)	4.73	(19.0)	-0.5	(-2.0)	549	(8.7)	-
			185	4.4	(1.75)	3.8	(1.5)	4.73	(19.0)	0.5	(2.0)	549	(8.7)	-
			205	2.5	(1.0)	2.8	(1.1)	5.97	(24.0)	1.0	(4.0)	416	(6.6)	-
6	50×250	Wet	0	10.7	(4.2)	0.3	(0.1)	2.74	(11.0)	0.87	(3.5)	631	(10.0)	-
			29	2.03	(0.8)	0.5	(0.2)	6.22)	(25.0)	0.62	(2.5)	397	(6.3)	-
			40	3.0	(1.2)	21.6	(8.5)	4.98	(20.0)	-0.5	(-2.0)	378	(6.0)	-
			220	4.3	(1.7)	5.1	(2.0)	4.73	(19.0)	0.25	(1.0)	492	(7.8)	-
			240	3.8	(1.5)	3.0	(1.2)	5.22	(21.0)	1.0	(4.0)	454	(7.2)	-
7	50×250	Wet	0	0	(0)	0	(0)	2.24	(9.0)	0.5	(2.0)	0	(0)	-
			5	0.5	(0.2)	24.6	(9.7)	1.74	(7.0)	-0.5	(-2.0)	0	(0)	-
			60	5.3	(2.1)	21.8	(8.6)	0.75	(3.0)	-0.5	(-2.0)	0	(0)	-
			90	5.3	(2.1)	19.8	(7.8)	0.25	(1.0)	-0.5	(-2.0)	0	(0)	-
8	50×250	Wet	0	0	(0)	0	(0)	1.24	(5.0)	0.25	(1.0)	0	(0)	-
			5	1.3	(0.5)	25.5	(10.2)	1.24	(5.0)	-0.5	(-2.0)	0	(0)	-
			35	5.6	(2.2)	23.9	(9.4)	0.75	(3.0)	-0.5	(-2.0)	0	(0)	-
			60	5.6	(2.2)	23.9	(9.4)	0.75	(3.0)	-0.5	(-2.0)	0	(0)	-
9	50×250	Wet	0	6.9	(2.7)	0	(0)	1.0	(4.0)	0.87	(3.5)	510.9	(8.1)	-
			27	1.27	(0.5)	0	(0)	6.22	(25.0)	0.75	(3.0)	302.8	(4.8)	-
			30	1.78	(0.7)	26.2	(10.3)	5.35	(21.5)	0.50	(-2.0)	473.1	(7.5)	-
			50	2.5	(1.0)	26.2	(10.3)	4.73	(19.0)	0.50	(-2.0)	378.0	(6.0)	-
10	50×250	Dry	0	0	(0)	0	(0)	0	(0)	0	(0)	0	(0)	-
			3	0	(0)	12.4	(4.9)	0	(0)	0	(0)	0	(0)	-
			10	13.2	(5.2)	17.5	(6.9)	0.25	(1.0)	0	(0)	0	(0)	-
			12	13.5	(5.3)	19.6	(7.7)	0.37	(1.5)	0	(0)	0	(0)	-
			13	13.5	(5.3)	20.6	(8.1)	0.37	(1.5)	0	(0)	567.7	(9)	-
			35	13.5	(5.3)	22.9	(9.0)	0.62	(2.5)	0	(0)	757.0	(12)	-
11 M	50×250	Dry	0	0	(0)	0	(0)	0	(0)	0	(0)	0	(0)	-
			1	0	(0)	5.8	(2.3)	0	(0)	0	(0)	0	(0)	-
			7	0	(0)	9.7	(3.8)	0	(0)	0	(0)	0	(0)	-
			35	13.7	(5.4)	19.3	(7.6)	-0.75	(-3.0)	0	(0)	0	(0)	-
			40	13.7	(5.4)	17.8	(7.0)	-0.75	(-3.0)	0	(0)	0	(0)	-
12 M	50×250	Wet	0	1.3	(0.5)	0.3	(0.1)	0.87	(3.5)	0.12	(0.5)	0	(0)	-
			2	1.3	(0.5)	6.9	(2.7)	0.87	(3.5)	0.12	(0.5)	0	(0)	-
			40	4.8	(1.9)	23.1	(9.1)	0.50	(2.0)	-0.62	(-2.5)	0	(0)	-
			50	4.8	(1.9)	21.6	(8.5)	0.50	(2.0)	0.62	(-2.5)	0	(0)	-
13 M	50×250	Dry/Wet	0	4.8	(1.9)	0.8	(0.3)	2.23	(9.0)	0.75	(3.0)	662.3	(10.5)	-
			5	3.8	(1.5)	11.4	(4.5)	5.47	(22.0)	-0.25	(-1.0)	700.2	(11.1)	-
			13	4.3	(1.7)	25.0+	(10.0+)	5.72	(23.0)	-0.25	(-1.0)	927.3	(14.7)	-
			50	4.3	(1.7)	25.0+	(10.0+)	5.72	(23.0)	-0.25	(-1.0)	927.3	(14.7)	-

Table 2-1. Refilling Test Data (Continued)

Run No.	Basket Top Screen	Initial Top Screen Wetting	Time, sec.	Start Basket Internal Liquid Level, cm (in)	Start Basket External Liquid Level, cm (in)	Flow Channel, ΔP, kN/m² (in H_2O)	Start Basket, ΔP, kN/m² (in H_2O)	Flow Rate, cm³/sec (GPM)	Start Basket Top Temp., K (F)
14	50×250	Dry	0	3.8 (1.5)	1.5 (0.6)	1.17 (4.7)	-0.12 (-0.5)	100.9 (1.6)	292 (66)
			1	3.8 (1.5)	10.4 (4.1)	1.47 (5.9)	-0.12 (-0.5)	100.9 (1.6)	292 (66)
			2	4.6 (1.8)	16.3 (6.4)	1.17 (4.7)	0 (0)	94.6 (1.5)	292 (66)
			4	8.1 (3.2)	18.8 (7.4)	0.6 (2.4)	-0.5 (-2.0)	94.6 (1.5)	292 (66)
			10	9.4 (3.7)	23.4 (9.2)	0.37 (1.5)	-0.37 (-1.5)	107.2 (1.7)	292 (66)
			47	13.5 (5.3)	21.6 (8.5)	0 (0)	-0.25 (-1.0)	100.9 (1.6)	292 (66)
			315	14.2 (5.6)	16.3 (6.4)	0.17 (0.7)	-0.12 (-0.5)	107.2 (1.7)	292 (66)
			350	14.0 (5.5)	15.2 (6.0)	0.17 (0.7)	-0.12 (-0.5)	107.2 (1.7)	292 (66)
15	50×250	Dry	0	2.5 (1.0)	2.39 (0.9)	2.79 (11.2)	0.27 (1.1)	126.2 (2.0)	287 (57)
			1	2.5 (1.0)	8.1 (3.2)	2.79 (11.2)	0.54 (2.2)	126.2 (2.0)	287 (57)
			2	3.6 (1.4)	17.3 (6.8)	1.87 (7.5)	-0.12 (-0.5)	126.2 (2.0)	287 (57)
			7	5.3 (2.1)	24.4 (9.6)	1.17 (4.7)	-0.25 (-1.0)	145.1 (2.3)	287 (57)
			35	8.4 (3.3)	23.6 (9.3)	0.87 (3.5)	-0.25 (-1.0)	126.2 (2.0)	287 (57)
			135	10.9 (4.3)	21.1 (7.9)	0.60 (2.4)	0 (0)	132.5 (2.1)	287 (57)
			335	13.5 (5.3)	15.5 (6.1)	0.37 (1.5)	0.1 (0.4)	126.2 (2.0)	287 (57)
			435	13.5 (5.3)	13.2 (5.2)	0.37 (1.5)	0.25 (1.0)	126.2 (2.0)	287 (57)
16	50×250	Wet	0	2.3 (0.9)	1.3 (0.5)	4.0 (16.1)	1.69 (6.8)	88.3 (1.4)	289 (60)
			2	2.5 (1.0)	17.5 (6.9)	4.0 (16.1)	-0.50 (-2.0)	100.9 (1.6)	289 (61)
			7	2.8 (1.1)	23.9 (9.4)	3.9 (15.5)	-0.50 (-2.0)	107.2 (1.7)	289 (61)
			1357	3.8 (1.5)	3.3 (1.3)	2.2 (8.8)	0.37 (1.5)	82.0 (1.3)	289 (61)
			1407	3.8 (1.5)	2.8 (1.1)	2.1 (8.5)	0.70 (2.8)	82.0 (1.3)	289 (61)
17	No Data								
18	50×250	Wet	0	2.5 (1.0)	1.3 (0.5)	0.87 (3.5)	1.04 (4.2)	0 (0)	290 (63)
			2	2.8 (1.1)	18.8 (7.4)	1.0 (4.1)	-0.62 (-2.5)	0 (0)	290 (63)
			6	3.0 (1.2)	25.7 (10.1)	0.87 (3.5)	-0.75 (-3.0)	0 (0)	290 (63)
			64	5.6 (2.2)	25.1 (9.9)	0.6 (2.4)	-0.75 (-3.0)	0 (0)	290 (63)
			1176	6.6 (2.6)	24.6 (9.7)	0.6 (2.4)	-0.50 (-2.0)	0 (0)	290 (63)
19M	No Data								
20 M	50×250 Stand-Pipe	Wet	0	0 (0)	0.8 (0.3)	1.09 (4.4)	0.12 (0.5)	0 (0)	291 (65)
			2	0 (0)	17.5 (6.9)	1.32 (5.3)	-0.62 (-2.5)	0 (0)	291 (64)
			7	3.0 (1.2)	25.7 (10.1)	1.02 (4.1)	-0.25 (-1.0)	0 (0)	291 (64)
			22	8.1 (3.2)	25.7 (10.1)	0.60 (2.4)	-0.25 (-1.0)	0 (0)	291 (64)
			128	12.4 (4.9)	25.4 (10.0)	0 (0)	-0.05 (-0.2)	0 (0)	291 (64)
			468	15.2 (6.0)	24.6 (9.7)	0 (0)	0 (0)	0 (0)	291 (64)
21 M	50×250 Stand-Pipe	Wet	0	2.3 (0.9)	0.8 (0.3)	2.79 (11.2)	1.54 (6.2)	82.0 (1.3)	291 (65)
			2	2.54 (1.0)	17.5 (6.9)	2.79 (11.2)	-0.50 (-2.0)	88.3 (1.4)	291 (65)
			7	4.1 (1.6)	25.9 (10.2)	1.72 (6.9)	-0.25 (-1.0)	100.9 (1.6)	291 (65)
			21	8.1 (3.2)	25.9 (10.2)	0.82 (3.3)	-0.25 (-1.0)	100.9 (1.6)	291 (65)
			59	10.4 (4.1)	25.7 (10.1)	0.37 (1.5)	-0.12 (-0.5)	100.9 (1.6)	291 (65)
			339	15.0 (5.9)	16.5 (6.5)	0.30 (1.2)	0 (0)	94.6 (1.5)	291 (65)
			539	15.0 (5.9)	13.5 (5.3)	0.30 (1.2)	0 (0)	94.6 (1.5)	291 (65)
21A	50×250 Stand-Pipe	Wet	0	2.0 (0.8)	0.8 (0.3)	3.3 (13.3)	0.8 (3.1)	88.3 (1.4)	293 (68)
			2	2.3 (0.9)	18.8 (7.4)	3.3 (13.4)	-0.5 (-2.0)	94.6 (1.5)	293 (68)
			7	4.1 (1.6)	27.2 (10.7)	2.0 (8.0)	-0.25 (-1.0)	100.9 (1.6)	293 (68)
			21	8.4 (3.3)	27.2 (10.7)	8.5 (3.4)	-0.25 (-1.0)	107.2 (1.7)	293 (68)
			48	10.4 (4.1)	26.7 (10.5)	0.5 (2.1)	-0.25 (-1.0)	113.5 (1.8)	293 (68)
			161	13.5 (5.3)	23.4 (9.2)	0.3 (1.2)	-0.05 (-0.2)	119.9 (1.9)	293 (68)
			376	15.0 (5.9)	18.3 (7.2)	0.3 (1.3)	0 (0)	119.9 (1.9)	293 (68)
			426	15.0 (5.9)	6.6 (2.6)	0.3 (1.3)	0 (0)	119.9 (1.9)	293 (68)
22 M	50×250 Stand-Pipe	Wet	0	5.3 (2.1)	0.8 (0.3)	4.5 (18.1)	1.3 (5.1)	492.0 (7.8)	293 (68)
			2	5.0 (2.0)	16.3 (6.4)	4.9 (19.6)	-0.25 (-1.0)	511.0 (8.1)	293 (68)
			7	5.6 (2.2)	25.5 (10.5)	4.7 (18.7)	-0.25 (-1.0)	574.0 (9.1)	293 (67)
			93	7.6 (3.0)	18.8 (7.4)	3.2 (13.0)	-0.25 (-1.0)	606.0 (9.6)	293 (68)
			140	7.8 (3.1)	10.7 (4.2)	3.1 (12.3)	0 (0)	606.0 (9.6)	293 (68)

Table 2-1. Refilling Test Data (Continued)

Run No.	Basket Top Screen	Initial Top Screen Wetting	Time, sec.	Start Basket Internal Liquid Level, cm (in)	Start Basket External Liquid Level, cm (in)	Flow Channel, ΔP, kN/m^2 (in H_2O)	Start Basket, ΔP, kN/m^2 (in H_2O)	Flow Rate, cm^3/sec (GPM)	Start Basket Top Temp., K (F)
23 M	50×250 Stand-Pipe	Dry	0	0 (0)	0 (0)	-	0 (0)	0 (0)	292 (66)
			2	0 (0)	17.0 (6.7)	-	0.25 (1.0)	0 (0)	292 (66)
			4	4.1 (1.6)	20.6 (8.1)	-	-0.50 (-2.0)	0 (0)	292 (66)
			7	4.8 (1.9)	23.6 (9.3)	-	-0.50 (-2.0)	0 (0)	292 (66)
			108	15.5 (6.1)	20.6 (8.1)	-	-0.50 (-2.0)	0 (0)	292 (66)
			138	15.5 (6.1)	20.1 (7.9)	-	-0.62 (-2.5)	0 (0)	292 (66)
23A M	50×250 Stand-Pipe	Wet	0	1.7 (0.6)	1.3 (0.5)	-	-0.12 (-0.5)	0 (0)	292 (65)
			2	2.5 (1.0)	18.8 (7.4)	-	-0.50 (-2.0)	0 (0)	292 (65)
			3	3.7 (1.4)	21.3 (8.4)	-	-0.75 (-3.0)	0 (0)	292 (65)
			7	3.8 (1.5)	25.7 (10.1)	-	-0.87 (-3.5)	0 (0)	292 (65)
			25	4.2 (1.6)	25.7 (10.1)	-	-0.92 (-3.7)	0 (0)	292 (65)
			55	4.1 (1.6)	24.4 (9.6)	-	-0.95 (-3.8)	0 (0)	292 (65)
24 M	200×600	Dry	0	0 (0)	1.8 (0.7)	0 (0.1)	-0.12 (-0.5)	0 (0)	294 (69)
			2	0 (0)	17.0 (6.7)	0 (0)	0.27 (1.1)	0 (0)	294 (69)
			3	4.1 (1.6)	19.6 (7.7)	-0.1 (-0.5)	-0.50 (-2.0)	0 (0)	294 (69)
			6	4.8 (1.9)	25.4 (10.0)	-0.2 (-0.9)	-0.47 (-1.9)	0 (0)	294 (69)
			35	10.9 (4.3)	25.4 (10.0)	-0.5 (-2.0)	-0.10 (-0.4)	0 (0)	294 (69)
			75	12.7 (5.0)	25.1 (9.9)	-0.6 (-2.5)	-0.07 (-0.3)	0 (0)	294 (69)
			300	14.2 (5.6)	24.6 (9.7)	-0.5 (-2.0)	0.05 0.2	0 (0)	294 (69)
25 M	200×600	Dry	0	3.6 (1.4)	3.0 (1.2)	2.8 (11.2)	0.1 (0.5)	157.7 (2.5)	296 (73)
			2	4.1 (1.6)	16.6 (6.5)	2.3 (9.1)	0.4 (1.6)	157.7 (2.5)	296 (73)
			3	5.6 (2.2)	19.8 (7.8)	1.7 (6.9)	-0.15 (-0.6)	164.0 (2.6)	296 (73)
			6	6.1 (2.4)	26.4 (10.4)	1.4 (5.8)	-0.1 (-0.5)	170.3 (2.7)	296 (73)
			61	11.6 (4.5)	26.2 (10.3)	0.6 (2.4)	0 (0)	170.3 (2.7)	296 (73)
			422	14.2 (5.6)	16.3 (6.4)	0.3 (1.2)	0.1 (0.5)	157.7 (2.5)	296 (73)
26	200×600	Dry	0	8.9 (3.5)	10.4 (4.1)	7.4 (29.6)	0.3 (1.1)	2523 (40.0)	297 (76)
			1	8.5 (3.3)	17.5 (6.9)	6.7 (27.0)	0.5 (2.2)	2523 (40.0)	297 (76)
			8	10.4 (4.1)	26.9 (10.6)	6.4 (25.9)	0.5 (2.2)	2965 (47.0)	297 (75)
			34	12.7 (5.0)	13.2 (5.2)	6.2 (24.8)	0.8 (3.3)	2744 (43.5)	297 (76)
			44	12.7 (5.0)	5.8 (2.3)	6.0 (24.0)	2.1 (8.3)	2681 (42.5)	298 (77)
27 M	200×600	Wet	0	8.6 (3.4)	0 (0)	7.3 (29.2)	1.1 (4.6)	2397 (38.0)	297 (75)
			2	8.6 (3.4)	18.8 (7.4)	6.7 (27.0)	0.4 (1.8)	2523 (40.0)	297 (75)
			6	9.4 (3.7)	25.9 (10.2)	6.6 (26.5)	0.5 (2.1)	2649 (42.0)	297 (75)
			36	12.7 (5.0)	10.9 (4.3)	6.3 (25.4)	1.0 (4.2)	2681 (42.5)	297 (76)
			45	12.7 (5.0)	4.3 (1.7)	6.1 (24.4)	2.4 (9.8)	2596 (41.0)	298 (77)

7. Continue outflow from the basket (through the channels) until pullthrough occurs.

Test data from Table 2-1 was studied for selection of test runs to be compared with REFILL program computer predictions.

2.4 REFILLING MODEL CORRELATION AND VEHICLE PREDICTION

The REFILL computer program was successfully correlated with test data. The computer program was then utilized to predict refilling for Centaur D-1S LH_2 and LO_2 start baskets.

2.4.1 REFILLING COMPUTER MODEL CORRELATION. Five test runs were selected for computer program correlation: test runs 13 to 16 and 22 as listed in Table 2-1. Several computer program improvements were made at this point, as described in Section 2.1, in order to accurately simulate the test runs. These modifications were: addition of a table for pullthrough height vs flow rate, an option to eliminate spilling at initiation of outflow, and an option to allow the standpipe to remain dry during refilling independent of the liquid level outside the basket.

Computer runs were made with both air and ethanol vapor as the gas inside and surrounding the basket. The data was best correlated with air properties for vapor flow across the start basket. Tank liquid level vs time obtained from test data was an input for each computer run. Given the initial liquid level in the basket and the tank liquid level versus time the major variables used in obtaining the correlation were AST, NDR, NW and DBP2. AST is the screen area of the standpipe. NDR is a flag that keeps the standpipe screen dry if not set equal to zero. If NDR = 0 the standpipe screen is wet. NW is a flag that determines wetting conditions of the uncovered screen excluding the standpipe. If NW = 1 wetting of the screen does not occur above the liquid level outside the basket. If NW = 2 the basket is wetted to the base of the standpipe. (If NW = 3, Subroutine SWET is used to calculate screen wetting based on screen/plate wicking.) DBP2 is the bubble point of the top or standpipe screen. (The top screen consisting of a single screen layer is treated as a "standpipe" in the computer simulations.) Comparisons of test data and post test computer simulation are shown in Figures 2-11 to 2-15. For runs no. 14 and 15 the screen is initially dry, thus NDR = 1. Minimal screen wetting is assumed (NW = 1). The top screen bubble point is 65 microns for 50 × 250 screen. The standpipe area that remained dry during refilling was determined parametrically by fixing the initial basket level and varying the standpipe unwetted area until the basket level at the final time (46 seconds for run no. 14 and 34 seconds for run no. 15) was matched. Results are plotted in Figures 2-12 and 2-13 with straight lines connecting the data points and simulation points.

For runs no. 13, 16 and 22 the standpipe screen was initially wet (NDR = 0) and the basket screen was initially wet (NW = 2). For runs no. 13 and 16 a 50 × 250 flat 5.08 cm (2.0 in) dia top screen was used as the "standpipe." For run no. 22 a 3.81 cm (1.5 in) high by

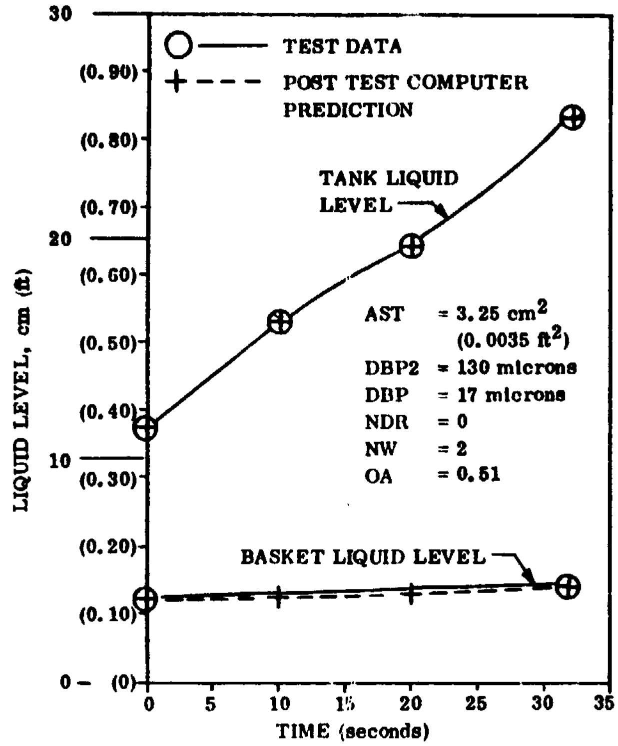


Figure 2-11. REFILL Computer Program Simulation of Test Run No. 13

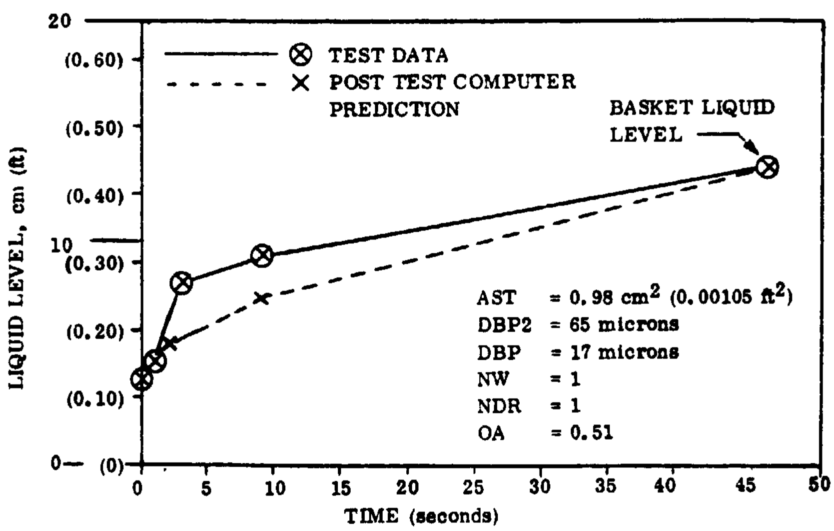


Figure 2-12. REFILL Computer Program Simulation of Test Run No. 14

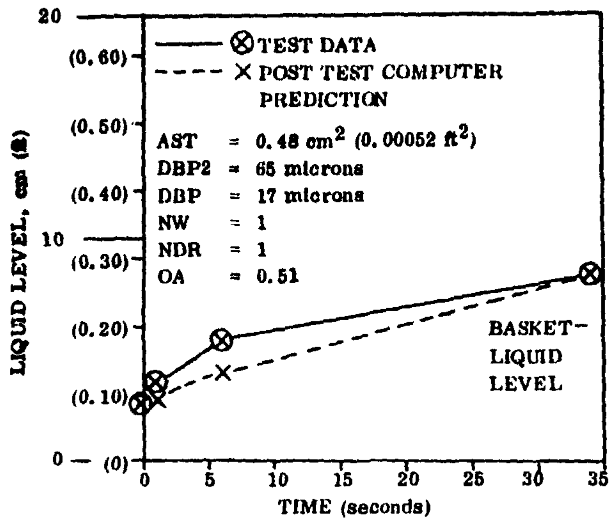


Figure 2-13. REFILL Computer Program Simulation of Test Run No. 15

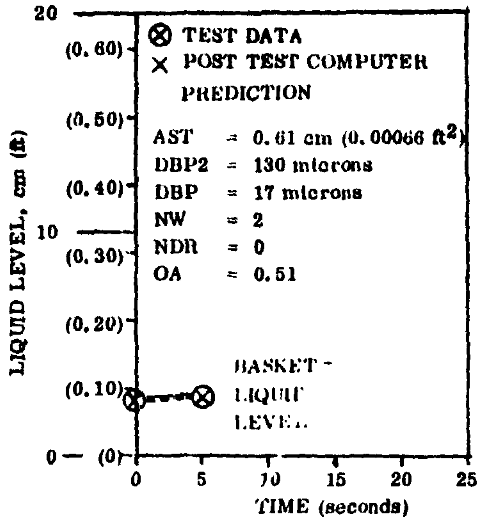


Figure 2-14. REFILL Computer Program Simulation of Test Run No. 16

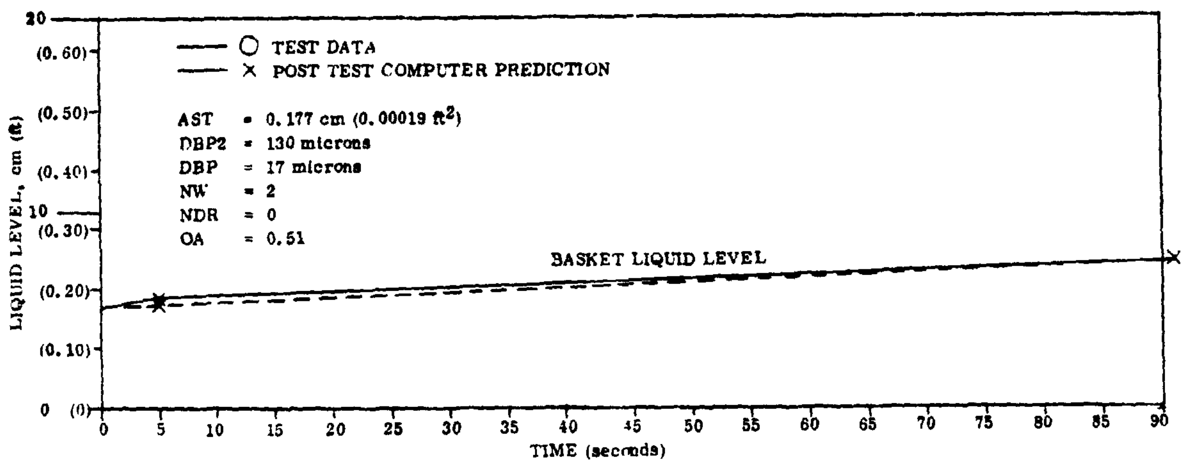


Figure 2-15. REFILL Computer Program Simulation of Test Run No. 22

5.08 cm (2.0 in) diameter cylindrical standpipe was used. Initial computer runs made for test runs no. 13, 16 and 22 indicated that no refilling should occur. Inspection of test notes and movies indicated that some leakage had occurred around the standpipe screen/main screen attachment ring. Computer runs were then made to determine this leakage area. From the initial runs with no filling the minimum size leak that would produce refilling was determined to be approximately 130 microns. Parametric evaluation of the standpipe area, using a bubble point of 130 microns, determined the areas required to produce the desired refilling for each run. This evaluation was similar to that used for runs no. 14 and 15 with the initial basket level fixed and the area of the leak varied until the "final" liquid level was matched.

Although only five runs were evaluated in detail because of time limitations, these runs represent a wide range of geometry, wetting and outflow conditions. The usefulness of the program in predicting test conditions qualified the program as a versatile and apparently accurate tool for predicting actual start basket refilling under mission conditions.

2.4.2 CENTAUR D-1S START BASKET REFILLING. Refilling analysis of the Centaur D-1S LO_2 and LH_2 start baskets was completed using the REFILL computer program. Three reference missions described in detail in Tables 1-1, 1-2 and 1-3 were used for capillary device design and performance evaluation. The missions were a single-burn planetary mission, a two-burn synchronous equatorial mission and a five-burn low earth orbit mission. Each burn for these three missions was examined as a possible worst case condition for refilling. Three burns were selected for analysis based on the refilling gravity level and engine burn time. The first burn of the two-burn and five-burn missions were selected because of their relatively low gravity refill conditions. The fourth burn of the five-burn mission was selected because it required refilling to be accomplished in the shortest time period. Refilling time was computed by subtracting the settling time under main engine thrust (after settling produced by the start sequence) from the main engine burn time. Settling time was computed using five times the free fall time with the start sequence and main engine thrust levels. For both of the first burn conditions examined (the two burn synchronous equatorial mission and the five-burn low earth orbit mission) the start sequence thrust was predicted to be sufficient to settle the propellants. This allowed the full burn time to be used for refilling. For burn four of the five-burn low earth orbit mission (burn time = 18.9 sec) some settling with main engine thrust will be required. This reduces the allowable refilling time to 16 seconds for LH_2 and 16.9 seconds for LO_2.

No liquid collection was assumed to occur around the basket during settling of the tank contents. Liquid collection was assumed to occur instantaneously after settling was complete. Liquid refilling calculations commenced at this point. (The computer program can handle refilling calculations during settling and collection, however the conservative assumption of instantaneous collection simplified the calculations required to generate the input for the simulation.) Schematics of the LO_2 and LH_2 baskets are shown in Figures 2-16 and 2-17. The LO_2 basket was modelled as two layers of 50 × 250 screen around the entire screen surface with the exception of a 5.5 cm standpipe which is a single layer of 50 × 250. The LH_2 basket was modelled as a double layer 50 × 250 surface with a 40 × 200 mesh 10.7 cm standpipe. The standpipe was input with an 84 micron bubble point and the flow properties of 50 × 250 screen. The actual configuration consists of a 50 × 250 double screened lower surface and 40 × 200 double screened upper surface with a 40 × 200 single screened standpipe. An 18 × 18 mesh cross screen separates the 50 × 250 lower and 40 × 200 upper compartments. The assumptions used in modelling the LH_2 configurations were made because no data is available for 40 × 200 screen flow/pressure drop and the REFILL program does not have the capability to handle multiple compartments. Initial basket liquid volume was based on subtracting the thermal conditioning usage between burns and the liquid outflow from the basket prior to settling from the start basket volume.

Results of the analysis are shown in Figures 2-18, 2-19 and 2-20. The volume versus height relationships used for both baskets are shown in Figures 2-21 and 2-22.

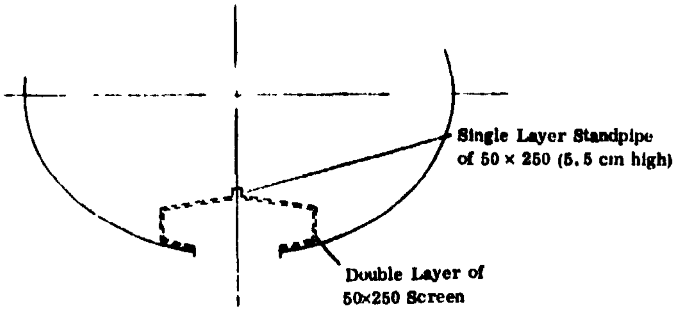


Figure 2-16. Schematic of LO_2 Start Basket

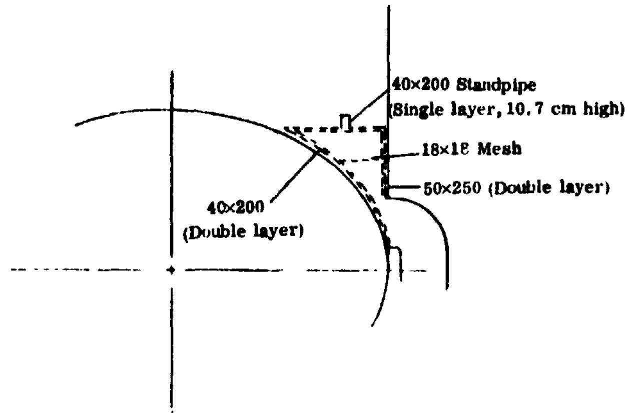


Figure 2-17. Schematic of LH_2 Start Basket

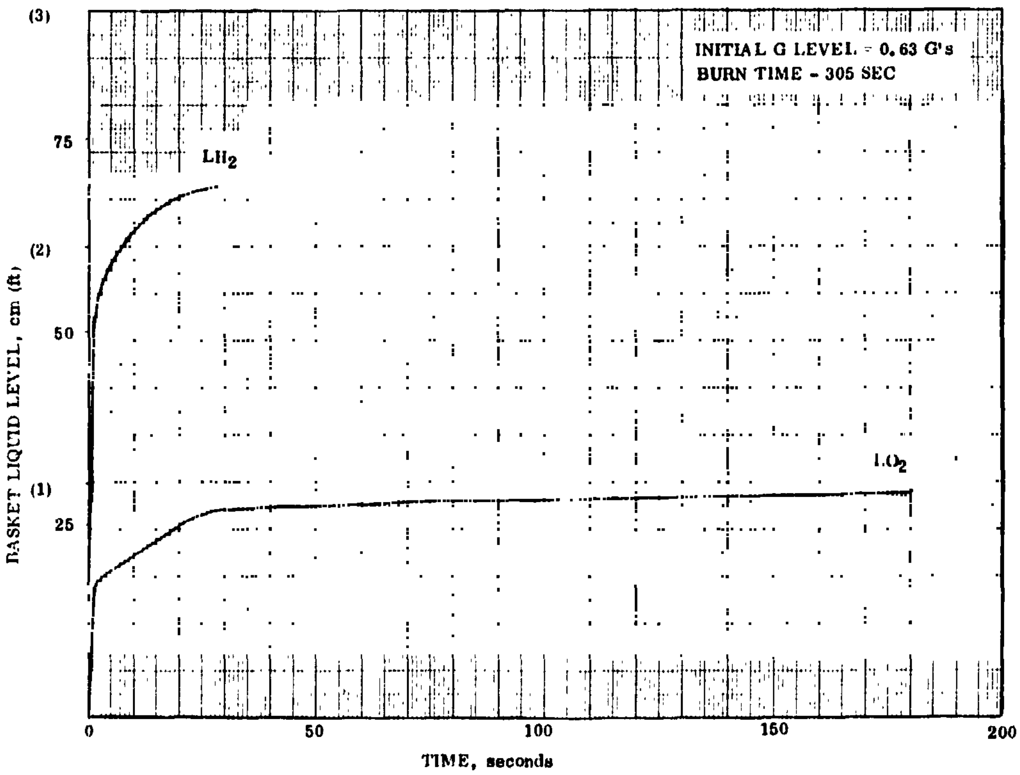


Figure 2-18. Centaur D-1S LO_2 and LH_2 Basket Refilling, Burn One - Synchr. ıous Equatorial Mission

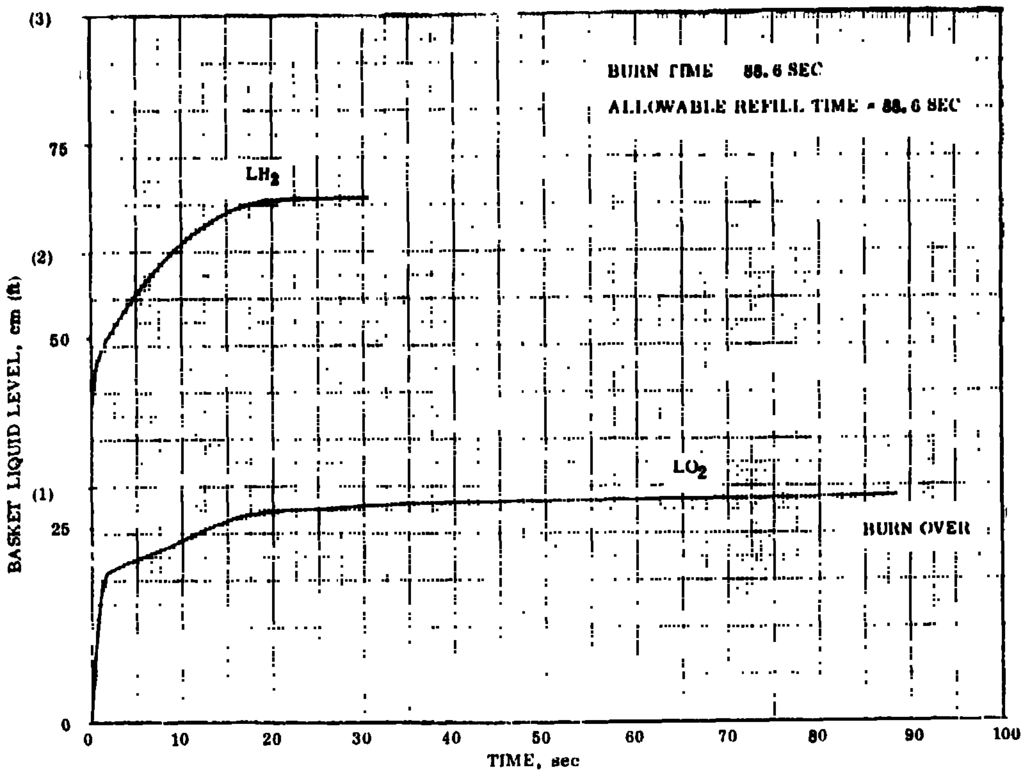


Figure 2-19. Centaur D-1S LO_2 and LH_2 Basket Refilling, Burn One - Low Earth Orbit Mission

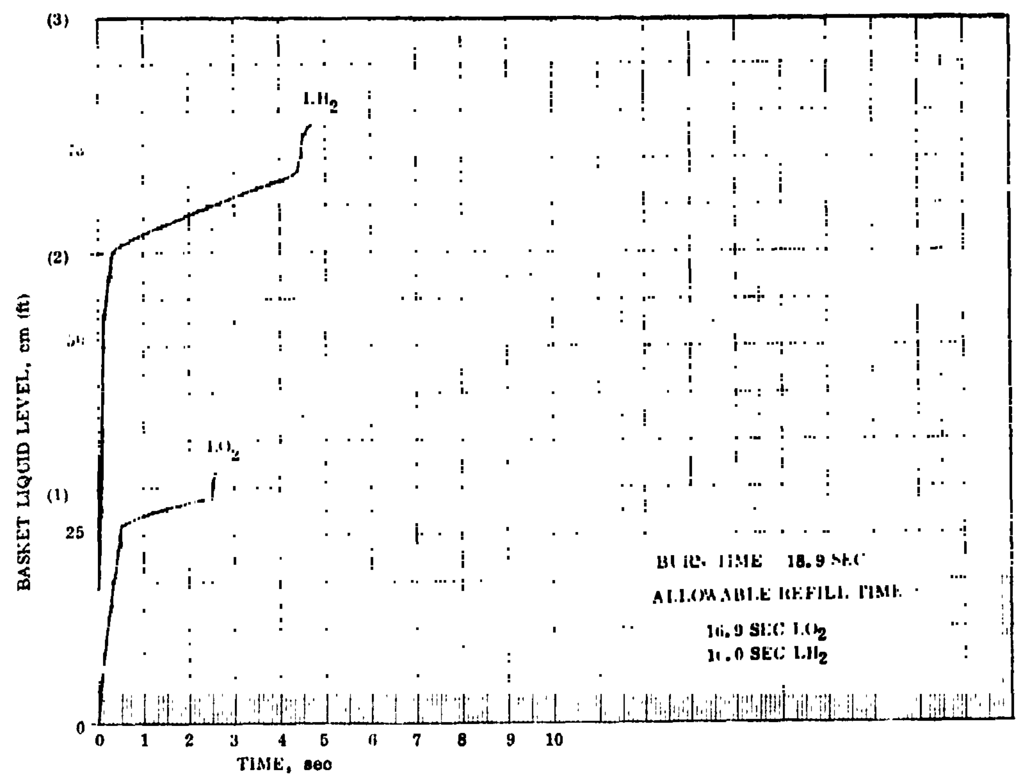


Figure 2-20. Centaur D-1S LO_2 and LH_2 Basket Refilling, Burn Four - Low Earth Orbit Mission

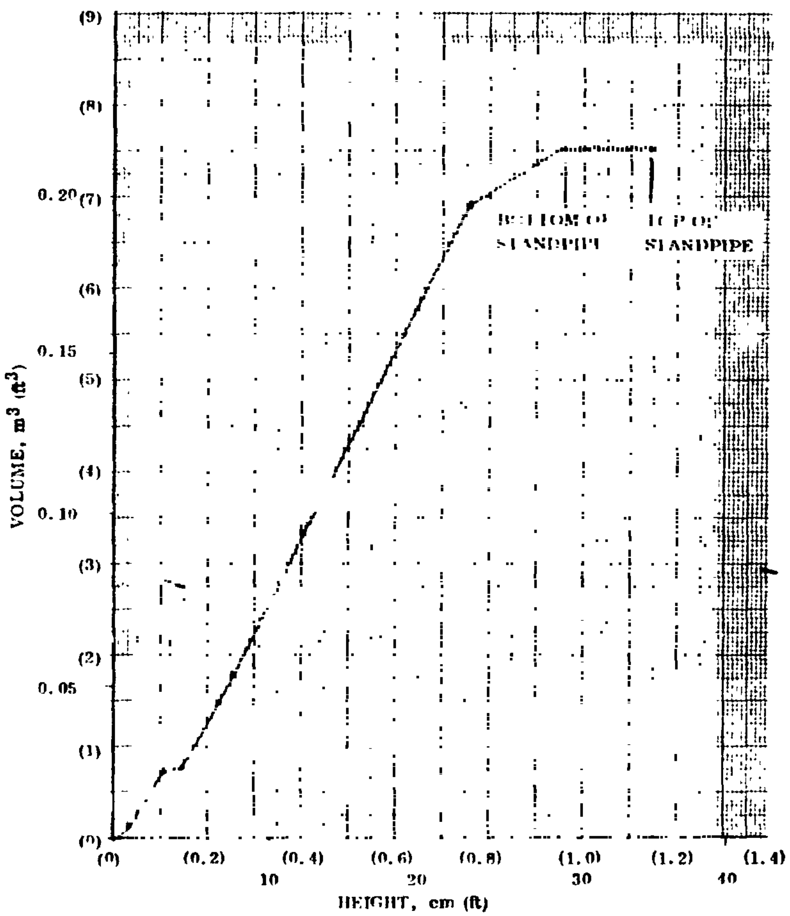


Figure 2-21. Centaur D-1S LO_2 Start Basket, Volume Versus Height

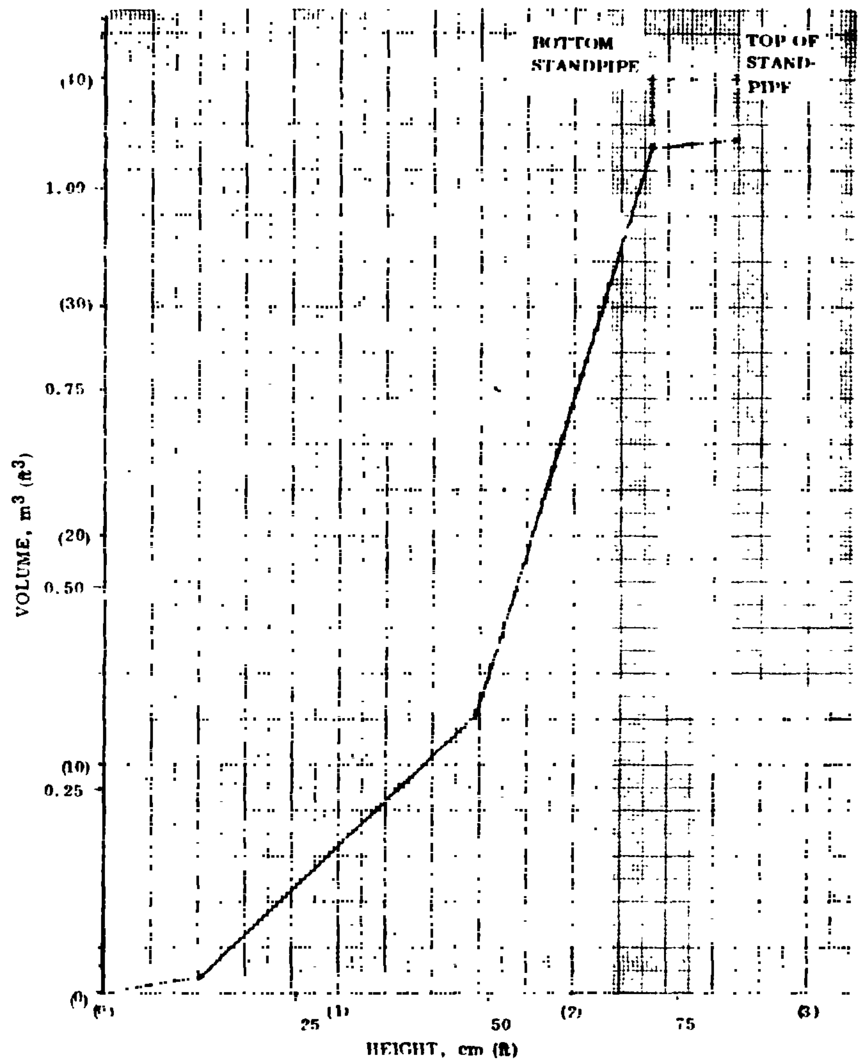


Figure 2-22. Centaur D-1S LH_2 Start Basket, Volume Versus Height

The refill computer program with variable g-level capability was used for this analysis. For the three burns considered, the results indicate that start basket refilling will occur at the imposed g-level and within the refilling time constraints.

