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PRESSURE CONTROL AND ANALYSIS REPORT
HYDROGEN THERMAL TEST ARTICLE (HTTA)

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PREFACE

This report was prepared by Beech Aircraft Corporation, Boulder Division, Boulder, Colorado, under Contract NAS 9-12105, Hydrogen Thermal Test Article (HTTA), from the Manned Spacecraft Center, Houston, Texas.

This "Pressure Control and Analysis Report" is the result of tasks which were accomplished during the HTTA Program study period, including: (1) perform a literature review to provide system guidelines; (2) develop the analytical procedures needed to predict system performance; (3) design and analysis of the HTTA pressurization system considering (a) future utilization of results in the design of a spacecraft maneuvering system propellant package, (b) ease of control and operation, (c) system safety, and (d) hardware cost; and (4) make conclusion and recommendation for systems design.

NOTATION

C	=	ratio of wall-to-gas effective thermal capacity
c_p	=	specific heat at constant pressure
D	=	equivalent tank diameter (diameter of a cylindrical volume having same total volume and wall surface area as tank under investigation)
h_c	=	gas-to-wall free convection heat transfer coefficient
p	=	tank pressure during liquid expulsion
$\dot{q}$	=	heat flux from ambient to tank wall, per surface area of wall
Q	=	ratio of total ambient heat input to effective thermal capacitance of gas
S	=	modified Stanton number
t_w	=	equivalent tank wall thickness
T_o	=	pressure inlet temperature
T_s	=	saturation temperature of propellant at initial tank pressure
w_p	=	total pressurant mass
w_p^o	=	total pressurant mass under conditions of zero, heat and mass transfer
w_p/w_p^o	=	collapse factor
ΔV	=	expelled liquid volume
θ_T	=	total liquid outflow time
ρ	=	density

Subscripts

G refers to gas

W refers to wall

NOTATION (Continued)

Superscript

0 refers to variables at a temperature equal to inlet pressurant temperature and a pressure equal to tank pressure during expulsion.

COMPONENT IDENTIFICATION

Fill Valve	-	FV
Isolation Valve	-	IV
Vent Valve	-	VV
Shutoff Valve	-	SV
Three-Way Valve	-	YV
Check Valve	-	CV
Pressure Regulator	-	PR
High-Pressure Pump	-	HP
Turbine	-	GT
Control Orifice	-	CO
Heat Exchanger	-	HX
Burst Disc	-	BD
Relief Valve	-	RV
Flow Meter	-	FM
Circulation Fan	-	CF
Pressure Switch	-	PS
Pressure Transducer	-	PT
Gas Generator	-	GG
Expansion Valve	-	EV
Remote Operated Valve	-	ROV
Solenoid Valve	-	SOV
Thermal Conditioning Unit	-	TCU

1.0 INTRODUCTION

The purpose of this report is to define an optimized pressure control system for the Hydrogen Thermal Test Article (HTTA). The report covers the following three basic considerations for pressure control:

1. pressurization technique selection
2. external pressurization considerations
3. relief system considerations design criteria and selection

The purpose of a pressurization system is to provide stored energy which can be utilized in the expulsion of the liquid propellant for spacecraft requirements. Several different types of gas generating systems exist and they have been analyzed in previous pressurization system studies [1]. Some of these systems are:

1. stored gas
2. evaporated propellants
3. evaporated non-propellants
4. products of chemical reaction
5. mechanical expulsion

For any given mission, several propellant pressurization systems may be capable of meeting the performance requirements. Therefore, the advantages and disadvantages of each system must be considered in the selection of the most suitable system. A generalized breakdown of the advantages and disadvantages of various pressurization systems are shown in Table I.

TABLE I

Type of Pressurization System	Advantages	Disadvantages
Stored gas	Simplicity Availability of Components	Weight Volume
Evaporated Propellant	Single Fluid	External Energy or Large Heat Exchanger
Evaporated Nonpropellant	Weight Volume	Complexity External Energy
Combustion Products	Weight Volume Cost	Contamination by Solids Repressurization after Coast Restart
Mechanical Expulsion	Weight Volume	Complexity Reliability Cost

To select the most suitable system, the relative performance of the various systems must be evaluated. Qualitative and quantitative factors must be established for each candidate system and the final selection made after consideration of these factors. Examples of the two categories of factors are shown.

Qualitative Factors	Quantitative Factors
Propellant Compatibility	Reliability
Mission Life Capability	Weight
Restart Capability	Size
Variable Flow Capability	Control Accuracy
	Cost

Some of the quantitative factors could become qualitative factors if future system design dictates maximum and/or minimum values such as reliability, weight, and size (volume). These quantitative factor values have not been specified for the HTTA. Qualitative factors were either acceptable or not, i.e., "go or no-go" and if the particular pressurization system under study did not meet the requirements, it was eliminated.

The stored gas type of pressurization system was selected for use on HTTA and analysis was limited to this type of system.

2.0 LITERATURE REVIEW - SUMMARY

Two approaches have primarily been taken in the design of gas pressurizations systems. Most investigators [2, 3, 4] have considered either stored gas or recirculation-type pressurization systems or both. The Grumman-Boeing [2] pressurization study concerned itself with the analysis of a cold autogenous gas tapped off the Orbit Maneuvering System engine. Lockheed's [3] systems optimization study primarily investigated both stored gas and recirculative-type pressurization systems. The AiResearch reports [4] were concerned with the study of recirculation-type pressurization systems.

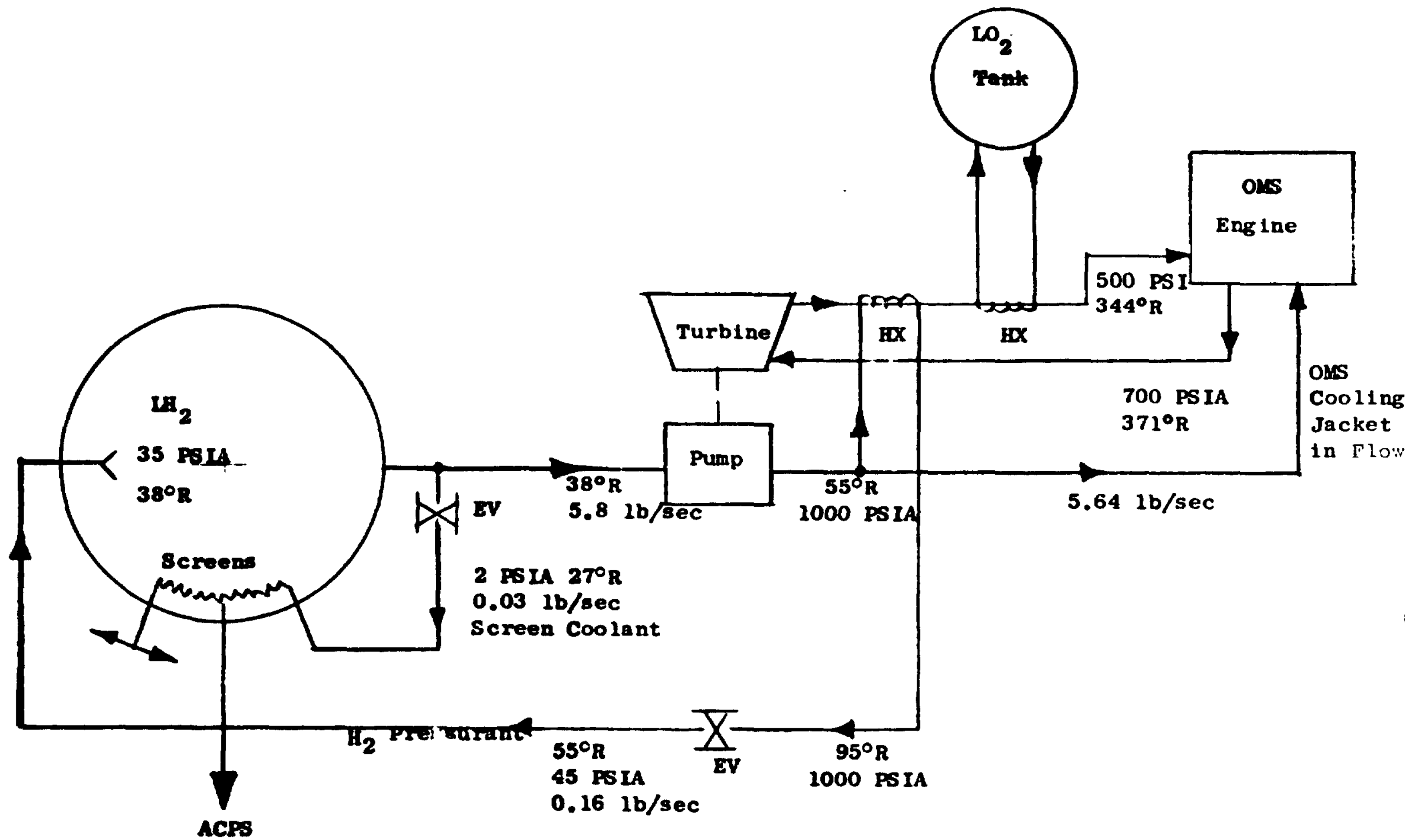
2.1 Shuttle Orbiter Reports

A review was made of the Grumman-Boeing study [2], the only Alternate Space Shuttle Concepts Study currently available to Beech, concerning the pressurization system of the Orbit Maneuvering System. The report recommends cold autogenous gas tapped off the Orbit Maneuvering System engine for tank pressurization. This type of system has the inherent advantages of not requiring a helium system or use of Attitude Control Propulsion System conditioning. The operating characteristics of the system are shown schematically in Figure 1. This simplified schematic shows the salient features of the autogenous pressurization system during steady-state Orbit Maneuvering System operation.

2.2 Cryogenics Systems Optimization Study

The Lockheed optimization study was originally formulated with the basic premise that helium gas would not be used as the pressurant for LH_2 tanks. This premise was established because the solubility of helium gas in LH_2 creates a fuel cell contamination problem. However, due to the small amount of gas required, helium gas was considered as a prepressurant to produce engine startup in recirculation-type pressurization systems. Helium was considered as a pressurant in the Orbit Maneuvering System/Attitude Control Propulsion System integrated system since the fuel cell system was not included. Ambient, as well as cold storage of the helium, was considered in the optimization analysis.

The Thermodynamics Optimization Program (computer program) completed by Lockheed [3] for a nonintegrated system indicated that the helium pressurant weight would be greater than the combined weights of a prepressurant and a pressurant using hydrogen gas. In addition, the weight of boiled-off liquid during the pressurized flow process is larger for a helium than for a hydrogen pressurization system. The optimization program provided a parametric analysis which included the following variables:



OMS Autogenous Pressurization System Operating Characteristics

Figure 1

1. pressure inlet temperature
2. expulsion pressure
3. vent pressure
4. insulation thickness
5. tank geometry
6. duty cycle

The various types of nonintegrated prepressurization and pressurization systems analyzed in the optimization study, utilizing the above combinations of variables, including their advantages and disadvantages, are listed in Table II. In the analysis both the prepressurization and the pressurization functions were controlled by the same pressure control components.