2.4.3 CONCLUSIONS AND RECOMMENDATIONS. The computer program REFILL is an important capillary device design tool that permits refilling time for start baskets (using settled fluid) to be predicted. The program as documented in Appendix A has been correlated with ground test data and demonstrated to be a useful predictive tool. The program is recommended for use as a design tool to determine start basket volume and geometry. In fact, the program has already been used extensively at General Dynamics Convair to evaluate the capability of a start basket designed for ground testing with LH_2 to be refilled with LN_2. Test data to be obtained from the on-going program (NAS8-31778) will provide additional verification of program accuracy in predicting start basket refilling.

3

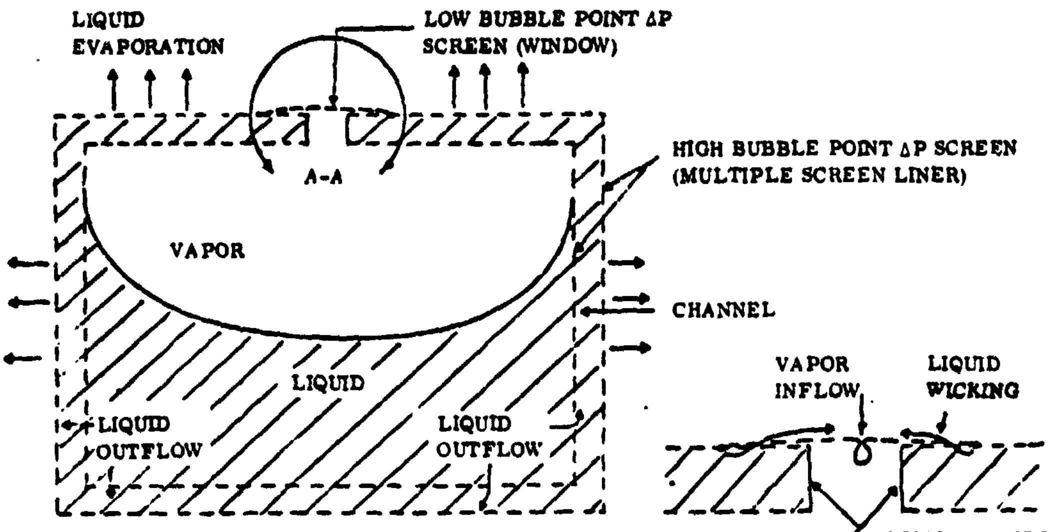
CAPILLARY DEVICE RETENTION/VAPOR INFLOW

In order for cryogenic capillary devices to function properly between engine restarts, screen retention capability must be maintained by keeping screens in a wetted condition. For partial acquisition devices, such as the LO_2 and LH_2 start baskets designed for the Centaur D-1S in Reference 3-1 and 3-2, contact between the screen surfaces and main liquid pool will not be continuously maintained between burns. The screen surfaces will dry out due to heat input to the surface if liquid is not continuously resupplied to the screen. Supply of thermal conditioning liquid to the screen surface by use of wicking between multiple screen/plate combinations was discussed in detail in Reference 3-2. Analysis and testing performed showed that liquid could be supplied to the screen surfaces in sufficient quantity to prevent screen dry out during all possible heat flux, adverse acceleration and wicking distance conditions.

One concern that was not within the scope of the NAS3-19693 effort reported in Reference 3-2 was how to handle vapor inflow. Vapor must enter the start basket volume to replace the liquid being evaporated from the screen surface. Unless this vapor can be directed to specific areas of the start basket, the vapor will detrimentally affect wicking flow and screen retention capability.

If vapor enters the multiple screen/plate wicking barriers, the path for wicking flow will be reduced to the point where liquid retention is lost. Figure 3-1 illustrates a typical multiple barrier wicking configuration. The gap between the innermost layers will be in the order of 0.064 cm (0.025 in) for low gravity application. This approach is satisfactory as long as sufficient liquid remains within the gap to provide wicking flow. However, eventually the gap will become filled with enough vapor that wicking flow rate is insufficient to intercept heat input to the outer screen. Outer screen dry-out results and liquid in the channel is lost. Because the gap between the wicking barriers is small, only a small amount of liquid will be retained in the gap and the time required for screen dryout will not be significant compared to the time between burns.

A concept which successfully avoids the adverse effects of vapor penetration is a multiple screen liner device with a window, shown schematically in Figure 3-1. The so-called "window" is a single screen that enables communication between the ambient and the inner volume of the surface tension device. This communication is established by providing a larger bubble point diameter screen for the window than for the multiple screens, to guarantee that vapor penetration will occur at the window screen and enter the device inner volume. The advantage of allowing vapor penetration at the window screen is that the multiple screens will remain wetted and not dry out. Consequently, heat interception capability of the device is maintained.



NOTE: LIQUID EVAPORATED AT OUTER SCREEN BARRIER IS REPLACED BY LIQUID FROM INNER VOLUME. LIQUID PUMPING IS DUE TO DIFFERENCE IN MULTIPLE SCREEN AND WINDOW BUBBLE POINT ΔP's.

Figure 3-1. Multiple Screen Liner With Window

Vapor inflow across wetted screened windows was examined in detail during this study. An extensive program of small scale bench tests was conducted in order to verify and correlate the equations. Persistent difficulties were experienced in obtaining repeatable results.

The remainder of this section discusses the equations believed to govern the operation of a single window screen within a multiple screen barrier configuration. Descriptions, drawings and photographs of the experimental apparatus and test specimens used are presented with a discussion of results, analytical model correlations and recommendations for additional experimentation.

3.1 VAPOR INFLOW ANALYTICAL MODEL DEVELOPMENT

Analytical evaluation of the vapor inflow process was performed in conjunction with some simple bench tests to obtain empirical factors for developing the governing equations. A small transparent box, representing a multiple screen/window configuration, was tested in hexane for this purpose. The box is shown schematically in Figure 3-2 along with the nomenclature used in the analysis. Figure 3-3 illustrates the interface conditions and pressures at the screened window. Using the nomenclature of Figures 3-2 and 3-3, the driving pressure for wicking across the window screen, ΔP_{wick} is determined to be

$$\Delta P_{wick} = P_{L_2} - P_L \tag{3-1}$$

$$\Delta P_{\sigma_2} = P_a - P_L \tag{3-2}$$

at the point of vapor breakthrough across the window screen.

$$\therefore \quad \Delta P_{wick} = P_{L_2} - (P_a - \Delta P_{\sigma_2}) \tag{3-3}$$

where ΔP_{wick} as defined by Equation 3-3 is a maximum due to the minimum value of the liquid film pressure P_L being used. ΔP_{σ_2} is the bubble point of the window screen. For wicking flow to occur along the window screen $P_{L_2} > P_A - \Delta P_{\sigma_2}$.

The heat intercept capability of a single horizontal screen is found from Reference 3-3 to be

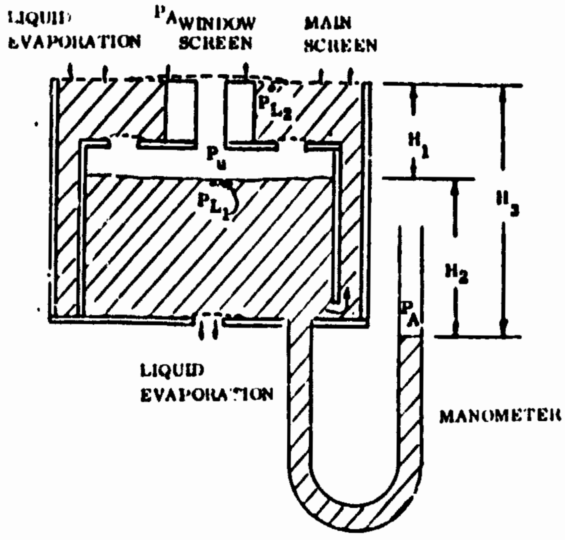


Figure 3-2. Multiple Screen Liner With Window

$$\dot{Q}/A_s = \dot{m}\lambda/A_s = \rho\lambda\varepsilon\,(C/L^2)\,(\sigma/\mu) \tag{3-4}$$

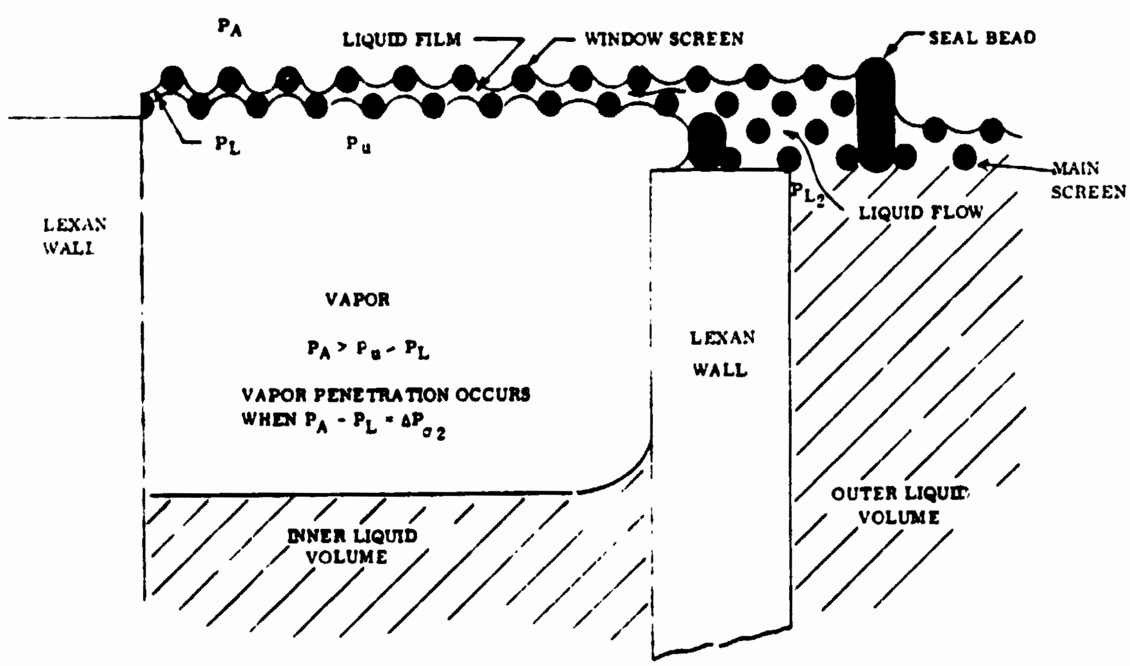


Figure 3-3. Interface Curvature at the Screen Window

where

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

A_s is the screen surface area

ρ is the liquid density

λ is the latent heat of vaporization

δ is the screen thickness

C is a correlation constant

L is the distance from the liquid source to the wicking front

σ is the liquid surface tension

μ is the liquid viscosity

The derivation of Equation 3-4 is based on the assumption that ΔP_{wick} and screen bubble point ΔP are equivalent. For the window screen application, however, these terms are not equivalent and Equation 3-4 must be adjusted accordingly. The adjustment has been to introduce a correction factor, F_σ, which results in

$$\dot{Q}/A_s = \dot{m}\,\lambda/A_s = \rho\,\lambda\,\delta\,(C/L^2)\,(\sigma/\mu)\,(F_\sigma) \tag{3-5}$$

where $F_\sigma = \Delta P_{wick}/\Delta P_{\sigma_2}$ (3-6)

From Equation 3-5 one can show that

$$\dot{Q}/A \propto F_\sigma/L^2 \tag{3-7}$$

The window screen will remain wetted as long as its wicking capability is equal to, or exceeds the incident heat flux, $\dot{Q}/A$. Because liquid wicking capability is decreased as F_σ (i.e., ΔP_{wick}) is reduced, the screen will begin to dry once F_σ drops below a minimum level. Screen drying can be explained from Equation 3-7 which shows that as F_σ drops in value, L must also be reduced in order to maintain a constant $\dot{Q}/A$. A reduction in L is equivalent to having a portion of the screen become dry because of the unavailability of liquid. Vapor flow will occur through the screen at this point. The flow of vapor into the inner volume will increase P_u, P_{L_2} and F_σ. The increase in F_σ will increase window screen wicking flow rate capability. Eventually the dry portion of the screen will re-wet, and vapor penetration will cease. Thus the pressure difference across the window screen cycles between minimum and maximum values.

Using the nomenclature of Figure 3-2, where $H_{3_{max}}$ is the maximum liquid head that can be retained by the window screen and $H_{3_{min}}$ is this value just after vapor breakthrough

$$\Delta P_{\sigma 2} = \rho g H_{3_{max}} \tag{3-8}$$

$$P_{L_2} = P_A - \rho g H_{3_{min}} \tag{3-9}$$

$$\Delta P_{wick} = P_A - \rho g H_{3_{min}} - (P_A - \rho g H_{3_{max}}) - \rho g (H_{3_{max}} - H_{3_{min}}) \tag{3-10}$$

and F_σ is found experimentally from

$$F_\sigma = (H_{3_{max}} - H_{3_{min}}) / H_{3_{max}} \tag{3-11}$$

F_σ is a quantity to be determined from testing and is a direct measure of the ability of the window screen to rewet and remain wetted. Substituting back into Equation 3-5 allows the heat interception capability of the configuration to be determined.

Also to be determined from the testing is a factor that measures when the screen cannot rewet. As the liquid level in the capillary device under the window screen drops, the capability for wicking across the window screen is reduced. Experimentally, a relationship was found that predicted the limit of the window/main screen system. This equation

$$P_{u_{(max)}} = P_A - K_u \Delta P_{\sigma_2} \tag{3-12}$$

is a pressure balance at the time of screen breakdown. (The exploratory tests conducted prior to formulation of the analysis and test plan had shown that the quantity K_u was a constant equal to 0.44 for the apparatus shown schematically in Figure 3-2 using hexane as the test fluid.) The following equations transform Equation 3-12 into an expression that can be evaluated from experimentally measured quantities.

Combining Equation 3-3 with the relationship $P_u = P_{L_2} + \rho g H_1$ (from Figure 3-2) gives

$$P_u - \rho g H_1 = (P_A - \Delta P_{\sigma_2}) + \Delta P_{wick} \tag{3-13}$$

Substituting Equation 3-12 into 3-13 results in

$$P_A - K_u \Delta P_{\sigma_2} - \rho g H_1 = (P_A - \Delta P_{\sigma_2}) + \Delta P_{wick} \tag{3-14}$$

or

$$\rho g H_1 = (1 - K_u) \Delta P_{\sigma_2} - \Delta P_{wick} \tag{3-15}$$

Substituting Equations 3-8 and 3-10 into 3-15

$$H_1 = (1 - K_u)\, H_{3_{max}} - (H_{3_{max}} - H_{3_{min}}) \tag{3-16}$$

or

$$H_1 = H_{3_{min}} - K_u\, H_{3_{max}} \tag{3-17}$$

Dividing Equation 3-17 by $H_{3_{max}}$ gives

$$H_1/H_{3_{max}} = H_{3_{min}}/H_{3_{max}} - K_u \tag{3-18}$$

Since Equation 3-11 shows $H_{3_{min}}/H_{3_{max}} = 1 - F_\sigma$

$$H_1/H_{3_{max}} = 1 - F_\sigma - K_u \tag{3-19}$$

Equation 3-19 identifies the maximum head difference that can exist between the inner volume and the outer volume liquid levels before window screen drying occurs. At this point H_1 is replaced by H_{1Cr} to designate a critical head difference and Equation 3-19 becomes

$$H_{1Cr}/H_{3_{max}} = 1 - F_\sigma - Ku \tag{3-20}$$

The heat interception capability and H_{1Cr} can be related by combining Equations 3-5 and 3-20

$$\frac{H_{1Cr}}{H_{3_{max}}} = 1 - K_u - \left[\frac{\dot{Q}/A_s}{\rho \lambda \delta\, (C/L^2)\, \sigma/\mu} \right] \tag{3-21}$$

The single unknown in Equation 3-21 is K_u. An extensive program of normal gravity bench tests was conducted to determine values of F_σ and K_u (using Equations 3-11 and 3-20) for a variety of screen configurations and test fluids. This information would then be extrapolated to cryogenic fluids and low gravity start basket configurations based on the physical property and geometric relationships found. A corollary objective of the testing was to increase the basic understanding of the physical processes controlling the wetting of screens subjected to transverse vapor flow.

3.2 VAPOR INFLOW APPARATUS AND TESTING

A series of tests were run in order to evaluate the equations presented in Section 3.1. Initial testing with a single test article using hexane provided repeatable results that were used to formulate the analytical model. Additional tests using several test fluids and test articles were planned based on the initial results. These results, however, were found to be disappointing both in repeatability of runs and rewetting performance. Considerable effort was expended in refining both test conditions and test article geometry in order to achieve results consistent with that obtained with the initial test article. Only limited success was achieved in this effort.

The following section chronologically describes the test configurations and test conditions employed during the study. Testing was conducted in five test series. The first test series used a single small test article and produced repeatable results. Based on these results six new articles were built and tested with hexane. The configurations were designed to yield parametric data on the screen wetting process when subjected to vapor flow. Results obtained were less repeatable than the first test series and showed poorer wicking performance. Some of the problems were felt to be a result of (1) lack of control of wicking between the main screen and window-screen, (2) reduced volume under the window and (3) increased screen deflection because of the increased screen span between supports. New articles were fabricated with reduced span, improved main screen/window screen wicking and increased volume under the window. The third test series was conducted with hexane using a bell jar for improved environmental control with the new test article as well as the original article. Somewhat better results were obtained under these conditions. Two additional boxes were then fabricated with different window lengths and tested in the fourth test series using hexane, ethanol and Freon TF. The test data was not as consistent as that obtained in the third test series. In the fifth test series two of the boxes were modified and tested with hexane and Freon TF. One of the boxes used Teflon dams to promote unidirectional wicking. The other box used screens with higher retention capability than previously tested.

Quantitative experimental results and the analytical model correlation are presented in Section 3.2. Recommendations for additional testing are presented in Section 3.3.

3.2.1 VAPOR INFLOW TESTING - INITIAL TEST ARTICLE 10/76 TO 11/76. Tests were initially conducted using the device illustrated in Figure 3-4, using hexane as the test fluid. Test observations for the first test (test no. 1) were run as follows.

1. After the inner and outer volumes were filled with hexane, the fill valve was closed and the model oriented as shown in Figure 3-5.

2. The vapor pressure of hexane was sufficiently high that evaporation readily occurred at ambient pressure and temperature conditions. Consequently, evaporation commenced immediately at the screen.

3. Bubble penetration at the $50 \times 250\ \mu$ window screen was observed to occur at 20 second intervals for flow periods of about 2 seconds (Figure 3-5a). It was believed that liquid evaporation at the screen caused liquid flow from the inner volume to the outer volume through a slot at the bottom of the device. This

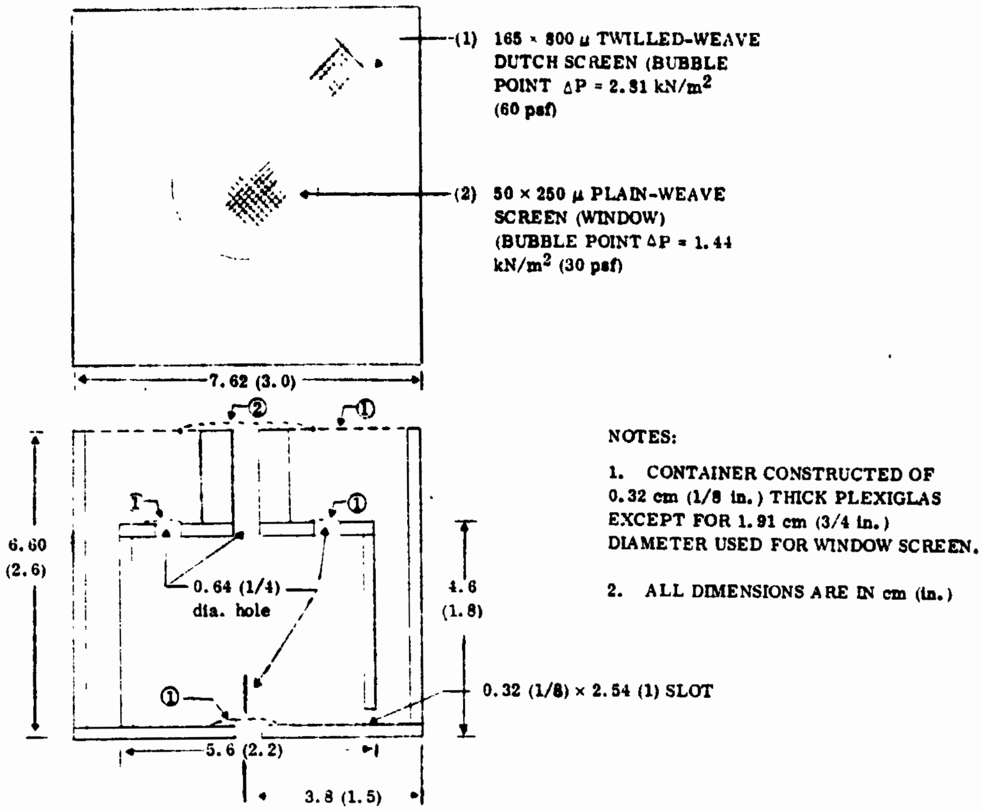
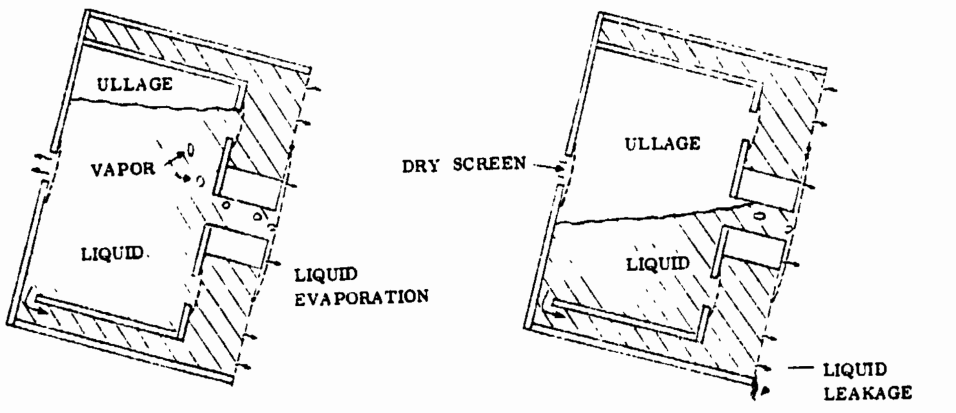


Figure 3-4. Multiple Screen Liner With Window Test Device



(a) Liquid evaporated at screen is replaced by liquid from inner volume, which is replaced by vapor penetration at window

(b) Liquid leakage begins once level drops below base of screen. This is evidence that screen dry-out has occurred.

Figure 3-5. Multiple Screen Liner With Window - Initial Test Series - Test No. 1

liquid flow reduced the inner volume pressure sufficiently to cause bubble penetration (about ten to twelve 0.32 cm (1/8 in) diameter bubbles in two seconds). Apparently the eighteen seconds between bursts of bubble flow was the liquid flow time required to exceed the bubble point ΔP capability of the window screen.

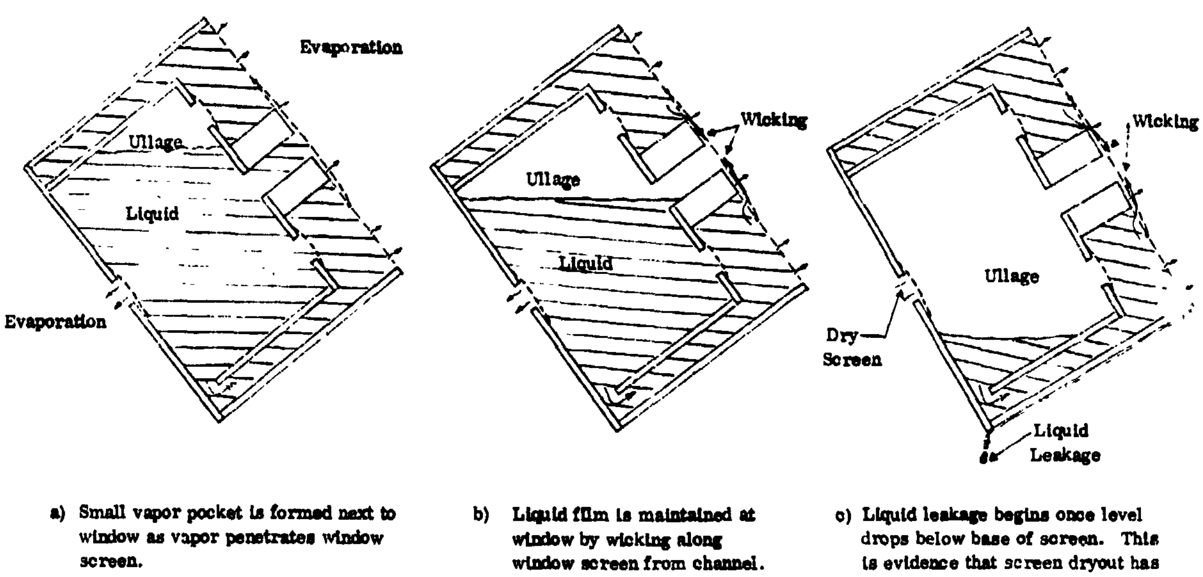
4. Surface evaporation at the screen continued until the inner volume liquid level dropped below the screen at the base of device (Figure 3-5b). Once the screen dried out due to surface evaporation, liquid retention was lost and liquid leakage began. The test was terminated at this time.

5. By visual observation bubbling rates and bubble sizes were used to determine an approximate liquid evaporation rate of 0.008 cm^3/sec (1.8 in^3/hour), which translates to a heat flux at the screen of 419.5 watts/m^2 (133 Btu/hr-ft^2). During testing an air stream was directed at the screen surface for a short period. It was estimated that liquid evaporation rate was increased by a factor of five to ten. Screen drying did not occur in the time period observed.

The next test run (test no. 2) provided the following observations.

1. After the inner and outer volumes were filled with hexane, the fill valve was closed and model oriented as shown in Figure 3-6.

2. While the inner volume liquid level remained above the window (Figure 3-6a), bubble penetration at the $50 \times 250\,\mu$ window screen was observed to occur at 20 second intervals. This was an identical observation to that in test no. 1



a) Small vapor pocket is formed next to window as vapor penetrates window screen.

b) Liquid film is maintained at window by wicking along window screen from channel.

c) Liquid leakage begins once level drops below base of screen. This is evidence that screen dryout has occurred.

Figure 3-6. Multiple Screen Liner With Window - Initial Test Series - Test No. 2

3. Surface evaporation at the screen continued even after the liquid level dropped below the window screen. Beyond this time, a liquid film was maintained on the window screen by wicking from the outer liquid volume (Figure 3-6b).

4. The test was terminated after the liquid level had dropped below the screen at the base of the device (Figure 3-6c). Liquid leakage began at this time, indicating that screen dry-out occurred.

5. Liquid evaporation rates were the same as for test no. 1, approximately 0.008 cm^3/sec (1.8 in^3/hr). As with test no. 1, evaporation rates were increased for short time periods by directing an air stream at the screen surface.

These tests were strong evidence that use of a window with a multiple screen liner could provide high heat flux interception capability, minimize wicking distance to prevent screen dryout and preferentially allow vapor to penetrate the capillary device while maintaining screen retention capability.

Additional tests in this initial test series were conducted to gain further insight into the mechanism of vapor penetration. Tests were performed to determine internal fluid pressure during liquid flow from the outer volume (main screen) to the window screen. A manometer was connected to the inner volume under the window to allow visual determination of the article internal pressures. Test observations for the subsequent test (test no. 3) were as follows.

1. After the inner and outer volumes were filled with hexane the model was oriented as shown in Figure 3-2.

2. Evaporation commenced immediately at the screen surfaces, which resulted in liquid flow from the inner volume to the outer volume. This flow demand resulted in manometer level drop as the inner volume pressure decreased.

3. Once steady-state conditions were established, bubble penetration of the 50 × 250 mesh window screen occurred at about 180 second intervals for flow periods of about 7 seconds.

   The manometer level increased during vapor penetration to reflect increasing inner volume pressure.

4. Figure 3-7 describes the observed liquid head variations with time. Note that vapor penetration of the window screen commenced each time that liquid in the manometer dropped 11.5 cm (4.53 inches) below the fine mesh screen. Note further that vapor penetration ceased each time that liquid in the manometer rose to within 4.95 cm (1.95 inches) of the inner volume liquid level.

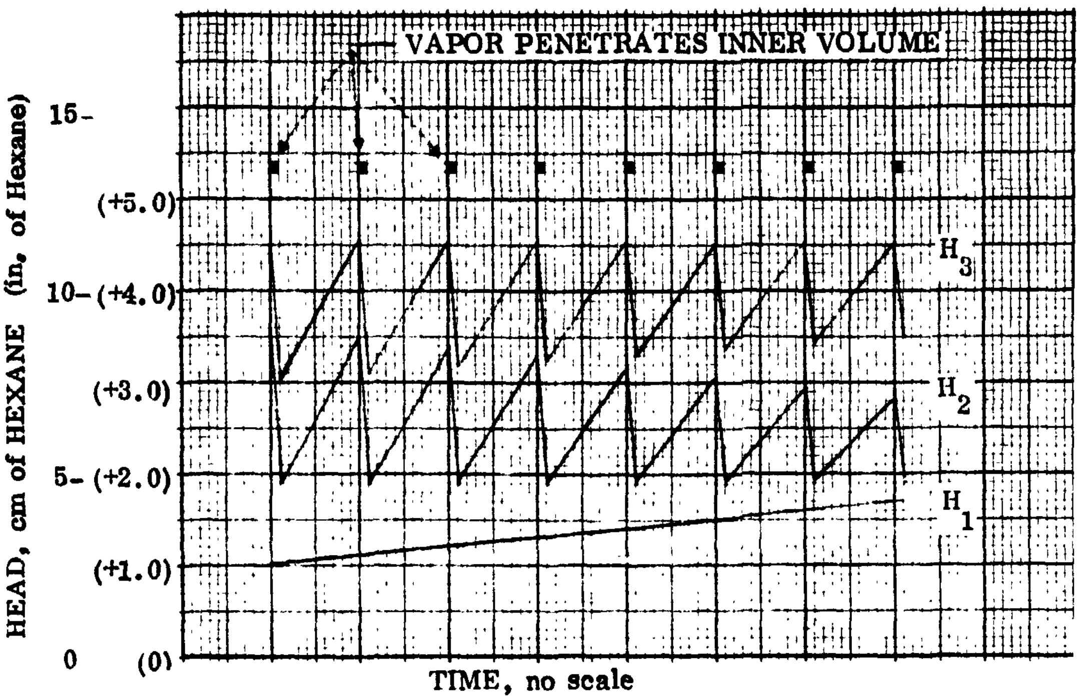


Figure 3-7. Manometer Liquid Head Readings During Test

5. Figure 3-8 describes inner volume ullage pressure, P_u, and outer volume liquid pressure at the screen, P_{L_2}. These pressures are referenced to ambient pressure, P_A, and are given in terms of window screen bubble point ΔP, ΔP_{σ_2}, which is equivalent to 11.5 cm (4.53 inches) of liquid hexane.

6. The test was terminated when H_1 reached 4.32 cm (1.7 inches). The screen device was still performing satisfactorily. Liquid evaporation rates were the same as found in tests no. 1 and 2, approximately 0.008 cm^3/sec (1.8 in^3/hr).

Several conclusions were drawn from Figure 3-8. Fluid pumping from the outer volume to the window is a function of $P_u - P_{L_2}$ as defined in Figure 3-3. This quantity is a function of the window screen bubble point ΔP_{σ_2} as shown in Section 3.1. Window screen retention capability must be less than the main screen retention capability.

Based on these initial tests, the analysis presented in Section 3.1 was developed. A comprehensive test plan was prepared (Reference 3-4) based on this analysis. The operation of the test article was demonstrated to NASA/LeRC personnel. After presentation to NASA/LeRC, the test plan was approved and the test configurations were fabricated.

3.2.2 APPARATUS FABRICATION AND VAPOR INFLOW TESTING OF SECOND SET OF TEST ARTICLES - JUNE-AUGUST, 1977. Five test articles were fabricated according to the drawings of Figures 3-9 and 3-10. Article characteristics are tabulated in Table 3-1. A schematic of the test apparatus used is shown in Figure 3-11.

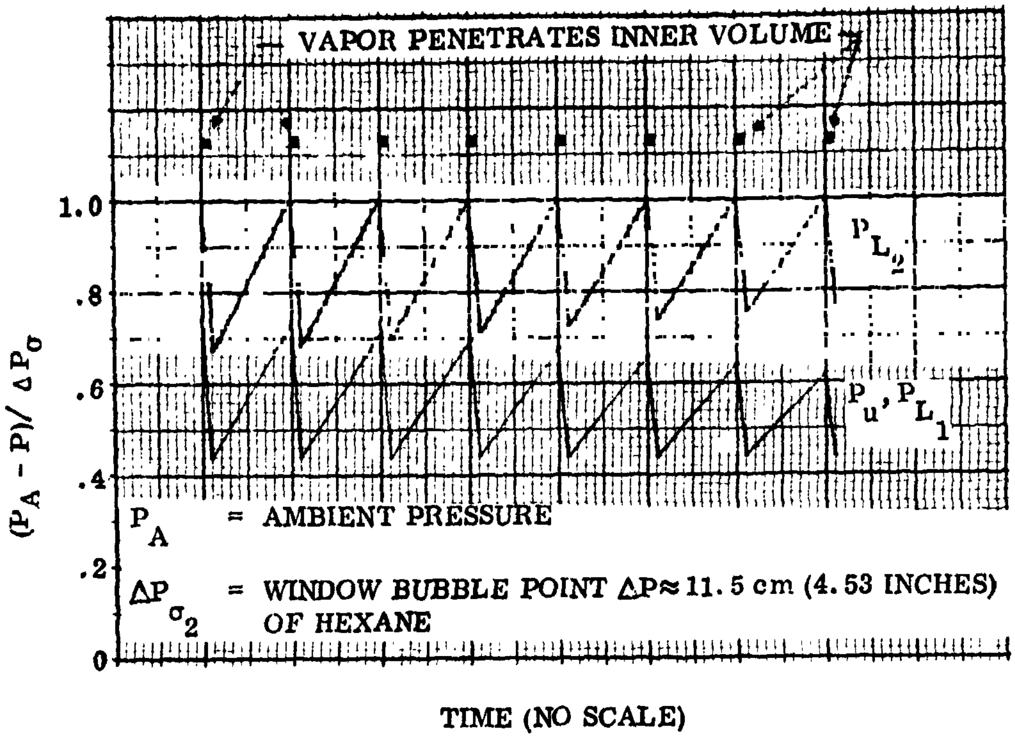
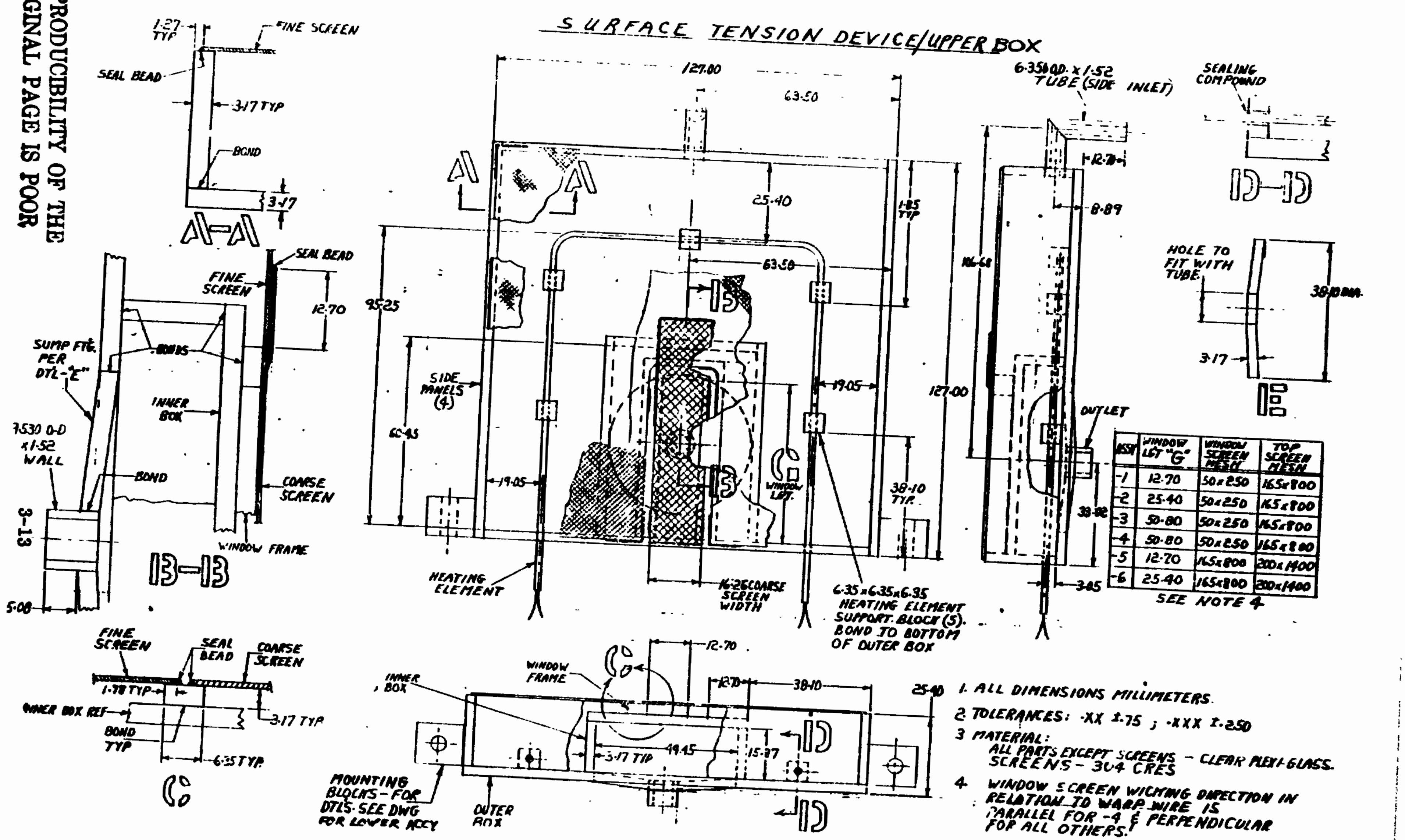


Figure 3-8. Liquid Internal Pressures During Test

Table 3-1. Surface Tension Device Configurations

(1) Configuration	Upper Box Ass'y	Window Length cm (in.)	Window Screen Mesh	Top Screen Mesh	Window Screen Wicking Direction in Relation to Warp Wire
A	-1	1.27 (0.50)	50 × 250	165 × 800	Perpendicular
B	-2	2.54 (1.00)	50 × 250	165 × 800	Perpendicular
C	-3	5.08 (2.00)	50 × 250	165 × 800	Perpendicular
D	-4	5.08 (2.00)	50 × 250	165 × 800	Parallel
E	-5	1.27 (0.50)	165 × 800	200 × 1400	Perpendicular
F	-6	2.54 (1.0)	165 × 800	200 × 1400	Perpendicular

(1) Only one lower box will be required. The bottom screen will be 200 × 1400 mesh.



ASSY	WINDOW LGT "G"	WINDOW SCREEN MESH	TOP SCREEN MESH
-1	12.70	50x250	165x800
-2	25.40	50x250	165x800
-3	50.80	50x250	165x800
-4	50.80	50x250	165x800
-5	12.70	165x800	200x1400
-6	25.40	165x800	200x1400

SEE NOTE 4

1. ALL DIMENSIONS MILLIMETERS.
2. TOLERANCES: .XX ±.75 ; .XXX ±.250
3. MATERIAL:
   ALL PARTS EXCEPT SCREENS – CLEAR PLEXI-GLASS.
   SCREENS – 304 CRES
4. WINDOW SCREEN WICKING DIRECTION IN RELATION TO WARP WIRE IS PARALLEL FOR -4 & PERPENDICULAR FOR ALL OTHERS.