The candidate subsystems were analyzed for system composition and arrangement, operation modes (including redundant considerations), structural and thermal considerations, and fluid utilization. Two different nonintegrated system concepts were analyzed for nominal operation conditions [3] .

The selections provided for gaseous hydrogen as the pressurant with one case using a gaseous helium prepressurant. The pressurant supply conditions were:

System 1 - GH_2 at 37° to 520°R at 0 to 4000 psia

System 2 - GH_2 at 37°R at 20 psia

SYSTEM 1 - The hydrogen propellant tank was pressurized during engine operation by gaseous hydrogen supplied by a recirculation-type pressurization system heated by the engine nozzle. Propellant orientation devices were used to initially supply gas-free propellants for engine start until propellant orientation was maintained by engine operation. The tank pressure was controlled by tank pressure switches that operated flow control valves. During periods that the engine was not in operation, the tank pressure was controlled by a thermal conditioning unit.

The schematic for System 1 is shown in Figure 2 and the corresponding characteristic data in Table III.

SYSTEM 2 - This system used stored gas propellants for tank prepressurization. During engine operation the tank pressurization was accomplished by tapping off propellant downstream of the propellant tank boost pumps and vaporizing it in heat exchangers. Tank pressure was controlled by a combination orifice/regulator where the orifice supplies minimum

TABLE II

NONINTEGRATED SYSTEM COMPONENT ARRANGEMENTS

Function	Candidate	Description	Favorable Selection Factors	Unfavorable Selection Factors	Selection Status
Pressurization	1	• Pulse modulated valving • Tank mounted pressure switches open and close valves to control the flow of the pressurants and maintain tank pressures as required.	• Eliminates regulators • Simplifies adding redundancy, can concentrate on least reliable component • Multi-pressure level capability if add pressure switches	• Functioning component count is increased • High response valves and switches may be required	Candidate for evaluation
	2	• Regulator/orifice pressure control • Tank pressures are maintained by an orifice/regulator controlling pressurant. The orifice is sized to meet minimum flow requirements and the regulator supplies the remainder required.	• Reduced regulator size • No functioning component required for minimum flow rates	• Redundant regulators probably required • Regulator size not critical	Eliminated due to no significant gain over a normal regulated system
	3	• Regulated pressure control • Tank pressures are maintained by regulators controlling pressurant flow.	• Proven component	• High regulator reliability is required	Candidate for evaluation
	4	• Orifice pressure control • Tank pressures are maintained by fixed orifices controlling pressurant flow.	• Simplicity, no functioning components	• Multi-start requirement at various ullage volumes result in wide pressure variations for a fixed orifice system	Eliminated due to probable unacceptable pressure variations.
	5	• Helium pressurant • Separately stored helium maintains tank pressures during rocket engine operation and is controlled by the above pressure control methods	• Lighter than gaseous oxygen • No condensation possible • If RL10 rocket engine is used do not have to develop version which has GO_2 supply capability • Will aid inerting of tanks	• Helium cost • Increased system weight if used for both tanks pressurant • Helium solubility	• Candidate for O_2 tank pressurant • Eliminated for H_2 tank pressurant due to weight penalty
	6	• Gaseous propellant pressurants • Gaseous O_2 and H_2, conditioned by separate heat exchangers or the rocket engine(s), maintain tank pressures during propellant withdrawal and are controlled by the above pressure control methods	• Eliminates use of helium • Increased integration potential • Minimizes GSE requirements	• Propellant condensation will increase quantity of pressurant required • Requires use of heat exchangers or development of OMS rocket engine with capability to supply gaseous O_2 and H_2	Candidate for evaluation
Pre-pressurization	1	• Stored helium • Helium is stored at ambient temperature (or in the cryogenic storage tanks) and prepressurizes using the components of the tank pressure control system	• Candidate O_2 OMPS tank pressurant • No condensation possible • Light weight pressurant	• Helium cost • Tank pressure control equipment will have to handle two gases	Candidate for evaluation
	2	• Gaseous propellants • Gaseous O_2 and H_2, stored at high pressure, prepressurize the propellant tanks using the components of the tank pressure control system.	• Eliminates helium use • Increased integration potential • Less volume and weight as storage tanks can be recharged during rocket engine operation	• Propellant condensation will increase pressurant required	Candidate for evaluation

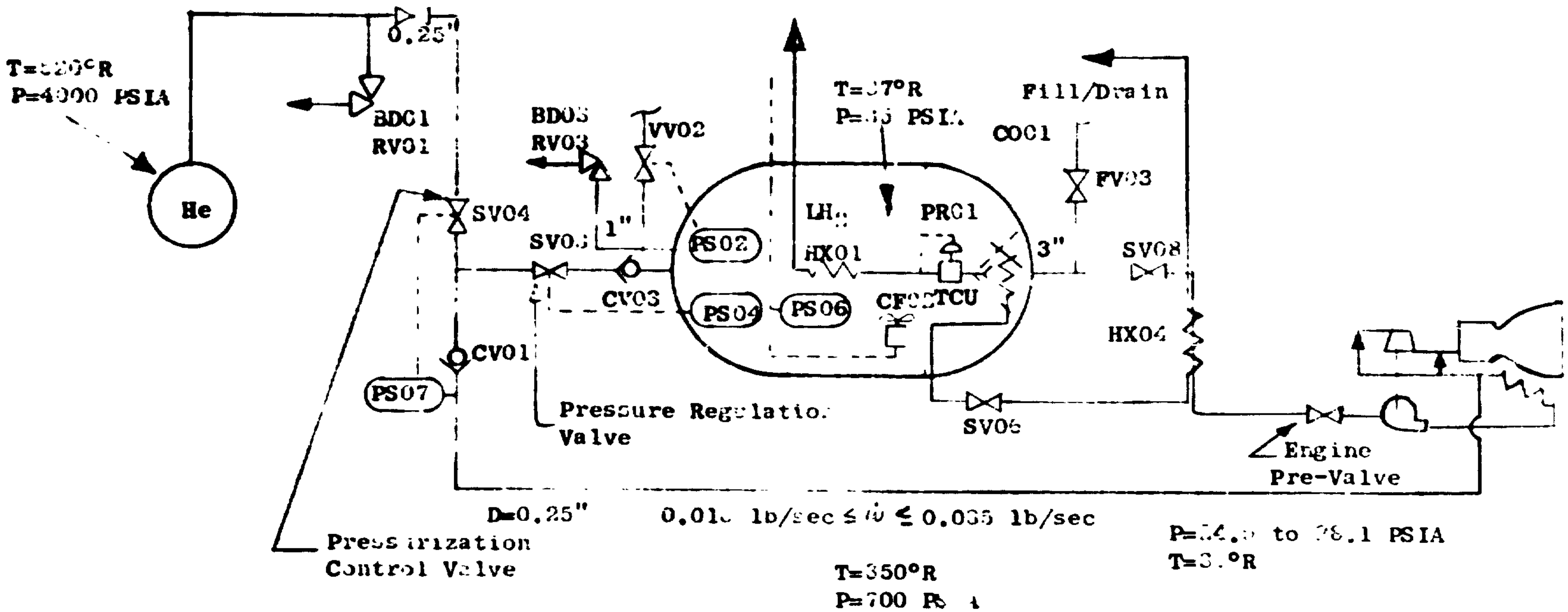


Figure 2

RECIRCULATION TYPE PRESSURIZATION SYSTEM

TABLE III

COMPONENT CHARACTERISTICS

Component Identification	FV03	VV02	SV01	SV03	SV04	SV06	SV08	CV01	CV03	PR01
Fluid	H_2	H_2/He	He	He/H_2	He	H_2	H_2	H_2	H_2	H_2
Inlet Fluid Pressure (psia)	0 to 35	15	0 to 4000	0 to 4000	0 to 4000	4	0 to 35	0 to 700	0 to 4000	35
Inlet Fluid Temperature (°R)	37 to 520	37 to 520	520	350 to 520	520	35	37 to 520	350	350 to 520	37
Fluid Flow Rate (lb/sec)	7.3	0.18	0.02	0.07	0.01	10^{-6}	5.6	0.07	0.07	4×10^{-4}
Outlet Pressure (psia)	0 to 35	0 to 15	0 to 4000	0 to 4000	0 to 4000	4	0 to ~30	0 to 4000	0 to 4000	4
Outlet Temperature (°R)	37 to 520	37 to 520	520	350 to 520	520	35	37 to 520	350	37 to 520	30
Inlet Line Dia. (in.)	3	1	0.25	0.25	0.25	0.125	3	0.25	0.25	0.125
No. of Cycles/Mission	3	3	7	1500	8		4			
Total Op. Time (min)	120	120						15	15	
Response Time	1000	30	1000	30	30					
Normal Position	Closed	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed

Component Identification	BD01	BD03	RV01	RV03	CF02	PS02	PS04	PS06	PS07	HX01	HX03	HX04	C001
Fluid	He	H_2/He	He	H_2/He	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2
Inlet Fluid Pressure (psia)	4000	35	4000	35		20	25		700	4	4	4	35
Inlet Fluid Temperature (°R)	520	37	520	37	37					30	30	25	37
Fluid Flow Rate (lb/sec)	0 to 15	0 to 15	0 to 15	0 to 15		15				4			4
Outlet Pressure (psia)	520	37	520	37						35	35	37	30
Outlet Temperature (°R)													
Inlet Line Dia. (in.)	0.25	1	0.25	1					8	0.125	0.125	0.125	
No. of Cycles/Mission	0	0				3	1500		800				
Total Op. Time (min)						168 hr	168 hr	168 hr	168 hr				
Response Time	30	30	30	30		30	30		30				
Normal Position	Closed	Closed	Closed	Closed									

pressurant and the regulator accommodates peak demands.

During periods that the engine was not in operation, as tank pressure increased, the ullage was vented to space through tank wall heat exchangers (vapor cooled shield) with part of the incoming heat being intercepted. Propellant orientation was required for liquid delivery. The schematic for this system is shown in Figure 3 and the corresponding characteristics data in Table IV.

In addition to the nonintegrated systems analyzed, various integrated systems analysis were performed by Lockheed. This analysis resulted in several different integrated systems with varying degrees of integration. For the purposes of this pressurization analysis, two integrated systems will be used as HTTA design guidelines. These are: 1) integrated Orbit Maneuvering System/Attitude Control Propulsion System with common pumps as shown in Figure 4, and 2) integrated Orbit Maneuvering System/Attitude Control Propulsion System with pumps at engine as shown in Figure 5.

These selections provide two different pressurant supply gas conditions. They are:

1. GH_2 at 2000 psia & 250°R (Figure 4)
2. GHe at 4000 psia & 37°R (Figure 5)

2.3 Study of External Pressurization Systems - AiResearch

A review of the monthly progress reports from AiResearch Manufacturing Company [4] was made. The reports described work performed during a period between 15 July 1970 and 15 May 1971 under Contract No. NAS9-10453 for NASA-MSC. The contract was concerned with the study of recirculation type pressurization systems for pressure control of cryogenic storage systems. The information developed was to yield flexibility in design of cryogenic systems and low cost replacement of dynamic components that are external to the cryogenic pressure vessel.