Figure 3-9. Surface Tension Device/Upper Box

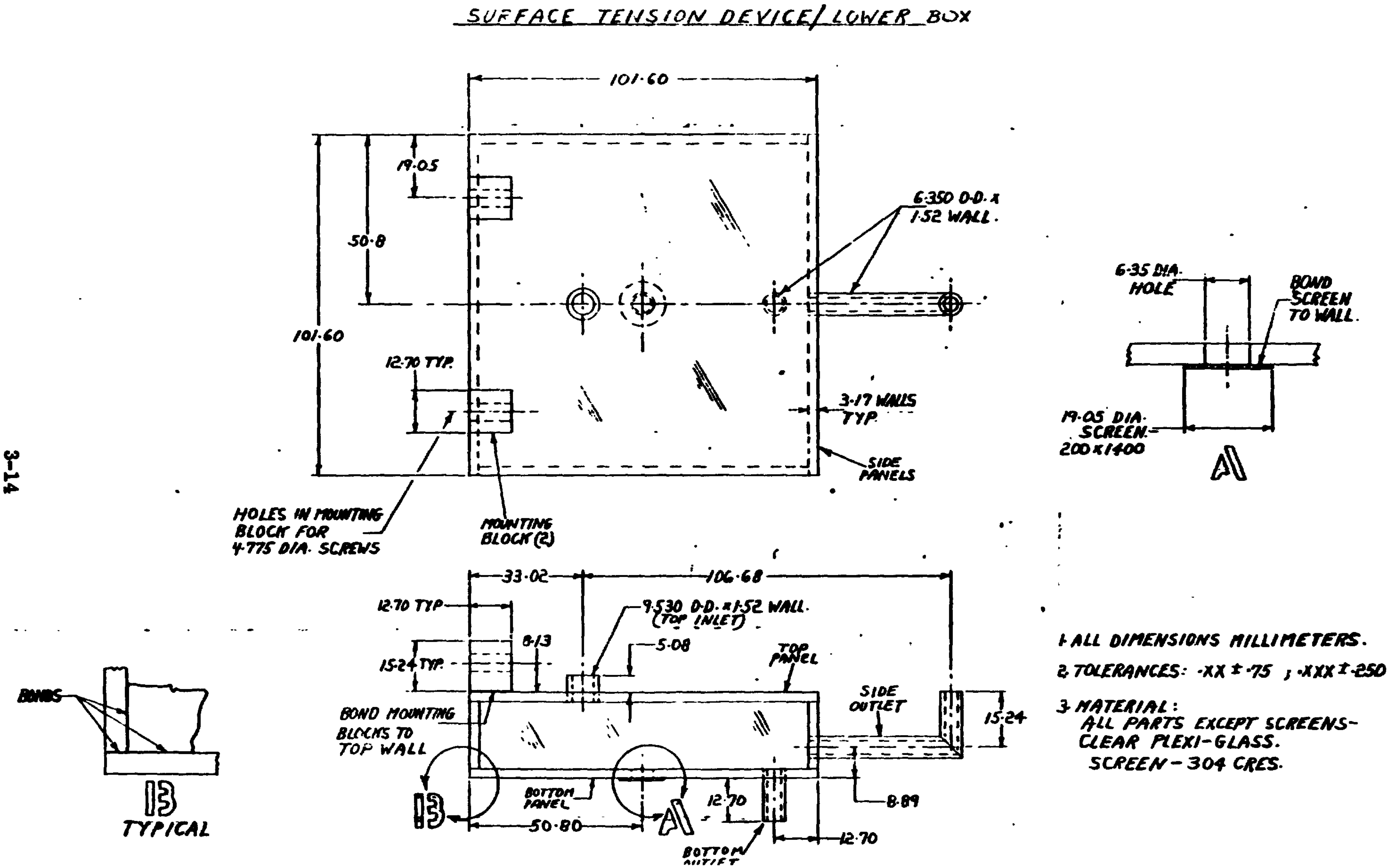


Figure 3-10 Surface Tension Device/Lower Box

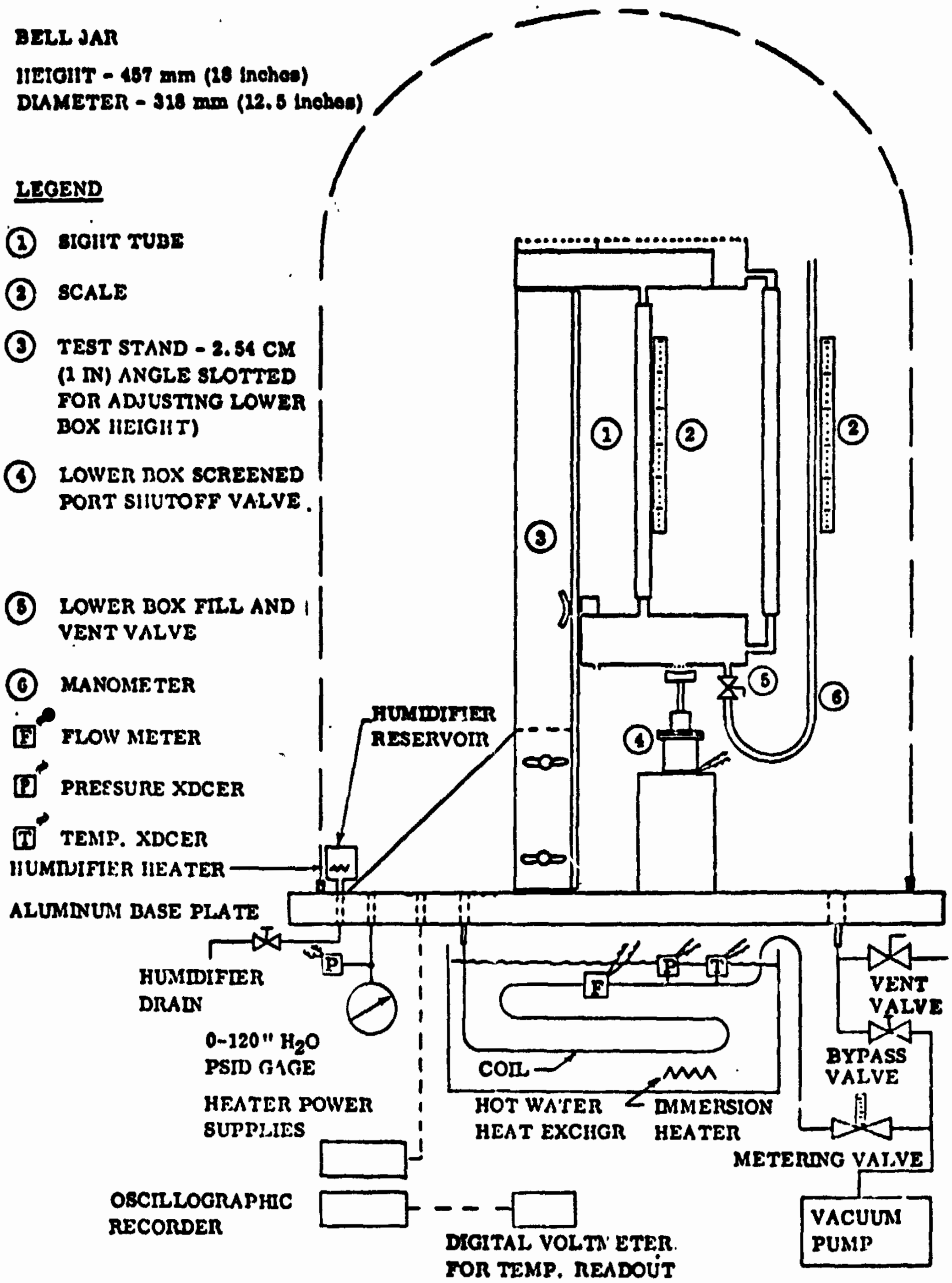


Figure 3-11. Vapor Inflow and Test Schematic

The test plan of Reference 3-4 describes the test conditions planned for evaluating screen dryout under heating conditions and determination of K_u under zero heat flux conditions.

3.2.2.1 Test Apparatus. In order to achieve near uniform evaporation at the window screen a bell jar is used to contain the test article and a vacuum is pumped on the bell jar atmosphere at controlled flow rates. The flow rates and pressures can be used to compute equivalent incident heat flux conditions to the screen surface based on test fluid vapor pressure. The test article assembly consists of an upper box and a lower box which are joined together at the inlets and outlets by tubing. Each box is constructed of Lexan and metallic Dutch weave screen. Details of the upper box are given in Figure 3-9. The six configurations of Table 3-1 are identical in every respect except for the top screen and window screen mesh and window screen length.

A single lower box configuration common to all upper boxes was assembled according to the details of Figure 3-10. The box is constructed of plexiglas with 200 × 1400 mesh screen over the bottom port.

3.2.2.2 Instrumentation. The liquid heads (H_1 and H_3) were determined by visual observation and were measured from the top plane of the upper box to the respective levels in the sight tube and manometer. An etched scale was included in the apparatus for each liquid head measurement.

The test setup incorporated two methods of measuring liquid evaporation. One method used a Flow Technology Omniflo turbine flow transducer. This type of transducer features interchangeable orifices which allows use of the same transducer for up to six over-lapping flow ranges. For the tests using hexane and Freon as the test fluids, the range of evaporation rates was expected to vary between 0.01 and 0.10 ACFM (actual cubic feet per minute). Two transducer orifice sizes were selected; one for the 0.01 to 0.05 ACFM range and one for the 0.05 to 0.10 range.

The flow transducer installation used is shown in Figure 3-11. In order to avoid problems associated with saturated vapor flow rate measurement, gas temperature could be increased by passing it through a hot water heat exchanger as illustrated in the test schematic. The water temperature could be maintained at approximately 100F. The flow transducer output was monitored on a Flow Technology MdL PR1-102 Flow Rate Indicator and also recorded on an oscillographic recorder. The downstream temperature and pressure was also oscillographically recorded for flow correction to volume (SCFM) or mass flow units. Because most tests were run without using the vacuum pumps, this measurement method was limited in use and the method below became the primary method.

The primary method for determining evaporation rate at the screens was by measuring the inner volume liquid level. Referring to Figure 3-11, both the inner volume of the upper box and the sight tube were calibrated such that mass or volume can be determined directly from inner volume liquid levels. By noting time intervals between level measurements average mass evaporation rates were known for specified intervals during the test.

The bell jar chamber pressure was monitored using a Statham strain gage type absolute pressure transducer. This pressure and the flowmeter outlet pressure were oscillographically recorded.

Chromel/Constantan thermocouples were used to monitor temperatures in the test article as shown in Figure 3-9. Humidifier reservoir and bell jar atmosphere temperature were also measured.

3.2.2.3 Test Procedure. The configurations shown in Table 3-1 were tested. A large matrix of tests were planned as documented in Reference 3-4. Only a small fraction of these tests were actually run as a result of difficulties with repeating the data. Zero heat flux tests were planned to be run by manually increasing the separation distance between filled boxes to as much as 25.4 cm (10 in) until vapor breakthrough at the upper box window occurs. The test specimens were then to be reassembled with rigid glass tubes, filled with test fluid and tested in the bell jar using the vacuum pump. Liquid head data was to be recorded until loss of retention at the lower box screen.

The testing actually proceeded as described in the following narrative. Assembly of all seven boxes was completed and leaks repaired as required. Two of the boxes (the lower box and upper box no. 4 from Table 3-1) are shown in Figure 3-12. The two boxes mounted in the test setup are shown in Figure 3-13. The overall test setup is shown in Figure 3-14.

Initial vapor inflow checkout runs were made with ethanol, hexane and Freon TF using several of the boxes listed in Table 3-1. These runs illustrated that the concept functioned in a reasonable manner, but the results differend from those obtained in the initial tests (see Section 3.2.1). Pressure recovery within the window area was much less than previously experienced. Figure 3-15 shows results obtained with the small box used in initial testing and the results obtained in this second series of tests. The difference in results is believed to be partially due to the greater screen deflection with the boxes described in Figure 3-9 and 3-10.

To compare these results with those obtained in the initial test series, the small article tested in the initial test series was returned by NASA/LeRC. The article had been damaged and repaired at NASA/LeRC. The window screen as received at General Dynamics Convair was clogged and was replaced with new 50 × 250 screen. A series of tests were run with both technical grade and reagent grade hexane. Screens were cleaned and tested. A set of tests was also conducted with both a new top screen (154 × 800) and window screen (50 × 250). Results indicated that original observations could be duplicated but pressure fluctuations and screen breakdown were erratic. This was felt to be caused by the sensitivity of the rewetting process to the space for wicking between the window screen and the top screen. This spacing can change during a test due to pressure fluctuations and heating variations. The spacing also changes between test articles due to the difficulty in exactly repeating the screen geometry during attachment.

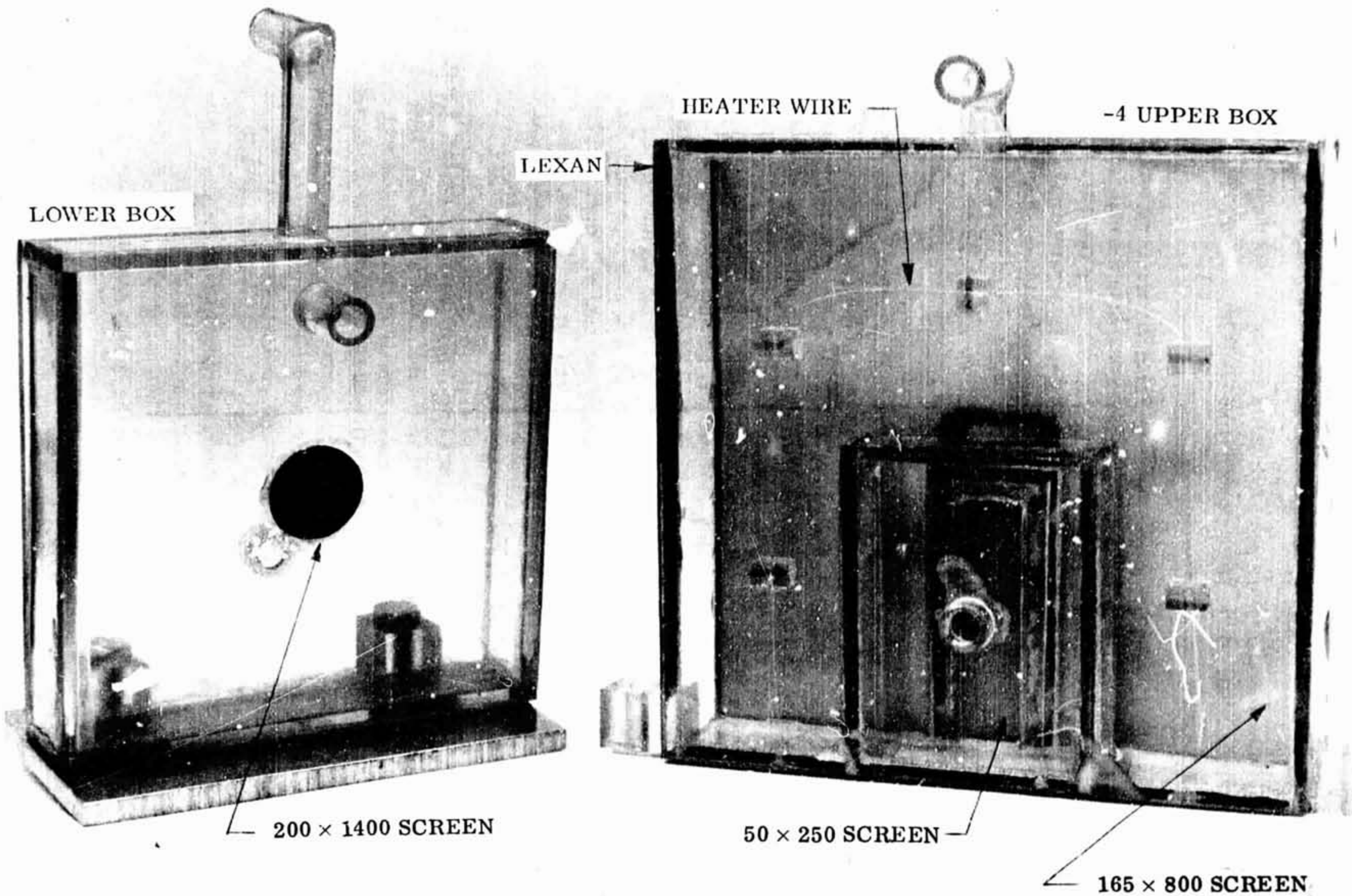


Figure 3-12. Lower and Upper Box (Typical)

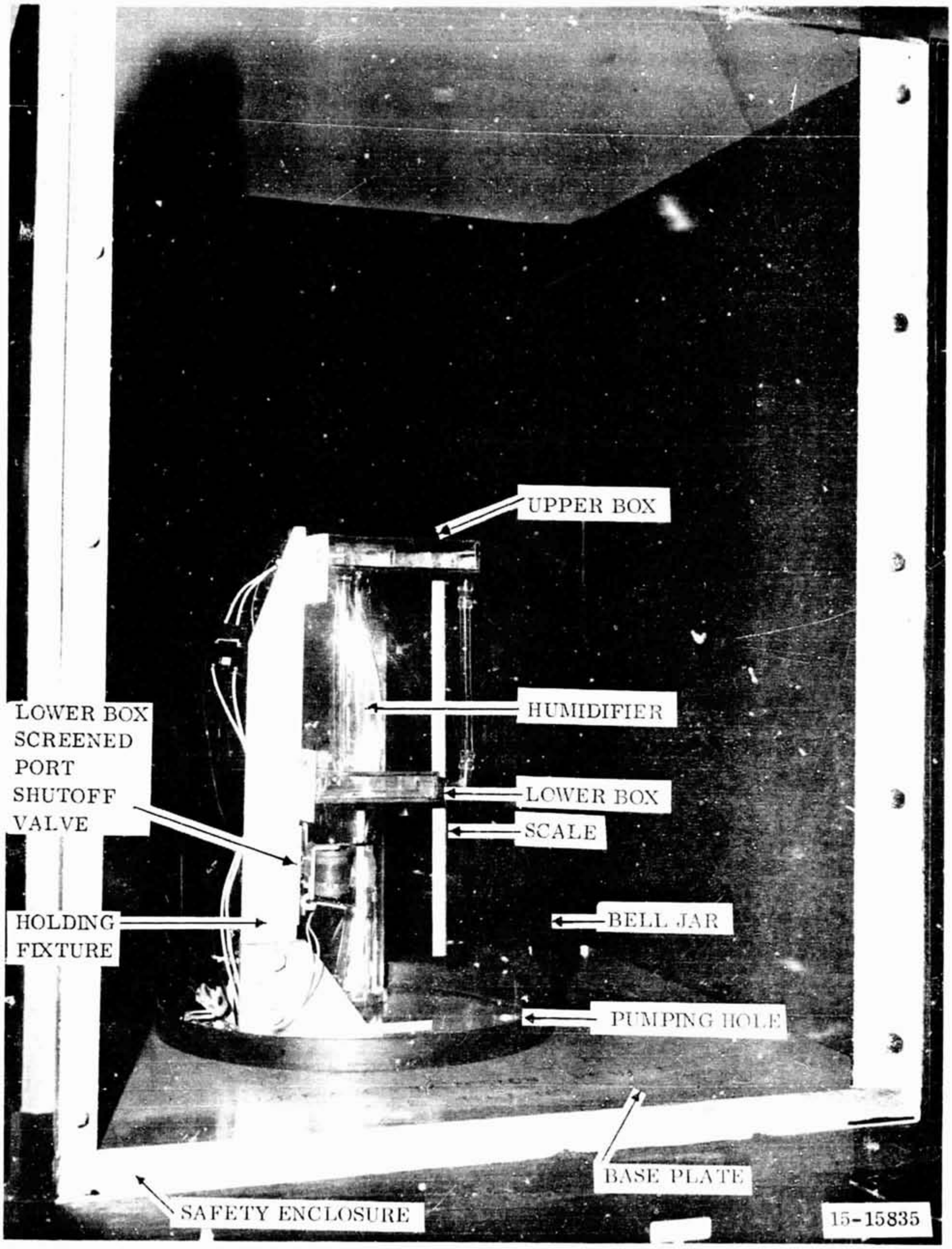


Figure 3-13. Vapor Flow Test Model Setup

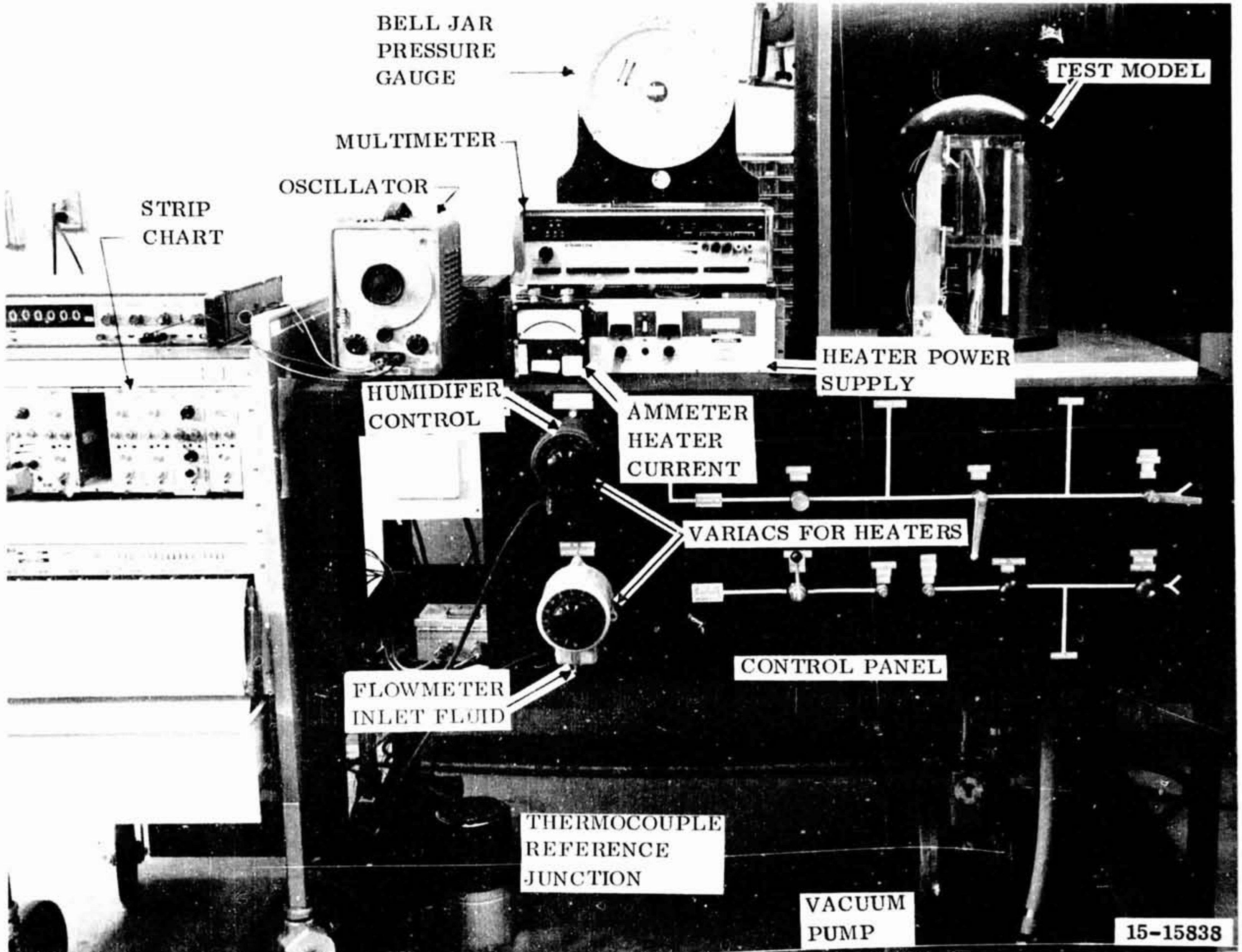


Figure 3-14. Overall Vapor Flow Test Apparatus Setup

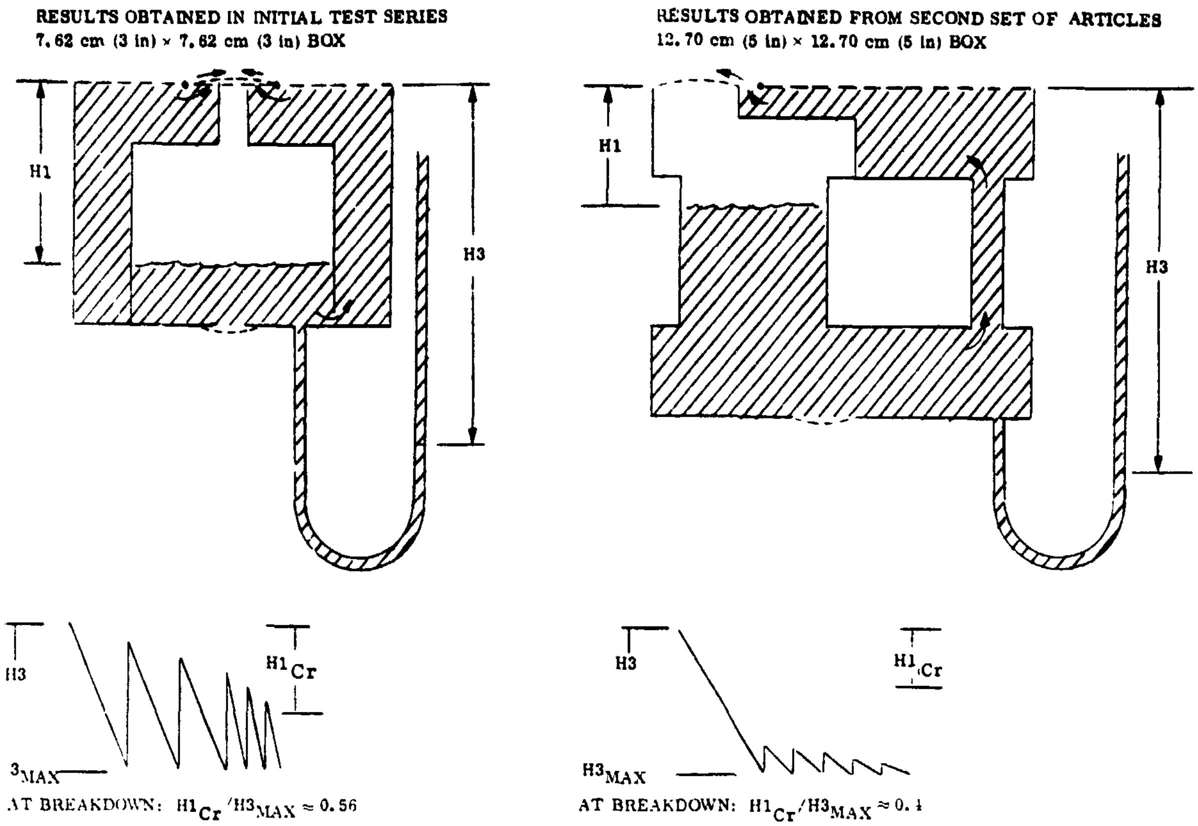
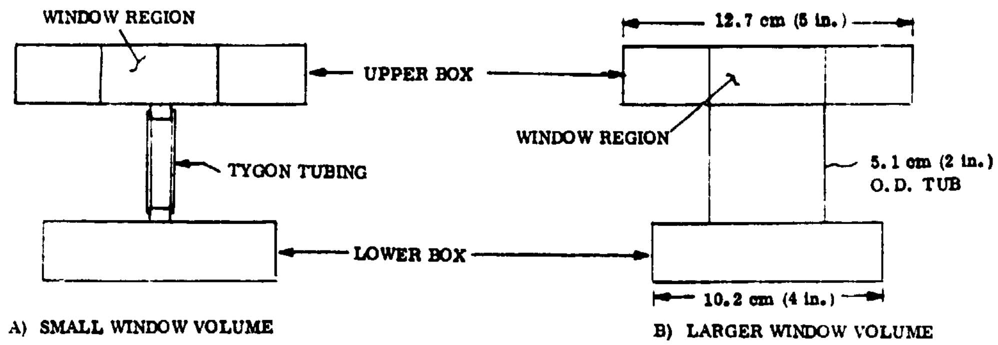


Figure 3-15. Vapor Inflow Test Results

Tests were then run using top boxes nos. 2 and 3 with the lower box (similar to those shown in Table 3-1 and Figures 3-9 and 3-10). The top boxes had 165 × 800 main screen and 50 × 250 window screen. The lower box had 200 × 1400 mesh screen. Runs were made using hexane with either small or large tubing connecting the upper and lower boxes as shown in Figure 3-16. A total of 17 test runs were made. All runs were made with the boxes exposed to ambient conditions.

Several observations were immediately evident from the runs; condensation of water on the apparatus affected test results (results were improved with increased condensation). This is probably due to the water reducing heat input. Fewer pressure cycles were obtained per test using the small tubing compared to using the large tubing between boxes. This is because of the increased volume in the window section using large tubing. Resealing of upper box no. 3 was less rapid than the box no. 2 tests. This is because the window length for box no. 3 is 5.08 cm (2.0 in) compared to a length of 2.54 cm (1.0 in) for box no. 2. Additionally, tests run with both technical grade and reagent grade hexane gave similar results. This indicated that technical grade was sufficiently pure for testing purposes.



(MANOMETER PORT AND PORTS CONNECTING MAIN SCREEN TO BOTTOM BOX ARE NOT SHOWN.)

BOXES ARE LEXAN WITH STAINLESS STEEL 50 × 250 MESH WINDOW SCREEN, 165 × 800 MESH SCREEN FOR THE REMAINDER OF THE UPPER BOX AND 200 × 1400 MESH SCREEN FOR THE LOWER BOX.

Figure 3-16. Large Box Test Configurations

The data obtained was reduced and compared to the analytical model presented in Section 3.1. Evaluation of the data centered on solving Equations 3-11 and 3-19 for the quantities F_σ and K_u. Data was reduced to determine H_{1Cr}, $H3_{max}$ and $H3_{min}$ for each run and is presented in Table 3-2. Considerable variation was found in $H3_{max} - H3_{min}$ for a given run. (In runs made in the initial test series, $H3_{max} - H3_{min}$ was found to be fairly constant). Values of H_{1Cr} did not approach the value anticipated based on Task II testing. (H_{1Cr} was generally in the 1.5 to 2 cm range where it had been projected to exceed 4.3 cm).

Examining the test data and test procedures used, several possible explanations were found for the anomalous results. The variation in $H3_{max} - H3_{min}$ during a run was likely due to environmental conditions such as changes in heat flux, water condensation and fluid temperature. This could be eliminated using the bell jar and other environmental controls such as outlined previously and shown in Figure 3-11. The observation that H_1 did not reach its full value with the larger boxes was possibly due to changes in internal pressure differential causing wicking potential to decrease. The lower pressure differential across the screens causes screen spacing to increase when $H3_{min}$ occurs. This resulted in a longer wicking distance and lower driving pressure for wicking. The recommended solution to this problem was to systematically spot weld the window screen to the main screen in the region of overlap and wicking.

The larger boxes 12.7 cm × 12.7 cm (5 in × 5 in) exhibited considerable screen deflection. Volume under the window was small, allowing only a few vapor breakthrough cycles to occur before H_1 reached its critical value. In the third test series wicking variations were controlled by controlling screen deflections, screen spacing variations and wicking length. Environmental conditions such as temperature, humidity (water), test fluid partial pressure, vapor velocity around the boxes and test fluid purity were controlled by using a bell jar, heaters and other equipment described in Figure 3-11. The test fluid was filtered prior to use.

Table 3-2. Summary of Runs Made During Later Portion of Second Test Series

Run Number	$H3_{max}$ (cm)	$H3_{min}$ (cm)	H_{1Cr} (cm)	No. of Cycles	F_{σ} $(H3_{max}-H3_{min})/H3_{max}$	$H_{1Cr}/H3_{max}$	Ku	Comments
1A	11.7	7.54	4.7	19	0.34	0.402	0.26	Original Box
1B	12.1	7.7	1.6	5	0.36	0.132	0.51	Box No. 2
2B	12.5	9.9	3.4	13	0.20	0.276	0.52	Large Tubing
3B	13.6	12.3	2.2	26	0.09	0.159	0.75	
1C	12.7	6.4	2.0	1	0.5	0.16	0.34	Box No. 2
2C	12.7	9.8	1.6	1	0.23	0.126	0.65	Small Tubing
3C	13.6	9.5	1.3	2	0.30	0.093	0.61	
4C	13.7	8.4	1.7	1	0.39	0.120	0.49	
5C	13.5	9.9	1.5	7	0.26	0.113	0.63	
6C	13.7	10.7	1.8	5	0.21	0.130	0.66	
1D	13.7	9.1	1.7	1	0.333	0.120	0.55	Box No. 3
2D	11.6	7.0	1.7	2	0.396	0.143	0.47	Small Tubing
3D	13.5	10.0	1.8	1	0.254	0.132	0.62	
1E	12.8	8.1	3.4	3	0.37	0.267	0.37	Box No. 3
2E	13.3	9.1	1.8	1	0.314	0.133	0.56	Large Tubing
3E	13.3	6.4	2.0	3	0.52	0.152	0.33	

3.2.3 VAPOR INFLOW TESTING - THIRD TEST SERIES, AUGUST 1977 TO OCTOBER 1977. A new test article was fabricated to the configuration shown in Figure 3-17. While these articles were being fabricated tests were run with the box used in the initial testing to illustrate the effect of the bell jar on controlling test conditions. The test article was filled with hexane, mounted on the test stand and covered with the bell jar. Four test runs were made. Cycling time was significantly longer for runs within the bell jar than with ambient runs, increasing up to 15 minutes per cycle as the bell jar became saturated with hexane.

Vacuum pumping of the bell jar was used to increase the heat flux to the screen surfaces. Rapid pressure decay produced bulk boiling under the main screen. Pumping down caused the pressure within the box to be above the pressure in the bell jar. The placement of the top of the manometer below the level of the top of the box was used to relieve

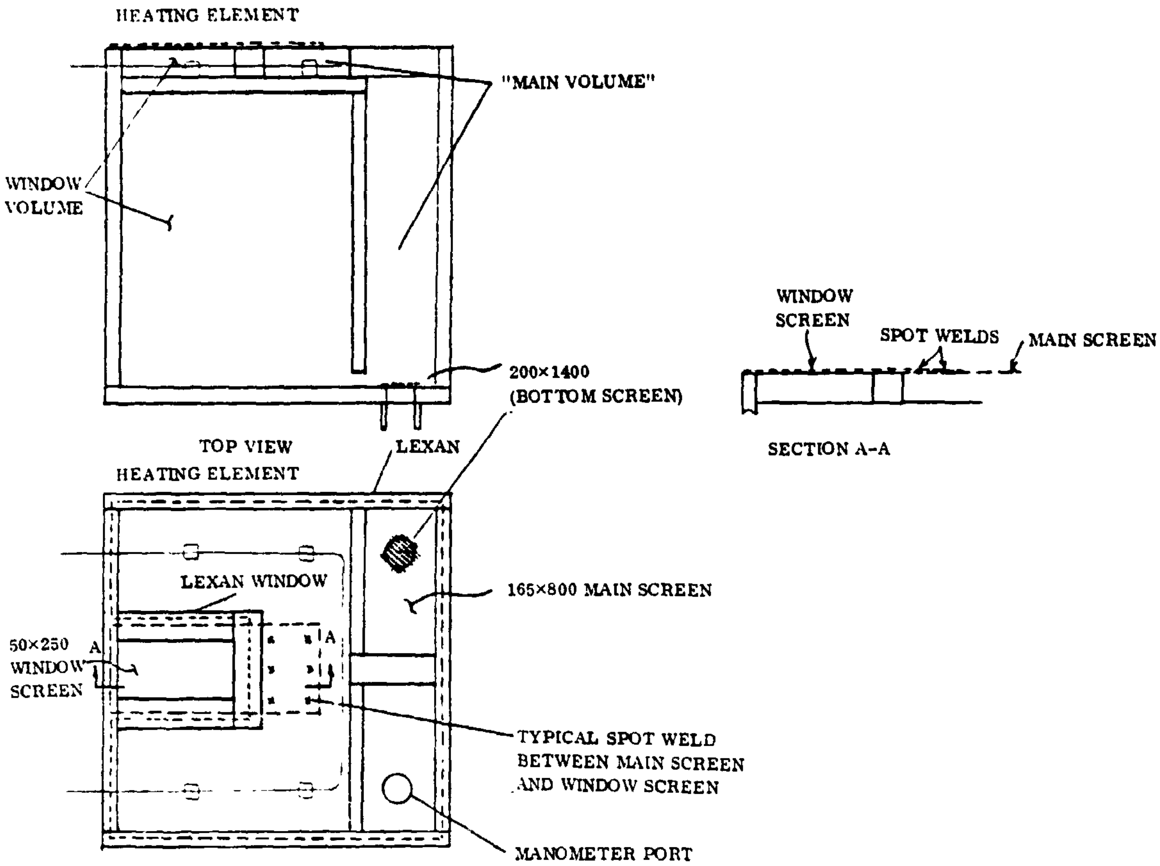


Figure 3-17. Box Design to Limit Deflection and Control Screen Spacing

the box internal pressure by overflowing from the manometer. Reducing the pressure slowly to 68.9 kN/m^2 (10 psi) allowed runs to be made at an increased heat flux without causing bulk boiling in the main chamber. Data was fairly consistent at this pressure, however,H_3 minimum was below the level of the bottom of the box. (This caused spilling from the box). The tests indicated that the bell jar was satisfactory in controlling environmental conditions and that increased heat fluxes could be obtained by vacuum pumping, however,careful control of system pressures is required to obtain acceptable data for simulated heating conditions.

The new box configuration for the third test series,shown in Figures 3-17 and 3-18, was fabricated and tested using hexane under ambient conditions and in the bell jar under both atmospheric pressure and reduced pressure conditions. Atmospheric pressure data was more consistent than data obtained in the second test series. $H_{3_{min}}$ stayed above 7.62 cm (3 in) until H_1 fell below 1.91 cm (0.75 in). (Since the box is 7.62 cm (3 in) high, dripping from the 200 × 1400 screen occurred if $H_{3_{min}}$ was less than 7.62 cm (3 in).) Subsequent tests showed the window screen remained wetted until the outer and inner compartments were almost completely empty. This box had a 2.54 cm window length.

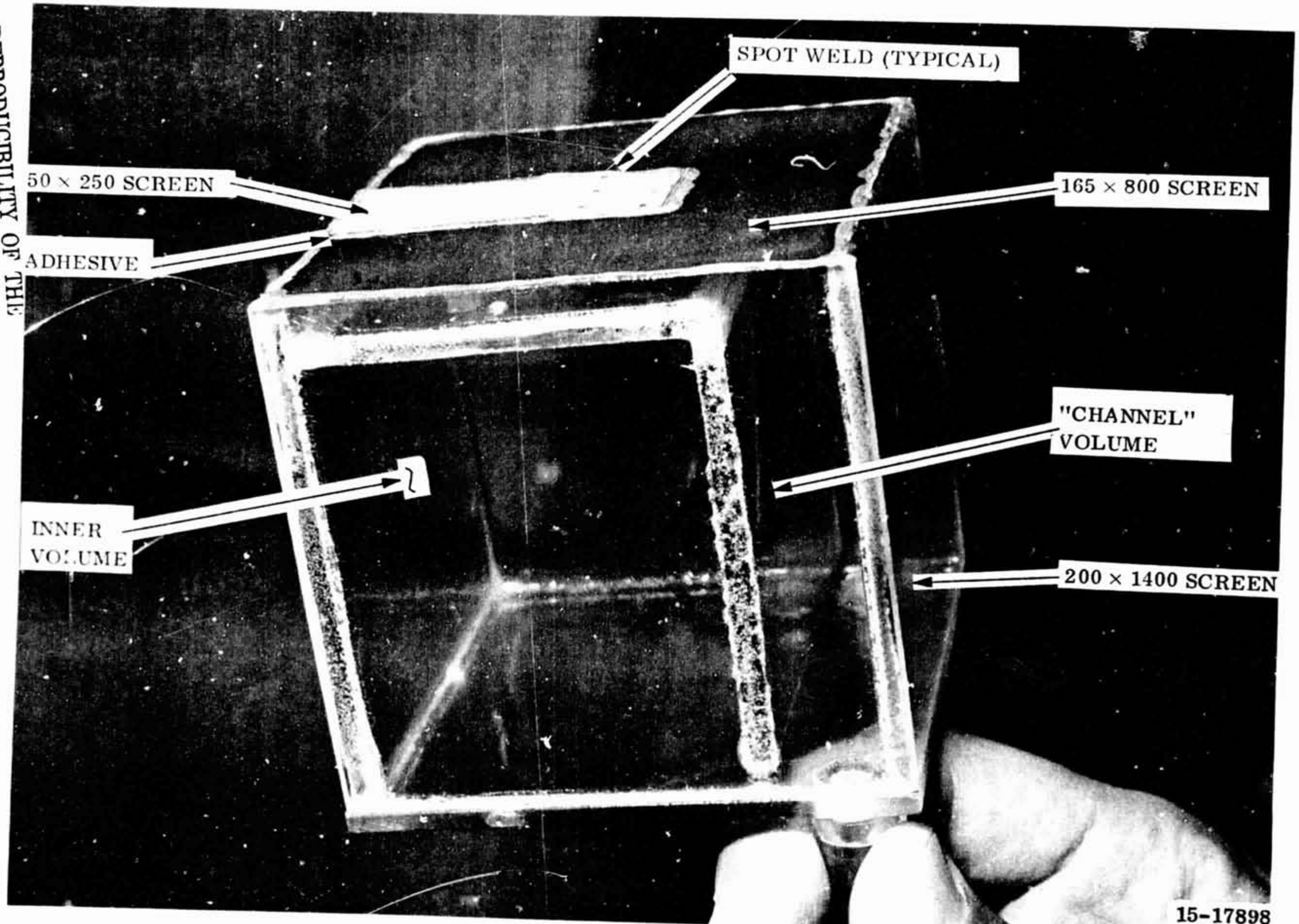


Figure 3-18. Vapor Inflow Test Configuration

Pump down tests were run at low pump down rates at pressures ranging from 101 kN/m^2 (14.7 psia) to 55 kN/m^2 (8 psia). During all runs, vapor appeared under the main screen when the pressure was reduced below 90 kN/m^2 (13 psia). Some vapor may have been attributable to dissolved air coming out of solution, and some may have formed by bulk boiling.

Based on the favorable results obtained with the new box, two additional boxes with window lengths of 1.27 cm (0.5 in) and 3.81 cm (1.5 in) were fabricated using an ethanol compatible adhesive. Testing was performed using ethanol, Freon and hexane.

3.2.4 VAPOR INFLOW TESTING - FOURTH TEST SERIES, DECEMBER 1977. Two additional boxes were fabricated similar to the configuration shown in Figure 3-17. The three configurations tested in the fourth test series are summarized in Table 3-3. Tests were run using hexane, ethanol and Freon-TF.

Table 3-3. Vapor Inflow Test Configurations - Fourth Test Series

Config.	Window Length cm (in)	Window Screen Mesh	Main Screen Mesh	Bottom Screen Mesh
I	1.27 (0.5)	50 × 250	165 × 800	200 × 1400
II	2.54 (1.0)	50 × 250	165 × 800	200 × 1400
III	3.81 (1.5)	50 × 250	165 × 800	200 × 1400

Data was obtained using the bell jar for tests run without heating and for those tests run using a 150 watt lamp for heating the top screen. One test was run using a blow dryer for convective heating without the bell jar. All tests run with an external heat input resulted in fluid dripping out of the bottom screen or complete screen breakdown. As described in the third test series, dripping of fluid out of the bottom screen will occur if the pressure at the box bottom exceeds the ambient pressure at vapor breakthrough. A chronological summary of the tests run during the fourth test series is shown in Table 3-4.

3.2.5 VAPOR INFLOW TESTING - FIFTH TEST SERIES, FEBRUARY 1978. Boxes no. I and no. III were altered in preparation for additional testing. The screens of box no. III (see Table 3-3) were replaced with 200 × 1400 window screen, 250 × 1400 main screen and 325 × 2300 bottom screen. (These screens are similar to those typically used for start basket ground testing.) For box no. I, an attempt was made to restrict wicking to the window length (from the window/main screen overlap towards the front of the box) by eliminating other sources of wicking. A pair of Teflon strips were treated and bonded along the main screen/ window screen as shown in Figure 3-19.

A series of tests were run with the new boxes. The boxes are designated as shown in Table 3-5.

Table 3-4. Test Log - Fourth Test Series

Test Fluid: H - hexane
E - ethanol
F - Freon TF

Box Number: I - 1.27 cm window
II - 2.54 cm window
III - 3.2 cm window

Run No.	Box No.	Test Fluid	External Inputs	Test Comments	Date	Overall Observations
1	I	H	Spot light	Run overnight	11/30/77 12/1/77	Small separation between bell jar and base plate, cycling, no dripping, dripping occurred shortly after application of heat from spot light.
2	I	H	Spot light		12/1/77	Cycling, no dripping prior to application of heat, breakdown almost immediately following application of heat from spot light.
3	I	H	Spot light		12/1/77	Dripping occurred shortly after application of heat from spot light.
4	I	H	Flood light		12/1/77	Dripping occurred shortly after application of heat from flood light (no data).
5	I	H		Run overnight	12/1/77 12/2/77	Cycling slowly, dripping (no data).
6	I	H	Flood light		12/2/77	Dripping prior to application of heat, dripping during application of heat from flood light, large amounts of vapor under main screen.
7	I	H	Flood light		12/2/77	Cycling prior to application of heat, no dripping, dripping occurred shortly after application of heat from flood light.
8	I	H		Run for one cycle	12/2/77	No observations.
9	I	H		Run for one cycle	12/2/77	Dripping.
10	III	H		W/o bell jar.	12/2/77	Dripping after first cycle.

Table 3-4. Test Log - Fourth Test Series (Continued)

Run No.	Box No.	Test Fluid	External Inputs	Test Comments	Date	Overall Observations
11	I	H		Run for 3 cycles	12/5/77	Cycling between H_3 = 9.53 and 13.1 cm (see Figure 3-2 for nomenclature)
12	III	H		Run overnight	12/5/77	Cycling and dripping
13	I	H			12/8/77	Dripping after first cycle.
14	I	H		Run for one cycle	12/12/77	Test run to determine what affect the leak has on the first cycle, dripping occurs after first cycle (box was repaired).
15	III	H		Run for 3 cycles	12/12/77	Dripping
16	I	H			12/13/77	Dripping
17	I	H			12/13/77	Cycling between H_3 = 9.65 and 10.2 cm, levelled off at 9.78 cm, run terminated
18	I	H		Run for 2 cycles	12/13/77	No observations
19	I	E		Run overnight	12/13/77 12/14/77	Cycling slowly, run terminated because of excessive cycling time
20	III	E			12/14/77	During bell jar placement the box cycled to 6.6 cm, run terminated (no data)
21	I	F		Bell jar and ambient air	12/14/77	General result of several tests was that the first cycle went to an H_{3max} of 4.06 to 5.08 cm with recovery to 3.05 cm and hovering between 3.05 to 3.18 cm until breakdown, which occurred at H_1 = 1.14 to 1.27 cm.
22	III	F		Bell jar and ambient air	12/14/77	Results similar to those described in run 21 for Box I.

Table 3-4. Test Log - Fourth Test Series (Continued)

Run No.	Box No.	Test Fluid	External Inputs	Test Comments	Date	Overall Observations
23	I	H			12/15/77	During bell jar placement the box cycled to 6.35 cm, run terminated
24	I	H		Run for one cycle	12/15/77	Dripping after first cycle
25	I	H		Run for one cycle	12/15/77	Dripping after first cycle
26	I	H		Rewet screen after run 25, run for 1 cycle	12/15/77	Dripping after first cycle
27	II	H	Blow ..ryer	Without bell jar	12/16/77	Breakdown occurred immediately upon application of air stream from dryer, leak in top screen.

Table 3-5. Boxes Used in Test Series 5

Box No.	Window Length	Window Screen Mesh	Main Screen Mesh	Bottom Screen Mesh	Comments
II	2.54 cm (1.0 in)	50 × 250	165 × 800	200 × 1400	Teflon Strips
IV	1.27 cm (0.5 in)	50 × 250	165 × 800	200 × 1400	
V	3.81 cm (1.5 in)	200 × 1400	250 × 1400	325 × 2300	

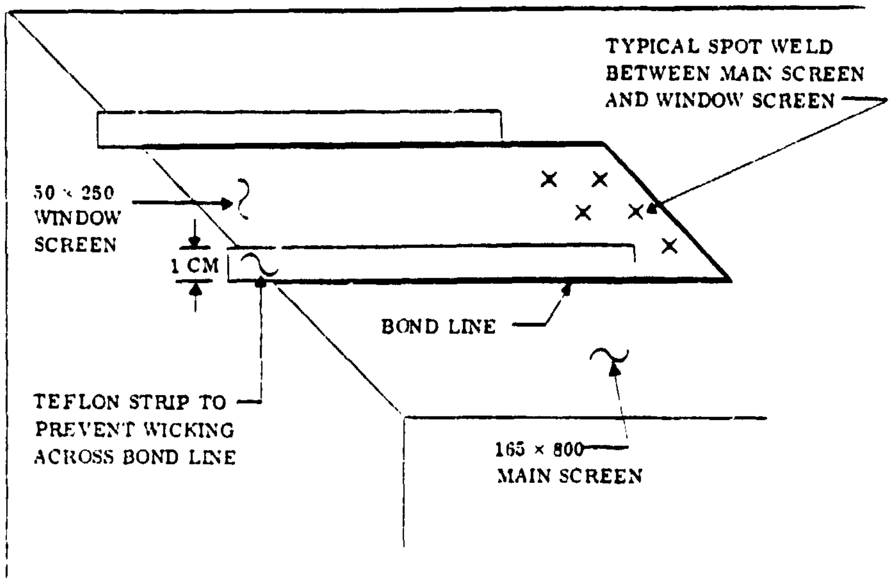


Figure 3-19. Box Design to Control Direction of Wicking (Box No. IV)

Initially box no. V was run with Freon TF in the bell jar under ambient heat flux conditions. The general observation for the six runs made was that only one full cycle down to the window screen bubble point of 24 cm (9.4 in) could be obtained. Vapor breakthrough and pressure recovery was not reproducible. Twice the pressure hovered at 1 8 cm (6.9 in) before large amounts of vapor broke through. In all cases there was an intermediate cycle from close to the top of the box to about 6.6 cm (2.6 in), then both the window and main screen dried out.

Box no. V was also tested with hexane. Since the 200 × 1400 window screen could hold more than 50 cm of head, the bell jar was too small to contain the apparatus during these tests. The single test run was therefore accomplished in ambient air. For this test, the first cycle went down to an H_{3max} of 57 cm (22.3 in) with cycling then occurring over a narrow range between 50 cm (19.5 in) and 57 cm (22.25 in). The first cycle took 25 minutes. Subsequent cycling between the levels noted occurred for more than half an hour until H_1 was greater than 3.3 cm (1.3 in). At H_1 = 4.1 cm (1.6 in) the pressure (H_3) was down to 11.7 cm (4.6 in). Breakdown occurred at an H_1 level greater than 4.1 cm (1.6 in).

A series of tests was then run using box no. IV with Teflon "dams" installed as shown in Figure 3-19, using hexane in the bell jar under ambient heat flux conditions. Two tests were run to breakdown. For the first test, which lasted four days, complete breakdown occurred at H_1 (the level in the window area below the top of the box) = 4.1 cm (1.6 in). Dripping commenced when H_1 was approximately 2.3 cm (0.9 in). For the second complete run (which ran eight days) screen breakdown occurred when H_1 was 3.0 cm (1.2 in). Dripping occurred when H_1 was below 1.27 cm (0.5 in).

Several tests were run with box no. II in preparation for heat flux testing with hexane. Box no. 2 is the box with the 50 × 250 window screen, 165 × 800 main screen and 2.54 cm (1 in) window length. A test was run in the bell jar under ambient conditions. Cycling without dripping occurred until H_1 was below 3.7 cm (1.45 in). Breakdown occurred at H_1 below 3.9 cm (1.55 in). (Breakdown level occurred during the evening and was not observed.) Tests were then run with a vortex tube, using the hot side air to heat the screen. Ambient temperature was 298K. Hot side vortex tube temperature was in excess of 333K. The vortex tube was attached to a ring stand directly over the screen. Tests were conducted in ambient air under a vented hood. Temperature just above the surface of the screen was measured with a thermometer. Two tests were conducted with the vortex tube. The first test started with the hot end of the vortex tube approximately 2.54 cm (1 in) above the screen. (The outlet of the tube hot side was a 2.54 cm (1 in) AN elbow.) After ten minutes, with the H_1 at 1.8 cm (0.7 in) and cycling occurring between 7.1 cm (2.8 in) and 8.1 cm (3.2 in), the vortex tube outlet was moved up to 7.6 cm (3 in) away from the surface of the screen. Temperature of the impinging gas above the screen surface was 311K. After 5 minutes, with rapid cycling continuing between 7.1 cm (2.8 in) and 8.1 cm (3.2 in), the vortex tube was moved up to 2.54 cm (1 in) above the screen with H_1 - 2.3 cm (0.9 in). Ambient temperature at the screen was 61C. Cycling continued between the same limits for about 2 minutes, then cycling occurred between 6.6 cm (2.6 in) and 7.1 cm (2.8 in) for 7 minutes from t = 18 minutes until t = 25 minutes. At t = 25 minutes, H_1 was 5.3 cm (2.1 in). Cycling continued with H_3 hovering around 7.6 cm (3 in) as the entire window area drained. Vapor could then enter the main compartment. Window screen dryout occurred with the liquid level a few tenths of an inch below the top of the main compartment.

Another run was made with hexane and the vortex tube with box no. V. The run was continued until the window screen dried out. Two cycles were run under ambient conditions. The vortex tube was then placed 2.54 cm (1 in) above the window area. Rapid cycling occurred during the test with H_2 being as low as 5.6 cm (2.2 in). Generally, however, performance was similar to that of the previous test with the window area draining completely without breakdown and liquid level under the main screen dropping to below 1.0 cm (0.4 in) of the bottom of the box without breakdown.

This concluded the vapor inflow testing performed under this contract.

3.3 ANALYTICAL MODEL CORRELATION

Test results obtained in the five test series were examined, reduced and compared to the analytical models presented in Section 3.1. Unfortunately, for this data analysis no quantitative data was available to evaluate K_u or F_σ for the first test series and the early runs of the second test series. Data from test series 2, 3, 4 and 5 was available for analysis and correlation. Evaluation of the data centered on solving Equations 3-11 and 3-19 for the quantities F_σ and K_u. Data evaluation performed for the second test series has already been presented in Table 3-2. Similar data reduction was performed for test series 3, 4 and 5 and is presented in Table 3-6.

Each line of Table 3-6 represents the results of a number of runs, as shown in Column 7. For each run, many cycles were run and F_σ was determined for each cycle and averaged to produce an average value of F_σ for that run. The data from each run was then taken and grouped with other similar runs in that series. For example, with box no. II using hexane and 50 × 250 window screen under ambient conditions in test series No. 3, six runs were made. The data shown in the table represents the minimum, maximum and nominal values of F_σ and K_u for these six runs.

A set of runs was made with a heat lamp for heating the screen in series no. 4 with box no. I in the bell jar. In series no. 5 a vortex tube was used to heat the screen directly.

Inspection of the data shows that F_σ and K_u vary significantly. There does not appear to be any correlation between window length and F_σ or K_u. For example, for bell jar runs made with hexane and 50 × 250 window screen, for the 1.27 cm window, $\bar{F}_\sigma$ = 0.35; for the 2.54 cm window, $\bar{F}_\sigma$ = 0.34; and for the 3.05 cm window, $\bar{F}_\sigma$ = 0.39. For the ambient runs, however, $\bar{F}_\sigma$ was 0.38, 0.21 and 0.45 for the 1.27, 2.54 and 3.05 cm window lengths respectively.

Using Freon as the test fluid, higher values of K_u and F_σ were obtained for the 200 × 1400 screen (box no. V) than for the 50 × 250 screen (box no. III). Results with 50 × 250 screen were consistent from box no. I to box no. III. Tests with 50 × 250 screen were not run in a bell jar because breakdown occurred too quickly for the boxes to be placed in a bell jar. These results are therefore not directly comparable because the 200 × 1400 screen/Freon tests were run in a bell jar.

The results shown in Table 3-6 give a general range of F_σ and K_u that can be used for preliminary design purposes. Because of the lack of clear trends, this information should be used conservatively.

Heat flux was applied to box no. I using a 150 watt spotlight with the box in the bell jar. Calculations indicated that a heat flux of approximately 0.02 watt/cm^2 was incident on the screen surfaces. Wicking calculations showed that the main screen wicking capability was less than 0.01 watt/cm^2 and the window screen capability was greater than 1 watt/cm^2. Theory would indicate that the box should remain wetted and function properly. In fact, the window screen dried out shortly after the lamp was turned on. This may have been due to radiant heat transfer directly into the sides of the transparent box causing vapor to form in the box at screen/box intersections or in other areas that would cause precipitous failure.

Heat flux runs were made with box no. II in test series no. 5 using a vortex tube. The vortex tube flowed warm air at 333K directly onto the screen surface. Heat flux incident on the screen averaged 0.07 watt/cm^2 and peaked at 0.39 watt/cm^2. Pressure cycling of the box occurred on a regular basis with no apparent degradation due to heat flux. In two runs, draining of the entire window volume was possible before the window

Table 3-6. Vapor Inflow Test Summary

Test Series	Test Dates	Box No.	Fluid	Window Screen	Min/Nom/Max F_σ (Range)	No. of Runs	Min/Nom/Max K_u (Range)	No. of Runs	Conditions
3	8/77	Original	Hexane	50 × 250	.354	1	.24	1	Ambient
	10/77	II	Hexane	50 × 250	.074/.206/.28	6	.069/.32/.55	4	Ambient
	10/77	II	Hexane	50 × 250	.32/.34/.37	2			Bell Jar
4	12/77	I	Hexane	50 × 250	.22/.38/.46	3			Ambient
	12/77	I	Hexane	50 × 250	.15/.35/.55	13	.17	1	Bell Jar
	12/77	I	Hexane	50 × 250	.03/.207/.45	5	.105/.43/.83	3	Heat Lamp[1]
	12/77	I	Freon	50 × 250	.333	12	.083	12	Ambient
	12/77	II	Hexane	50 × 250	.12	1			Bell Jar
	12/77	III	Hexane	50 × 250	.45	1			Ambient
	12/77	III	Hexane	50 × 250	.32/.39/.46	2			Bell Jar
	12/77	III	Freon	50 × 250	.333	1	.083		Ambient
5	2/78	IV	Hexane	50 × 250	.065/.161/.248	3			Bell Jar
	2/78	II	Hexane	50 × 250	.107/.24/.37	2	.52	1	Bell Jar
	2/78	II	Hexane	50 × 250	.06/.11/.33	3	.671/.804/.937	2	Vortex Tube[2]
	2/78	V	Freon	200 × 1400	.27/.57/1.0	6	.41	6	Bell Jar
	2/78	V	Hexane	200 × 1400	.06	1			Ambient Air

1. $\dot{Q}/A$, 0.0205 watt/cm^2 (avg).

2. $\dot{Q}/A$, 0.07 watt/cm^2 (avg) and 0.389 watt/cm^2 (local).

screen dried out. The wicking capability of the window screen was equivalent to 64 watt/cm^2.

The nonrepeatability of the data as well as the importance of understanding vapor inflow for start basket thermal conditioning require that more work be done in this area. Work done under the present contract has produced some test results that appear encouraging for future efforts in this area. Better control should be sought in providing cleanliness of the apparatus and test fluid, controlling screen geometry, and controlling environmental variables such as temperature and humidity. A description of recommended action is presented in Section 3.4.

3.3.1 CENTAUR D-1S CAPILLARY DEVICE THERMAL CONDITIONING. Thermal conditioning calculations were performed to determine whether the window screen on the LO_2 and LH_2 basket would dry out when subjected to heating. Calculations were made to determine the values of the parameters, F_σ, $H_{1Cr}/H3_{max}$ and K_u (defined in Section 3.1) that would be required to permit the window screen to function properly over the entire set of mission conditions. Values of F_σ were determined by calculating the heat flux interception capability of wicks in low gravity using the equations formulated for screens in Table 2-2 of Reference 3-2. Screen properties were obtained from Reference 3-3. The maximum wicking distance for the standpipe windows was taken to be the standpipe height plus one half the standpipe diameter. For the LO_2 start basket, standpipe height is 5.52 cm (2.17 in) and standpipe diameter is 2.10 cm (0.828 in). For the LH_2 start basket, standpipe height is 10.98 cm (4.32 in) and standpipe diameter is 4.14 cm (1.63 in). Heat flux incident on the standpipe region was obtained from Table 2-1 of Reference 3-2. The maximum heat flux interception requirement was 4.41 watts/m^2 (1.4 Btu/hr ft^2) for LO_2 and 2.52 watts/m^2 (0.8 Btu/hr ft^2) for LH_2. Required values of F_σ were found from

$$F_\sigma = \frac{\dot{Q}/A_{incident}}{\dot{Q}/A_{wicking\ capability}} \tag{3-22}$$

For the LO_2 standpipe the worst case F_σ was found to be a maximum of 0.0076. For the LH_2 standpipe the worst case F_σ was found to be a maximum of 0.058. Both these values are well below the majority of F_σ's found in Table 3-6.

The critical height at which breakdown could occur was evaluated by determining the maximum vapor volume that could be generated by incident heating to the start basket. Calculations were performed for the period between the first and second burns of the two burn synchronous equatorial mission. Maximum liquid volume expended was 0.15 m^3 (5.37 ft^3) for LH_2 and 9.36×10^{-4} m^3 (0.026 ft^3) for LO_2. The vapor volume was converted into a liquid level below the top of the standpipe. H_{1Cr} must be at least as great as this height. For LH_2, H_{1Cr} was 13.5 cm (5.3 in) and $H_{1Cr}/H3_{max}$ was 0.0022 where $H3_{max}$ is the height of liquid that can be supported by surface tension. Similarly, for LO_2, H_{1Cr} was 7.32 cm (2.88 in) and $H_{1Cr}/H3_{max}$ was 0.00149. Using

Equation 3-20 values of K_u were determined to be a minimum of 0.92 for LH_2 and 0.991 for LO_2. In order for the H_{1Cr}/H_{3max} requirements to be satisfied, at the F_J values given above, K_u values must be less than these quantities. Only one value out or 30 runs had a K_u greater than that required to make the window screen operate properly.

Based on these calculations, the window screens should be capable of remaining wet during the complete set of mission conditions. The main screen multiple barriers should perform successfully based on the testing reported in Reference 3-2.

3.3.2 CONCLUSIONS. The data presented in Table 3-6 can be used as a rough estimate to find the limits of the thermal conditioning capability of a given configuration. For detailed thermal conditioning design data, additional experimental work will be required. This work is described in Section 3.4.

3.4 VAPOR INFLOW TESTING RECOMMENDATIONS

As described in previous sections, difficulties in obtaining repeatable data were experienced during the vapor inflow testing. Because of funding limitations many of these difficulties could not be overcome within the scope of this contract. The following pages describe the recommended experimental program to be implemented in order to resolve the operating characteristics of screen window configurations required for allowing vapor to pass into a cryogenic capillary device subjected to incident heating. The specific problems uncovered during testing are listed in Table 3-7 along with their proposed solution.

The general plan recommended is to separately evaluate wicking of screens fed by overlapping screens and vapor flow across wetted screens. Following these tests an overall test of the window concept is recommended, with an objective similar to that of the testing described in Section 3.2. All tests should be conducted with a controlled environment, minimized handling during filling and testing, and automatic recording of data.

The basic chamber to be used is shown schematically in Figure 3-20. This will be used for all three types of tests: wicking across an overlap joint, and vapor flow across wetted screens with both small specimens and with a simulated capillary device and configuration. The chamber incorporates the recommendations of Table 3-7. Visual data will only be required during wicking tests.

Wicking across an overlap screen joint will be studied first. Fabrication of overlap joints that produce high wicking rates that are repeatable from test to test will be studied. Primary configurations will be spot welded screen sandwiches. Use of spacers and perforated plates will also be considered. The overlap joints will be tested using techniques developed in References 3-2 and 3-3. The wick will be stretched across knife edges with the innermost section of the overlap immersed in the test fluid in the chamber shown in Figure 3-20. For each specimen, wicking results with the overlap joint will be compared to that of screen alone in order to obtain a measure of the fraction of wicking that is still available with the overlap joint.

Table 3-7. Vapor Inflow Test Improvements

Problem	Solution
1. Basic evaluation of the specific mechanisms involved in successful operation of the window configuration have not been separately evaluated.	1. Analyze each specific mechanism (e.g., screen wicking from overlap screen joints, and vapor flow across a wetted barrier) separately by developing a model for each mechanism and testing it separately after determining the individual analytical relationships
2. Apparatus is moved during each test in order to fill and mount the test article. Filling and mounting are time consuming, nonrepeatable due to the uncontrolled environment. Operations during filling are hazardous.	2. Remotely fill the test article that is mounted in the test chamber. Use valves and lines to control filling, venting, etc. Use an enclosed test chamber to control environment.
3. Limited measurements were made due to time restrictions and paucity of instrumentation.	3. Monitor and record all significant variables to determine the significance of all events that could have an effect on performance. Monitor temperatures in all areas where heating is occurring, (particularly in the heater area). Monitor pressures in all significant areas. Pressure measurements will be sensitive enough to detect pressure changes of 0.05" of test fluid head. Monitor liquid levels (of window and main screen volumes) versus time.
4. Heat flux to the screen was difficult to quantify.	4. Apply heat flux directly using guarded heaters. Perhaps use screen as the heater element or use an overlay type heater with holes for venting and insulation on the top and side, protecting the box from heating away from the screen and concentrating all the heat to the screen.
5. Net heat flux (or evaporation) varies as liquid is boiled off and saturates environment.	5. Maintain atmosphere partial pressure by venting the container enclosing the apparatus over a narrow pressure band (perhaps use the baratron or barastat).
6. Temperature variations will cause changes in property values that could affect results.	6. Control the temperature of the apparatus by using thermocouples and and heaters or coolers (air conditioning). Run tests in an air conditioned room.
7. Cleanliness of apparatus and measuring tools was not carefully maintained.	7. Clean the screen and other portions of the apparatus and the instrumentation carefully before the tests and preceding each test after the apparatus has been disassembled.
8. Water condenses on the screen surface from the atmosphere during handling. No control was maintained on the humidity (H_2O) of the atmosphere around the test specimen.	8. Control the atmosphere using boiled off LN_2 bubbled through test fluid through fittings into the transparent test enclosure.
9. Test fluid purity is not controlled and could contribute to poor repeatability of results.	9. Use clean test fluid on an open loop basis or use filtration and purification processes to allow reuse of fluid. (If necessary, use reagent grade fluid).
10. Control the geometry more precisely than can be done with glue joints between screens and support.	10. Consider an all welded configuration for controlling spacing, minimizing geometric variations and preventing leakage. (If a transparent apparatus is desired some glue joints will be required between the supports and the transparent material).
11. Control the wicking from the window screen to the main screen transverse to the desired wicking path.	11. Use nonwetting strips such as Teflon to prevent wicking from other than the desired direction.
12. Control spacing between the screens in the window/main screen overlap area.	12. Use spot welding to join materials. Conduct separate fabrication evaluation to determine the optimum welding pattern and specimen overlap configuration.

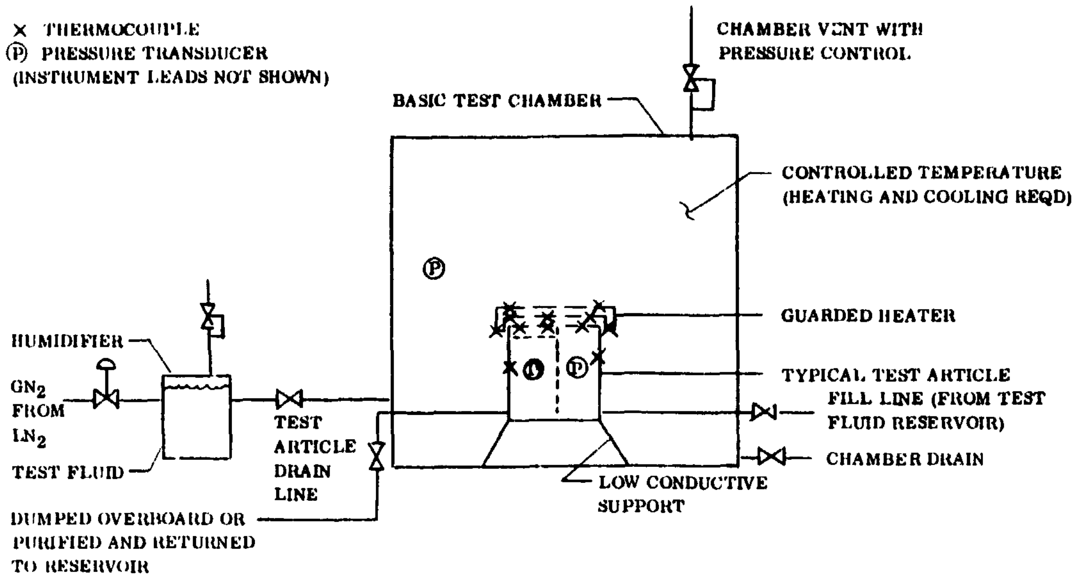


Figure 3-20. Schematic of Basic Test Chamber

Vapor flow across wetted screens would be tested in the basic chamber with the apparatus shown in Figure 3-21. The circular screen is wetted from an annular reservoir. Pressure will be cc.,trolled independently on both sides of the screen. A typical test run would reduce pressure in one of the chambers until vapor broke through the screen from the higher pressure chamber. The mechanics of rewetting the screen would be studied by manipulating the pressures in each chamber. Many screens should be tested with at least two test fluids. The apparatus would function as follows. The bottom box is the low pressure side of the apparatus and is held at constant pressure with a relief valve. The high pressure side would have a regulator that could be adjusted to regulate to a pressure above the bottom box pressure. The

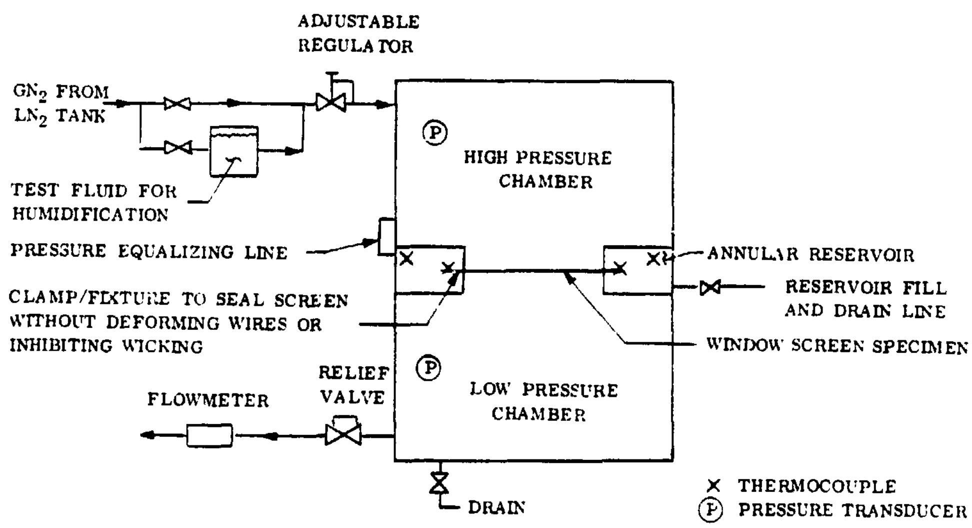


Figure 3-21. Schematic of Test Article for Vapor Flow Across Wetted Screens

pressure in the upper chamber would be raised to exceed the bubble point ΔP across the screen. Flow across the screen would be noted by flow across the relief valve. Pressure in both chambers will be carefully measured. Pressure will then be reduced to a lower level until the screen reseals and flow is stopped. Cycles will be repeated to assure reliability. Other variables will be steady state flow rate across the screen and time at this flow rate. Analysis should be performed, prior to testing, to predict the wetting capability of the screen subjected to vapor flow. This analysis will be used to correlate test results.

Combine fabrication and test information to design an apparatus to test vapor flow across a window of coarser screen within a main screen surface. The configuration may be similar to that used in the test articles described in Section 3.2. Changes that appear possible will be barriers to wicking between the window and main screen transverse to the wicking path being measured. The use of larger specimens more closely approximating a real configuration is made possible by the automatic recording of data making the resulting long test runs more feasible. Tests would be run with several screens and test fluids. An analytical model, combining the basic theory developed in Section 3.1 with the correlated models for screen wicking with an overlap joint and vapor flow across a wetted screen, will be compared to the test data. The result of the total test program will be information that can be used for design of capillary devices for propulsion stages.

4

FEED SYSTEM COMPARISONS

Feed system alternatives were developed for pressure fed engines and combinations of feed system components in order to determine the optimum propellant feed system for the Centaur D-1S. Comparisons were made between propellant settling and capillary acquisition, thermal subcooling and pressurization for boost pump NPSP (net positive suction pressure), boost pumps, thermal subcooling and pressurization for turbopump NPSP, uncooled and cooled propellant ducts, and pumping coolant back into the tank or dumping coolant overboard. Capillary device designs used for the Centaur D-1S reflect the refilling and vapor inflow analysis described in Sections 2 and 3.

Comparisons were made on the basis of payload penalty, hardware weight, reliability, electrical power consumption and mission profile flexibility. The comparisons were made for three engine candidates: (1) the existing RL10A-3-3, and two lower NPSP alternatives, (2) the RL10A-3-3A and (3) the RL10 Category 1. Characteristics for these two advanced engines are described in Reference 4-1. Three missions were considered for each engine candidate: (1) a one-burn planetary mission, (2) a two-burn synchronous equatorial mission, and (3) a five-burn low earth orbit mission (Tables 1-1, 1-2 and 1-3, respectively). A total of ten feed system concepts were compared for each of the three engines and three missions.

4.1 SELECTION OF FEED SYSTEM ALTERNATIVES

In order to select the most promising feed system alternatives for comparison, a matrix of system candidates was constructed by selecting an alternative from each of the following subsystems or operations.

A. Acquisition	1. Propellant Settling 2. Capillary Device
B. Boost Pump NPSP	1. Boost Pump Pressurization 2. Boost Pump Thermal Subcooling 3. No Boost Pump
C. Turbopump NPSP	1. Boost Pump 2. Thermal Subcooler 3. Pressurization
D. Propellant Duct Cooling	1. Uncooled 2. Cooled

E. Coolant Handling

1. No Coolant Required
2. Coolant Pumped Back Into the Tank
3. Coolant Dumped Overboard

Selecting all the possible combinations produced 108 alternatives. Infeasible combinations were then identified. For example, boost pumps cannot be used with cooled propellant ducts because boost pump cooling is impractical. Pressurization and capillary acquisition were shown to be infeasible in NAS3-17802. Other incompatibilities are turbopump subcooler or pressurization with a boost pump; no coolant required and a cooled feedline, turbopump thermal subcooler, or boost pump thermal subcooler; turbopump NPSP from a boost pump and no boost pump; coolant pumped or coolant dumped with uncooled duct and a pressure fed system; no cooling required with coolant pumped or dumped; and coolant pumped or dumped with no subcoolers or cooled duct. Candidates using cooled propellant ducts and not having capillary devices are also infeasible because liquid could not positively be contained within the duct or supplied for cooling the propellant duct without a capillary device.

The screening process resulted in twelve combinations that were feasible. These are listed in Table 4-1. Candidates selected for additional analyses are circled. The reasons for selecting these ten concepts are described in the following paragraphs. Comparisons performed on previous studies (NAS3-17802 and NAS3-19693) have shown that boost pump thermal subcoolers have weight advantages compared to boost pump pressurization, pumping cooling fluid back into the tank is advantageous over dumping fluid overboard, boost pumps are lighter than turbopump thermal subcooling and uncooled propellant ducts are lower in weight penalty than cooled propellant ducts. These comparisons were used as guidelines in selecting the feed system alternatives to consider. Several key comparisons were desirable in order to determine the best feed system candidate.

A critical comparison to be made was between capillary acquisition and settling. Several pairs of concepts in Table 4-1 could have been compared for this purpose (i.e., B and K, C and L, D and M, or E and N). Based on comparisons done on previous contracts, concepts B and K should be the lowest weight of all these pairs and, therefore, were selected as the primary comparison pair for propellant settling versus capillary acquisition.

Concepts A and B were selected for comparing pressure fed boost pumps to thermally subcooled boost pumps.

Concepts B, D and H compared the use of a boost pump, thermal subcooler, or pressure feed for supplying turbopump NPSP.

Another comparison involved the propellant duct cooling. Uncooled propellant ducts, cooled propellant ducts with cooling fluid dumped overboard and cooled propellant ducts with cooling fluid pumped back into the tank were compared by considering concepts O, N and P.

Table 4-1. Feed System Candidates

	Concept											
	A	B	C	D	E	H	K	L	M	N	O	P
A. Acquisition												
1. Propellant Settling	x	x	x	x	x	x						
2. Capillary Device							x	x	x	x	x	x
B. Boost Pump NPSP												
1. Boost Pump Pressurization	x											
2. Boost Pump Thermal Subcooling		x	x				x	x				
3. No Boost Pump				x	x	x			x	x	x	x
C. Turbopump NPSP												
1. Turbopump NPSP - Boost Pump	x	x	x				x	x				
2. Turbopump NPSP - Thermal Subcooler				x	x				x	x	x	x
3. Turbopump NPSP - Pressurization						x						
D. Propellant Duct Cooling												
1. Uncooled Propellant Duct	x	x	x	x	x	x	x	x	x	x		
2. Cooled Propellant Duct											x	x
E. Coolant Handling												
1. No Coolant Required	x					x						
2. Coolant Pumped Back Into The Tank		x		x			x		x		x	
3. Coolant Dumped Overboard			x		x			x		x		x

Comparison of subcooling coolant flow being dumped or pumped could have been made for boost pump subcooling by comparing concepts B and C or concepts K and L. Concepts K and L were evaluated for this purpose since most of the data for this comparison had already been generated on NAS3-17802.

For comparing pumping or dumping subcooler flow that provides turbopump NPSP, concepts D and E and concepts O and P were compared.

Based on the considerations described in the preceding paragraphs, analysis of concepts A, B, D, E, H, K, L, N, O and P will be required to provide the necessary comparisons. (This is the same number of concepts originally proposed for analysis.)

Candidates that were analyzed in Reference 4-2, NAS3-17802, and Reference 4-3, NAS3-19693, have their letters underlined.

Each of the feed system candidates circled in Table 4-1 was analyzed for the one-burn, two-burn and five-burn missions described in Reference 4-2. The matrix of engine alternatives analyzed for each candidate feed system is shown in Table 4-2. Concepts using boost pumps were only examined for the existing RL10A-3-3 engine since new boost pump designs were required for the other two engines.

Table 4-2. Matrix of Feed System Concepts and Engine Alternatives Compared

Feed System Concept	Alternatives		
(See Table 4-1)	RL10A-3-3	RL10A-3-3A	RL10 Category 1
A	x		
B	x		
D	x	x	x
E	x	x	x
H		x	x
K	x		
L	x		
N	x	x	x
O	x	x	x
P	x	x	x

4.2 PAYLOAD PENALTY

Payload penalty calculations were performed using payload sensitivity factors given in Table 4-3. These factors were applied to the differential propellant and jettison weights for each of the ten concepts. Information generated for the systems comparisons presented in References 4-2 and 4-3 were used as a foundation for conducting this study.

Capillary device weight calculations were performed to incorporate changes in capillary device volume and corner construction. The increased capillary device volume was associated with concepts N, O and P. These concepts considered turbopump thermal subcoolers with greater volume than the boost pump thermal subcoolers previously used in the weight calculations of Reference 4-2. Corner construction techniques that would aid in wicking and case fabrication requirements were incorporated into capillary device designs. These changes both resulted in increased capillary device weight.

Table 4-3. Centaur D-1S Payload Sensitivity Factors

Criteria		Mission		
		Planetary	Sync. Equatorial	Low Altitude
Jettison Weight		-1.000	-1.000	-1.000
Propellant Weight		+0.646	+0.587	+0.420
LH_2 and LO_2 Loss Before Burn (Without I_{SP} Effect)	No. 1	-0.646	-0.587	-0.420
	No. 2		-0.946	-0.510
	No. 3			-0.771
	No. 4			-1.215
	No. 5			-1.337
LH_2 and LO_2 Lost After Last Burn (Residual or FPR)		-1.646	-1.587	-1.419
Auxiliary Propellant Used Prior to Burn	No. 1	0	0	0
	No. 2		-0.459	-0.072
	No. 3			-0.352
	No. 4			-0.796
	No. 5			-0.917
Auxiliary Propellant Used After Last Burn (Residual)		-1.000	-1.000	-1.000

Pressurization system weights for all systems were computed using a detailed inventory of Centaur pressurization system weights. These computations revealed that the original pressurization system weights documented in Table 2-6, Reference 4-2, included excessive vent system weight for the baseline system and insufficient support system weight for the system not requiring main tank pressurization. This is a significant revision, resulting in a weight increase of 13.5 kg (29.8 lbs) for the pressurization system used with thermal subcoolers and a reduction in weight of 30.3 kg (66.8 lbs) for the baseline system (Concept A).

Lower tanking density penalties were computed based on increased tank pressure requirements for "blowdown" options not using boost pumps and using the RL10A-3-3 or RL10A-3-3A engines. Pressure fed option with -3 engine also requires higher tank pressure.

Propellant supply duct weights were computed using weights taken from Reference 4-3. Recirculation weights, included in supply duct weights in Reference 4-3 are separated out into "other hardware" in this study.

Supply duct childown weights reflect the use of the recirculation system to childown the propellant ducts when boost pumps are used. Cooled ducts do not have any duct childown requirements. Other childown weight data was taken from Reference 4-3.

Supply duct cooling fluid dumped overboard was changed considerably from Reference 4-3. The cooling of the sump area was neglected in Reference 4-3. Calculations were performed to include the sump area.

Hardware for keeping supply ducts wet was taken directly from Reference 4-3, Table 3-12 for all concepts using cooled feedlines. Excess LO_2 in the duct over the amount required for childown of these options and engine childown requirements were also taken directly from Reference 4-3, Table 3-12.

Subcooler weights were calculated based on schematics described in Reference 4-3. Subcooler cooling fluid dumped overboard was taken directly from Reference 4-3, Table 3-12. Boost pump weights, peroxide usage and settling system penalty were taken directly from Reference 4-3, Table 3-10.

Pumping system weights to return coolant to the tank were computed for feedline coolant, thermal subcooler coolant (turbopump or boost pump NPSP) and combinations of both. System weight penalties included boiloff, battery and hardware (sump, pump, lines and and accumulator) weights.

Sump assembly weights are a function of whether a boost pump is used. Sump assembly weights with and without a boost pump are taken from Reference 4-3. The volume penalty of the added hardware is calculated as the volume of propellant which cannot be tanked because of this additional tank hardware. Calculations included capillary device, subcooler, pressure bottle, and thrust barrel revisions. The volume penalty of increased tank skin weight for concepts requiring tank pressures in excess of the baseline levels is taken from Reference 4-3. Pumping options are assumed to have hardware outside the tank.

Subcooler cold side residuals were computed based on cold side volume and appropriate payload partials. Thrust barrel revisions required to aid in refilling the capillary devices were determined from Reference 4-2. Other hardware weight included in the payload weight comparison is that of the recirculation system for options containing boost pumps and dump valves, propellant utilization probe revisions and bypass lines for options containing capillary devices. Weight data was obtained from Reference 4-2.

All payload penalties are included in Table 4-4 through 4-12 for the three engines and three missions of interest.

Tabulations were made of the feed system alternatives to illustrate the relative merits of the subsystem alternatives. These comparisons are shown in Tables 4-13 through 4-21.

In Tables 4-13 and 4-14 a capillary acquisition system is compared to a propulsive settling system. Capillary devices are heavier than propulsive settling for the missions considered. For missions with greater than five burns, capillary device payload weight penalties will increase at a lower rate than propulsive settling payload weight penalties.

Table 4-15 compares boost pump thermal subcooling to pressure fed boost pumps. It appears, for the cases considered, that thermal subcooling is lower in weight penalty for missions having more than two burns.

Table 4-16 compares the three methods of supplying turbopump NPSP. It appears that using a boost pump to supply turbopump NPSP is the best option.

Table 4-17 compares propellant duct cooling options. The best option is to not cool the duct and to pump any other coolant back into the tank. (This option, concept M, was assessed by adding the weight of the pumping system of concept O to concept N and deleting the coolant loss from concept N). After this, the next best option is to cool the duct and pump the coolant back into the tank. The next best option is not to cool the duct. The worst, from a payload penalty standpoint, is to cool the duct and to dump the coolant overboard.

Tables 4-18, 4-19 and 4-20 compare pumping coolant back into the tank versus dumping the coolant overboard. In all cases the coolant pumping system is lower in payload weight penalty than dumping the coolant overboard.

Pressurization system options are compared in Table 4-21. Options considered were cryostored or ambient stored helium for an autogeneously pressurized LH_2 tank and cryostored gaseous helium for the entire LH_2 tank pressurization requirement. Autogeneous LH_2 tank pressurization with cryogenic helium storage is the lowest weight alternative. Ambient storage of GHe with autogeneous LH_2 tank pressurization is heavier than cryogenic storage. The option with the highest payload penalty is the one using GHe pressurization and cryogenic storage. (Because of the added complexity of cryogenic storage, ambiently stored systems are baselined for the pressure fed system, H, wherever possible.)