The reports contain information on preliminary component selection and results of the tankage thermodynamic analysis. The components considered were heat exchangers, recirculation loop lines and pumps and fans. The results of the tankage thermodynamic analysis determined the recirculation rates required to maintain given pressures. This analysis covered the following cases:

- subcritical and supercritical
- varying return temperatures
- complete mixing and complete nonmixing
- both liquid and vapor recirculation for subcritical tanks

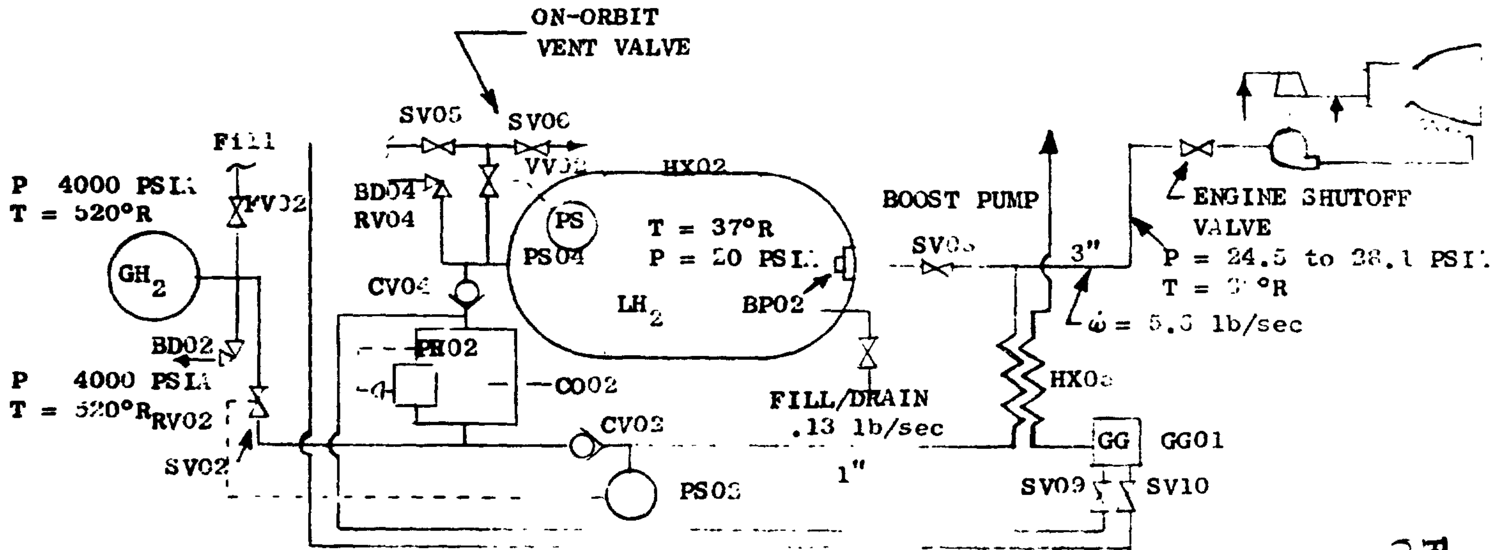


Figure 3

STORED GAS PRESSURIZATION SYSTEM

TABLE IV

COMPONENT CHARACTERISTICS

COMPONENT IDENTIFICATION	FV02	FV04	VV02	SV02	SV05	SV06	SV08	SV09	SV10	CV02	CV04	PR02	CO02	HX05	BD02	BD04	RV02	RV04	PS02	PS04	BP02	GG01
Fluid	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	O_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	O_2/H_2
Inlet Fluid Pressure, psia	0-4000	0-35	23	0-4000	23	23	0-35	20	20	40	20	40-4000	40-4000	40	4000	25	4000	25	40	23	20	20
Inlet Fluid Temperature, °R	520	37-520	37-520	520	37-520	37	37-520	37	165	37	37	37-520	37-520	37	520	37	520	37			37	37/165
Fluid Flow Rate, lb/sec		7.2	0.18	0.[illegible]1	0.18		5.6			0.13	0.13	0.13	0.13	0.13		0.18		0.18			5.6	f(MR)
Outlet Fluid Pressure, psia	0-4000	0-35	0.15	0-4000	0-15	5	0-30	20	20	0-4000	20	20	20	40	0-15	0-15	0-15	0-15			40	
Outlet Fluid Temperature, °R	520	37-520	37-520	520	37-520		37-520	37	165	37-520	37	37-520	165-520	37	520	37	520	37			37	f(MR)
Inlet Line Diameter, in.	0.25	3	1	1		1	0.25	0.25	1	1	1	1	1	0.25	1	0.25	1			3	3	0.25/ 0.25
No. of Cycles/Mission	3	3		8	3	3	7	7	7						0	0			8		8	7
Total Operating Time, min	120	120	170 hrs.	5	120	150	15	15	15										168 hrs.		15	15
Response Time, msec	1000	1000	30	30	30	30	1000	30	30						30	30	30	30	30			
Normal Position	Closed	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed	Closed				Closed	Closed	Closed	Closed				