Summarizing the payload weight comparisons, the following conclusions are true. Settling is superior to capillary devices for the missions considered. Subcooling of boost pumps by thermal or pressure means is a close trade-off, with thermal

Table 4-4. Payload Weight Penalties for System Comparisons, kg (lb_m), One Burn Mission, RL10A-3-3 Engine

Weight Penalty Element / Feed System Concept		A: Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Req'd.	H_1: Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Req'd.	H_2: Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Req'd.	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2	-	-	-	-				85 (187)	85 (187)	102 (225)	102 (225)	102 (225)
	LO_2	-	-	-	-				20 (45)	20 (45)	21 (47)	21 (47)	21 (47)
2. Lower Tanking Density	LH_2	-	-	46 (101)	46 (101)				-	-	46 (101)	46 (101)	46 (101)
	LO_2	-	-	370 (816)	370 (816)				-	-	370 (816)	370 (816)	370 (816)
3. Pressurization System		89 (196)	43 (94)	43 (94)	43 (94)				43 (94)	43 (94)	43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2	10 (23)	10 (23)	10 (23)	10 (23)				10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
	LO_2	10 (23)	10 (23)	10 (23)	10 (23)				10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
5. Supply Duct Chilldown Propellant	LH_2	-	-	2 (5)	2 (5)				-	-	2 (5)	-	-
	LO_2	-	-	2 (5)	2 (5)				-	-	2 (5)	-	-
6. Supply Duct Cooling Dumped Overboard	LH_2	-	-	-	-				-	-	-	-	1 (2)
	LO_2	-	-	-	-				-	-	-	-	7 (15)
7. Hardware to Keep Ducts Wet	LH_2	-	-	-	-				-	-	-	16 (36)	16 (36)
	LO_2	-	-	-	-				-	-	-	5 (12)	5 (12)
8. Excess LO_2 in Lines Over Chilldown		-	-	-	-				-	-	-	33 (73)	33 (73)
9. Engine Chilldown Propellant	LH_2	8 (18)	8 (18)	8 (18)	8 (18)				8 (18)	8 (18)	8 (18)	8 (18)	8 (18)
	LO_2	2 (4)	2 (4)	2 (4)	2 (4)				2 (4)	2 (4)	2 (4)	2 (4)	2 (4)
10. Subcooler	LH_2	-	9 (19)	49 (107)	49 (107)				9 (19)	9 (19)	49 (107)	49 (107)	49 (107)
	LO_2	-	11 (24)	20 (43)	20 (43)				11 (24)	11 (24)	20 (43)	20 (43)	20 (43)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2	-	-	-	188 (414)				-	10 (23)	188 (414)	-	188 (414)
	LO_2	-	-	-	657 (1448)				-	33 (73)	657 (1448)	-	657 (1448)
12. Boost Pump	LH_2	39 (85)	39 (85)	-	-				39 (85)	39 (85)	-	-	-
	LO_2	24 (64)	29 (64)	-	-				29 (64)	29 (64)	-	-	-
13. H_2O_2 Usage, Boost Pump		9 (20)	9 (20)	-	-				9 (20)	9 (20)	-	-	-
14. Settling System Including H_2O_2 Penalty		40 (89)	40 (89)	40 (89)	40 (89)				-	-	-	-	-
15. Sump Assembly	LH_2	6 (14)	6 (14)	3 (7)	3 (7)				6 (14)	6 (14)	3 (7)	3 (7)	3 (7)
	LO_2	8 (17)	8 (17)	7 (15)	7 (15)				8 (17)	8 (17)	7 (15)	7 (15)	7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2	-	6 (13)	10 (23)	-				6 (13)	-	-	11 (24)	-
	LO_2	-	5 (12)	10 (21)	-				5 (12)	-	-	10 (23)	-
17. Volume Penalty Due to Hardware Added	LH_2	-	-	1 (2)	1 (2)				1 (3)	1 (3)	2 (5)	2 (5)	2 (5)
	LO_2	-	3 (6)	5 (11)	5 (11)				10 (21)	10 (21)	12 (26)	12 (26)	12 (26)
18. Fluid Residuals Cold Side Subcooler	LH_2	-	4 (9)	22 (49)	22 (49)				4 (9)	4 (9)	22 (49)	22 (49)	22 (49)
	LO_2	-	39 (86)	53 (117)	53 (117)				39 (86)	39 (86)	53 (117)	53 (117)	53 (117)
19. Thrust Barrel Revisions		-	-	-	-				5 (11)	5 (11)	5 (11)	5 (11)	5 (11)
20. Other Hardware		3 (7)	3 (7)	-	-				8 (18)	8 (18)	5 (11)	5 (11)	5 (11)
21. Tank Skin & Weight Over Baseline	LH_2	-	-	55 (122)	55 (122)				-	-	55 (122)	55 (122)	55 (122)
	LO_2	-	-	36 (79)	36 (79)				-	-	36 (79)	36 (79)	36 (79)
TOTALS		253 (559)	284 (627)	804 (1774)	1629 (3592)				367 (810)	399 (881)	1730 (3815)	956 (2111)	1788 (3943)

C-2

Table 4-5. Payload Weight Penalties for System Comparisons, kg (lb_m), Two Burn Mission, RL10A-3-3 Engine

WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
		A	B	D	E	H	H_1	H_2	K	L	N	O	P
1. Capillary Device	LH_2 LO_2	- -	- -	- -	- -				85 (187) 20 (45)	85 (187) 20 (45)	102 (225) 21 (47)	102 (225) 21 (47)	102 (225) 21 (47)
2. Lower Tanking Density	LH_2 LO_2	- -	- -	69 (151) 438 (965)	69 (151) 438 (965)				- -	- -	69 (151) 438 (965)	69 (151) 438 (965)	69 (151) 438 (965)
3. Pressurization System		109 (241)	43 (94)	43 (94)	43 (94)				43 (94)	43 (94)	43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2 LO_2	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)				10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)
5. Supply Duct Chilldown Propellant	LH_2 LO_2	- -	- -	3 (7) 5 (10)	3 (7) 5 (10)				- -	- -	3 (7) 5 (10)	- -	- -
6. Supply Duct Cooling Dumped Overboard	LH_2 LO_2	- -	- -	- -	- -				- -	- -	- -	- -	5 (12) 54 (120)
7. Hardware to Keep Ducts Wet	LH_2 LO_2	- -	- -	- -	- -				- -	- -	- -	16 (36) 5 (12)	16 (36) 5 (12)
8. Excess LO_2 in Lines Over Chilldown		-	-	-	-				-	-	-	80 (176)	80 (176)
9. Engine Chilldown Propellant	LH_2 LO_2	11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)				11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)
10. Subcooler	LH_2 LO_2	- -	9 (19) 11 (24)	49 (107) 20 (43)	49 (107) 20 (43)				9 (19) 11 (24)	9 (19) 11 (24)	49 (107) 20 (43)	49 (107) 20 (43)	49 (107) 20 (43)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2 LO_2	- -	- -	- -	179 (394) 568(1251)				- -	13 (29) 40 (88)	179 (394) 568(1251)	- -	179 (394) 568(1251)
12. Boost Pump	LH_2 LO_2	39 (85) 29 (64)	39 (85) 29 (64)	- -	- -				39 (85) 29 (64)	39 (85) 29 (64)	- -	- -	- -
13. H_2O_2 Usage, Boost Pump		6 (14)	6 (14)	-	-				6 (14)	6 (14)	-	-	-
14. Settling System Including H_2O_2 Penalty		49 (109)	49 (109)	49 (109)	49 (109)				-	-	-	-	-
15. Sump Assembly	LH_2 LO_2	6 (14) 8 (17)	6 (14) 8 (17)	3 (7) 7 (15)	3 (7) 7 (15)				6 (14) 8 (17)	6 (14) 8 (17)	3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (16)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2 LO_2	- -	6 (13) 5 (12)	10 (22) 11 (25)	- -				6 (13) 5 (12)	- -	- -	12 (27) 11 (25)	- -
17. Volume Penalty Due to Hardware Added	LH_2 LO_2	- -	- 3 (6)	1 (2) 4 (10)	1 (2) 4 (10)				1 (3) 9 (19)	1 (3) 9 (19)	2 (5) 11 (23)	2 (5) 11 (23)	2 (5) 11 (23)
18. Fluid Residuals Cold Side Subcooler	LH_2 LO_2	- -	4 (8) 38 (83)	21 (47) 51 (112)	21 (47) 51 (112)				4 (8) 38 (83)	4 (8) 38 (83)	21 (47) 51 (112)	21 (47) 51 (112)	21 (47) 51 (112)
19. Thrust Barrel Revisions		-	-	-	-				5 (11)	5 (11)	5 (11)	5 (11)	5 (11)
20. Other Hardware		3 (7)	3 (7)	-	-				8 (18)	8 (18)	5 (11)	5 (11)	5 (11)
21. Tank Skin & Weight Over Baseline		-	-	72 (158) 40 (89)	72 (158) 40 (89)				-	-	72 (158) 40 (89)	72 (158) 40 (89)	72 (158) 40 (89)
TOTALS		282 (627)	292 (645)	929(2049)	1655(3647				365 (806)	407 (899)	1747(3848	1116(2462	1899(4187

Figure 4-6. Payload Weight Penalties for System Comparisons, kg (lb_m), Five Burn Mission, RL10A-3-3 Engine

FEED SYSTEM CONCEPT / WEIGHT PENALTY ELEMENT		Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required A	Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped B	Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped D	Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped E	Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd. H	Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd. H_1	Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd. H_2	Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant K	Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant L	Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped N	Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped O	Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped P
1. Capillary Device	LH_2 LO_2	- -	- -	- -	- -				85 (187) 20 (45)	85 (187) 20 (45)	102 (225) 21 (47)	102 (225) 21 (47)	102 (225) 21 (47)
2. Lower Tanking Density	LH_2 LO_2	- -	- -	86 (189) 505(1113)	86 (189) 505(1113)				- -	- -	86 (189) 505(1113)	86 (819) 505(1113)	86 (189) 505(1113)
3. Pressurization System		165 (364)	43 (94)	43 (94)	43 (94)				43 (94)	43 (94)	43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2 LO_2	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)				10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)	10 (23) 10 (23)
5. Supply Duct Childown Propellant	LH_2 LO_2	- -	- -	6 (14) 10 (23)	6 (14) 10 (23)				- -	- -	6 (14) 10 (23)	- -	- -
6. Supply Duct Cooling Dumped Overboard	LH_2 LO_2	- -	- -	- -	- -				- -	- -	- -	- -	7 (16) 74 (163)
7. Hardware to Keep Ducts Wet	LH_2 LO_2	- -	- -	- -	- -				- -	- -	- -	16 (36) 5 (12)	16 (36) 5 (12)
8. Excess LO_2 in Lines Over Childown		-	-	-	-				-	-	-	226 (497)	226 (497)
9. Engine Childown Propellant	LH_2 LO_2	20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)				20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)
10. Subcooler	LH_2 LO_2	- -	9 (19) 11 (24)	49 (107) 20 (43)	49 (107) 20 (43)				9 (19) 11 (24)	9 (19) 11 (24)	49 (107) 20 (43)	49 (107) 20 (43)	49 (107) 20 (43)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2 LO_2	- -	- -	- -	144 (318) 520(1146)				- -	17 (38) 54 (119)	144 (318) 520 (1146)	- -	144 (318) 520(1146)
12. Boost Pump	LH_2 LO_2	39 (85) 29 (64)	39 (85) 29 (64)	- -	- -				39 (85) 29 (64)	39 (85) 29 (64)	- -	- -	- -
13. H_2O_2 Usage, Boost Pump		8 (18)	8 (18)	-	-				8 (18)	8 (18)	-	-	-
14. Settling System Including H_2O_2 Penalty		75 (165)	75 (165)	75 (165)	75 (165)				-	-	-	-	-
15. Sump Assembly	LH_2 LO_2	6 (14) 8 (17)	6 (14) 8 (17)	3 (7) 7 (15)	3 (7) 7 (15)				6 (14) 8 (17)	6 (14) 8 (17)	3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2 LO_2	- -	6 (13) 5 (12)	12 (27) 10 (23)	- -				6 (13) 5 (12)	- -	- -	13 (29) 12 (27)	- -
17. Volume Penalty Due to Hardware Added	LH_2 LO_2	- -	- 2 (4)	-(1) 3 (7)	-(1) 3 (7)				1 (2) 6 (14)	1 (2) 6 (14)	2 (3) 8 (17)	2 (3) 8 (17)	2 (3) 8 (17)
18. Fluid Residuals Cold Side Subcooler	LH_2 LO_2	- -	4 (8) 34 (74)	19 (42) 46 (100)	19 (42) 46 (100)				4 (8) 34 (74)	4 (8) 34 (74)	19 (42) 46 (100)	19 (42) 46 (100)	19 (42) 46 (100)
19. Thrust Barrel Revisions		-	-	-	-				5 (11)	5 (11)	5 (11)	5 (11)	5 (11)
20. Other Hardware		3 (7)	3 (7)	-	-				8 (18)	8 (18)	5 (11)	5 (11)	5 (11)
21. Tank Skin Δ Weight Over Baseline		- -	- -	97 (213) 49 (109)	97 (213) 49 (109)				- -	- -	97 (213) 49 (109)	97 (213) 49 (109)	97 (213) 49 (109)
TOTALS		376 (830)	325 (714)	1083(2388)	1725(3802)				370 (815)	430 (948)	1790(3943)	1382(3043)	2102(4630)

Table 4-7. Payload Weight Penalties for System Comparison, kg (lb_m), One Burn Mission, RL10A-3-3A

WEIGHT PENALTY ELEMENT \ FEED SYSTEM CONCEPT		A: Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	H_1: Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	H_2: Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2			-	-	-	-				94 (207)	94 (207)	94 (207)
	LO_2			-	-	-	-				18 (40)	18 (40)	18 (40)
2. Lower Tanking Density	LH_2			37 (82)	37 (82)	17 (37)	17 (37)				37 (82)	37 (82)	37 (82)
	LO_2			270 (594)	270 (594)	185 (407)	185 (407)				270 (594)	270 (594)	270 (594)
3. Pressurization System				43 (94)	43 (94)	131 (289)	130 (287)				43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)	18 (40)				18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)	14 (31)				14 (31)	14 (31)	14 (31)
5. Supply Duct Chilldown Propellant	LH_2			4 (8)	4 (8)	4 (8)	4 (8)				4 (8)	-	-
	LO_2			3 (7)	3 (7)	3 (7)	3 (7)				3 (7)	-	-
6. Supply Duct Cooling Dumped Overboard	LH_2			-	-	-	-				-	-	1 (1)
	LO_2			-	-	-	-				-	-	6 (13)
7. Hardware to Keep Ducts Wet	LH_2			-	-	-	-				-	16 (36)	16 (36)
	LO_2			-	-	-	-				-	4 (9)	4 (9)
8. Excess LO_2 in Lines Over Chilldown				-	-	-	-				-	28 (62)	28 (62)
9. Engine Chilldown Propellant	LH_2			8 (18)	8 (18)	8 (18)	8 (18)				8 (18)	8 (18)	8 (18)
	LO_2			2 (4)	2 (4)	2 (4)	2 (4)				2 (4)	2 (4)	2 (4)
10. Subcooler	LH_2			18 (40)	18 (40)	-	-				18 (40)	18 (40)	18 (40)
	LO_2			13 (29)	13 (29)	-	-				13 (29)	13 (29)	13 (29)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2			-	88 (194)	-	-				88 (194)	-	88 (194)
	LO_2			-	418 (920)	-	-				418 (920)	-	418 (920)
12. Boost Pump	LH_2			-	-	-	-				-	-	-
	LO_2			-	-	-	-				-	-	-
13. H_2O_2 Usage, Boost Pump				-	-	-	-				-	-	-
14. Settling System Including H_2O_2 Penalty				40 (89)	40 (89)	40 (89)	40 (89)				-	-	-
15. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)	3 (7)				3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)	7 (15)				7 (15)	7 (15)	7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2			8 (16)	-	-	-				-	9 (19)	-
	LO_2			8 (18)	-	-	-				-	9 (20)	-
17. Volume Penalty Due to Hardware Added	LH_2			- (1)	- (1)	-	3 (6)				2 (4)	2 (4)	2 (4)
	LO_2			3 (7)	3 (7)	-	-				11 (22)	11 (22)	11 (22)
18. Fluid Residuals Cold Side Subcooler	LH_2			7 (16)	8 (16)	7 (16)	-				7 (16)	7 (16)	7 (16)
	LO_2			34 (75)	34 (75)	34 (75)	-				34 (75)	34 (75)	34 (75)
19. Thrust Barrel Revisions				-	-	-	-				5 (11)	5 (11)	5 (11)
20. Other Hardware				-	-	-	-				5 (11)	5 (11)	5 (11)
21. Tank Skin & Weight Over Baseline				42 (93)	42 (93)	28 (62)	-				42 (93)	42 (93)	42 (93)
				27 (59)	27 (59)	286 (631)					27 (59)	27 (59)	27 (59)
TOTALS				609(1345)	1099(2423)	787(1736)	434 (956)				1191(2621)	744(1636)	1239(2727)

Table 4-8. Payload Weight Penalties for System Comparison, kg (lb_m), Two Burn Mission, RL10A-3-3A Engine

WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A: Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	H_1: Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	H_2: Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2 LO_2			- -	- -	- -	- -				94 (207) 18 (40)	94 (207) 18 (40)	94 (207) 18 (40)
2. Lower Tanking Density	LH_2 LO_2			51 (113) 337 (742)	51 (113) 337 (742)	15 (34) 168 (370)	15 (34) 168 (370)				51 (113) 337 (742)	51 (113) 337 (742)	51 (113) 337 (742)
3. Pressurization System				43 (94)	42 (94)	183 (402)	122 (268)				43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2 LO_2			18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)				18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)
5. Supply Duct Chilldown Propellant	LH_2 LO_2			5 (12) 6 (13)	5 (12) 6 (13)	5 (12) 6 (13)	5 (12) 6 (13)				5 (12) 6 (13)	- -	- -
6. Supply Duct Cooling Dumped Overboard	LH_2 LO_2			- -	- -	- -	- -				- -	- -	5 (10) 45 (100)
7. Hardware to Keep Ducts Wet	LH_2 LO_2			- -	- -	- -	- -				- -	16 (36) 4 (9)	16 (36) 4 (9)
8. Excess LO_2 in Lines Over Chilldown				-	-	-	-				-	69 (151)	69 (151)
9. Engine Chilldown Propellant	LH_2 LO_2			11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)				11 (25) 2 (5)	11 (25) 2 (5)	11 (25) 2 (5)
10. Subcooler	LH_2 LO_2			18 (40) 13 (29)	18 (40) 13 (29)	- -	- -				18 (40) 13 (29)	18 (40) 13 (29)	18 (40) 13 (29)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2 LO_2			- -	17 (170) 383 (843)	- -	- -				77 (170) 383 (843)	- -	77 (170) 383 (843)
12. Boost Pump	LH_2 LO_2			- -	- -	- -	- -				- -	- -	- -
13. H_2O_2 Usage, Boost Pump				-	-	-	-				-	-	-
14. Settling System Including H_2O_2 Penalty				49 (109)	49 (109)	49 (109)	49 (109)				-	-	-
15. Sump Assembly	LH_2 LO_2			3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)				3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2 LO_2			9 (19) 9 (19)	- -	- -	- -				- -	9 (20) 10 (22)	- -
17. Volume Penalty Due to Hardware Added	LH_2 LO_2			- (1) 3 (7)	- (1) 3 (7)	4 (8) -	- -				2 (4) 10 (20)	2 (4) 10 (20)	2 (4) 10 (20)
18. Fluid Residuals Cold Side Subcooler	LH_2 LO_2			7 (15) 33 (73)	7 (15) 33 (73)	7 (15) 33 (73)	- -				7 (15) 33 (73)	7 (15) 33 (73)	7 (15) 33 (73)
19. Thrust Barrel Revisions				-	-	-	-				5 (11)	5 (11)	5 (11)
20. Other Hardware				-	-	-	-				5 (11)	5 (11)	5 (11)
21. Tank Skin & Weight Over Baseline				55 (122) 31 (69)	55 (122) 31 (69)	28 (62) 286 (631)	- -				55 (122) 31 (69)	55 (122) 31 (69)	55 (122) 31 (69)
TOTALS				724(1600)	1166(2578)	841(1352)	422 (929)				1248(2751)	885(1951)	1376(3032)

Figure 4-9. Payload Weight Penalties for System Comparisons, kg (lb_m), Five Burn Mission, RL10A-3-3A Engine

WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A: Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	H_1: Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	H_2: Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2 LO_2			- -	- -	- -	- -				94 (207) 18 (40)	94 (207) 18 (40)	94 (207) 18 (40)
2. Lower Tanking Density	LH_2 LO_2			69 (151) 387 (853)	69 (151) 387 (853)	11 (24) 120 (265)	11 (24) 120 (265)				69 (151) 387 (853)	69 (151) 387 (853)	69 (151) 337 (353)
3. Pressurization System				43 (94)	43 (94)	273 (602)	170 (374)				43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2 LO_2			18 (40) 14 (31)	18 (40) 14 (31)	81 (40) 14 (31)	18 (40) 14 (31)				18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)
5. Supply Duct Chilldown Propellant	LH_2 LO_2			11 (25) 15 (32)	11 (25) 15 (32)	11 (25) 15 (32)	11 (25) 15 (32)				11 (25) 15 (32)	- -	- -
6. Supply Duct Cooling Dumped Overboard	LH_2 LO_2			- -	- -	- -	- -				- -	- -	6 (4) 61 (136)
7. Hardware to Keep Ducts Wet	LH_2 LO_2			- -	- -	- -	- -				- -	16 (36) 4 (9)	16 (36) 4 (9)
8. Excess LO_2 in Lines Over Chilldown				-	-	-	-				-	194 (428)	194 (428)
9. Engine Chilldown Propellant	LH_2 LO_2			20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)				20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)
10. Subcooler	LH_2 LO_2			18 (40) 13 (29)	18 (40) 13 (29)	- -	- -				18 (40) 13 (29)	18 (40) 13 (29)	18 (40) 13 (29)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2 LO_2			- -	64 (142) 359 (790)	- -	- -				64 (142) 359 (790)	- -	64 (142) 359 (790)
12. Boost Pump	LH_2 LO_2			- -	- -	- -	- -				- -	- -	- -
13. H_2O_2 Usage, Boost Pump				-	-	-	-				-	-	-
14. Settling System Including H_2O_2 Penalty				75 (165)	75 (165)	75 (165)	75 (165)				-	-	-
15. Sump Assembly	LH_2 LO_2			3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)				3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2 LO_2			9 (20) 9 (20)	- -	- -	- -				- -	10 (22) 11 (24)	- -
17. Volume Penalty Due to Hardware Added	LH_2 LO_2			- 2 (5)	- 2 (5)	7 (16) -	- -				1 (3) 7 (14)	1 (3) 7 (14)	1 [illegible] 7 (14)
18. Fluid Residuals Cold Side Subcooler	LH_2 LO_2			6 (13) 28 (64)	6 (13) 29 (64)	6 (13) 29 (64)	- -				6 (13) 29 (64)	6 (13) 29 (64)	6 (13) 29 (64)
19. Thrust Barrel Revisions				-	-	-	-				5 (11)	5 (11)	5 (11)
20. Other Hardware				-	-	-	-				5 (11)	5 (11)	5 (11)
21. Tank Skin Δ Weight Over Baseline				70 (154) 36 (79)	70 (154) 36 (79)	28 (62) 286 (631)	- -				70 (154) 36 (79)	70 (154) 36 (79)	70 (154) 36 (79)
TOTALS				857(1887)	1260(2779)	927(2042)	463(1019)				1314(2896)	1100(2425)	1570(3460)

Table 4-10. Payload Weight Penalties for System Comparisons, One Burn Mission, RL10 Category I Engine

WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
		A	B	D	E	H	H_1	H_2	K	L	N	O	P
1. Capillary Device	LH_2			-	-	-	-	-			92 (202)	92 (202)	92 (202)
	LO_2			-	-	-	-	-			22 (48)	22 (48)	22 (48)
2. Lower Tanking Density	LH_2			-	-	-	-	-			-	-	-
	LO_2			-	-	-	-	-			-	-	-
3. Pressurization System				43 (94)	43 (94)	115 (254)	102 (225)	163 (359)			43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)	18 (40)	18 (40)			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
5. Supply Duct Chilldown Propellant	LH_2			4 (8)	4 (8)	4 (8)	4 (8)	4 (8)			4 (8)	-	-
	LO_2			3 (7)	3 (7)	3 (7)	3 (7)	3 (7)			3 (7)	-	-
6. Supply Duct Cooling Dumped Overboard	LH_2			-	-	-	-	-			-	-	1 (1)
	LO_2			-	-	-	-	-			-	-	9 (20)
7. Hardware to Keep Ducts Wet	LH_2			-	-	-	-	-			-	16 (35)	16 (35)
	LO_2			-	-	-	-	-			-	9 (19)	9 (19)
8. Excess LO_2 in Lines Over Chilldown				-	-	-	-	-			-	26 (57)	26 (57)
9. Engine Chilldown Propellant	LH_2			8 (18)	8 (18)	8 (18)	8 (18)	8 (18)			8 (18)	8 (18)	8 (18)
	LO_2			2 (4)	2 (4)	2 (4)	2 (4)	2 (4)			2 (4)	2 (4)	2 (4)
10. Subcooler	LH_2			14 (30)	14 (30)	-	-	-			14 (30)	14 (30)	14 (30)
	LO_2			27 (60)	27 (60)	-	-	-			27 (60)	27 (60)	27 (60)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2			-	54 (118)	-	-	-			54 (118)	-	54 (118)
	LO_2			-	512(1127)	-	-	-			512(1127)	-	512(1127)
12. Boost Pump	LH_2			-	-	-	-	-			-	-	-
	LO_2			-	-	-	-	-			-	-	-
13. H_2O_2 Usage, Boost Pump				-	-	-	-	-			-	-	-
14. Settling System Including H_2O_2 Penalty				40 (89)	40 (89)	40 (89)	40 (89)	40 (89)			-	-	-
15. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)	7 (15)	7 (15)			7 (15)	7 (15)	7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2			7 (15)	-	-	-	-			-	7 (16)	-
	LO_2			8 (17)	-	-	-	-			-	9 (19)	-
17. Volume Penalty Due to Hardware Added	LH_2			- (1)	- (1)	-	2 (4)	7 (15)			2 (4)	2 (4)	2 (4)
	LO_2				7 (15)	-	-	-			15 (31)	15 (31)	15 (31)
18. Fluid Residuals Cold Side Subcooler	LH_2			5 (10)	5 (10)	-	-	-			5 (10)	5 (10)	5 (10)
	LO_2			85 (188)	85 (188)	-	-	-			85 (188)	85 (188)	85 (188)
19. Thrust Barrel Revisions				-	-	-	-	-			5 (11)	5 (11)	5 (11)
20. Other Hardware				-	-	-	-	-			5 (11)	5 (11)	5 (11)
21. Tank Skin & Weight Over Baseline				3 (7)	3 (7)	-	-	-			3 (7)	3 (7)	3 (7)
				5 (10)	5 (10)	-	-	-			5 (10)	5 (10)	5 (10)
TOTALS				303 (666)	854(1879)	214 (473)	203 (448)	269 (593)			948(2089)	442 (967)	1002(2198)

Table 4-11. Payload Weight Penalties for System Comparisons, kg (lb_m), Two Burn Mission, RL10 Category I Engine

WEIGHT PENALTY ELEMENT \ FEED SYSTEM CONCEPT		A: Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	H_1: Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	H_2: Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2			-	-	-	-	-			92 (202)	92 (202)	92 (202)
	LO_2			-	-	-	-	-			22 (48)	22 (48)	22 (48)
2. Lower Tanking Density	LH_2			-	-	-	-	-			-	-	-
	LO_2			67 (148)	67 (148)	-	-	-			67 (148)	67 (148)	67 (148)
3. Pressurization System				43 (94)	43 (94)	143 (314)	100 (220)	172 (378)			43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)	18 (40)	18 (40)			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
5. Supply Duct Childown Propellant	LH_2			5 (12)	5 (12)	5 (12)	5 (12)	5 (12)			5 (12)	-	-
	LO_2			6 (13)	6 (13)	6 (13)	6 (13)	6 (13)			6 (13)	-	-
6. Supply Duct Cooling Dumped Overboard	LH_2			-	-	-	-	-			-	-	5 (10)
	LO_2			-	-	-	-	-			-	-	71 (157)
7. Hardware to Keep Ducts Wet	LH_2			-	-	-	-	-			-	16 (35)	16 (35)
	LO_2			-	-	-	-	-			-	9 (19)	9 (19)
8. Excess LO_2 in Lines Over Childown				-	-	-	-	-			-	64 (140)	64 (140)
9. Engine Childown Propellant	LH_2			11 (25)	11 (25)	11 (25)	11 (25)	11 (25)			11 (25)	11 (25)	11 (25)
	LO_2			2 (5)	2 (5)	2 (5)	2 (5)	2 (5)			2 (5)	2 (5)	2 (5)
10. Subcooler	LH_2			14 (30)	14 (30)	-	-	-			14 (30)	14 (30)	14 (30)
	LO_2			27 (60)	27 (60)	-	-	-			27 (60)	27 (60)	27 (60)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2			-	-	-	-	-			47 (104)	-	47 (104)
	LO_2			-	493(1087)	-	-	-			493(1087)	-	493(1087)
12. Boost Pump	LH_2			-	-	-	-	-			-	-	-
	LO_2			-	-	-	-	-			-	-	-
13. H_2O_2 Usage, Boost Pump				-	-	-	-	-			-	-	-
14. Settling System Including H_2O_2 Penalty				49 (109)	49 (109)	49 (109)	49 (109)	49 (109)			-	-	-
15. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)	7 (15)	7 (15)			7 (15)	7 (15)	7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2			7 (16)	-	-	-	-			-	8 (17)	-
	LO_2			9 (19)	-	-	-	-			-	10 (22)	-
17. Volume Penalty Due to Hardware Added	LH_2			-	-	-	1 (2)	7 (16)			2 (3)	2 (3)	2 (3)
	LO_2			7 (15)	7 (15)	-	-	-			14 (30)	14 (30)	14 (30)
18. Fluid Residuals Cold Side Subcooler	LH_2			5 (11)	5 (11)	-	-	-			5 (11)	5 (11)	5 (11)
	LO_2			82 (180)	82 (180)	-	-	-			82 (180)	82 (180)	82 (180)
19. Thrust Barrel Revisions				-	-	-	-	-			5 (11)	5 (11)	5 (11)
20. Other Hardware				-	-	-	-	-			5 (11)	5 (11)	5 (11)
21. Tank Skin & Weight Over Baseline	LH_2			3 (7)	3 (7)	-	-	-			3 (7)	3 (7)	3 (7)
	LO_2			9 (20)	9 (20)	-	-	-			9 (20)	9 (20)	9 (20)
TOTALS				388 (857)	912 (2013)	258 (571)	216 (479)	294 (651)			996(2194)	553(1211)	1150(2530)

Table 4-12. Payload Weight Penalties for System Comparisons, kg (lb_m) Five Burn Mission, RL10 Category I Engine

WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A: Settling, Pressurization Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Autogenous + Amb. Stored He, Uncooled Duct, No Coolant Reqd.	H_1: Settling, Pressure Fed Engine, Autogenous + Cryo Stored He, Uncooled Duct, No Coolant Reqd.	H_2: Settling, Pressure Fed Engine, Cryo Stored GHe for LH_2, Uncooled Duct, No Coolant Reqd.	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2 LO_2			- -	- -		- -	- -			92 (202) 22 (48)	92 (202) 22 (48)	92 (202) 22 (48)
2. Lower Tanking Density	LH_2 LO_2			23 (50) 101 (223)	23 (50) 101 (223)		- -	- -			23 (50) 101 (223)	23 (50) 101 (223)	23 (50) 101 (223)
3. Pressurization System				43 (94)	43 (94)		128 (281)	185 (407)			43 (94)	43 (94)	43 (94)
4. Propellant Supply Duct	LH_2 LO_2			18 (40) 14 (31)	18 (40) 14 (31)		18 (40) 14 (31)	18 (40) 14 (31)			18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)
5. Supply Duct Childown Propellant	LH_2 LO_2			11 (25) 15 (32)	11 (25) 15 (32)		11 (25) 15 (32)	11 (25) 15 (32)			11 (25) 15 (32)	- -	- -
6. Supply Duct Cooling Dumped Overboard	LH_2 LO_2			- -	- -		- -	- -			- -	- -	6 (13) 97 (214)
7. Hardware to Keep Ducts Wet	LH_2 LO_2			- -	- -		- -	- -			- -	16 (35) 9 (19)	16 (35) 9 (19)
8. Excess LO_2 in Lines Over Childown				-	-		-	-			-	179 (394)	179 (394)
9. Engine Childown Propellant	LH_2 LO_2			20 (43) 3 (7)	20 (43) 3 (7)		20 (43) 3 (7)	20 (43) 3 (7)			20 (43) 3 (7)	20 (43) 3 (7)	20 (43) 3 (7)
10. Subcooler	LH_2 LO_2			14 (30) 27 (60)	14 (30) 27 (60)		- -	- -			14 (30) 27 (60)	14 (30) 27 (60)	14 (30) 27 (60)
11. Subcooler Cooling Fld. Dumped Overboard	LH_2 LO_2			- -	41 (91) 458(1009)		- -	- -			41 (91) 458(1009)	- -	41 (91) 458(1009)
12. Boost Pump	LH_2 LO_2			- -	- -		- -	- -			- -	- -	- -
13. H_2O_2 Usage, Boost Pump				-	-		-	-			-	-	-
14. Settling System Including H_2O_2 Penalty				75 (165)	75 (165)		75 (165)	75 (165)			-	-	-
15. Sump Assembly	LH_2 LO_2			3 (7) 7 (15)	3 (7) 7 (15)		3 (7) 7 (15)	3 (7) 7 (15)			3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)
16. Pumping Sys. to Return Coolant to Tank Incl. Boiloff, Batt. & Hdwr.	LH_2 LO_2			8 (17) 9 (19)	- -		- -	- -			- -	8 (18) 10 (23)	- -
17. Volume Penalty Due to Hardware Added	LH_2 LO_2			- 4 (10)	- 4 (10)		- -	- 8 (18)			1 (2) 9 (20)	1 (2) 9 (20)	1 (2) 9 (20)
18. Fluid Residuals Cold Side Subcooler	LH_2 LO_2			5 (10) 73 (161)	5 (10) 73 (161)		- -	- -			5 (10) 73 (161)	5 (10) 73 (161)	5 (10) 73 (161)
19. Thrust Barrel Revisions				-	-		-	-			5 (11)	5 (11)	5 (11)
20. Other Hardware				-	-		-	-			5 (11)	5 (11)	5 (11)
21. Tank Skirt Weight Over Baseline				18 (62) 9 (20)	28 (62) 9 (20)		- -	- -			28 (62) 9 (20)	28 (62) 9 (20)	28 (62) 9 (20)
TOTALS				510(1121)	992(2185)		298 (655)	359 (700)			1047(2304)	744(1636)	1324 (2922)

Table 4-13. Settling Versus Capillary Device Payload Penalty Comparison (Systems B & K)

Engine Option	Mission (No. of Burns)	Payload Penalties, kg (lbm)	
		Feed System	Feed System
		B	K
		Propulsive Settling	Capillary Device
RL10 CAT I	1	-	-
	2	-	-
	5	-	-
RL10A-3-3A	1	-	-
	2	-	-
	5	-	-
RL10A-3-3	1	284 (627)	367 (810)
	2	292 (645)	365 (803)
	5	325 (714)	370 (815)

Note: Both contain boost pumps, coolant pumped.

Table 4-14. Settling Versus Capillary Device Payload Penalty Comparison (Systems E & N)

Engine Option	Mission (No. of Burns)	Payload Penalties kg (lb_m)	
		Feed System	Feed System
		E	N
		Propulsive Settling	Capillary Device
RL10 CAT I	1	854 (1879)	948 (2089)
	2	912 (2013)	996 (2194)
	5	992 (2185)	1047 (2305)
RL10A-3-3A	1	1099 (2423)	1191 (2621)
	2	1160 (2575)	1248 (2751)
	5	1260 (2779)	1314 (2895)
RL10A-3-3	1	1629 (3592)	1730 (3815)
	2	1655 (3647)	1747 (3848)
	5	1725 (3802)	1790 (3943)

Note: Turbopump subcooling, coolant dumped.

Table 4-15. Boost Pump NSPS, Pressure Fed Vs Thermal Subcooling Payload Penalty Comparison, (Systems A & B)

Engine Option	Mission (No. of Burns)	Payload Penalties kg (lb_m)	
		Feed System	Feed System
		A	B
		Pressure Fed Boost Pump	Thermally Subcooled Boost Pump
RL10 Cat 1	1	-	-
	2	-	-
	5	-	-
RL10A-3-3A	1	-	-
	2	-	-
	5	-	-
RL10A-3-3	1	253 (559)	284 (627)
	2	282 (627)	292 (645)
	5	376 (830)	325 (714)

Note: Boost pump thermal subcooling; coolant pumped back into the tank; subcooler penalty is less sensitive to the number of burns

Table 4-16. Methods for Supplying Turbopump NPSP Payload Penalty Comparison (Systems B, D & H)

Engine Option	Mission (No. of Burns)	Payload Penalties, kg (lb_m)		
		Feed Systems		
		B	D	H
		Boost Pump for Turbopump NPSP	Thermal Subcooling for Turbo-pump NPSP	Pressurization for Turbopump NPSP
RL10 Cat 1	1	-	303 (666)	214 (473)
	2	-	388 (857)	258 (571)
	5	-	510 (1121)	298 (655)*
RL10A-3-3A	1	-	609 (1345)	767 (1736)
	2	-	724 (1600)	841 (1852)
	5	-	857 (1887)	927 (2042)
RL10A-3-3	1	284 (627)	804 (1774)	-
	2	292 (645)	929 (2049)	-
	5	325 (714)	1083 (2388)	-

Note: All feed systems use propellant settling.

*H_1 used because H is not feasible.

Table 4-17. Propellant Duct Cooling Options Payload Penalty Comparison (Systems N, O, P & M)

Engine Option	Mission (No. of Burns)	Payload Penalties, kg (lb_m)			
		Feed Systems			
		N	O	P	M
		Uncooled Duct	Coolant Pumped	Coolant Dumped	Uncooled Duct Pumped
RL10 Cat I	1	948 (2089)	442 (967)	1002 (2198)	399 (879)
	2	996 (2194)	552 (1211)	1150 (2530)	473 (1042)
	5	1047 (2304)	744 (1636)	1328 (2922)	566 (1245)
RL10A-3-3A	1	1191 (2621)	744 (1638)	1239 (2727)	702 (1546)
	2	1248 (2751)	885 (1951)	1376 (3032)	808 (1780)
	5	1314 (2896)	1100 (2425)	1570 (3460)	912 (2009)
R10A-3-3	1	1730 (3815)	956 (2111)	1788 (3943)	922 (2030)
	2	1747 (3848)	1116 (2462)	1899 (4187)	1010 (2225)
	5	1790 (3943)	1382 (3043)	2102 (4630)	1151 (2535)

Note: All options have capillary devices and turbopump thermal subcoolers.

Table 4-18. Boost Pump Subcooler Coolant Disposal Payload Penalty Comparison (Systems K & L)

Engine Option	Mission (No. of Burns)	Payload Penalties kg (lb_m)	
		Feed Systems	
		K	L
		Coolant Pumped	Coolant Dumped
RL10 Cat I	1	-	-
	2	-	-
	5	-	-
RL10A-3-3A	1	-	-
	2	-	-
	5	-	-
RL10A-3-3	1	367 (810)	399 (881)
	2	365 (806)	407 (898)
	5	370 (815)	430 (948)

Note: Coolant disposal from boost pump subcooling (capillary system).

Table 4-19. Turbopump Thermal Subcooler Coolant Disposal Payload Penalty Comparison Settling System (Systems D & E)

Engine Option	Mission (No. of Burns)	Payload Penalties kg (lb_m)	
		Feed Systems	
		D	E
		Coolant Pumped	Coolant Dumped
RL10 Cat I	1	303 (666)	854 (1879)
	2	388 (857)	912 (2013)
	5	510 (1121)	992 (2185)
RL10A-3-3A	1	609 (1345)	1099 (2423)
	2	724 (1600)	1166 (2575)
	5	857 (1887)	1260 (2779)
RL10A-3-3	1	804 (1774)	1629 (3592)
	2	929 (2049)	1655 (3647)
	5	1083 (2388)	1725 (3802)

Note: Coolant disposal from turbopump thermal subcooling.

Table 4-20. Turbopump Thermal Subcooling Disposal Payload Penalty Comparison Capillary Devices (Systems O and P)

Engine Option	Mission (No. of Burns)	Payload Penalties kg (lb_m) Feed Systems O Coolant Pumped	Payload Penalties kg (lb_m) Feed Systems P Coolant Dumped
RL10 Cat I	1	442 (967)	1002 (2198)
	2	552 (1211)	1150 (2530)
	5	744 (1636)	1328 (2922)
RL10A-3-3A	1	744 (1638)	1239 (2727)
	2	885 (1951)	1376 (3032)
	5	1100 (2425)	1570 (3460)
RL10A-3-3	1	956 (2111)	1788 (3943)
	2	1116 (2462)	1899 (4187)
	5	1382 (3043)	2102 (4630)

Note: Coolant disposal for turbopump subcooling.

Table 4-21. Pressurization System Options Payload Penalty Comparison (Systems H, H_1 & H_2)

Engine Option	Mission (No. of Burns	Payload Penalties, kg (lb_m) Feed Systems H: Autogenous LH_2 Tank Ambient Stored GHe	H_1: Autogenous LH_2 Tank Cryostored GHe	H_2: GHe for LH_2 Tank Cryostored GHe
RL10 Cat I	1	214 (473)	203 (448)	269 (593)
	2	258 (571)	216 (479)	294 (651)
	5	*	298 (655)	369 (790)

Note: Ambient storage is simpler than cryogenic storage and would be selected (generally) on that basis alone.

subcooling preferred for the multiburn missions. Pumping coolant back into the tank is better than dumping overboard. Uncooled propellant ducts are better than cooled propellant ducts and boost pumps are the best method of supplying turbopump NPSP. Based on these comparisons of relative payload weight penalties, feed system concepts A or B appear best for the Centaur D-1S application. Feed system concept A is the baseline system. Feed system concept B is the baseline system with the substitution of thermal subcooling for main tank pressurization.

4.3 HARDWARE WEIGHT COMPARISONS

Hardware weight penalties are shown in Table 4-22 through 4-30. Hardware weight comparisons are shown in Tables 4-31 through 4-39. Hardware weight comparisons are not as meaningful as the payload weight penalty comparisons shown in Section 4.1 because they do not reflect differences in fluid weight penalty.

Table 4-31 and 4-32 compare settling to capillary devices. Capillary devices are generally about 80 to 90 kg heavier than settling in terms of hardware weight for one, two and five burn missions.

Table 4-33 shows that thermally subcooled boost pumps have lower hardware weight than pressure fed boost pumps. Table 4-34 shows that boost pumps have the lightest hardware weight of the turbopump NPSP supply methods (boost pump, pressure, thermal subcooler). If pressurant is cryogenically stored then concept H_1 is comparable in weight to boost pumps. For the Category I engine thermal subcooling is lighter than pressurization for supplying turbopump NPSP while for the RL10A-3-3A engine, pressurization is lighter than thermal subcooling for supplying turbopump NPSP.

Table 4-22. Hardware Weight Penalties for System Comparisons, kg (lb_m), One Burn Mission, RL10A-3-3 Engine

HARDWARE WEIGHT PENALTY ELEMENT	FEED SYSTEM CONCEPT	A: Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2	-	-	-	-		85 (187)	85 (187)	102 (225)	102 (225)	102 (225)
	LO_2	-	-	-	-		20 (45)	20 (45)	21 (47)	21 (47)	21 (47)
2. Pressurization		86 (190)	41 (90)	41 (90)	41 (90)		41 (90)	41 (90)	41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2	10 (23)	10 (23)	10 (23)	10 (23)		10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
	LO_2	10 (23)	10 (23)	10 (23)	10 (23)		10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
4. Hardware to Keep Ducts Wet	LH_2	-	-	-	-		-	-	-	16 (36)	16 (36)
	LO_2	-	-	-	-		-	-	-	5 (12)	5 (12)
5. Subcooler	LH_2	-	9 (19)	49 (107)	49 (107)		9 (19)	9 (19)	49 (107)	49 (107)	49 (107)
	LO_2	-	11 (24)	20 (43)	20 (43)		11 (24)	11 (24)	20 (43)	20 (43)	20 (43)
6. Boost Pump	LH_2	39 (85)	39 (85)	-	-		39 (85)	39 (85)	-	-	-
	LO_2	29 (64)	29 (64)	-	-		29 (64)	29 (64)	-	-	-
7. Settling System		35 (77)	35 (77)	35 (77)	35 (77)		-	-	-	-	-
8. Sump Assembly	LH_2	6 (14)	6 (14)	3 (7)	3 (7)		6 (14)	6 (14)	3 (7)	3 (7)	3 (7)
	LO_2	8 (17)	8 (17)	7 (15)	7 (15)		8 (17)	8 (17)	7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2	-	6 (13)	10 (23)	-		6 (13)	-	-	11 (24)	-
	LO_2	-	5 (12)	10 (23)	-		5 (12)	-	-	10 (23)	-
10. Thrust Barrel Revisions		-	-	-	-		5 (11)	5 (11)	5 (11)	5 (11)	5 (11)
11. Other Hardware		3 (7)	3 (7)	-	-		8 (18)	8 (18)	5 (11)	5 (11)	5 (11)
12. Tank Skin Delta		-	-	55 (122)	55 (122)		-	-	55 (122)	55 (122)	55 (122)
		-	-	36 (79)	36 (79)		-	-	36 (79)	36 (79)	36 (79)
TOTALS		226 (500)	212 (468)	289 (630)	266 (586)		292 (645)	281 (620)	364 (803)	406 (898)	386 (851)

Table 4-23. Hardware Weight Penalties for System Comparisons, kg (lb_m), Two Burn Mission, RL10A-3-3 Engine

HARDWARE WEIGHT PENALTY ELEMENT	FEED SYSTEM CONCEPT	A Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2	-	-	-	-		85 (187)	85 (187)	102 (225)	102 (225)	102 (225)
	LO_2	-	-	-	-		20 (45)	20 (45)	21 (47)	21 (47)	21 (47)
2. Pressurization		106 (233)	41 (90)	41 (90)	41 (90)		41 (90)	41 (90)	41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2	10 (23)	10 (23)	10 (23)	10 (23)		10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
	LO_2	10 (23)	10 (23)	10 (23)	10 (23)		10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
4. Hardware to Keep Ducts Wet	LH_2	-	-	-	-		-	-	-	16 (36)	16 (36)
	LO_2	-	-	-	-		-	-	-	5 (12)	5 (12)
5. Subcooler	LH_2	-	9 (19)	49 (107)	49 (107)		9 (19)	9 (19)	49 (107)	49 (107)	49 (107)
	LO_2	-	11 (24)	20 (43)	20 (43)		11 (24)	11 (24)	20 (43)	20 (43)	20 (43)
6. Boost Pump	LH_2	39 (85)	39 (85)	-	-		39 (85)	39 (85)	-	-	-
	LO_2	29 (64)	29 (64)	-	-		29 (64)	29 (64)	-	-	-
7. Settling System		35 (77)	35 (77)	35 (77)	35 (77)		-	-	-	-	-
8. Sump Assembly	LH_2	6 (14)	6 (14)	3 (7)	3 (7)		6 (14)	6 (14)	3 (7)	3 (7)	3 (7)
	LO_2	8 (17)	8 (17)	7 (15)	7 (15)		8 (17)	8 (17)	7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2	-	6 (13)	10 (11)	-		6 (13)	-	-	12 (27)	-
	LO_2	-	5 (12)	11 (25)	-		5 (12)	-	-	11 (25)	-
10. Thrust Barrel Revisions		-	-	-	-		5 (11)	5 (11)	5 (11)	5 (11)	5 (11)
11. Other Hardware		3 (7)	3 (7)	-	-		8 (18)	8 (18)	5 (11)	5 (11)	5 (11)
12. Tank Skin Delta	LH_2	-	-	72 (158)	72 (158)		-	-	72 (158)	72 (158)	72 (158)
	LO_2	-	-	40 (89)	40 (89)		-	-	40 (89)	40 (89)	40 (89)
TOTALS		246 (543)	212 (468)	308 (679)	287 (632)		292 (645)	281 (620)	385 (849)	429 (949)	406 (897)

Table 4-24. Hardware Weight Penalties for System Comparisons, kg (lb_m), Five Burn Mission, RL10A-3-3 Engine

HARDWARE WEIGHT PENALTY ELEMENT	FEED SYSTEM CONCEPT	A Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2	-	-	-	-		85 (187)	85 (187)	102 (225)	102 (225)	102 (225)
	LO_2	-	-	-	-		20 (45)	20 (45)	21 (47)	21 (47)	21 (47)
2. Pressurization		159 (350)	41 (90)	41 (90)	41 (90)		41 (90)	41 (90)	41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2	10 (23)	10 (23)	10 (23)	10 (23)		10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
	LO_2	10 (23)	10 (23)	10 (23)	10 (23)		10 (23)	10 (23)	10 (23)	10 (23)	10 (23)
4. Hardware to Keep Ducts Wet	LH_2	-	-	-	-		-	-	-	16 (36)	16 (36)
	LO_2	-	-	-	-		-	-	-	5 (12)	5 (12)
5. Subcooler	LH_2	-	9 (19)	49 (107)	49 (107)		9 (19)	9 (19)	49 (107)	49 (107)	49 (107)
	LO_2	-	11 (24)	20 (43)	20 (43)		11 (24)	11 (24)	20 (43)	20 (43)	20 (43)
6. Boost Pump	LH_2	39 (85)	39 (85)	-	-		39 (85)	39 (85)	-	-	-
	LO_2	29 (64)	29 (64)	-	-		29 (64)	29 (64)	-	-	-
7. Settling System		35 (77)	35 (77)	35 (77)	35 (77)		-	-	-	-	-
8. Sump Assembly	LH_2	6 (14)	6 (14)	3 (7)	3 (7)		6 (14)	6 (14)	3 (7)	3 (7)	3 (7)
	LO_2	8 (17)	8 (17)	7 (15)	7 (15)		8 (17)	8 (17)	7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2	-	6 (13)	12 (27)	-		6 (13)	-	-	13 (29)	-
	LO_2	-	5 (12)	10 (23)	-		5 (12)	-	-	12 (27)	-
10. Thrust Barrel Revisions		-	-	-	-		5 (11)	5 (11)	5 (11)	5 (11)	5 (11)
11. Other Hardware		3 (7)	3 (7)	-	-		5 (19)	9 (18)	5 (11)	6 (11)	5 (11)
12. Tank Skin Delta		-	-	97 (213)	97 (213)		-	-	97 (213)	97 (213)	97 (213)
		-	-	49 (109)	49 (109)		-	-	49 (109)	49 (109)	49 (109)
TOTALS		299 (660)	212 (468)	343 (757)	321 (707)		292 (645)	281 (620)	419 (924)	465 (1028)	440 (972)

Table 4-25. Hardware Weight Penalties for System Comparisons, kg (lb_m), One Burn Mission, RL10A-3-3A Engine

HARDWARE WEIGHT PENALTY ELEMENT \ FEED SYSTEM CONCEPT		A: Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2			-	-	-			94 (207)	94 (207)	94 (207)
	LO_2			-	-	-			18 (40)	18 (40)	18 (40)
2. Pressurization				41 (90)	41 (90)	123 (272)			41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
4. Hardware to Keep Ducts Wet	LH_2			-	-	-			-	16 (36)	16 (36)
	LO_2			-	-	-			-	4 (9)	4 (9)
5. Subcooler	LH_2			18 (40)	18 (40)	-			18 (40)	18 (40)	18 (40)
	LO_2			13 (29)	13 (29)	-			13 (29)	13 (29)	13 (29)
6. Boost Pump	LH_2			-	-	-			-	-	-
	LO_2			-	-	-			-	-	-
7. Settling System				35 (77)	35 (77)	35 (77)			-	-	-
8. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)			7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2			8 (18)	-	-			-	9 (19)	-
	LO_2			8 (18)	-	-			-	9 (20)	-
10. Thrust Barrel Revisions				-	-	-			5 (11)	5 (11)	5 (11)
11. Other Hardware				-	-	-			5 (11)	5 (11)	5 (11)
12. Tank Skin Delta				42 (93)	42 (93)	28 (62)			42 (93)	42 (93)	42 (93)
				27 (59)	27 (59)	286 (631)			27 (59)	27 (59)	27 (59)
TOTALS				235 (517)	218 (481)	515 (1135)			305 (673)	343 (757)	326 (718)

Table 4-26. Hardware Weight Penalties for System Comparisons, kg (lb_m), Two Burn Mission, RL10A-3-3A Engine

HARDWARE WEIGHT PENALTY ELEMENT \ FEED SYSTEM CONCEPT		A: Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2 LO_2			- -	- -	- -			94 (207) 18 (40)	94 (207) 18 (40)	94 (207) 18 (40)
2. Pressurization				41 (90)	41 (90)	92 (202)			41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2 LO_2			18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)			18 (40) 14 (31)	18 (40) 14 (31)	18 (40) 14 (31)
4. Hardware to Keep Ducts Wet	LH_2 LO_2			- -	- -	- -			- -	16 (36) 4 (9)	16 (36) 4 (9)
5. Subcooler	LH_2 LO_2			18 (40) 13 (29)	18 (40) 13 (39)	- -			18 (40) 13 (29)	18 (40) 13 (29)	18 (40) 13 (29)
6. Boost Pump	LH_2 LO_2			-	-	-			-	-	-
7. Settling System				35 (77)	35 (77)	35 (77)			-	-	-
8. Sump Assembly	LH_2 LO_2			3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)			3 (7) 7 (15)	3 (7) 7 (15)	3 (7) 7 (15)
9. Coolant Pumping System	LH_2 LO_2			9 (19) 9 (19)	- -	- -			- -	9 (20) 10 (22)	- -
10. Thrust Barrel Revisions				-	-	-			5 (11)	5 (11)	5 (11)
11. Other Hardware				-	-	-			5 (11)	5 (11)	5 (11)
12. Tank Skin Delta				55 (122) 31 (69)	55 (122) 31 (69)	28 (62) 286 (631)			55 (122) 31 (69)	55 (122) 31 (69)	55 (122) 31 (69)
TOTALS				253 (558)	236 (520)	483 (1065)			323 (712)	362 (799)	343 (757)

Table 4-27. Hardware Weight Penalties for System Comparisons, kg (lb_m), Five Burn Mission, RL10A-3-3A Engine

HARDWARE WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2			-	-	-			94 (207)	94 (207)	94 (207)
	LO_2			-	-	-			18 (40)	18 (40)	18 (40)
2. Pressurization				41 (90)	41 (90)	110 (243)			41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
4. Hardware to Keep Ducts Wet	LH_2			-	-	-			-	16 (36)	16 (36)
	LO_2			-	-	-			-	4 (9)	4 (9)
5. Subcooler	LH_2			18 (40)	18 (40)	-			18 (40)	18 (40)	18 (40)
	LO_2			13 (29)	13 (29)	-			13 (29)	13 (29)	13 (29)
6. Boost Pump	LH_2			-	-	-			-	-	-
	LO_2			-	-	-			-	-	-
7. Settling System				35 (77)	35 (77)	35 (77)			-	-	-
8. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)			7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2			9 (20)	-	-			-	10 (22)	-
	LO_2			9 (20)	-	-			-	11 (24)	-
10. Thrust Barrel Revisions				-	-	-			5 (11)	5 (11)	5 (11)
11. Other Hardware				-	-	-			5 (11)	5 (11)	5 (11)
12. Tank Skin Delta				70 (154)	70 (154)	28 (62)			70 (154)	70 (154)	70 (154)
				36 (79)	36 (79)	286 (631)			36 (79)	36 (79)	36 (79)
TOTALS				273 (602)	255 (562)	502 (1106)			342 (754)	383 (845)	362 (799)

Table 4-28. Hardware Weight Penalties for System Comparisons, kg (lb_m), One Burn Mission, RL10 Category I Engine

HARDWARE WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A: Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2			-	-	-			92 (202)	92 (202)	92 (202)
	LO_2			-	-	-			22 (48)	22 (48)	22 (48)
2. Pressurization				41 (90)	41 (90)	109 (241)			41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
4. Hardware to Keep Ducts Wet	LH_2			-	-	-			-	16 (35)	16 (35)
	LO_2			-	-	-			-	9 (19)	9 (19)
5. Subcooler	LH_2			14 (30)	14 (30)	-			14 (30)	14 (30)	14 (30)
	LO_2			27 (60)	27 (60)	-			27 (60)	27 (60)	27 (60)
6. Boost Pump	LH_2			-	-	-			-	-	-
	LO_2			-	-	-			-	-	-
7. Settling System				35 (77)	35 (77)	35 (77)			-	-	-
8. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)			7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2			7 (15)	-	-			-	7 (16)	-
	LO_2			8 (17)	-	-			-	9 (19)	-
10. Thrust Barrel Revisions				-	-	-			5 (11)	5 (11)	5 (11)
11. Other Hardware				-	-	-			5 (11)	5 (11)	5 (11)
12. Tank Skin Delta	LH_2			3 (7)	3 (7)	-			3 (7)	3 (7)	3 (7)
	LO_2			5 (10)	5 (10)	-			5 (10)	5 (10)	5 (10)
TOTALS				182 (399)	167 (377)	186 (411)			256 (562)	297 (651)	281 (616)

Table 4-29. Hardware Weight Penalties for System Comparisons, kg (lb_m), Two Burn Mission, RL10 Category I Engine

HARDWARE WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A: Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2			-	-	-			92 (202)	92 (202)	92 (202)
	LO_2			-	-	-			22 (48)	22 (48)	22 (48)
2. Pressurization				41 (90)	41 (90)	134 (296			41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
4. Hardware to Keep Ducts Wet	LH_2			-	-	-			-	16 (35)	16 (35)
	LO_2			-	-	-			-	9 (19)	9 (19)
5. Subcooler	LH_2			11 (25)	11 (25)	-			11 (25)	11 (25)	11 (25)
	LO_2			2 (5)	2 (5)	-			2 (5)	2 (5)	2 (5)
6. Boost Pump	LH_2			-	-	-			-	-	-
	LO_2			-	-	-			-	-	-
7. Settling System				35 (77)	35 (77)	35 (77)			-	-	-
8. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15			7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2			7 (16)	-	-			-	8 (17)	-
	LO_2			9 (19)	-	-			-	10 (22)	-
10. Thrust Barrel Revisions				-	-	-			5 (11)	5 (11)	5 (11)
11. Other Hardware				-	-	-			5 (11)	5 (11)	5 (11)
12. Tank Skin Delta				3 (7)	3 (7)	-			3 (7)	3 (7)	3 (7)
				5 (10)	5 (10)	-			5 (10)	5 (10)	5 (10)
TOTALS				155 (358)	139 (307)	211 (466)			228 (502)	271 (595)	253 (556)

Table 4-30. Hardware Weight Penalties for System Comparisons, kg (lb_m), Five Burn Mission, RL10 Category I Engine

HARDWARE WEIGHT PENALTY ELEMENT / FEED SYSTEM CONCEPT		A: Settling, Pressurization, Boost Pump, Uncooled Duct, No Coolant Required	B: Settling, Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Pumped	D: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Required	E: Settling, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	H: Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required	K: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant	L: Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Dumped Coolant	N: Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped	O: Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped	P: Capillary Device Turbopump Subcooling, Cooled Duct, Coolant Dumped
1. Capillary Device	LH_2								92 (202)	92 (202)	92 (202)
	LO_2								22 (48)	22 (48)	22 (48)
2. Pressurization				41 (90)	41 (90)	94 (207)			41 (90)	41 (90)	41 (90)
3. Propellant Supply Duct	LH_2			18 (40)	18 (40)	18 (40)			18 (40)	18 (40)	18 (40)
	LO_2			14 (31)	14 (31)	14 (31)			14 (31)	14 (31)	14 (31)
4. Hardware to Keep Ducts Wet	LH_2			-	-	-			-	16 (35)	16 (35)
	LO_2			-	-	-			-	9 (19)	9 (19)
5. Subcooler	LH_2			14 (30)	14 (30)	-			14 (30)	14 (30)	14 (30)
	LO_2			27 (60)	27 (60)	-			27 (60)	27 (60)	27 (60)
6. Boost Pump	LH_2			-	-	-			-	-	-
	LO_2			-	-	-			-	-	-
7. Settling System				35 (77)	35 (77)	35 (77)			-	-	-
8. Sump Assembly	LH_2			3 (7)	3 (7)	3 (7)			3 (7)	3 (7)	3 (7)
	LO_2			7 (15)	7 (15)	7 (15)			7 (15)	7 (15)	7 (15)
9. Coolant Pumping System	LH_2			8 (17)	-	-			-	8 (18)	-
	LO_2			9 (19)	-	-			-	10 (23)	-
10. Thrust Barrel Revisions				-	-	-			5 (11)	5 (11)	5 (11)
11. Other Hardware				-	-	-			5 (11)	5 (11)	5 (11)
12. Tank Skin Delta				28 (62)	28 (62)	28 (62)			28 (62)	28 (62)	28 (62)
				9 (20)	9 (20)	9 (20)			9 (20)	9 (20)	9 (20)
TOTALS				213 (468)	196 (432)	208 (459)			285 (627)	328 (722)	310 (681)

Table 4-31. Settling and Capillary Device Hardware Weight Comparison (Systems B & K)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m): Feed System B, Propulsive Settling	Feed System K, Capillary Device
RL10A-3-3	1	212 (468)	292 (645)
	2	212 (468)	292 (645)
	5	212 (468)	292 (645)

Note: Both contain boost pumps, coolant pumped.

Table 4-32. Settling and Capillary Device Hardware Weight Comparison (Systems E & N)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m): Feed System E, Propulsive Settling	Feed System N, Capillary Device
RL10 Cat 1	1	167 (377)	256 (562)
	2	139 (307)	228 (502)
	5	196 (432)	285 (627)
RL10A-3-3A	1	218 (481)	305 (673)
	2	236 (520)	323 (712)
	5	255 (562)	342 (754)
RL10A-3-3	1	266 (586)	364 (803)
	2	287 [illegible]2)	385 (849)
	5	321 (707)	419 (924)

Not[illegible] [illegible]pump subcooling, coolant dumped.

4-33. Boost Pump NPSP, Pressure Fed System and Thermal Subcooling System Hardware Weights Comparison (Systems A & B)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m): Feed System A, Pressure Fed Boost Pump	Feed System B, Thermally Subcooled Boost Pump
RL10A-3-3	1	226 (500)	212 (468)
	2	246 (543)	212 (468)
	5	299 (660)	212 (468)

Note: Boost pump thermal subcooling; coolant pumped back into the tank.

Table 4-34. Turbopump NPSP, Boost Pump System; Pressure Fed System and Thermal Subcooling System Hardware Weight Comparison (Systems B, D & H)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m): Feed System B, Boost pump for Turbopump NPSP	Feed System D, Thermal Subcooling for Turbopump NPSP	Feed System H, Pressurization for Turbopump NPSP
RL10 Cat 1	1		182 (399)	186 (411)
	2		155 (358)	211 (466)
	5		213 (468)	208 (459)*
RL10A-3-3A	1		235 (517)	515 (1135)
	2		253 (558)	483 (1065)*
	5		273 (602)	502 (1106)*
RL10A-3-3	1	212 (468)	289 (630)	
	2	212 (468)	308 (679)	
	5	212 (468)	343 (757)	

Note: Turbopump NPSP comparison; (all feed systems use propellant settling).
* H_1 used because H is not feasible.

Propellant duct cooling options M, N, O and P, shown in Table 4-35, illustrate that the lowest weight option, N, has an uncooled duct with other coolant dumped overboard. The highest hardware weight has cooled ducts with coolant pumped back into the tank. Concepts M and P are very close in hardware weight (uncooled duct with other coolant pumped versus cooled duct with coolant dumped).

Table 4-36 shows lower hardware weight for dumping boost pump thermal subcooler coolant versus pumping it back into the tank. Tables 4-37 and 4-38 show the same result for turbopump thermal subcooler coolant disposal. The weight of the coolant pumping system accounts for the added weight.

Table 4-39 shows that cryogenically stored pressurant with autogeneous steady state LH_2 pressurization is the lightest pressure fed system because of the lower weight cryo-bottles. (All increments are due to bottles and support hardware.)

4.4 RELATIVE RELIABILITY

Relative reliability for each of the ten concepts identified in Table 4-1 was determined by analyzing each major subsystem component to determine mean missions between failures (MMBF). Component features are similar to those presented in Reference 4-2, Appendix A. For pressure fed systems, not previously analyzed, component characteristics are as shown in Table 4-40 and Figure 4-1.

Elements used in determining the relative reliability of each candidate concept are identified in Figures 4-2 to 4-11.

Table 4-35. Propellant Duct Cooling Options, Hardware Weight Comparison (Systems N, O, P & M)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m)			
		Feed System N	Feed System O	Feed System P	Feed System M
		Uncooled Duct Coolant Dumped	Cooled Duct Coolant Pumped	Cooled Duct Coolant Dumped	Uncooled Duct Coolant Pumped
RL10 Cat 1	1	256 (562)	297 (651)	281 (616)	271 (597)
	2	228 (502)	271 (595)	253 (556)	246 (541)
	5	285 (627)	328 (722)	310 (681)	303 (668)
RL10A-3-3A	1	305 (673)	343 (757)	326 (718)	323 (712)
	2	323 (712)	362 (799)	343 (757)	342 (754)
	5	342 (754)	383 (845)	362 (799)	363 (800)
RL10A-3-3	1	364 (803)	406 (898)	385 (851)	386 (850)
	2	385 (849)	429 (949)	406 (897)	409 (901)
	5	419 (924)	465 (1028)	440 (972)	445 (980)

Note: Propellant duct cooling options all have capillary devices and turbopump thermal subcoolers; M = N + Pumping System.

Table 4-36. Boost Pump Subcooler Coolant Disposal Hardware Weight Comparison (Systems K & L)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m)	
		Feed System K	Feed System L
		Coolant Pumped	Coolant Dumped
RL10A-3-3	1	292 (645)	281 (620)
	2	292 (645)	281 (620)
	5	292 (645)	281 (620)

Note: Coolant disposal from boost pump subcooling (capillary devices)

Table 4-37. Turbopump Thermal Subcooler Coolant Disposal Hardware Weight Comparison, Settling System (Systems D & E)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m)	
		Feed System D	Feed System E
		Coolant Pumped	Coolant Dumped
RL10Cat 1	1	182 (399)	167 (377)
	2	155 (358)	139 (307)
	5	213 (468)	196 (432)
RL10A-3-3A	1	235 (517)	218 (481)
	2	253 (556)	236 (520)
	5	273 (602)	255 (562)
RL10A-3-3	1	289 (630)	266 (586)
	2	308 (679)	287 (632)
	5	343 (757)	321 (707)

Note: Coolant disposal from turbopump thermal subcooling for settling systems.

Table 4-38. Turbopump Thermal Subcooling Coolant Pumped Versus Dumped Hardware Weight (Systems O & P)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties, kg (lb_m)	
		Feed System O	Feed System P
		Coolant Pumped	Coolant Dumped
RL10Cat 1	1	297 (651)	281 (616)
	2	271 (595)	253 (556)
	5	328 (722)	310 (681)
RL10A-3-3A	1	343 (757)	326 (718)
	2	362 (799)	343 (757)
	3	383 (845)	362 (799)
RL10A-3-3	1	406 (898)	385 (851)
	2	429 (949)	406 (897)
	5	465 (1028)	440 (972)

Note: Coolant disposal for turbopump subcooling with capillary devices.

Table 4-39. Pressurization System Options Hardware Weight Comparisons (Systems H, H_1 and H_2)

Engine Option	Mission (No. of Burns)	Hardware Weight Penalties (kg (lb_m))		
		Feed System H	Feed System H_1	Feed System H_2
		Autogenous LH_2 Tank Ambient Stored GHe	Autogenous LH_2 Tank Cryostored GHe	GHe for LH_2 Tank Cryostored GHe
RL10Cat 1	1	186 (411)	175 (380)	223 (492)
	2	211 (466)	169 (374)	230 (506)
	5	*	227 (501)	278 (612)
		Attributable to pressurization only.		
RL10 Cat 1	1	109 (241)	95 (209)	143 (314)
	2	134 (296)	89 (197)	149 (328)
	5	*	113 (249)	160 (352)

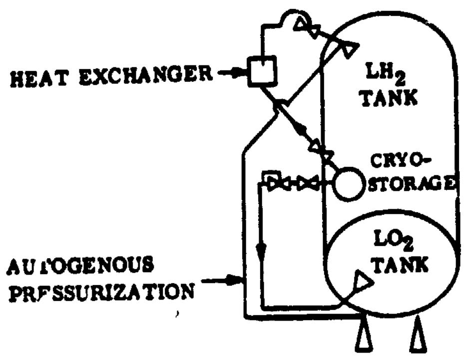
* Insufficient room for ambient stored bottles.

Table 4-40. Pressurization System Bottles for Pressure Fed Turbopumps

MISSION	RL10A-3-3A ENGINE	RL10 CATEGORY I ENGINE
ONE BURN	3 SMALL AMBIENT BOTTLES	1 LARGE AMBIENT BOTTLE +1 SMALL AMBIENT BOTTLE
TWO BURN	1 SMALL CRYOGENICALLY STORED BOTTLE +1 SMALL AMBIENT BOTTLE	1 LARGE AMBIENT BOTTLE +2 SMALL AMBIENT BOTTLES
FIVE BURN	2 LARGE CRYOGENICALLY STORED BOTTLES +1 SMALL AMBIENT BOTTLE	1 SMALL CRYOGENICALLY STORED BOTTLE +1 SMALL AMBIENT BOTTLE

Table 4-41. Mission Profile and Environment Summary

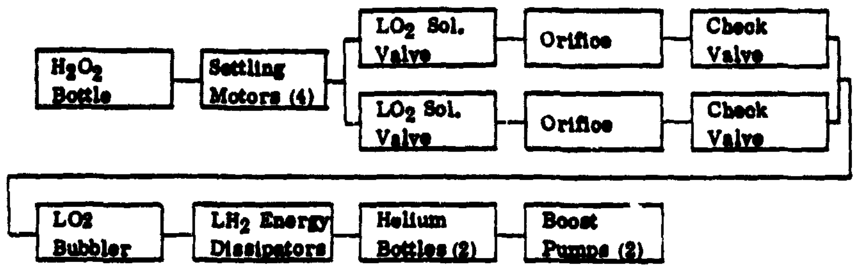
One Burn Mission Phase	Time, t (hr)	Env. Factor, K	Kt (hr)
Boost	0.18	50	9.00
Burn	0.123	20	2.46
Coast	0.814	1	0.814
	One Burn Kt =		12.27
Two Burn Mission Phase			
Boost	0.18	50	9.00
Burns	0.122	20	2.44
Coast	6.098	1	6.10
	Two Burn Kt =		17.54
Five Burn Mission Phase			
Boost	0.18	50	9.00
Burns	0.119	20	2.38
Coast	8.917	1	8.92
	Five Burn Kt =		20.30



HELIUM PRESSURE BOTTLES ARE STORED IN THE LIQUID HYDROGEN TANK. A HEAT EXCHANGER IS USED TO RAISE PRESSURANT TEMPERATURE TO USAGE LEVELS IN THE LH_2 TANK. COLD HELIUM IS USED FOR PRESSURIZING THE LO_2 TANK.

FOR SYSTEM H" CRYOGENIC HELIUM IS USED FOR ALL MAIN TANK PRESSURIZATION. FOR SYSTEM H AND H' THE HYDROGEN TANK IS AUTOGENEOUSLY PRESSURIZED AFTER THE INITIAL BURP WITH HELIUM.

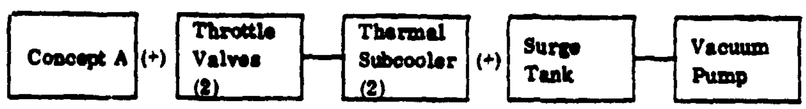
Figure 4-1. Cryogenically Stored Helium Pressurant



Failure Rates:

	λ		λ
Bottle (H_2O_2, He)	0.5×10^{-6}	Check Valve	3.5×10^{-6}
Settling Motor	5.0×10^{-6}	Bubbler, Dissipator	1.0×10^{-6}
Solenoid Valve	4.0×10^{-6}	Boost Pump	18.0×10^{-6}
Orifice	0.5×10^{-6}	Pressure Transducer	10×10^{-6}

Figure 4-2. Schematic and Failure Rates for Concept A (Settli... Pressurization, Boost Pump, Uncooled Duct, No Coolant Required)



Failure Rates:

	λ
Throttle Valve	3.5×10^{-6}
Thermal Subcooler	1.8×10^{-6}
Surge Tank	0.5×10^{-6}
Vacuum Pump	9.0×10^{-6}

Figure 4-3. Schematic and Failure Rates for Concept B (Settling, Thermal Subcooling, Boost Pumps, Uncooled Duct, Coolant Pumped)

Figure 4-4. Schematic for Concept D (Settling, Turbopump Subcooling, Uncooled Duct, Coolant Pumped)

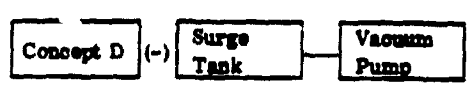


Figure 4-5. Schematic for Concept E (Settling, Turbopump, Subcooling, Uncooled Duct, Coolant Dumped)

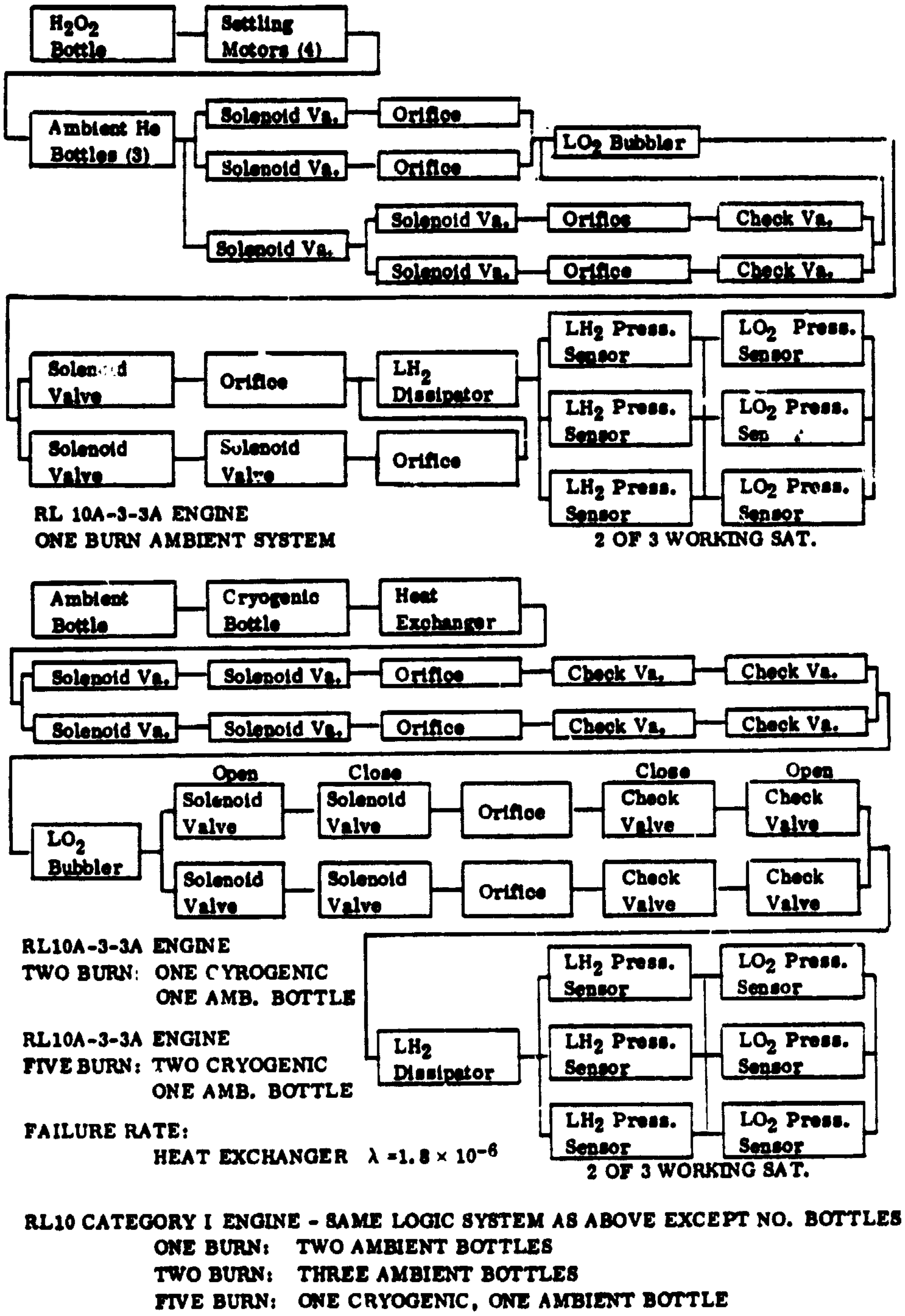
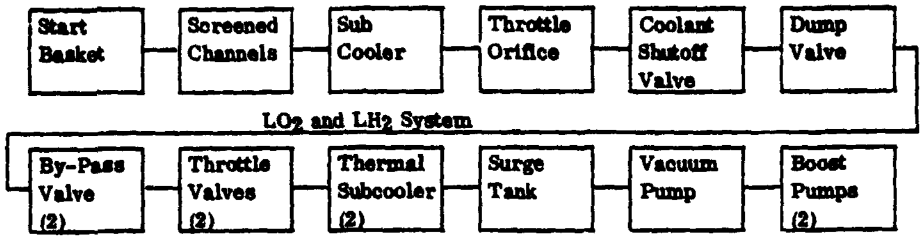


Figure 4-6. Schematic for Concept H (Settling, Pressure Fed Engine, Uncooled Duct, No Coolant Required)



Failure Rates:

	λ
Start Basket	1.4×10^{-6}
Screened Channels	1.4×10^{-6}
Subcooler Heat Exchanger	1.8×10^{-6}
Orifice	0.15×10^{-6}
Dump Valve/Shutoff Valve	5.0×10^{-6}
By-Pass Valve	4.0×10^{-6}

Figure 4-7. Schematic and Failure Rates for Concept K (Capillary Device, Thermal Subcooling, Boost Pump, Uncooled Duct, Pumped Coolant)

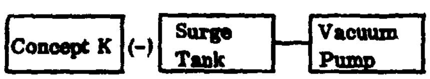


Figure 4-8. Schematic for Concept L (Capillary Device. Thermal Subcooling, Boost Pump, Uncooled Duct, Coolant Dumped)

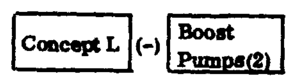


Figure 4-9. Schematic for Concept N (Capillary Device, Turbopump Subcooling, Uncooled Duct, Coolant Dumped)

Failure Rates:

	λ
Throttle Valve	15.0×10^{-6}
Shutoff Valve	5.0×10^{-6}
Cooling Coil	0.5×10^{-6}

Figure 4-10. Schematic and Failure Rates for Concept O (Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Pumped)

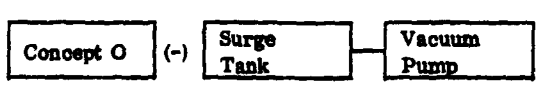


Figure 4-11. Schematic for Concept P (Capillary Device, Turbopump Subcooling, Cooled Duct, Coolant Dumped)

The reliability of any system is expressed by the equation

$$R = e^{-\lambda K t}$$

where

λ is the failure rate for a system component

Kt is the time-environment factor product

For the reliability of propellant feed systems the values of λ for the components are shown in Figure 4-2 to 4-11 below the concept schematics. The mission profiles considered were the one, two, and five burn missions for the Centaur D-1S vehicle. The Kt factors are shown in Table 4-41 where the environments of boost, main engine burn and coast are considered. The environmental factor K, a measure of the severity of the environment, was determined in an earlier Titan/Centaur-Viking (Ref. 4-5).

The analysis used Concept A as the baseline with other concepts evaluated as modifications to this concept. The results of the reliability analysis are summarized in Table 4-42 and indicate the reliability of the eleven concepts relative to each other. A second indicator is also shown, the mean number of missions between failures (MMBF) defined by ($1/\ln R$). Concept H has the highest reliability rating; this is achieved by replacing both boost pumps with a pressurization system for turbopump NPSP. The pressurization system has many components, as indicated in Figure 4-6, however reliability achieved by

Table 4-42. Comparison of Relative Reliability for Concept Under Study

Concept	One Burn		Two Burn		Five Burn	
	R*	MMBF**	R*	MMBF**	R*	MMBF**
A	0.999271	1371	0.998957	958	0.998792	827
B	0.999025	1025	0.998605	716	0.998384	618
D	0.999466	1872	0.999236	1308	0.999114	1128
E	0.999582	2392	0.999403	1675	0.999307	1443
H (RL10A-3-3A)	0.999670	3030	0.999503	2012	0.999415	1709
H (RL10-Cat I)	0.999676	3086	0.999524	2100	0.999425	1739
K	0.998853	871	0.998360	609	0.998101	526
L	0.998969	969	0.998527	678	0.998294	586
N	0.998528	679	0.997897	475	0.997564	410
O	0.997910	478	0.997013	334	0.996542	289
P	0.997927	482	0.997205	357	0.996734	306

* Reliability

** MMBF = mean missions between failure defined as $1/\ln R$.

parallel paths exceeds that of two boost pumps. The reliability of all acquisition systems is lower than that of all settling systems by relative reliabilities of 0.999712 versus 0.999540 for settling and acquisition components, respectively (single burn mission, Kt = 12.26). This is further illustrated by the comparison of systems B and K where the difference in settling versus acquistion accounts for a delta of 154 MMBF for a one-burn mission.

Other comparisons can be made on reliability of subsystems. Components in boost pump pressurization give it a reliability of 0.999559 versus boost pump thermal subcooling 0.999429 indicating the higher reliability without the throttle valve and thermal subcooler components. When considering turbopump NPSP, the boost pump alternative has a reliability of 0.999428 versus 0.999869 from the thermal subcooler without boost pump versus 0.999958 for pressurization, reflecting the high reliability of the latter system. Components added for a cooled propellant duct reduce the reliability by a factor of 0.999497. For coolant handling, pumping the coolant back into the tank reduces the reliability by the factor 0.999883 while dumping coolant overboard incurs no penalty.

Referring again to Table 4-42, the analysis shows that concept H using the Category 1 engine gives the highest reliability and MMBF, while Concept O will give the lowest. Concept H is a significant improvement over the baseline Concept A. Failure rates used in the analysis are from RADC Notebook RADC-TR-75-22 (Reference 4-6), and from Reference 4-2.

4.5 ELECTRICAL POWER CONSUMPTION

Electrical power consumption calculations were performed, and the results of this analysis are summarized in Tables 4-43, 4-44 and 4-45. Power consumption for the valves and sensors was neglected. The two main power requirements are for pumping cooling fluid back into the tank and for warming cryostored helium to usage temperature. Heat exchanger power requirements are relatively high. Table 4-43, for the RL10A-3-3 engine, shows that the highest power requirement is for the option that pumps turbopump thermal subcooling fluid and propellant duct cooling fluid back into the tanks (Concept O). This consumption is only slightly greater than Concepts D and M which only pump turbopump subcooler fluid back into the tank. Concepts B and K, pumping boost pump subcooler fluid back into the tank, have lower power consumption than the other concepts requiring electrical power. Concept H was not designed for the RL10A-3-3 engine. Concepts A, E, L, O and P do not require electrical power.

Table 4-44 for the RL10A-3-3A engine, shows that the highest power requirement is for the option that uses cryostored helium (Option H_1) and the associated heat exchanger to warm the pressurant. Option O, pumping turbopump thermal subcooling fluid and propellant duct cooling fluid back into the tank uses the next highest power requirement. This consumption is slightly greater than Concepts D and M which only pump turbopump subcooler fluid back into the tank. Concepts A, B, H_2, K and L were not designed for the

Table 4-43. System Power Consumption With RL10A-3-3 Engine

(Power in watt-hours)

Power Consumption Element	A	B	D	E	H	H_1	H_2	K	L	M	N	O	P
ONE-BURN MISSION													
Pumping Power - Coolant Return	-	28.98	503.04	-				28.98	-	503.04	-	507.50	-
Battery Power - Pressurant Heat Exchanger	-	-	-	-				-	-	-	-	-	-
Total Power Consumption	-	28.98	503.04	-				28.98	-	503.04	-	507.50	-
TWO-BURN MISSION													
Pumping Power - Coolant Return	-	30.11	649.92	-				30.11	-	649.92	-	692.30	-
Battery Power - Pressurant Heat Exchanger	-	-	-	-				-	-	-	-	-	-
Total Power Consumption	-	30.11	649.92	-				30.11	-	649.92	-	692.30	-
FIVE-BURN MISSION													
Pumping Power - Coolant Return	-	33.44	782.88	-				33.44	-	782.88	-	841.92	-
Battery Power - Pressurant Heat Exchanger	-	-	-	-				-	-	-	-	-	-
Total Power Consumption	-	33.44	782.88	-				33.44	-	782.88	-	841.92	-

Table 4-44. System Power Consumption With RL10A-3-3A Engine

(Power in watt-hours)

Power Consumption Element	A	B	D	E	H	H_1	H_2	K	L	M	N	O	P
ONE-BURN MISSION													
Pumping Power - Coolant Return			250.08	-	-	-	Not Analyz.			250.08	-	254.38	-
Battery Power - Pressurant Heat Exchanger			-	-	-	336	-			-	-	-	-
Total Power Consumption			250.08	-	-	336	-			250.08	-	254.38	-
TWO-BURN MISSION													
Pumping Power - Coolant Return			311.04	-	-	-	Not Analyz.			311.04	-	342.38	-
Battery Power - Pressurant Heat Exchanger			-	-	-	864	-			-	-	-	-
Total Power Consumption			311.04	-	-	864	-			311.04	-	342.38	-
FIVE-BURN MISSION													
Pumping Power - Coolant Return			406.08	-	-	-	Not Analyz.			406.08	-	449.76	-
Battery Power - Pressurant Heat Exchanger			-	-	-	2016	-			-	-	-	-
Total Power Consumption			406.08	-	-	2016	-			406.08	-	449.76	-

Table 4-45. System Power Consumption With RL10-Category I Engine

(Power in watt-hours)

Power Consumption Element	A	B	D	E	H	H_1	H_2	K	L	M	N	O	P
ONE-BURN MISSION													
Pumping Power - Coolant Return			161.76	-	-	-	-			161.76	-	165.98	-
Battery Power - Pressurant Heat Exchanger			-	-	-	248	2112			-	-	-	-
Total Power Consumption			161.76	-	-	248	2112			161.76	-	165.98	-
TWO-BURN MISSION													
Pumping Power - Coolant Return			215.04	-	-	-	-			215.04	-	244.8	-
Battery Power - Pressurant Heat Exchanger			-	-		864	2304			-	-	-	-
Total Power Consumption			215.04	-	-	864	2304			215.04	-	244.8	-
FIVE-BURN MISSION													
Pumping Power - Coolant Return			273.60	-	-	-	-			273.60	-	317.3	-
Battery Power - Pressurant Heat Exchanger			-	-	-	2016	2640			-	-	-	-
Total Power Consumption			273.6	-	-	2016	2640			273.6	-	317.3	-

RL10A-3-3A engine. Concepts E, H, N and P do not require electrical power.

For the RL10 Category I engine, Table 4-45 shows that the highest power requirement is for the option that uses helium pressurization for the LH_2 tank and cryostored helium (Option H2). This is followed by the option using autogeneous LH_2 tank pressurization and cryostored helium. Option O, pumping turbopump thermal subcooling flow and propellant duct cooling flow back into the tanks is the next highest in electrical power consumption. This consumption is slightly greater than that required for Option D, pumping only turbopump subcooled flow back into the tank. Options A, B, K and L were not designed for the RL10 Category I engine. Options E, H, N and P do not use electrical power.

4.6 MISSION PROFILE FLEXIBILITY

Mission profile flexibility assessments were made. For systems using settling, added start sequence time will be required to accomplish settling. This will have an impact on the existing mission profiles for the Centaur D-1S. Main engine firing with capillary devices can be initiated more quickly than with settling thrusters.

For other missions, capillary devices could have a limiting influence on minimum burn time and maximum time between burns. Minimum burn time, with a start basket capillary device is the required time (in excess of the start sequence) to settle and refill the start baskets under main engine thrust. Capillary device thermal conditioning requirements are directly determined from the maximum time between burns and are a factor in determining the capillary device volume. Large capillary device volumes are incompatible with short final burns because liquid level in the tank will be insufficient to allow the capillary device to refill. The considerations discussed in this paragraph have no bearing on Centaur D-1S mission profile flexibility and are presented only for general information and extrapolation to other missions and vehicles.

4.7 CONCLUSIONS AND RECOMMENDATIONS

For the Centaur D-1S, feed systems using capillary devices have the greatest mission profile flexibility. Feed systems having the lowest hardware weight are those using propellant settling and thermally subcooled boost pumps with coolant pumped back into the tank (Concept B). Feed systems having the lowest payload weight penalty are Concepts A and B. Concept A uses propellant settling and pressure fed boost pumps. For missions with significantly greater burns than those required by the Centaur D-1S vehicle, capillary device payload weight penalty will be less than that of propellant settling. Concepts with no electrical power consumption are Concepts A,E,L,N and P. The highest reliability concept is Concept H which utilizes pressure fed turbopumps.

The study shows that several areas are worthy of investigation depending on the direction taken by new vehicle design requirements. If high reliability is the major criteria, then pressure fed vehicles should be studied. If low payload penalty and low power consumption are most significant then the baseline Centaur D-1S using propellant settling and boost pumps (Concept A) is best. If low hardware weight is most important and missions of two burns or less are required (payload penalty is then also lowest) then propellant settling with thermal subcooling and coolant returned to the tank should be selected. For missions greater than five burns (approximately 10 burns), capillary devices are attractive (using thermally subcooled boost pumps with coolant returned to the tank, Concept K).

The study has shown that the baseline system is attractive and, under a specific set of assumptions, pressure fed turbopumps, thermally subcooled boost pumps with coolant pumped back into the tank and capillary devices are worthy of additional study.

5

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APPENDIX A

REFILLING PROGRAM DOCUMENTATION

A.1 PROGRAM CAPABILITY

Program REFILL predicts start basket refilling conditions as a function of vehicle and mission conditions, capillary device characteristics and engine requirements. A flow chart of the program is given in Figure 2-2. The program determines capillary device liquid level as a function of time. The analysis includes the effects of dynamic pressure, screen wicking, multiple screen barriers, window (standpipe) screens that can be of a different mesh than the main screens, time dependent liquid collection, and variable acceleration level due to changes in vehicle mass. Outflow from the tank is included either as an input or calculated based on feed system pressures. Vapor pullthrough height is accounted for as a function of tank outflow rate. Options are included for simulating spilling, wetted or dry standpipes and wicking between screen/plate barriers.

The following pages present a listing of the program and a sample input and output.

A.2 PROGRAM LISTING

The following pages give a brief description of the main program and each program subroutine followed by a listing of the corresponding program element.