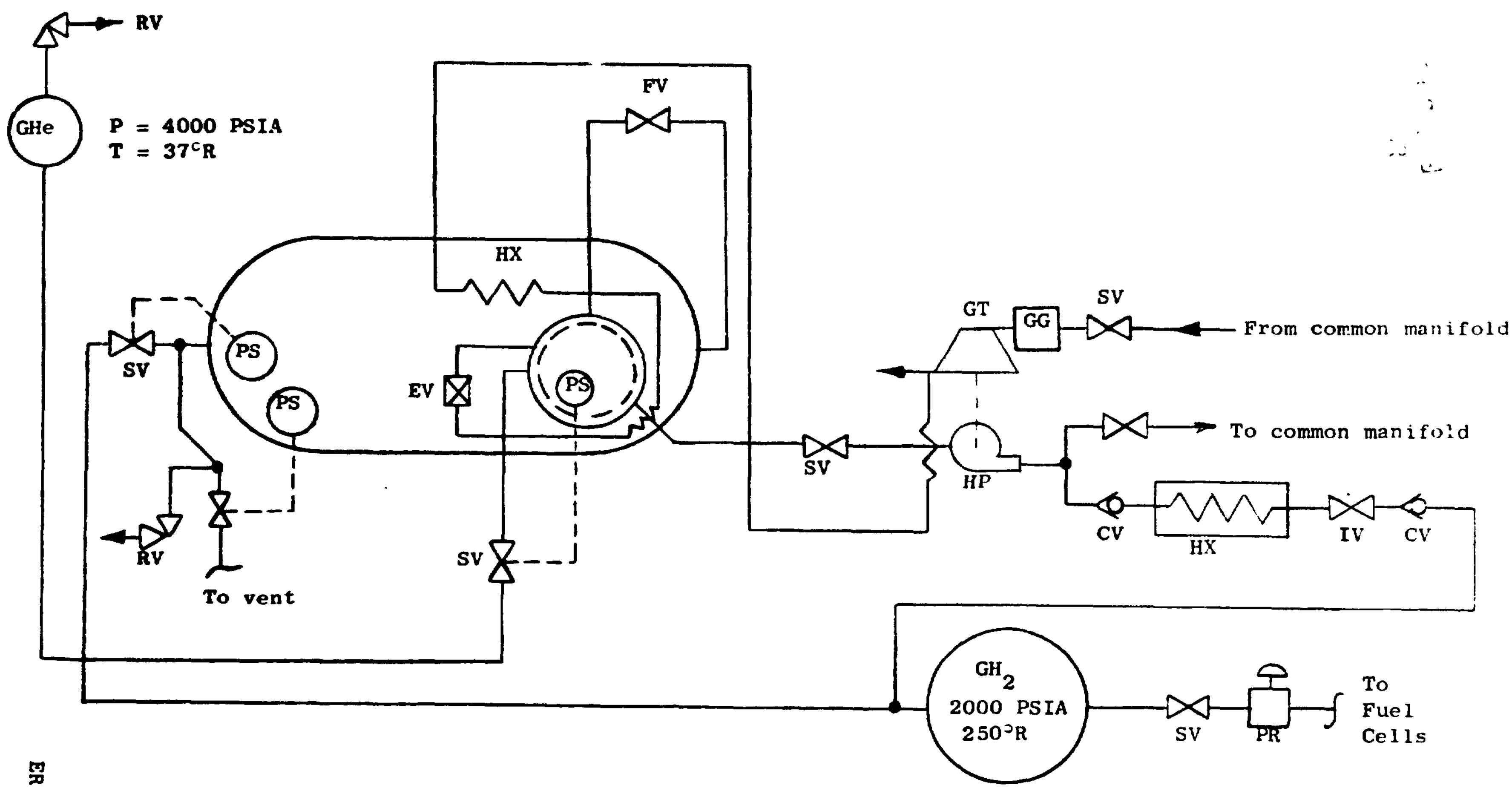
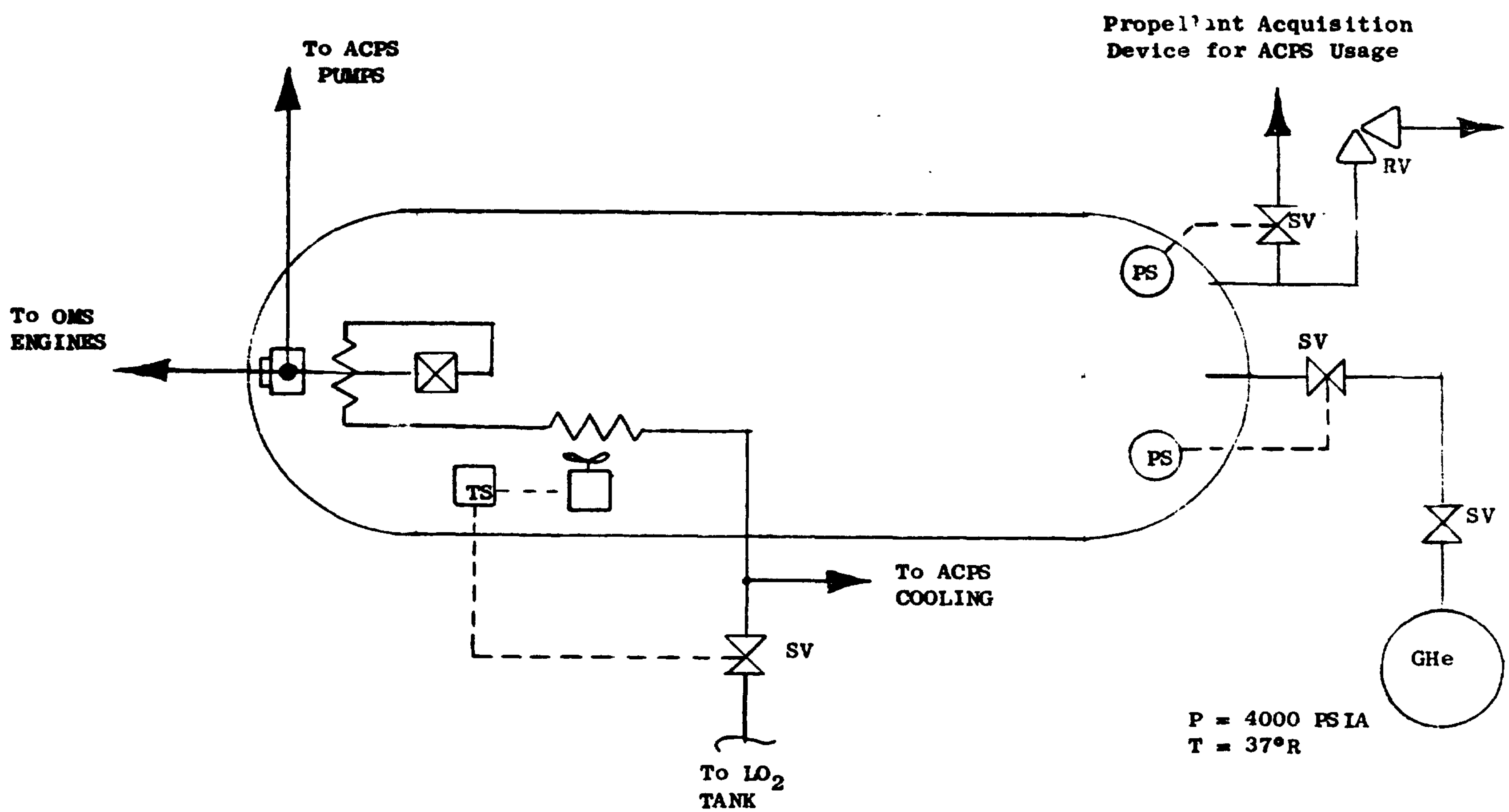