Listings are presented for the following program elements:

<u>DRIVER PROGRAM</u>

REFILL

<u>SUBROUTINES</u>

DVCOL
FLOW
IMPOUT
INPUT
OUTFLOW
STAND
SWET
TIME
WRIT
DIAGNOS

PROGRAM REFILL

The main program serves as a driver for the flow subroutines after initializing boundary conditions for each time step. Flags for spilling, screen wetting, standpipe calculations, screen impingement, and outflow calculations are used to direct control to the appropriate subroutines. Vehicle acceleration level is calculated. Collected liquid height outside the basket is determined from tables. Impingement calculations for determining the dynamic pressure due to collected fluid velocity outside the start basket are performed. Pullthrough tables are used to determine if the liquid level in the basket has dropped below the point at which vapor will enter the channels. Liquid levels inside and outside the basket are calculated. Initial conditions for the first time step are determined and printed.

```
      PROGRAM REFILL(INPUT,TAPE5=INPUT,OUTPUT,TAPE6=OUTPUT)
C     PROGRAM COMPUTES START BASKET REFILLING UNDER VARIABLE DRIVING HEAD,
C  VARIABLE WETTING,VARIABLE DYNAMIC PRESSURE,MULTIPLE COMPARTMENTS,AND
C  MULTIPLE SCREEN BARRIERS
C
C  CALCULATED QUANTITIES-INTERMEDIATE
C
C     AL = AREA FOR LIQUID INFLOW,  FT2
C     ALI = AREA ADJACENT TO LIQUID INSIDE THE BASKET,FT2
C     ALO = AREA ADJACENT TO LIQUID OUTSIDE THE BASKET,FT2
C     AV = AREA FOR VAPOR OUTFLOW ACROSS UNWETTED SCREEN,    FT2
C     AVW= AREA FOR VAPOR OUTFLOW THROUGH WETTED SCREEN ADJACENT TO VAPOR, FT2
C     B= SPACING BETWEEN SCREEN BARRIERS,FT, IN SUBROUTINE SWET
C     CVOL(N)= COLLECTED VOLUME AT TC(N), FT3
C     DPIN= BASKET INTERNAL PRESSURE MINUS ULLAGE PRESSURE,PSF
C     DPS = MAXIMUM SURFACE TENSION DELTA P,PSF
C     DPS2=SURFACE TENSION PRESSURE DIFFERENTIAL FOR TOP SCREEN,PSF
C     G=AMBIENT ACCELERATION, FT/SEC2
C     HI=LIQUID LEVEL INSIDE BASKET, FT
C     HLEV=COMPUTED LIQUID LEVEL WHEN START BASKET AND TANK LEVEL ARE EQUAL,FT
C     HO=LIQUID LEVEL OUTSIDE BASKET, FT
C     HS = HEAD THAT CAN BE SUPPORTED BY SURFACE TENSION, FT
C     IFBAD =FLAG FOR INTERPOLATION CALCULATIONS. IFBAD=1 FOR GOOD EXIT,=2 BAD
C     QL = LIQUID VOLUME INFLOW RATE,   FT3/SEC
C     T = TIME, SEC
C     TVOL =TOTAL FLIUD VOLUME IN THE TANK DURING ONE TIME STEP,FT3,
C     VCL = COLLECTED VOLUME AT A GIVEN TIME STEP,FT3
C     VCL1= COLLECTED VOLUME FROM CURRENT TIME STOP,FT3
C     VCL2= COLLECTED VOLUME FROM LAST TIME STEP,FT3
C     VIL=LIQUID VOLUME INSIDE THE START BASKET AT START OF TIME STEP,FT3
C     VOL=LIQUID VOLUME OUTSIDE START BASKET AT START OF TIME STEP,FT3
C     VOREF = VOLUME FLOW INTO THE BASKET DURING THE LAST ITERATION,FT3
C     VV  = VAPOR INFLOW VELOCITY ACROSS UNWETTED SCREEN, FT/SEC
C     WT= WETTED HEIGHT OF SCREEN
C
      COMMON/FLOW/AL1,AL2,AV1,AV2,CONVERG,CONV1,CONV2,DPIN1,DPIN2,HOL1,
     1HOL2,NITER
      COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
      COMMON/IMPOUT/CVOL,DPS,HDPIN,HPULL,VOL
      COMMON/INFILL/CVI(20),DBP,DBP2,HCOL(20),HPT(10),J,K,MPROP,MR,MVEH,
     1N,NG,NS,NSP,QOUT(10),TC(20),THRST,TIM(20),TITLE(7),VILI,VTOT(20)
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/TIME/HTOL,TMAX
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      REAL KC,MPROP,MR,MVEH
C     JUMP IS A VARIABLE USED TO RESTART NEW CASES                      MHB10/77
      ASSIGN 10 TO JUMP
```

```
   10 CALL INPUT
      ADL=AL=AV=AVL=AVT=AVW=CONV1=CONV2=DPIN=DPIN1=DPIN2=HDYN=HLEV=
     1QL=QO=T=VCL=VILMAX=VL=VO=VOLOUT=VOREF=VT=VV=VVL=VVW=WT=0
      WRITE(6,20) (TITLE(L),L=1,7)
   20 FORMAT(1H1,7A10)
      IF(NS.LE.1) GO TO 30
      A=NS*A*0.95
      B=NS*B*0.95
      Y=NS*Y*0.95
      Z=NS*Z*0.95
C     INITIALIZED BASKET HEIGHT *****************************************MHB10/77
   30 CALL TABL(VILI,HI,VOLI(1),HT(1),1,1,1,I,IFBAD)
      VIL=VILI
      CALL TABL(T,HO,TC(1),HCOL(1),1,1,1,N,IFBAD)
      CALL TABL(HO,VCL1,HT(1),VOLO(1),1,1,1,I,IFBAD)
      VOL=VCL1
      IF(NSP.EQ.0.OR.HI.LT.HO) GO TO 40
      VILI=VILI+VCL1
      CALL TABL(VILI,HLEV,VTOT(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(HLEV,VOL,HT(1),VOLO(1),1,1,1,I,IFBAD)
      CALL TABL(HLEV,VIL,HT(1),VOLI(1),1,1,1,I,IFBAD)
      HO=HLEV
      HI=HLEV
   40 WRITE(6,50) T,HO,HI
   50 FORMAT(*  INITIAL CONDITIONS,  TIME =*F8.4*SEC,  TANK LIQUID LEVEL
     1 =*F8.4*FT,  BASKET LIQUID LEVEL =*F8.4*FT*)
      CALL TABL(HCOL(K),CVOL,HT(1),VOLO(1),1,1,1,I,IFBAD)
      DPS=SIGMA*2.72*3.048E05/DBP
      IF(DBP2.EQ.0.)DBP2=DBP
      DPS2=SIGMA*2.72*3.048E05/DBP2                                      MHB10/77
      IF(NDR.EQ.1) DPS2=0
      GO TO 120
  100 T=T+DT
      VCL2=VCL1
      CALL TABL(T,HO,TC(1),HCOL(1),1,1,1,N,IFBAD)
      CALL TABL(HO,VCL1,HT(1),VOLO(1),1,1,1,I,IFBAD)
      VCL=VCL1-VCL2
      TVOL=VOL+VIL
C     CALCULATION TO DETERMINE LIQUID LEVEL OUTSIDE AND INSIDE BASKET IFMHB10/77
C     LEVELS ARE EQUAL **************************************************MHB10/77
      CALL TABL(TVOL,HLEV,VTOT(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(HLEV,VIL1,HT(1),VOLI(1),1,1,1,I,IFBAD)
      CALL TABL(HLEV,VOL1,HT(1),VOLO(1),1,1,1,I,IFBAD)
      CALL TABL(HTOT,VTOP,HT(1),VTOT(1),1,1,1,I,IFBAD)
      VOLMAX=VOL-VOL1
      IF(VOLMAX.LT.VOL-VTOP) VOLMAX=VOL-VTOP
      IF(VOREF.GT.VOLMAX) VOREF=VOLMAX
      VILMAX=VIL1-VIL
C     CALCULATIONS IF LIQUID HAS BEEN COLLECTED OUTSIDE BASKET *********MHB10/77
      IF(VOREF.GT.VILMAX+VOLOUT) VOREF=VILMAX+VOLOUT
      VIL=VIL+VOREF-VOLOUT
      VOL=VOL+VCL
      IF(VOL.LT.0.)VOL=0.
      IF(VIL.LT.0.)VIL=0.
      CALL TABL(VOL,HO,VOLO(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(VIL,HI,VOLI(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(QP,HPULL,QOUT(1),HPT(1),1,1,1,J,IFBAD)
      IF((NOUT.NE.0).A.(HI.LT.HPULL))GO TO 3007
      IF(NITER.GT.10)CALL DIAGNOS
      CALL TIME
      IF(T.GE.TMAX) GO TO 10
  120 IF(NIM.EQ.0)GO TO 103
      CALL TABL(T,VJ,TIM(1),CVI(1),1,1,1,NIM,IFBAD)
      F=2.
      BK=4.
C     VO IS THE IMPINGEMENT VELOCITY CALCULATED FROM SYMON=S CORRELATION********
      VO=(-F*BK*A+SQRT((F*BK*A)**2+4.*(RHOL*VJ**2)*(F*BK*B+RHOL*BK)))/(2
     1.*(F*BK*B+RHOL*BK))
  103 IF(NG.EQ.1) GO TO 150
      MPROP=MPROP-QP*RHOL*DT
      G=32.17*THRST/(MVEH+MPROP*(1+MR))
```

```
 150 HS=32.17*DPS/(G*RHOL)
     HX=HS
     IF(NST.NE.0) HX=32.17*DPS2/(G*RHOL)
     IF(HO.GT.HTOT)HO=HTOT
C    SELECTION OF WETTING CALCULATIONS *******************************MHB10/77
     IF(NW.EQ.1)WT=HO
     IF(NW.EQ.2)WT=HTOT
     IF(NW.EQ.3)CALL SWET
C    OUTER LIQUID BELOW TOP OF BASKET AND EQUAL TO WETTED HEIGHT ******MHB10/77
     IF(HO.EQ.WT.A.HO.LT.HTOT)GO TO 300
C    OUTER LIQUID   AT  TOP OF BASKET AND EQUAL TO WETTED HEIGHT ******MHB10/77
     IF(HO.EQ.WT.A.HO.EQ.HTOT)GO TO 340
C    WETTED HEIGHT GREATER THAN LIQUID LEVEL AND BELOW TOP OF BASKET***MHB10/77
     IF(WT.GT.HO.A.HO.LT.HTOT)GO TO 350
C    WETTED HEIGHT GREATER THAN LIQUID LEVEL AND EQUAL TO BASKET HEIGHTMHB10/77
     IF(WT.GT.HO.A.WT.GE.HTOT)GO TO 345
     WRITE(6,200)HO,WT,HTOT
 200 FORMAT(* ERROR IN COMPUTING HEIGHTS,HO=*F10.7,* WT=*F10.7,* HTOT=*
    1F10.7)
     GO TO 10
C  CASE1 ****  HO.LT.HTOT    HO.EQ.WT    ****                      ****
 300 CALL TABL(HO,ALO,HT(1),AREA(1),1,1,1,I,IFBAD)
     CALL TABL(HI,ALI,HT(1),AREA(1),1,1,1,I,IFBAD)
     IF(NOUT.NE.0)GO TO 350
     AL=ALO-ALI
     AV=ATOT-ALO
     IF(NIM.NE.0) CALL DVCOL
     IF(NIM.NE.0)GO TO 100
     IF(HO.GT.HI) CALL FLOW
     IF(HO.LE.HI) VV=0.0
     QL=AV*VV*OA
     DPIN=A*VV+B*VV**2
     HDPIN=DPIN*32.2/(RHOL*G)
     IF(HDPIN.GT.(HO-HI)/10.)GO TO 350
     VOREF=QL*DT
     IF(VOREF.GE.VILMAX)GO TO 100
     CALL  DVCOL
     GO TO 100
 340 AVW=0.0
 345 AV=0.0
 350 IF(NIM.NE.0) CALL DVCOL
     IF(NIM.NE.0)GO TO 100
     CALL FLOW
     GO TO 100
3007 WRITE(6,3017)HPULL
3017 FORMAT(*  PULLTHROUGH OCCURRED,HPULL=*F9.5)
     GO TO 10
     END
```

SUBROUTINE DVCOL

Subroutine DVCOL calculates flow when liquid level inside and outside the start basket are unequal at the end of the time step and net refilling occurs. Screen impingement calculations are included in the pressure balances. Standpipe areas are included in the calculation. Convergence calculations are performed.

```
      SUBROUTINE DVCOL
C     CALCULATIONS WHEN LIQUID LEVEL INSIDE AND OUTSIDE THE START BASKET ARE
C     UNEQUAL AT THE END OF THE TIME STEP AND REFILLING OCCURS *********MHB10/77
C     DVCOL=SUBROUTINE TO  COMPUTE FINAL HEAD WHEN VOREF.LT.VILMAX
C     AV1  = INITIAL UNWETTED VAPOR FLOW AREA,FT2
C     AV2  = FINAL UNWETTED VAPOR FLOW AREA,FT2
C     CONV1= CONVERGENCE VARIABLE FOR CONTINUITY EQUATION-CURRENT ITERATION
C     CONV2= CONVERGENCE VARIABLE FOR CONTINUITY EQUATION-LAST ITERATION
C     CONVERG= CONVERGENCE VARIABLE THAT MUST BE WITHIN ZERO +OR-RANGE
C     DPIN1= STORAGE FOR CURRENT DELTA P ITERATION
C     DPIN2= STORAGE FOR CURRENT DELTA P ITERATION
C     DPIN = PRESSURE DIFFERENCE OF GAS INSIDE AND OUTSIDE BASKET ******
C     FOR FLOW AND DVCOL,DPIN MUST BE POSITIVE AND THE GAS PRESSURE INSIDE
C     THE BASKET EXCEEDS THE PRESSURE OUTSIDE THE BASKET **************
C     HAL1 = INITIAL DISTANCE FOR LIQUID INFLOW,FT
C     HAL2 = FINAL DISTANCE FOR LIQUID INFLOW,FT
C     HAVL1= INITIAL DISTANCE FOR VAPOR FLOW INTO LIQUID,FT
C     HAVL2= FINAL DISTANCE FOR VAPOR FLOW INTO LIQUID,FT
C     HAVW1= INITIAL DISTANCE FOR VAPOR FLOW ACROSS WETTED SCREEN,FT
C     HAVW2= FINAL DISTANCE FOR VAPOR FLOW ACROSS WETTED SCREEN,FT
C     NITER =ITERATION COUNTER
C     VOR1= STORAGE FOR VOREF
C     WT1,WT2=WETTING PARAMETERS AT START AND END OF TIME STEP
      COMMON/FLOW/AL1,AL2,AV1,AV2,CONVERG,CONV1,CONV2,DPIN1,DPIN2,HOL1,
     1HOL2,NITER
      COMMON/DVCOL/AST,A2,B2,RANGE
      COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
      COMMON/IMPOUT/CVOL,DPS,HDPIN,HPULL,VOL
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/STAND/AVLR,AVR,AVWR
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      REAL KC
      WRITE(6,5)
    5 FORMAT(*                SUBROUTINE DVCOL*)
      NITER=0
      IF(NOUT.NE.0) DPIN=0.001
   10 VOR1=VOREF
      IF(NOUT.EQ.0)VOLOUT=0.
      VILX2=VIL+VOREF-VOLOUT
      VOLX2=VOL-VOREF
  200 CALL TABL(VIL,HIL1,VOLI(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(VOL,HOL1,VOLO(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(VILX2,HIL2,VOLI(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(VOLX2,HOL2,VOLO(1),HT(1),1,1,1,I,IFBAD)
      IF(HIL2.GE.HTOT)HIL2=HTOT
      IF(HOL2.GE.HTOT)HOL2=HTOT
      IF(HOL1.GE.HTOT)HOL1=HTOT
      CALL TABL(HOL1,AVLT1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HOL2,AVLT2,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HIL1,AVT1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HIL2,AVT2,HT(1),AREA(1),1,1,1,I,IFBAD)
C     AREA AND LIQUID LEVEL CALCULATIONS ******************************MHB10/77
      AVT=(AVT1+AVT2)/2.
```

```
      HO=HOL2
C     SELECTION OF WETTING CALCULATIONS ********************************MHB10/77
      IF(NW.EQ.1)WT=HO
      IF(NW.EQ.2)WT=HTOT
      IF(NW.EQ.3)CALL SWET
      WT2=WT
      HO=HOL1
      IF(NW.EQ.1)WT=HO
      IF(NW.EQ.2)WT=HTOT
      IF(NW.EQ.3)CALL SWET
      WT1=WT
      CALL TABL(WT1,AVWT1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(WT2,AVWT2,HT(1),AREA(1),1,1,1,I,IFBAD)
      AV1=ATOT-AVWT1
      AV2=ATOT-AVWT2
   20 CONTINUE
      HDPIN=DPIN*32.2/(RHOL*G)
      IF(NIM.NE.0) GO TO 1
      HAVL1=HIL1+HS
      HAVL2=HIL2+HS
      GO TO 11
    1 CONTINUE
C     ROUTINE CALCULATES BASKET REFILLING,SIMILAR TO DVCOL- LIQUID LEVELMHB10/77
C     INSIDE AND OUTSIDE THE BASKET UNEQUAL AFTER A TIME STEP - NET     MHB10/77
C     REFILLING OCCURS. VAPOR OUTFLOW TO ALLOW LIQUID TO ENTER**********MHB10/77
C     DYNAMIC PRESSURE CALCULATED FROM IMPINGEMENT VELOCITY ************MHB10/77
      WRITE(6,6)
    6 FORMAT(*            IMPINGE*)
C     DYNAMIC PRESSURE CALCULATED FROM IMPINGEMENT VELOCITY ************MHB10/77
      DPDYN=A*VO+B*VO**2
      HDYN=DPDYN*32.2/(RHOL*G)
      HAVL1=HIL1+HS+HDYN
      HAVL2=HIL2+HS+HDYN
   11 IF(HAVL1.GT.HOL1)HAVL1=HOL1
      IF(HAVL2.GT.HOL2)HAVL2=HOL2
      HAL1=HOL1-HDPIN
      HAL2=HOL2-HDPIN
      CALL TABL(HAVL1,AVL1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HAVL2,AVL2,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HAL1,AL1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HAL2,AL2,HT(1),AREA(1),1,1,1,I,IFBAD)
      AVW1=AVWT1-AVLT1
      AVW2=AVWT2-AVLT2
      AL1=AL1-AVT1
      IF(AL1.LT.0) AL1=0
      AL2=AL2-AVT2
      IF(AL2.LT.0) AL2=0
      AVL1=AVLT1-AVL1
      AVL2=AVLT2-AVL2
      IF(AVL1.LT.0.)AVL1=0.
      IF(AVL2.LT.0.)AVL2=0.
      IF(NIM.EQ.0) GO TO 2
      HADL1=HIL1+HDPIN-HDYN
      HADL2=HIL2+HDPIN-HDYN
      IF(HADL1.GT.HIL1)HADL1=HIL1
      IF(HADL2.GT.HIL2)HADL2=HIL1
      IF(HADL1.LT.0)HADL1=0.
      IF(HADL2.LT.0)HADL2=0.
      CALL TABL(HADL1,ADL1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HADL2,ADL2,HT(1),AREA(1),1,1,1,I,IFBAD)
      ADL3=AVT1-ADL1
      ADL4=AVT2-ADL2
      ADL1=ADL3/2.+AVLT1-AVT1
      ADL2=ADL4/2.+AVLT2-AVT2
      IF(ADL1.LT.0.)ADL1=0.
      IF(ADL2.LT.0.)ADL2=0.
      ADL=(ADL1+ADL2)/2.
    2 CONTINUE
      AV=(AV1+AV2)/2.
      AVW=(AVW1+AVW2)/2.
      AVL=(AVL1+AVL2)/2.
      AL =(AL1+AL2)/2.
      IF(DPIN.LE.0.0)VV=VVS=0.0
```

```
C     VAPOR FLOW ACROSS DRY SCREEN,OUT OF BASKET **********************MHB10/77
C     VVS =VAPOR VELOCITY FOR UNWETTED STANDPIPE             ***********MHB10/77
      IF(DPIN.GT.0.0.AND.NST.NE.0)VVS=(-A2+SQRT(A2**2+4*B2*DPIN))/(2*B2)
      IF(DPIN.GT.0.0)VV=(-A+SQRT(A**2+4*B*DPIN))/(2*B)
      IF(NIM.NE.0) GO TO 3
      IF(NST.EQ.0)GO TO 83                                          MHB10/77
      IF(DPIN-DPS2.LE.0.)GO TO 82
C     VVWS=VAPOR VELOCITY FOR WETTED  STANDPIPE              ***********MHB10/77
      VVWS=(-A2+SQRT(A2**2+4.*B2*(DPIN-DPS2)))/(2.*B2)              MHB10/77
C     VVLS=VAPOR VELOCITY FOR STANDPIPE SURROUNDED BY LIQUID    ********MHB10/77
      VVLS=(-A2+SQRT(A2**2+2.*B2*(DPIN-DPS2)))/(2.*B2)              MHB10/77
      GO TO 83                                                      MHB10/77
   82 VVWS=0.
   84 VVLS=0.
   83 CONTINUE                                                      MHB10/77
      IF(DPIN-DPS.LE.0.)GO TO 25
C     VAPOR FLOW ACROSS WETTED SCREEN INTO VAPOR,OUT OF BASKET*********MHB10/77
      VVW=(-A+SQRT(A**2+4.*B*(DPIN-DPS)))/(2.*B)
      VVL=(-A+SQRT(A**2+2.*B*(DPIN-DPS)))/(2.*B)
      GO TO 26
   25 VVW=0.
      VVL=0.
   26 CONTINUE
      GO TO 12
    3 CONTINUE
      IF(NST.EQ.0)GO TO 87
      IF(DPIN-DPS2.LE.0.)GO TO 86
C     VVWS=VAPOR VELOCITY FOR WETTED  STANDPIPE              ***********MHB10/77
      VVWS=(-A2+SQRT(A2**2+4.*B2*(DPIN-DPS2)))/(2.*B2)              MHB10/77
      GO TO 87
   86 VVWS=0.0
   87 CONTINUE
      IF(DPIN-DPS.LE.0.)GO TO 23
C     VAPOR FLOW ACROSS WETTED SCREEN INTO VAPOR,OUT OF BASKET*********MHB10/77
      VVW=(-A+SQRT(A**2+4.*B*(DPIN-DPS)))/(2.*B)
      GO TO 24
   23 VVW=0.0
   24 CONTINUE
      IF(DPIN-DPS-DPDYN.LE.0.)GO TO 27
C     VAPOR FLOW INTO LIQUID,OUT OF BASKET ***************************MHB10/77
C     DYNAMIC PRESSURE USED TO CALCULATE LIQUID AND VAPOR FLOW ********MHB10/77
      IF(NST.EQ.0)GO TO 85                                          MHB10/77
      IF(DPIN-DPS2-DPDYN.LE.0.)GO TO 88
C     VVLS=VAPOR VELOCITY FOR STANDPIPE SURROUNDED BY LIQUID    ********MHB10/77
      VVLS=(-A2+SQRT(A2**2+2.*B2*(DPIN-DPS2-DPDYN)))/(2.*B2)        MHB10/77
      GO TO 85
   88 VVLS=0.0
   85 CONTINUE                                                      MHB10/77
      VVL=(-A+SQRT(A**2+2.*B*(DPIN-DPS-DPDYN)))/(2.*B)
      GO TO 31
   27 VVL=0.
   31 CONTINUE
   12 CONTINUE
      HOPIN=2.*HDPIN
      IF(HOL1-HIL1+HOL2-HIL2-HOPIN.LE.0.)GO TO 28
C     LIQUID FLOW INTO VAPOR,INTO BASKET ******************************MHB10/77
      VL=(-Y+SQRT(Y**2+   Z*(HOL1-HIL1+HOL2-HIL2-2.*HDPIN)*RHOL*G/32.2))
     1/(2.*Z)
C     LIQUID FLOW INTO LIQUID.INTO BASKET *****************************MHB10/77
      VT=(-Y+SQRT(Y**2+2.*Z*(HOL1-HIL1+HOL2-HIL2-2.*HDPIN)*RHOL*G/32.2))
     1/(2.*Z)
      GO TO 29
   28 VL=0.
      VT=0.
   29 CONTINUE
C     **** CONVERGENCE CALCULATIONS  ***********************************
      DPIN1=DPIN
      IF(NST.EQ.0.AND.NIM.EQ.0) GO TO 93
      IF(NST.EQ.0.AND.NIM.NE.0) GO TO 103
      HI=(HIL1+HIL2)/2.
      CALL STAND
```

```
      IF(NIM.NE.0) GO TO 4
      CONVERG=AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS+AVLR*VVL+AVLS*VVLS-AL*VLMHB10/77
     1-AVT*VT                                                          MHB10/77
       CONVERG=CONVERG*2.
      QVO=AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS+AVLS*VVLS+AVLR*VVL
      GO TO 99                                                         MHB10/77
   93 CONTINUE                                                         MHB10/77
      CONVERG=(AV1+AV2)*VV+(AVW1+AVW2)*VVW+(AVL1+AVL2)*VVL-(AL1+AL2)*VL-
     1AVT*VT
      QVO=AV*VV+AVW*VVW+AVL*VVL
   99 CONTINUE                                                         MHB10/77
      QO=0.
      IF(NOUT.NE.0)CALL OUTFLOW
      QIN=VL*(AL1+AL2)*OA/2.+VT*AVT*OA
      QL=QIN
      GO TO 13
    4 CONTINUE
      CONVERG= AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS+AVLS*VVLS+AVLR*VVL-AL*VMHB11/77
     1L-ADL*VO-AVT*VT                                                  MHB10/77
      CONVERG=CONVERG*2.
      QVO=AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS+AVLS*VVLS+AVLR*VVL
      GO TO 98
  103 CONTINUE
      CONVERG=(AV1+AV2)*VV+(AVW1+AVW2)*VVW+(AVL1+AVL2)*VVL-(AL1+AL2)*VL
     1-(ADL1+ADL2)*VO-2.*AVT*VT
      QVO=AV*VV+AVW*VVW+AVL*VVL
   98 CONTINUE
      IF(NOUT.EQ.0)QO=0.
      IF(NOUT.NE.0)CALL OUTFLOW
      QIN=(ADL1+ADL2)*OA*VO+(AL1+AL2)*OA*VO+AVT*VT*OA
      QIN=QIN/2
   13 CONTINUE
      IF(NITER.GT.1)GO TO 73
      IF(QO.EQ.0.)GO TO 73
C     DETERMINES IF NET BASKET OUTFLOW EXISTS ************************MHB10/77
      IF(QO.GT.QIN)GO TO 71
   73 CONTINUE
      CONVERG=CONVERG*OA/2+QO
      CONV1=CONVERG
      IF(CONVERG.EQ.0..A.VL.EQ.0.)GO TO 35
      IF(ABS(CONVERG).LT.RANGE)GO TO 40
   35 CONTINUE
      IF(NITER.EQ.0)GO TO 30                                                  9
      IF(WT.LT.HTOT.OR.NDR.EQ.1) GO TO 36
      HCH=(HOL1+HOL2-HIL1-HIL2)/2.
      IF(HX.GE.HCH)GO TO 37
   36 CONTINUE
      IF(NITER.GE.75)GO TO 300
      IF(CONV1.EQ.CONV2)GO TO 30
      NITER=NITER+1
      IF(NITER.GT.10)CALL DIAGNOS
      DPIN=(DPIN2*CONV1-DPIN1*CONV2)/(CONV1-CONV2)
      HDPIN=DPIN*32.2/RHOL/G
      IF(NW.EQ.2.AND.NDR.NE.1) GO TO 43
      IF(WT.GE.HTOT.AND.NDR.NE.1) GO TO 43
      IF(AVS.NE.0) GO TO 41
   43 CONTINUE
      HOPIN=HDPIN*2.
      IF(HOPIN.GT.(HOL1-HIL1+HOL2-HIL2))HOPIN=HOL1-HIL1+HOL2-HIL2-(HOL1-
     1HIL1+HOL2-HIL2-HX)/(NITER*10000)
      HDPIN=HOPIN/2.
      IF(HDPIN.LE.HX)HDPIN=HX+(HOL1-HIL1+HOL2- HIL2-HX)/(NITER*10000)
      GO TO 42
   41 IF(DPIN.LE.0.)HDPIN=1./(NITER*10)
   42 CONTINUE
      DPIN=HDPIN*RHOL*G/32.2
      CONV2=CONV1
      DPIN2=DPIN1
      GO TO 20
```

```
   30 DPIN2=DPIN1
      CONV2=CONV1
      NITER=NITER+1
      IF(NITER.GT.10)CALL DIAGNOS
      DPIN=DPIN/2.
      HDPIN=DPIN*32.2/(RHOL*G)
      IF(NITER.EQ.1.A.WT.GE.HTOT.A.HX.NE.0.)HDPIN=HX
      DPIN=HDPIN*RHOL*G/32.2
      GO TO 20
   40 CONTINUE
C     ***  OUTFLOW RATE CALCULATION  **********************************
      IF(NIM.NE.0) GO TO 7
      QL=(AL1+AL2)/2.*VL*OA+VT*AVT*OA
      VOREF=QL*DT
      GO TO 14
    7 CONTINUE
      QL=(AL1+AL2)/2.*VL*OA+(ADL1+ADL2)/2.*VO*OA+VT*AVT*OA
      VOREF=QL*DT
        IF(NOUT.NE.0)CALL OUTFLOW
   14 CONTINUE
      IF(ABS(VOREF-VOR1).LE.RANGE)GO TO 72
      VOREF=(VOREF+VOR1)/2.
      IF(NITER.GT.10)CALL DIAGNOS
      GO TO 10
   37 IF(NOUT.NE.0)GO TO 71
       WRITE(6,38)
   38 FORMAT(*    HS IS GREATER THAN HOL1-HIL1+HOL2-HIL2, NO SOLUTION FO
     1R HDPIN*)
      VOREF=0.
      IF(VOLOUT.NE.0.)GO TO 72
      IF((HOL1.LT.HTOT).A.(VOL+VIL.LT.CVOL))GO TO 72
C     GO TO JUMP,TRANSFER CONTROL TO MAIN PROGRAM-STATEMENT 10, IN ORDERMHB10/77
C     TO RESTART A NEW CASE ******************************************MHB10/77
      GO TO JUMP,(20)
  301 FORMAT(*  TOO MANY ITERATIONS IN SUBROUTINE DVCOL *)
  300 WRITE(6,301)
      GO TO JUMP,(20)
   71 CALL IMPOUT
   72 RETURN
      END
```

SUBROUTINE FLOW

Subroutine FLOW calculates flow when the liquid level inside and outside the basket are equal at the end of the time step. (Generally, subroutine FLOW would only be used if collection was complete, the screens surrounded by vapor were dry, or the flow rate across screens was relatively high considering the time step.) Net refilling occurs. Dynamic pressure (screen impingement) effects are not included. Standpipe areas are included in the calculation. Convergence calculations are performed.

```
      SUBROUTINE FLOW
C     CALCULATIONS WHEN LIQUID LEVEL INSIDE AND OUTSIDE THE START BASKET ARE
C     EQUAL AT THE END OF THE TIME STEP AND REFILLING OCCURS ***********MHB10/77
C     CONV1= CONVERGENCE VARIABLE FOR CONTINUITY EQUATION- CURRENT ITERATION
C     CONV2= CONVERGENCE VARIABLE FOR CONTINUITY EQUATION- LAST ITERATION
C     CONVERG=CONVERGENCE VARIABLE FOR CONTINUITY EQUATION,ZERO REQUIRED
C     DPIN1= STORAGE FOR CURRENT DELTA P ITERATION
C     DPIN2= STORAGE FOR LAST DELTA P ITERATION
C     FOR FLOW AND DVCOL,DPIN MUST BE POSITIVE AND THE GAS PRESSURE INSIDE
C     THE BASKET EXCEEDS THE PRESSURE OUTSIDE THE BASKET ***************
C     HAL = HEIGHT WHERE LIQUID INFLOW OCCURS,FT
C     HAVL= HEIGHT WHERE VAPOR FLOWS ACROSS SCREEN SURROUNDED BY LIQUID,FT
C     HAVW= HEIGHT WHERE VAPOR  FLOW OCCURS ACROSS WETTED SCREEN,FT
C     NITER =ITERATION COUNTER
      COMMON/DVCOL/AST,A2,B2,RANGE
      COMMON/FLOW/AL1,AL2,AV1,AV2,CONVERG,CONV1,CONV2,DPIN1,DPIN2,HOL1,
     1HOL2,NITER
      COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
      COMMON/IMPOUT/CVOL,DPS,HDPIN,HPULL,VOL
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/STAND/AVLR,AVR,AVWR
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      REAL KC
      WRITE(6,5)
    5 FORMAT(*                 SUBROUTINE FLOW*)
      NITER=0
      IF(NOUT.NE.0)DPIN=0.001
      IF(DPIN.EQ.0.)DPIN=0.5*(HO-HI)/32.2*G*RHOL
      HDPIN=DPIN*32.2/(RHOL*G)
C     AREA AND LIQUID LEVEL CALCULATIONS ******************************MHB10/77
   10 CALL TABL(WT,AVWT,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HO,AVLT,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HI,AVT,HT(1),AREA(1),1,1,1,I,IFBAD)
      AV=ATOT-AVWT
      AVW=AVWT-AVLT
   20 CONTINUE
      HAVL=HI+HS
      IF(HAVL.GT.HO)HAVL=HO
      HAL=HO-HDPIN
      CALL TABL(HAVL,AVL,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HAL,AL,HT(1),AREA(1),1,1,1,I,IFBAD)
      AL=AL-AVT
      AVL=AVLT-AVL
      IF(HS.GE.HDPIN)AVL=0.
      IF(AL.LT.0.)AL=0.
      HDPIN=DPIN*32.2/(RHOL*G)
      IF(DPIN.LE.0.)GO TO 21
      IF(AV.EQ.0.)GO TO 21
      IF(NST.EQ.0)GO TO 80                                              MHB10/77
C     VVS =VAPOR VELOCITY FOR UNWETTED STANDPIPE             ***********MHB10/77
      VVS=(-A2+SQRT(A2**2+4.*B2*(DPIN)))/(2.*B2)                        MHB10/77
   80 CONTINUE                                                          MHB10/77
C     VAPOR FLOW ACROSS DRY SCREEN,OUT OF BASKET *********************MHB10/77
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```
      VV=(-A+SQRT(A**2+4.*B*(DPIN)))/(2.*B)
      GO TO 22
   21 VV=0.
      VVS=0.
   22 CONTINUE
      IF(NST.EQ.0)GO TO 83                                              MHB10/77
      IF(DPIN-DPS2.LE.0.)GO TO 82
C     VVWS=VAPOR VELOCITY FOR WETTED  STANDPIPE             ***********MHB10/77
      VVWS=(-A2+SQRT(A2**2+4.*B2*(DPIN-DPS2)))/(2.*B2)                  MHB10/77
C     VVLS=VAPOR VELOCITY FOR STANDPIPE SURROUNDED BY LIQUID    *******MHB10/77
      VVLS=(-A2+SQRT(A2**2+2.*B2*(DPIN-DPS2)))/(2.*B2)                  MHB10/77
      GO TO 83                                                          MHB10/77
   82 VVWS=0.
   84 VVLS=0.
   83 CONTINUE                                                          MHB10/77
      IF(DPIN-DPS.LE.0.)GO TO 25
C     VAPOR FLOW ACROSS WETTED SCREEN INTO VAPOR,OUT OF BASKET*********MHB10/77
      VVW=(-A+SQRT(A**2+4.*B*(DPIN-DPS)))/(2.*B)
      IF(AVW.EQ.0.)VVW=0.
C     VAPOR FLOW INTO LIQUID,OUT OF BASKET ****************************MHB10/77
      VVL=(-A+SQRT(A**2+2.*B*(DPIN-DPS)))/(2.*B)
      GO TO 26
   25 VVW=0.
      VVL=0.
   26 CONTINUE
      IF(HO-HI-HDPIN.LE.0.)GO TO 28
C     LIQUID FLOW INTO VAPOR,INTO BASKET ******************************MHB10/77
      VL=(-Y+SQRT(Y**2+2.*Z*(HO-HI-HDPIN)*RHOL*G/32.2))/(2.*Z)
C     LIQUID FLOW INTO LIQUID,INTO BASKET *****************************MHB10/77
      VT=(-Y+SQRT(Y**2+4.*Z*(HO-HI-HDPIN)*RHOL*G/32.2))/(2.*Z)
      GO TO 29
   28 VL=0.
      VT=0.
   29 CONTINUE
C     **** CONVERGENCE CALCULATIONS  *********************************
      DPIN1=DPIN
      IF(NST.EQ.0)GO TO 93                                              MHB10/77
      CALL STAND
      CONVERG=AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS+AVLR*VVL+AVLS*VVLS-AL*VLMHB10/77
     1-AVT*VT                                                           MHB10/77
      QVO=AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS+AVLS*VVLS+AVLR*VVL
      GO TO 99                                                          MHB10/77
   93 CONTINUE                                                          MHB10/77
      CONVERG=AV*VV+AVW*VVW+AVL*VVL-AL*VL-VT*AVT
      QVO=AV*VV+AVW*VVW+AVL*VVL
   99 CONTINUE                                                          MHB10/77
      QO=0.
      IF(NOUT.NE.0)CALL OUTFLOW
      QIN=AL*VL*OA+OA*VT*AVT
      QL=QIN
      IF(NITER.GT.1)GO TO 72
      IF(QO.EQ.0.)GO TO 72
C     DETERMINES IF NET BASKET REFILL  EXISTS *************************MHB10/77
      IF(QO.GT.QIN)GO TO 71
C     NO VAPOR OUTFLOW ************************************************MHB10/77
   72 CONTINUE
      CONVERG=CONVERG*OA+QO

      CONV1=CONVERG
      IF(ABS(CONVERG).LE.RANGE)GO TO 40
      IF(NITER.EQ.0)GO TO 30
      IF(WT.GE.HTOT.A.HX.GE.HO-HI)GO TO 37
      IF(NITER.GE.75)GO TO 300
      IF(CONV1.EQ.CONV2)GO TO 30
      NITER=NITER+1
      IF(NITER.GT.10)CALL DIAGNOS
      DPIN=(DPIN2*CONV1-DPIN1*CONV2)/(CONV1-CONV2)
      HDPIN=DPIN*32.2/(RHOL*G)
      IF(NW.EQ.2.AND.NDR.NE.1) GO TO 43
      IF(WT.GE.HTOT.AND.NDR.NE.1) GO TO 43
      IF(AV.NE.0.)GO TO 41
```

```
   43 CONTINUE
      IF(HDPIN.LE.HX)HDPIN=HX+(HO-HI-HX)/(NITER*100000)
      IF(HDPIN.GT.(HO-HI))HDPIN=(HO-HI)-(HO-HI-HX)/(NITER*10000)
      GO TO 42
   41 IF(DPIN.LE.0.)HDPIN=1./(NITER*10)
   42 CONTINUE
      IF(NITER.EQ.25.AND.ABS(HX-HDPIN).LT.HX/100) HDPIN=2*HDPIN
      DPIN=HDPIN*RHOL*G/32.2
      CONV2=CONV1
      DPIN2=DPIN1
      GO TO 20
   30 DPIN2=DPIN1
      CONV2=CONV1
      NITER=NITER+1
      IF(NITER.GT.10)CALL DIAGNOS
      DPIN=DPIN/2.
      HDPIN=DPIN*32.2/(RHOL*G)
      IF(NITER.EQ.1.A.WT.GE.HTOT.A.HX.NE.0.)HDPIN=HX
      DPIN=HDPIN*RHOL*G/32.2
      GO TO 20
   40 CONTINUE
C     ***  OUTFLOW RATE CALCULATION  **********************************
   60 QL=AL*VL*OA+AVT*VT*OA
      VOREF=QL*DT
      IF(NITER.GT.10)CALL DIAGNOS
      IF(VOREF.LT.VILMAX)GO TO 77
      GO TO 270
   77 CALL DVCOL
      GO TO 270
   37 IF(NOUT.NE.0)GO TO 71
       WRITE(6,38)
   38 FORMAT(*    HS IS GREATER THAN HO-HI, NO SOLUTION FOR HDPIN*)
      VOREF=0.
      IF((HO.LT.HTOT).A.(VOL+VIL.LT.CVOL))GO TO 270
      IF(VOLOUT.NE.0.)GO TO 270
C     GO TO JUMP,TRANSFER CONTROL TO MAIN PROGRAM-STATEMENT 10, IN ORDERMHB10/77
C     TO RESTART A NEW CASE *****************************************MHB10/77
      GO TO JUMP,(20)
  300 WRITE(6,301)
  301 FORMAT(*  TOO MANY ITERATIONS IN SUBROUTINE FLOW *)
      GO TO JUMP,(20)
   71 CALL IMPOUT
  270 RETURN
      END
```

SUBROUTINE IMPOUT

Subroutine IMPOUT performs flow calculations when liquid levels inside and outside the basket are unequal after a time step and net outflow from the basket occurs. (The basket is being drained rather than refilled.) A separate subroutine is needed for net outflow because the pressure differences inside and outside the basket are reversed compared to that when net refilling is occurring. Pressure of the vapor inside the basket is greater than the pressure outside the basket. Dynamic pressure (screen impingement) effects are not included. Standpipe areas are included in the calculations. Convergence calculations are performed.

```
      SUBROUTINE IMPOUT
C     ROUTINE CALCULATES BASKET REFILLING,SIMILAR TO DVCOL- LIQUID LEVELMHB10/77
C     INSIDE AND OUTSIDE THE BASKET UNEQUAL AFTER A TIME STEP - NET    MHB10/77
C     OUTFLOW OCCURS,CREATING VAPOR INFLOW TO REPLACE LIQUID LEAVING ***MHB10/77
C     DYNAMIC PRESSURE USED TO CALCULATE LIQUID AND VAPOR FLOW *********MHB10/77
C     FOR IMPOUT A POSITIVE VALUE OF DPIN AND HDPIN MEANS THAT GAS PRESSURE
C     INSIDE THE BASKET IS LESS THAN GAS PRESSURE OUTSIDE THE BASKET-THIS
C     IS OPPOSITE TO THE SIGN CONVENTION USED IN DVCOL AND FLOW.
C     DVCOL=SUBROUTINE TO  COMPUTE FINAL HEAD WHEN VOREF.LT.VILMAX
C     AV1  = INITIAL UNWETTED VAPOR FLOW AREA,FT2
C     AV2  = FINAL UNWETTED VAPOR FLOW AREA,FT2
C     CONV1= CONVERGENCE VARIABLE FOR CONTINUITY EQUATION-CURRENT ITERATION
C     CONV2= CONVERGENCE VARIABLE FOR CONTINUITY EQUATION-LAST ITERATION
C     CONVERG= CONVERGENCE VARIABLE THAT MUST BE WITHIN ZERO +OR-RANGE
C     DPIN1= STORAGE FOR CURRENT DELTA P ITERATION
C     DPIN2= STORAGE FOR CURRENT DELTA P ITERATION
C     DPIN = PRESSURE DIFFERENCE OF GAS INSIDE AND OUTSIDE BASKET ******
C     HAL1 = INITIAL DISTANCE FOR LIQUID INFLOW,FT
C     HAL2 = FINAL DISTANCE FOR LIQUID INFLOW,FT
C     HAVL1= INITIAL DISTANCE FOR VAPOR FLOW INTO LIQUID,FT
C     HAVL2= FINAL DISTANCE FOR VAPOR FLOW INTO LIQUID,FT
C     HAVW1= INITIAL DISTANCE FOR VAPOR FLOW ACROSS WETTED SCREEN,FT
C     HAVW2= FINAL DISTANCE FOR VAPOR FLOW ACROSS WETTED SCREEN,FT
C     NITER =ITERATION COUNTER
C     VOR1= STORAGE FOR VOREF
C     WT1,WT2=WETTING PARAMETERS AT START AND END OF TIME STEP
      COMMON/DVCOL/AST,A2,B2,RANGE
      COMMON/FLOW/AL1,AL2,AV1,AV2,CONVERG,CONV1,CONV2,DPIN1,DPIN2,HOL1,
     1HOL2,NITER
      COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
      COMMON/IMPOUT/CVOL,DPS,HDPIN,HPULL,VOL
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST.OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/STAND/AVLR,AVR,AVWR
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      COMMON/INFILL/CVI(20),DBP,DBP2,HCOL(20),HPT(10),J,K,MPROP,MR,MVEH,
     1N,NG,NS,NSP,QOUT(10),TC(20),THRST,TIM(20),TITLE(7),VILI,VTOT(20)
      REAL KC,MPROP,MR,MVEH
      WRITE(6,5)
    5 FORMAT(*                  SUBROUTINE IMPOUT *)
      NITER=0
      DPIN=0.001
   10 VOR1=VOREF
      IF(NOUT.EQ.0)VOLOUT=0.
      VILX2=VIL+VOREF-VOLOUT
      VOLX2=VOL-VOREF
  200 CALL TABL(VIL,HIL1,VOLI(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(VOL,HOL1,VOLO(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(VILX2,HIL2,VOLI(1),HT(1),1,1,1,I,IFBAD)
      CALL TABL(QP,HPULL,QOUT(1),HPT(1),1,1,1,J,IFBAD)
      IF((NOUT.NE.0).A.(HIL2.LE.HPULL))GO TO 302
      CALL TABL(VOLX2,HOL2,VOLO(1),HT(1),1,1,1,I,IFBAD)
```

```
C     DYNAMIC PRESSURE INCLUDED IN FLOW CALCULATIONS ******************MHB10/77
      DPDYN=A*VO+B*VO**2
      HDYN=DPDYN*32.2/(RHOL*G)
      IF(HIL2.GE.HTOT)HIL2=HTOT
      IF(HOL2.GE.HTOT)HOL2=HTOT
      IF(HOL1.GE.HTOT)HOL1=HTOT
C     AREA AND LIQUID LEVEL CALCULATIONS ******************************MHB10/77
   20 IF(DPIN.EQ.0.)DPIN=HS/(NITER+1)
      HDPIN=DPIN*32.2/(RHOL*G)
      HAL1=HOL1+HDPIN
      HAL2=HOL2+HDPIN
      IF(HDPIN.GT.0.)HAL1=HOL1
      IF(HDPIN.GT.0.)HAL2=HOL2
      CALL TABL(HAL1,AVLT1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HAL2,AVLT2,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HOL1,AVLJ1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HOL2,AVLJ2,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HIL1,AVT1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HIL2,AVT2,HT(1),AREA(1),1,1,1,I,IFBAD)
      AVT=(AVT1+AVT2)/2.
      HO=HOL2
      IF(HO.GT.HTOT)HO=HTOT
      IF(NW.EQ.1)WT=HO
      IF(NW.EQ.2)WT=HTOT
      IF(NW.EQ.3)CALL SWET
      WT2=WT
      HO=HOL1
      IF(HO.GT.HTOT)HO=HTOT
      IF(NW.EQ.1)WT=HO
      IF(NW.EQ.2)WT=HTOT
      IF(NW.EQ.3)CALL SWET
      WT1=WT
      CALL TABL(WT1,AVWT1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(WT2,AVWT2,HT(1),AREA(1),1,1,1,I,IFBAD)
      AV1=ATOT-AVWT1
      AV2=ATOT-AVWT2
      AVW1=AVWT1-AVLJ1
      AVW2=AVWT2-AVLJ2
      AL1=AVLT1-AVT1
      IF(AL1.LT.0) AL1=0
      AL2=AVLT2-AVT2
      IF(AL2.LT.0) AL2=0
      HDL1=HIL1-HDPIN-HDYN
      HDL2=HIL2-HDPIN-HDYN
      IF(HDL1.LT.0.)HDL1=0.
      IF(HDL2.LT.0.)HDL2=0.
      CALL TABL(HIL1,AVL1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HIL2,AVL2,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HDL1,ADL1,HT(1),AREA(1),1,1,1,I,IFBAD)
      CALL TABL(HDL2,ADL2,HT(1),AREA(1),1,1,1,I,IFBAD)
      ADL3=AVL1-ADL1
      ADL4=AVL2-ADL2
      ADL1=AVLT1-ADL1
      ADL2=AVLT2-ADL2
      IF(ADL1.LT.0.)ADL1=0.
      IF(ADL2.LT.0.)ADL2=0.
      ADL=(ADL1+ADL2)/2.+(ADL3+ADL4)/4.
      AV=(AV1+AV2)/2.
      AVW=(AVW1+AVW2)/2.
      AL =(AL1+AL2)/2.
      HDPIN=DPIN*32.2/(RHOL*G)
      IF(DPIN.LE.0.)GO TO 21
C     VAPOR FLOW ACROSS DRY SCREEN,OUT OF BASKET ***********************MHB10/77
      IF(NST.EQ.0)GO TO 80                                             MHB10/77
C     VVS =VAPOR VELOCITY FOR UNWETTED STANDPIPE            ***********MHB10/77
      VVS=(-A2+SQRT(A2**2+4.*B2*(DPIN)))/(2.*B2)                       MHB10/77
      VVS=-VVS                                                         MHB10/77
   80 CONTINUE                                                         MHB10/77
      VV=(-A+SQRT(A**2+4.*B*(DPIN. )/(2.*B)
      VV=-VV
      GO TO 22
```

```
   21 VV=0.
      VVS=0.
   22 CONTINUE
      IF(NST.EQ.0)GO TO 83                                               MHB10/77
      IF(DPIN-DPS2.LE.0.)GO TO 82
C     VVWS=VAPOR VELOCITY FOR WETTED  STANDPIPE            ***********MHB10/77
      VVWS=(-A2+SQRT(A2**2+4.*B2*(DPIN-DPS2)))/(2.*B2)                  MHB10/77
      VVWS=-VVWS                                                        MHB10/77
      GO TO 83                                                          MHB10/77
   82 VVWS=0.                                                           MHB10/77
   83 CONTINUE                                                          MHB10/77
      IF(DPIN-DPS.LE.0.)GO TO 25
C     VAPOR FLOW ACROSS WETTED SCREEN INTO VAPOR,OUT OF BASKET*********MHB10/77
      VVW=(-A+SQRT(A**2+4.*B*(DPIN-DPS)))/(2.*B)
      VVW=-VVW
      GO TO 26
   25 VVW=0.
   26 CONTINUE
      HOPIN=2.*HDPIN
      IF(HOL1-HIL1+HOL2-HIL2+HOPIN.LE.0.)GO TO 28
C     LIQUID FLOW INTO VAPOR,INTO BASKET ******************************MHB10/77
      VL=(-Y+SQRT(Y**2+    Z*(HOL1-HIL1+HOL2-HIL2+2.*HDPIN)*RHOL*G/32.2))
     1/(2.*Z)
C     LIQUID FLOW INTO LIQUID,INTO BASKET *****************************MHB10/77
      VT=(-Y+SQRT(Y**2+2.*Z*(HOL1-HIL1+HOL2-HIL2+2.*HDPIN)*RHOL*G/32.2))
     1/(2.*Z)
      GO TO 29
   28 VL=0.
      VT=0.
   29 CONTINUE
C     **** CONVERGENCE CALCULATIONS  ***********************************
      DPIN1=DPIN
      IF(NST.EQ.0)GO TO 93                                              MHB10/77
      HI=(HIL1+HIL2)/2.
      CALL STAND
      CONVERG=AVR*VV+AVS*VVS+AVWR*VVW+AVWS*VVWS-AL*VL-ADL*VO+QO-VT*AVT   MHB10/7
      GO TO 99                                                          MHB10/77
   93 CONTINUE                                                          MHB10/77
      CONVERG=AV*VV+AVW*VVW-AL*VL-ADL*VO+QO-VT*AVT
   99 CONTINUE                                                          MHB10/77
      QL=(AL1+AL2)/2.*VL*OA+(ADL1+ADL2)/2.*VO*OA+AVT*VT*OA
      CONVERG=(CONVERG-QO)*OA+QO
      CONV1=CONVERG
      IF(CONVERG.EQ.0..A.VL.EQ.0.)GO TO 35
      IF(ABS(CONVERG).LT.RANGE)GO TO 40
   35 CONTINUE
      IF(NITER.EQ.0)GO TO 30
      IF(NITER.GE.75)GO TO 300
      IF(CONV1.EQ.CONV2)GO TO 30
      NITER=NITER+1
      IF(NITER.GT.10)CALL DIAGNOS
      DPIN=(DPIN2*CONV1-DPIN1*CONV2)/(CONV1-CONV2)
      CONV2=CONV1
      DPIN2=DPIN1
      DX=DPS2
      IF(NST.EQ.0)DX=DPS
      IF(DPIN.LT.0..A.DPIN.LT.-DX)DPIN=-DX+DX/(NITER*10)
      HDPIN=DPIN*32.2/RHOL/G
      GO TO 20
   30 DPIN2=DPIN1
      CONV2=CONV1
      NITER=NITER+1
      IF(NITER.GT.10)CALL DIAGNOS
      DPIN=DPIN/2.
      HDPIN=DPIN*32.2/(RHOL*G)
      GO TO 20
   40 CONTINUE
```

```
C     ***  OUTFLOW RATE CALCULATION  *********************************
      QL=(AL1+AL2)/2.*VL*OA+(ADL1+ADL2)/2.*VO*OA+AVT*VT*OA
      VOREF=QL*DT
        IF(NOUT.NE.0)CALL OUTFLOW
      IF(ABS(VOREF-VOR1).LE.RANGE)GO TO 72
      VOREF=(VOREF+VOR1)/2.
      IF(NITER.GT.10)CALL DIAGNOS
      GO TO 10
  300 WRITE(6,301)
  301 FORMAT(*  TOO MANY ITERATIONS IN SUBROUTINE IMPOUT*)
      GO TO JUMP,(20)
  302 WRITE(6,303)HPULL
  303 FORMAT(* LIQUID LEVEL BELOW PULLTHROUGH HEIGHT,HT=*F9.5)
      GO TO JUMP,(20)
   72 RETURN
      END
```

SUBROUTINE INPUT

All inputs are defined and formatted in Subroutine INPUT. Namelist input is used. Comment cards define the inputs.

```
      SUBROUTINE INPUT
C  INPUT QUANTITIES
C
C     ALL TABLES MUST BE MONOTONIC FUNCTIONS  ************************* MHB3/78
C     A   = VISCOUS CONSTANT IN PRESSURE LOSS EQUATION FOR VAPOR
C     AREA(I)= BASKET SURFACE AREA BELOW HT(I),FT2
C     AST= STANDPIPE SURFACE AREA                                     MHB10/77
C     ATOT= TOTAL START BASKET AREA,FT2
C     AWIDTH=WIDTH OF SECTION,FT
C     A2=VISCOUS CONSTANT FOR TOP SCREEN PRESSURE LOSS
C     B = INERTIAL CONSTANT IN PRESSURE LOSS EXPRESSION FOR VAPOR
C     B2=INERTIAL CONSTANT FOR TOP SCREEN PRESSURE LOSS
C     CC=CORRECTION FACTOR FOR ORIFICE ROUNDED ENTRANCE,WAD FIG 3.22
C     CVI(N) = IMPINGEMENT VELOCITY FOR TIM(N)VS CVI(N) TABLE, FT/SEC
C     D= SPACING BETWEEN SCREEN BARRIERS,FT
C     DBP= SCREEN BUBBLE POINT DIAMETER, MICRONS
C     DBP2 = BUBBLE POINT FOR TOP SCREEN,MICRONS
C     DOR=OUTLET DIAMETER,FT
C     DPRESS= TANK PRESSURE DIFFERENCE ABOVE INTERFACE VAPOR PRESSURE,PSF
C     DPX = PRESSURE CORRECTION TERM FOR WICKING,PSF
C     DT = TIME STEP FOR FLOW CALCULATIONS,SEC
C     EN=NUMBER OF HOLES IN DIRECTION PERPENDICULAR TO WICKING FLOW
C     G=AMBIENT ACCELERATION FOR CONSTANT G CASE, FT/SEC2
C     HCOL(N)= COLLECTED HEIGHT FOR TC(N) VS HCOL(N) TABLE,FT
C     HPT(N) PULLTHROUGH HEIGHT FOR QOUT(N) VS HPT(N) TABLE,FT
C     HT(I)= BASKET HEIGHT CORRESPONDING TO VOLI(I),VOLO(I),VTOT(I)
C     HTOL=UNFILLED HEIGHT FRACTION
C     HTOT = MAXIMUM HEIGHT OF BASKET, FT
C     I=NUMBER OF ENTRIES IN INPUT TABLES, HT(I),VOLI(I),VOLO(I),VTOT(I),AREA(I)
C     J = NUMBER OF ENTRIES IN QOUT VS HPT TABLE
C     K = INDEX OF MAXIMUM HCOL VALUE
C     KC=CORRECTION FACTOR FOR ABRUPT CONTRACTION,WAD FIG.3.21
C     MPROP=PROPELLANT MASS, LBM
C     MR=MIXTURE RATIO, MR=6 FOR LH2, MR=1/6 FOR LO2
C     MUL = LIQUID VISCOSITY, LBM/FT-SEC
C     MVEH=VEHICLE MASS, LBM
C     N=NUMBER OF ENTRIES IN INPUT TABLES TC(N),AND CVOL(N)
C     NDR=STANDPIPE SCREEN WETTING FLAG, NDR=0: SCREEN WET, NDR.NE.0: SCREEN DRY
C     NG=G LEVEL FLAG, NG=0 FOR VARIABLE G CASE, NG=1 FOR CONSTANT G CASE
C     NIM=FLAG,IF.NE.0. IMPIMGEMENT TABLES ARE INPUT AND IMPINGEMENT CALCULATED
C     NOUT=FLAG FOR OUTFLOW,NO OUTFLOW IF NOUT =0
C     NS= NUMBER OF SECTIONS OF SCREEN
C     NSP = SPILLING FLAG,NSP=0-NO SPILLING.  NSP.NE.0,SPILLING
C     IF SPILLING DOES NOT OCCUR INITIAL BASKET LEVEL MUST BE LESS THAN TANK
C     NST=FLAG FOR STANDPIPE, NS=0-NO STANDPIPE                       MHB10/77
C     NTSCR= TYPE OF SCREEN BARRIER,NTSCR=1,P/S-S/P,NSCR=2,P/S-P/S
C     NW  = FLAG TO DETERMINE METHOD OF COMPUTING SCREEN WETTING
C     NW=1,WT=HO   NW=2,WT=HTOT   NW=3,WT IS COMPUTED ACCORDING TO WICKING
C     OA  = SCREEN SURFACE OPEN AREA FRACTION
C     P=POROSITY,SCREEN VOID FRACTION IN THE DIRECTION OF WICKING FLOW
C     PT= PLATE THICKNESS,FT
C     QOUT(N)= FLOW RATE USED IN OUTFLOW RATE VS PULLTHROUGH HEIGHT,FT3/SEC
C     QP =  CONSTANT OUTFLOW RATE(USED WHEN NOUT=5),FT3/SEC
C     RANGE = ITERATION TOLERANCE
C     RHOL= LIQUID DENSITY, LBM/FT3
C     SIGMA= SURFACE TENSION,LBF/FT
C     ST = SCREEN THICKNESS,FT
C     TC(N)=COLLECTION TIME AT HCOL(N),SEC
C     THETA= ANGLE BETWEEN SCREEN BARRIER AND HORIZONTAL
C     THRST=VEHICLE THRUST, LBF
C     TIM(N)= TIME AT IMPINGEMENT,CVI(N),SEC
C     TMAX = MAXIMUM TIME FOR CALCULATIONS,SEC
C     VILI=INITIAL LEVEL IN START BASKET,FT3
C     VOLI(I)=VOLUME INSIDE BASKET AT HT(I), FT3
```

```
C      VOLO(I)=VOLUME OUTSIDE THE BASKET AT HT(I), FT3
C      VTOT(I)= TOTAL TANK VOLUME AT LEVEL HT(I)
C      Y =VISCOUS CONSTANT FOR LIQUID FLOW ACROSS SCREENS
C      Z =INERTIAL CONSTANT FOR LIQUID FLOW ACROSS SCREEN
       COMMON/DVCOL/AST,A2,B2,RANGE
       COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
       COMMON/INFILL/CVI(20),DBP,DBP2,HCOL(20),HPT(10),J,K,MPROP,MR,MVEH,
      1N,NG,NS,NSP,QOUT(10),TC(20),THRST,TIM(20),TITLE(7),VILI,VTOT(20)
       COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
      1VOLI(20)
       COMMON/OUTFLOW/CC,DOR,DPRESS
       COMMON/SWET/AWIDTH,D,DPX,EN,MUL,NTSCR,P,PT,ST,THETA
       COMMON/TIME/HTOL,TMAX
       REAL KC,MPROP,MR,MUL,MVEH
       NAMELIST/INDATA/A,AREA,AST,ATOT,AWIDTH,A2,B,B2,CC,CVI,D,DBP,DBP2,
      1DOR,DPRESS,DPX,DT,EN,G,HCOL,HPT,HT,HTOL,HTOT,I,J,K,KC,MPROP,MR,
      2MUL,MVEH,N,NDR,NG,NIM,NOUT,NS,NSP,NST,NTSCR,NW,OA,P,PT,QOUT,QP,
      3RANGE,RHOL,SIGMA,ST,TC,THETA,THRST,TIM,TITLE,TMAX,VILI,VOLI,VOLO,
      4VTOT,Y,Z
       READ(5,INDATA)
       IF(EOF(5)) 10,20
    10 CALL EXIT
    20 WRITE(6,INDATA)
       RETURN
       END
```

SUBROUTINE OUTFLOW

Subroutine OUTFLOW calculates the outflow rate from the start basket based on tank pressure, outlet pressure, basket geometry and outlet geometry.

```
      SUBROUTINE OUTFLOW
C     CALCULATES OUTFLOW RATE BASED ON BASKET PRESSURE AND OUTLET GEOMETRY*****
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/OUTFLOW/CC,DOR,DPRESS
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      REAL KC
      IF(NOUT.EQ.5)GO TO 20
      DPF=RHOL*G/32.2*(HIL1+HIL2)/2.+DPRESS-DPIN
      WRITE(6,30)HIL1,HIL2,DPRESS,DPIN,DPF
   30 FORMAT(* HIL1=*F10.3,* HIL2=*F10.3,* DPRESS=*F10.3,* DPIN=*F10.3,
     1* DPF=*F10.3)
      IF(DPF.LE.0.)GO TO 10
C     DETERMINES START BASKET OUTFLOW RATE *****************************MHB10/77
      VOUT=SQRT(2.*32.2*DPF/(KC*CC*RHOL))
      GO TO 15
   10 DPF=0.
      VOUT=0.
   15 CONTINUE
      QO=(VOUT*3.14159*DOR**2)/4.
      GO TO 21
C     CONSTANT OUTFLOW RATE - INPUT ************************************MHB10/77
   20 QO=QP
   21 CONTINUE
      VOLOUT=QO*DT
      VILMAX=VILMAX+VOLOUT
      RETURN
      END
```

SUBROUTINE STAND

Subroutine STAND is used when a standpipe on top of the basket is employed. Standpipe flow areas are computed. The areas depend on screen wetting, basket pressure differences and liquid levels inside and outside the basket. Calculations determine vapor flow area of the standpipe for flow into or out of the start basket. Vapor flow area for flow across dry screen, wet screen and screen surrounded by liquid is computed.

(A flag is used to determine whether the screen is wet or dry independent of the calculations of SWET or flags for NW. This was used to simulate conditions that occurred during testing.)

```
      SUBROUTINE STAND
C     STAND COMPUTES STANDPIPE AREA FOR VAPOR AND LIQUID FLOW  *********
C     AVR =AREA FOR UNWETTED VAPOR FLOW OUTSIDE STANDPIPE   ***********MHB10/77
C     AVS =AREA FOR UNWETTED VAPOR FLOW ACROSS  STANDPIPE   ***********MHB10/77
C     AVWR=AREA FOR WETTED VAPOR FLOW OUTSIDE   STANDPIPE   ***********MHB10/77
C     AVWS=AREA FOR WETTED VAPOR FLOW  ACROSS    STANDPIPE  ***********MHB10/77
C     AVLR=AREA FOR VAPOR FLOW INTO LIQUID,OUTSIDE STANDPIPE***********MHB10/77
C     AVLS=AREA FOR VAPOR FLOW INTO LIQUID ACROSS  STANDPIPE***********MHB10/77
      COMMON/IMPOUT/CVOL,DPS,HDPIN,HPULL,VOL
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHCL,SIGMA,
     1VOLI(20)
      COMMON/DVCOL/AST,A2,B2,RANGE
      COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/STAND/AVLR,AVR,AVWR
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      HA=HI+HX
      CALL TABL(HA,AM,HT(1),AREA(1),1,1,1,I,IFBAD)
      IF(AV.LE.AST)GO TO 94                                             MHB10/77
      IF(AV.GT.AST)AVS=AST                                              MHB10/77
      AVR=AV-AST                                                        MHB10/77
      AVWS=0.                                                           MHB10/77
      AVLS=0.                                                           MHB10/77
      AVWR=AVW                                                          MHB10/77
      AVLR=AVL
      GO TO 97                                                          MHB10/77
   94 AVWTO=AV+AVW
      IF(AVWTO.LE.AST)GO TO 95
      IF(AVWTO.GT.AST)AVS=AV                                            MHB10/77
      AVR=0.                                                            MHB10/77
      AVWS=AST-AVS                                                      MHB10/77
      AVLS=0.                                                           MHB10/77
      AVWR=AVW-AVWS                                                     MHB10/77
      AVLR=AVL                                                          MHB10/77
      GO TO 97                                                          MHB10/77
   95 AVWX=AV+AVW+AVL
      IF(AVWX.LE.AST)GO TO 96
      IF(AVWX.GT.AST)AVS=AV                                             MHB10/77
      AVWS=AVW                                                          MHB10/77
      AVR=0.                                                            MHB10/77
      AVWR=0.                                                           MHB10/77
      AVLS=AST-AVS-AVWS                                                 MHB10/77
      IF(HO.GE.HTOT.A.HX.LT.HS.A.HO.GT.HI+HX)AVLS=ATOT-AM
      IF(AVLS.GT.AST)AVLS=AST
      AVLR=AVL-AVLS                                                     MHB10/77
      GO TO 97
```

```
96 AVS=AV                                                               MHB10/77
   AVR=0.                                                               MHB10/77
   AVWS=AVW
   AVWR=0.                                                              MHB10/77
   AVLS=AVL                                                             MHB10/77
   IF(HO.GE.HTOT.A.HX.LT.HS.A.HO.GT.HI+HX)AVLS=ATOT-AM
   IF(AVLS.GT.AST)AVLS=AST
   AVLR=0.                                                              MHB10/77
97 IF(NDR.EQ.1) AVS=AST
   RETURN
   END
```

SUBROUTINE SWET

Subroutine SWET computes wicking along the main screen using equations developed in "Centaur Propellant Thermal Conditioning Study," by M. H. Blatt, R. L. Pleasant and R. Erickson, NASA CR-135032, CASD-NAS-76-026, NAS3-19693, July 1976. Plate/screen-screen/plate and plate/screen-plate/screen, the two configurations that were found to be most promising, are programmed for wicking between the inner barriers. An iteration on time and wicking distance travelled is performed until a solution is reached that satisfies the time step taken.

The subroutine yields the distance wicked ahead of the level of liquid outside the start basket. (Options are available that do not use subroutine SWET to compute screen wetting. One option wets the entire screen instantaneously; the other option keeps the screen wetting at the liquid level with no wicking.)

```
      SUBROUTINE SWET
C     CALCULATES SCREEN WETTING CONDITIONS AS A RESULT OF WICKING
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/SWET/AWIDTH,D,DPX,EN,MUL,NTSCR,P,PT,ST,THETA
      REAL KC,MUL
      S1=0
      TI1=0.
      S=HO/5.
      AS=2*ST*P
C     PLATE/SCREEN-SCREEN/PLATE WICKING CALCULATION *******************MHB10/77
      IF(NTSCR.EQ.2)GO TO 10
      AF=D
    5 TI=AF/(AF-AS)*24.*MUL*SIGMA/RHOL**2/D**3/G**2*32.2/(SIN(THETA)**2)
     1*(-RHOL*G/32.2*D*S*SIN(THETA)/2./SIGMA-ALOG(1.-RHOL*G/32.2*D*S*SIN
     1(THETA)/2./SIGMA -DPX*D/2.)*(1.-DPX*D/2.))
      GO TO 30
C     PLATE/SCREEN-PLATE/SCREEN WICKING CALCULATIONS******************MHB10/77
   10 AF=D+PT*OA
   15 TIA=AF/(AF-AS)*192.*MUL*SIGMA*(AWIDTH+EN*PT)**3
      TIB=(AWIDTH**3*(2.*D+PT)**3*RHOL**2*G**2*(SIN(THETA))**2/32.2)
      TIC=(-RHOL*G/32.2*(2.*D+PT)*AWIDTH*SIN(THETA)*S)
      TID=4.*SIGMA*(AWIDTH+EN*PT)
      TIP=(1.-DPX*AWIDTH*(2.*D+PT))
      TIR=RHOL*G*S*SIN(THETA)*AWIDTH*(2.*D+PT)/32.2
      IF(TIR.LE.TIP) GO TO 26
      S=S/10.
      GO TO 15
   26 TIU=ALOG((TIP-TIR)/TID)
      TI=(TIA*TIB*TIC-TIP*TIU)/TID
   30 WRITE(6,150)TI,S
  150 FORMAT(*  TI= *F12.4,*  S = *F12.4)
C     CONVERGENCE CALCULATIONS ***************************************MHB10/77
      IF(TI-T.LT.T/10.)GO TO 100
      S2=S1
      S1=S
      TI2=TI1
      TI1=TI
      IF(TI2.NE.0.)GO TO 60
      IF(TI.LT.0.)GO TO 50
      S=S1/2.
      IF(NTSCR.EQ.2) 15,5
   50 S=S1*2
      IF(NTSCR.EQ.2) 15,5
   60 SLOPE=(TI1-TI2)/(S1-S2)
      S=(TI1-T)/SLOPE+S1
      IF(NTSCR.EQ.2) 15,5
C     END OF CONVERGENCE CALCULATIONS *********************************MHB10/77
  100 WT=HO+S
      RETURN
      END
```

SUBROUTINE TIME

Subroutine TIME increments the value of time and checks to see if the end time has been reached or the basket is full.

```
      SUBROUTINE TIME
C     INCREMENTS TIME,DETERMINES WHETHER BASKET IS FULL ***************MHB10/77
C     DELT=TRUNCATED VALUE OF DT DUE TO BASKET FILLING
C     VTIL2=VOLUME OF LIQUID IN THE BASKET IF FILLING IS UNCONSTRAINED
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/TIME/HTOL,TMAX
      REAL KC
      IF(WT.EQ.HTOT) HMAX=HTOT-HX
      IF(WT.LT.HTOT)HMAX=HTOT
      VTIL2=VIL+VOREF-QO*DT
      CALL TABL(VTIL2,HM,VOLI(1),HT(1),1,1,1,I,IFBAD)
      IF(HM.LT.HMAX)GO TO 240
C     DIAGNOSTIC ***************************************************** MHB11/77
      CALL TABL(HMAX,VMAX,HT(1),VOLI(1),1,1,1,I,IFBAD)
      WRITE(6,8)VTIL2,VMAX,VOREF,QO,DT                                 MHB11/77
    8 FORMAT(* VTIL2 =*F10.3*FT3, VMAX=*F10.3*FT3, VOREF=*F10.3*FT3,QO=*MHB11/77
     1F10.3*FT3/SEC, DT=*F10.3*SE(*)                                   MHB11/77
      DELT=DT*(VTIL2-VMAX)/(VOREF-QO*DT)                               MHB11/77
      WRITE(6,10)
   10 FORMAT(20X* BASKET FULL*)
      CALL WRIT
      HI=HMAX
      T=T+DELT
      WRITE(6,110)T,HO,HI
  110 FORMAT(*  TIME AT END OF TIME STEP = *F8.4*SEC, TANK LIQUID LEVEL
     1=*F8.4*FT, BASKET LIQUID LEVEL =*F8.4*FT*)
C     GO TO JUMP,TRANSFER CONTROL TO MAIN PROGRAM-STATEMENT 10, IN ORDERMHB10/77
C     TO RESTART A NEW CASE *******************************************MHB10/77
      GO TO JUMP,(20)
  240 CALL WRIT
      IF((ABS(HMAX-HM)).GT.(HX*HTOL))GO TO 20
      WRITE(6,21)HTOL
   21 FORMAT(20X,*FILLING LEVEL WITHIN HS TIMES *F8.5*FT*)
      GO TO JUMP,(20)
   20 CONTINUE
      RETURN
      END
```

SUBROUTINE WRIT

Subroutine WRIT formats and directs the output for each time step after time zero.

```
      SUBROUTINE WRIT
C     WRITES CONDITIONS AFTER EACH TIME STEP ***************************MHB10/77
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/TIME/HTOL,TMAX
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      REAL KC
      WRITE(6,11)QL
   11 FORMAT(*  INFLOW RATE DURING TIME STEP =*F8.4*CUBIC FEET/SEC*)
      WRITE(6,20)VV,VVW,VVL,VL,VT
      WRITE(6,30)AV,AVW,AVL,AL,AVT
   20 FORMAT(* VV=*F8.5*FT/SEC*7X*VVW=*F8.5*FT/SEC*5X*VVL=*F8.5*FT/SEC*5
     1X*VL=*F8.5*FT/SEC*5X* VT=*F8.5)
   30 FORMAT(* AV=*F8.4*FT2*5X*AVW=*F8.4*FT2*5X*AVL=*F8.4*FT2*5X*AL=*F8.
     14*FT2*5X* AVT=*F8.4)
      WRITE(6,31)VO,ADL,HDYN
   31 FORMAT(*        VO=*F8.5*     ADL=*F8.5*     HDYN=*F8.5)
   70 WRITE(6,71)VOREF,VCL,QO,VOLOUT
   71 FORMAT(* VOREF =*F10.4,* VCL = *F10.4,* QO =*F10.4,* VOLOUT =*F10.
     14)
      WRITE(6,72) DPIN,HX
   72 FORMAT(* DPIN=*F10.5*LBF/FT2        HX=  *F10.5*FT*)
      WRITE(6,73) AVS,AVLS,AVWS
   73 FORMAT(* AVS=*F8.4*FT2*5X*AVLS=*F8.4*FT2*5X*AVWS=*F8.4*FT2*)
      WRITE(6,74) VVS,VVLS,VVWS
   74 FORMAT(* VVS=*F8.5*FT/SEC*5X*VVLS=*F8.5*FT/SEC*5X*VVWS=*F8.5*FPS*)
      WRITE(6,110) T,HO,HI
  110 FORMAT(*  TIME AT END OF TIME STEP = *F8.4*SEC, TANK LIQUID LEVEL
     1=*F8.4*FT, BASKET LIQUID LEVEL =*F8.4*FT*)
      IF(T.GE.TMAX)GO TO 200
      DO 50 L=1,4
   50 WRITE(6,40)
   40 FORMAT(1H0)
      WRITE(6,10) T,HO,HI
   10 FORMAT(*  INITIAL CONDITIONS,  TIME =*F8.4*SEC,  TANK LIQUID LEVEL
     1 =*F8.4*FT,  BASKET LIQUID LEVEL =*F8.4*FT*)
  200 RETURN
      END
```

SUBROUTINE DIAGNOS

Subroutine DIAGNOS is used for debugging and following the convergence pattern in the main subroutines. A printout of significant values in each iteration is formatted and directed from this subroutine. (This subroutine is not normally required but is included for completeness of documentation. To delete the subroutine all CALL DIAGNOS references should be removed as well as SUBROUTINE DIAGNOS.)

```
      SUBROUTINE DIAGNOS
C     DIAGNOS USED FOR PRINT OUT FOR DEBUGGING ************************
      COMMON/DVCOL/AST,A2,B2,RANGE
      COMMON/FLOW/AL1,AL2,AV1,AV2,CONVERG,CONV1,CONV2,DPIN1,DPIN2,HOL1,
     1HOL2,NITER
      COMMON/IMPINGE/A,AREA(20),ATOT,B,NDR,NIM,NW,VOLO(20),Y,Z
      COMMON/IMPOUT/CVOL,DPS,HDPIN,HPULL,VOL
      COMMON/INPUT/DT,G,HT(20),HTOT,I,KC,NOUT,NST,OA,QP,RHOL,SIGMA,
     1VOLI(20)
      COMMON/REFILL/AL,AV,AVW,DPIN,DPS2,HI,HIL1,HIL2,HO,HS,HX,JUMP,QL,
     1QO,T,VCL,VIL,VILMAX,VO,VOLOUT,VOREF,VV,WT
      COMMON/WRIT/ADL,AVL,AVLS,AVS,AVT,AVWS,HDYN,VL,VT,VVL,VVLS,VVS,VVW,
     1VVWS
      REAL KC
      WRITE(6,311)CONVERG,DPIN,DPIN1,DPIN2,CONV1,CONV2
  311 FORMAT(* CONVERG =*F10.5* DPIN =*F10.5* DPIN1 =*F10.5* DPIN2 =*F10
     1.5* CONV1 =*F10.5* CONV2 =*F10.5)
      WRITE(6,312)HDPIN,HX,HOL1,HOL2,HIL1,HIL2
  312 FORMAT(* HDPIN=*F10.5* HX=*F10.5*HOL1=*F10.5* HOL2=*F10.5* HIL1=*F
     110.5* HIL2=*F10.5)
      WRITE(6,212)HO,HI
  212 FORMAT(* HO=*F10.5*   HI=*F10.5)
      WRITE(6,313)NITER,VV,VVW,VVL,VL,VT
  313 FORMAT(* ITERATION NUMBER *I3* VV=*F10.5*VVW=*F10.5* VVL=*F10.5*
     1VL=*F10.5,5X*VT=*F8.5)
      WRITE(6,30)AV,AVW,AVL,AL,AVT
   30 FORMAT(* AV=*F8.5*FT2*5X*AVW=*F8.5*FT2*5X*AVL=*F8.5*FT2*5X*AL=*F8.
     15*FT2*5X*AVT=*F8.5)
      WRITE(6,314)AV1,AV2,AL1,AL2,QL,QO
  314 FORMAT(* AV1= *F10.5* AV2= *F10.5* AL1= *F10.5*AL2=*F10.5* QL= *F1
     10.5* QO=*F10.5)
      WRITE(6,73) AVS,AVLS,AVWS
   73 FORMAT(* AVS=*F8.5*FT2*5X*AVLS=*F8.5*FT2*5X*AVWS=*F8.5*FT2*)
      WRITE(6,74) VVS,VVLS,VVWS
   74 FORMAT(* VVS=*F8.5*FT/SEC*5X*VVLS=*F8.5*FT/SEC*5X*VVWS=*F8.5*FPS*)
      WRITE(6,315)VOL,VIL,VOREF
  315 FORMAT(* VOL =*F10.5* VIL =*F10.5* VOREF= *F10.5)
      WRITE(6,316)
  316 FORMAT(1H )
      RETURN
      END
```

A.3 PROGRAM REFILL SAMPLE INPUT

The program input is in namelist format. Definitions of input variables are given in the initial portion of subroutine INPUT. The input shown on the following pages is for the Centaur D-1S LO_2 tank refilling during the fourth burn of the five burn low earth orbit mission.

PROGRAM INPUT

```
$INDATA
A=0.163,
AREA=0.0,2.016,6.581,8.088,9.023,9.397,11.061,14.145,24.601,24.644,
24.645,
AST=0.043,
ATOT=24.644,
AWIDTH=30.97,
A2=0.163,
B=0.11,
B2=0.11,
CC=1.0,
D=0.0015,
DBP=38.0,
DBP2=65.0,
DOK=0.208,
DPRESS=5000.0,
DPX=0.25,
DT=0.025,
EN=557.46,
G=69.74,
HCOL=2.295,2.3,2.31,
HPT=0.0,0.032,
HT=0.0,0.02083,0.1083,0.144,0.226,0.258,0.403,0.759,0.959,1.1425,
2.3042,
HTOL=0.05,
HTOT=1.1425,
I=11,
J=2,
K=3,
KC=0.6,
MUL=0.000108,
N=3,
NG=1,
NOUT=5,
NS=2,
NST=1,
NTSCR=1,
NW=2,
OA=0.51,
P=0.635,
PT=0.00208,
QO=0.835,
```

```
QOUT=0.0,0.835,
RANGE=0.0004,
RHOL=68.5,
SIGMA=0.000782,
ST=0.00103,
TC=0.0,0.01,50.0,
THETA=1.571,
TITLE=31HCENTAUR D-1S LO2 BASKET  50X250,
TMAX=17.0,
VILI=0.135,
VOLI=0.0,0.0325,0.701,0.732,1.45,1.79,3.31,6.91,7.57,7.5701,7.5702,
VOLO=0.3073,0.364,0.4486,0.7968,1.1006,1.2406,2.3384,8.3411,14.8523,
21.6389,94.942,
VTOT=0.3073,0.3965,1.1496,1.5288,2.5506,3.0306,5.6484,15.2511,22.4223,
29.209,102.5126,
Y=3.38,
Z=15.01,
$END
```

A.4 PROGRAM REFILL SAMPLE OUTPUT

The output shown on the following pages corresponds to the case input shown in A.3. Results for the 4th burn of the five-burn low earth orbit mission are shown for Centaur D-1S LO_2 start basket refilling.

Initial conditions are printed first. The first two time steps and the last time step are shown. For the first time step convergence was obtained in less than ten iterations. The second time step shows the printout driven from subroutine DIAGNOS if greater than ten iterations are required. This feature was used extensively in the debugging state of program development in order to eliminate convergence problems and programming errors. (Subroutine DIAGNOS and associated subroutine call statements can be eliminated from the program to reduce computer and printer costs. Calculations performed will be identical with or without subroutine DIAGNOS.)

The calculations show that the capillary device refills into the standpipe region in 2.5521 seconds. This is well below the allowable refilling time of 16.9 seconds for this burn.

PROGRAM OUTPUT

```
CENTAUR D-1S LO2 BASKET  50X250


 INITIAL CONDITIONS,  TIME =  0.0000SEC,  TANK LIQUID LEVEL =  2.2950FT,  BASKET LIQUID LEVEL =   .0342FT
              SUBROUTINE FLOW
 INFLOW RATE DURING TIME STEP = 19.4877CUBIC FEET/SEC
VV= 9.18168FT/SEC       VVW= 0.00000FT/SEC     VVL= 2.20652FT/SEC     VL= 1.48007FT/SEC      VT= 2.13696
AV=   .0000FT2      AVW=  0.0000FT2      AVL= 16.4975FT2      AL= 21.8957FT2      AVT=  2.7159
     VO= 0.00000     ADL= 0.00000     HDYN= 0.00000
VOREF =      .4872 VCL =       .3157 QO =      .8350 VOLOUT =      .0209:
DPIN=  20.46295LBF/FT2         HX=       .06717FT
AVS=   .0000FT2      AVLS=    .0430FT2      AVWS=  0.0000FT2
VVS=12.91834FT/SEC     VVLS= 6.20352FT/SEC      VVWS= 9.05201FPS
 TIME AT END OF TIME STEP =     .0250SEC, TANK LIQUID LEVEL =  2.3000FT, BASKET LIQUID LEVEL =   .0953FT


 INITIAL CONDITIONS,  TIME =   .0250SEC,  TANK LIQUID LEVEL =  2.3000FT,  BASKET LIQUID LEVEL =   .0953FT
              SUBROUTINE FLOW
              SUBROUTINE DVCOL
CONVERG =     .00046 DPIN =  20.97857 DPIN1 =  20.97857 DPIN2 =  20.97868 CONV1 =    .00046 CONV2 =    .00046:
HDPIN=     .14140 HX=     .06717HOL1=   1.14250 HOL2=   1.14250 HIL1=    .09526 HIL2=    .18301
HO=   1.14250    HI=     .13913
ITERATION NUMBER  11 VV=    9.30523VVW=   3.65145 VVL=   2.40883  VL=   1.38898    VT= 2.00796
AV=  .00000FT2      AVW= 0.00000FT2     AVL=15.29542FT2     AL=17.39430FT2     AVT= 7.21656
AV1=      .00000 AV2=      .00000 AL1=   18.71057AL2=  16.07803 QL=   19.71191 QO=     .83500
AVS=  .00000FT2      AVLS=   .04300FT2      AVWS= 0.00000FT2
VVS=13.08888FT/SEC     VVLS= 6.37027FT/SEC      VVWS= 9.28849FPS
VOL =  94.67717 VIL =     .60132 VOREF=     .49315

CONVERG =   -.73113 DPIN =  20.74165 DPIN1 =  20.74165 DPIN2 =  20.97857 CONV1 =   -.73113 CONV2 =    .00046:
HDPIN=     .13981 HX=     .06717HOL1=   1.14250 HOL2=   1.14250 HIL1=    .09526 HIL2=    .18301
HO=   1.14250    HI=     .13913
ITERATION NUMBER  12 VV=    9.24865VVW=   3.52045 VVL=   2.31754  VL=   1.39036    VT= 2.00992
AV=  .00000FT2      AVW= 0.00000FT2     AVL=15.29542FT2     AL=17.39468FT2     AVT= 7.21656
AV1=      .00000 AV2=      .00000 AL1=   18.71095AL2=  16.07841 QL=   19.73165 QO=     .83500
AVS=  .00000FT2      AVLS=   .04300FT2      AVWS= 0.00000FT2
VVS=13.01080FT/SEC     VVLS= 6.29414FT/SEC      VVWS= 9.18053FPS
VOL =  94.67717 VIL =     .60132 VOREF=     .49315

CONVERG =     .00001 DPIN =  20.97842 DPIN1 =  20.97842 DPIN2 =  20.74165 CONV1 =    .00001 CONV2 =   -.73113:
HDPIN=     .14140 HX=     .06717HOL1=   1.14250 HOL2=   1.14250 HIL1=    .09526 HIL2=    .18301
HO=   2.30001    HI=     .18297
ITERATION NUMBER  12 VV=    9.30519VVW=   3.65137 VVL=   2.40878  VL=   1.38898    VT= 2.00796
AV=  .00000FT2      AVW= 0.00000FT2     AVL=15.29542FT2     AL=17.39430FT2     AVT= 7.21656
AV1=      .00000 AV2=      .00000 AL1=   18.71057AL2=  16.07803 QL=   19.71192 QO=     .83500
AVS=  .00000FT2      AVLS=   .04300FT2      AVWS= 0.00000FT2
VVS=13.08884FT/SEC     VVLS= 6.37022FT/SEC      VVWS= 9.28842FPS
VOL =  94.67749 VIL =   1.07324 VOREF=     .49280
```

```
 INFLOW RATE DURING TIME STEP = 19.7119CUBIC FEET/SEC
VV= 9.30519FT/SEC       VVW= 3.65137FT/SEC      VVL= 2.40878FT/SEC      VL= 1.38898FT/SEC       VT= 2.00796
AV=    .0000FT2      AVW=  0.0000FT2       AVL= 15.2954FT2       AL= 17.3943FT2        AVT=  7.2166
     VO= 0.00000     ADL= 0.00000     HDYN= 0.00000

VOREF =      .4928 VCL =       .0003 QO =       .8350 VOLOUT =       .0209:
DPIN=  20.97842LBF/FT2        HX=        .06717FT
AVS=    .0000FT2      AVLS=    .0430FT2      AVWS=  0.0000FT2
VVS=13.08884FT/SEC      VVLS= 6.37022FT/SEC      VVWS= 9.28842FPS
TIME AT END OF TIME STEP =      .0500SEC, TANK LIQUID LEVEL =  2.3000FT, BASKET LIQUID LEVEL =    .1830FT
INITIAL CONDITIONS,  TIME =  2.5250SEC,  TANK LIQUID LEVEL =  2.3005FT,  BASKET LIQUID LEVEL =    .9574FT
              SUBROUTINE FLOW
              SUBROUTINE DVCOL
VTIL2 =      7.570FT3, VMAX=      7.570FT3, VOREF=       .024FT3,QO=       .835FT3/SEC, DT=       .025SE(
                   BASKET FULL
 INFLOW RATE DURING TIME STEP =    .9477CUBIC FEET/SEC
VV=10.59693FT/SEC       VVW= 6.10852FT/SEC      VVL= 4.13062FT/SEC      VL=  .04249FT/SEC       VT=  .07562
AV=    .0000FT2      AVW=  0.0000FT2      AVL=    .0164FT2      AL=    .0628FT2       AVT= 24.5389
     VO= 0.00000     ADL= 0.00000     HDYN= 0.00000
VOREF =      .0237 VCL =       .0003 QO =       .8350 VOLOUT =       .0209:
DPIN=  26.75153LBF/FT2        HX=        .06717FT
AVS=    .0000FT2      AVLS=    .0275FT2      AVWS=  0.0000FT2
VVS=14.87142FT/SEC      VVLS= 8.02320FT/SEC      VVWS=11.63125FPS
 TIME AT END OF TIME STEP =   2.5500SEC, TANK LIQUID LEVEL =  2.3005FT, BASKET LIQUID LEVEL =    .9582FT
```



```
 INITIAL CONDITIONS,  TIME =  2.5500SEC,  TANK LIQUID LEVEL =  2.3005FT,  BASKET LIQUID LEVEL =    .9582FT
 TIME AT END OF TIME STEP =   2.5521SEC, TANK LIQUID LEVEL =  2.3005FT, BASKET LIQUID LEVEL =  1.0753FT
```

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15. Supplementary Notes

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16. Abstract

A study was performed with three objectives (1) analyze and experimentally evaluate refilling of capillary devices with settled liquid, (2) analyze and experimentally evaluate vapor flow across wetted screens and (3) determine the best propellant management system for the Centaur D-1S vehicle.

The refilling investigation resulted in development of a versatile computer program that was successfully correlated with test data and used to predict Centaur D-1S LO_2 and LH_2 start basket refilling.

The vapor inflow investigation resulted in development of a semi-empirical model that was only partially correlated with data due to difficulties in obtaining repeatable test results.

The propellant management system comparison resulted in the baseline Centaur D-1S system (using pressurization, boost pumps and propellant settling) being selected as the best candidate based on payload weight penalty. However, other comparison criteria and advanced mission conditions were identified where pressure fed systems, thermally subcooled boost pumps and capillar" devices would be selected as attractive alternatives.

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