FIGURE 4 - Integrated OMPS/ACPS with Common Pumps



INTEGRATED OMPS/ACPS WITH PUMP-AT-ENGINE

Figure 5

In addition to the above, the thermodynamic analysis calculated the required heat addition rate and the pressure drop due to mixing of the stratified cases.

Considering the mass flow requirement of the HTTA, the amount of energy needed to vaporize cold liquid would require a rather large heat exchanger or very high temperature gas source for the hot side of the heat exchanger.

Although the use of recirculated pressurization system has been considered for the Shuttle Program, the use of this type system for the HTTA is impractical due to the added hardware involved. However, the use of stored gas pressurization can be related to this type of system and still make use of simpler, less expensive hardware associated with the stored gas system.

3.0 PRESSURIZATION SYSTEMS ANALYSIS

3.1 Selection of Pressurization System

Gaseous hydrogen has been selected as the primary pressurant for the HTTA tank. This selection was based on the requirements outlined in [2, 3]. The HTTA tank design and testing are based on parameters that applied initially to the Space Shuttle Orbit Maneuvering System. However, modifications have been made to facilitate a 180-day mission. The original 7-day mission duty cycle has been assumed to be as shown in Figure 6. The 180-day mission duty cycle has been assumed to be a full tank at the initiation of pressurization system operation, since thermal analysis indicates the boiloff mass will be small.

The selection of the pressurant for the HTTA was narrowed to either helium or hydrogen gas based upon the compatibility requirements between the pressurant and the propellant subsystem. When considering missions with multiple restart requirements and relatively long coast periods, the equilibrium temperature of the ullage will decrease to approximately the original bulk propellant temperature. If the pressurant freezing temperature is above the initial bulk temperature of the propellant, solids may form and interfere with the operation of the propellant feed and vent systems; therefore, pressurants with freezing temperatures at or below liquid hydrogen temperature must be used; i.e., hydrogen or helium gas.

The stored gas type of pressurization was selected for use on the HTTA. Consideration was given to simplicity, cost, and restart capability in the selection of the type of system to be used. An analysis has been performed for a stored gas type of pressurization system using gaseous hydrogen as the pressurant. This combination will be used during testing. Moreover the test data obtained may be adapted to the analysis of an evaporated propellant (recirculation) type system by the inclusion of information related to a recirculation-type pressurization system.

The mission storage pressure of 17 psia was selected for compatibility with the Cape Kennedy ground service equipment dewar pressure capability. Minimum boiloff loss would be achieved by allowing the liquid to absorb part or all of the heat leak. However, the resulting higher operating pressures would bring about greater pressurant and residual fluid losses. Rising fluid temperature and pressure also necessitate more complex pressure and delivery control systems. Therefore, constant pressure operation was considered advantageous. For constant pressure operation the lowest possible pressure provides thermal optimization. Overall heat leak was found to be insensitive to the short periods of ullage pressurization required to obtain the flow rates of 8.0 pounds per second for 3.5 minutes, the flow requirements for the HTTA. The pressure of 25 psia for high flow conditions was selected to allow a feasible pressure drop of 4 psi during flow from the tank outlet to the feed line coupling and maintain the required 4 psi above the saturation pressure of 17 psia.

7-Day Mission Duty Cycle

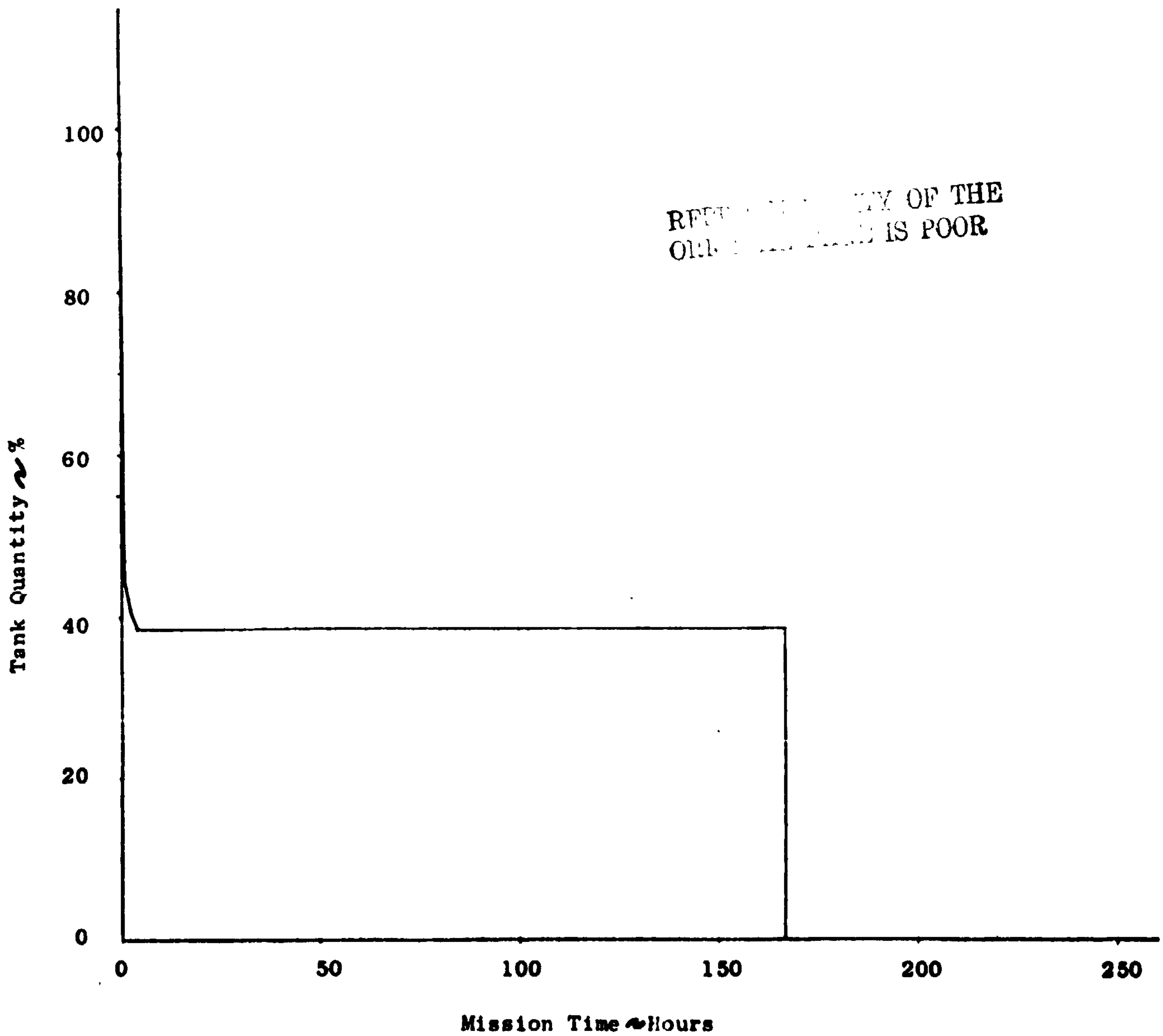


Figure 6

Since the pressurant gas temperature requirements have not been specified for a 180-day mission, a typical system configuration was chosen which would represent a mid-range pressurant gas mass transfer requirement. The pressurant inlet temperature of 250°R was selected primarily for two reasons:

1) The literature review indicated (see Section 3.3) that the gas-to-liquid heat and mass transfer would be negligibly small if: (a) the incoming gas does not impinge upon the liquid surface; (b) the system has low pressurant inlet temperature; and (c) the time of transfer is short compared to the effective time of interfacial transport.

2) Gas pressurant requirements are reduced as the inlet temperature increases.

Considering the above considerations, the selected gas inlet temperature is felt to be a satisfactory compromise to provide minimized pressurant gas quantity and minimized evaporation of stored liquid. The HTTA has been designed such that maximum technology will be generated and verified utilizing this unit. The internal pressure may be varied from 25 to 50 psia and any useful inlet temperature may be studied.

3.2 Gas Pressurant Requirements

When a predetermined quantity of cryogenic liquid must be transferred from a storage vessel within a certain time interval, two techniques have been used - pumps and ullage pressurization. Both techniques are in widespread use, each being more suitable for certain applications. Pumps are usually used in applications requiring low flow rates and long pumping times. Gas pressurized systems have been preferred in applications involving high flow rates.

One of the chief disadvantages of an ullage gas-pressurized system in the past has been the difficulty of estimating the quantity of gas required to pressurize the ullage. Two calculation methods exist for the determination of the mass of pressurant required to transfer a cryogenic propellant: (1) distributed parameter systems, and (2) lumped parameter solutions.

The distributed parameter systems are recommended for very precise calculations, particularly when varying inlet gas temperatures, ambient temperature, or ambient heat flux conditions are to be accounted for, and when extensive, detailed information about the behavior of the system is needed.

The advantages of the lumped parameter solutions are that simple forms of the Laplace transform methods and/or finite-difference approximations can be used. Analyses are thermostatic in character and are useful in obtaining approximate answers for design purposes. Customarily only mean properties of the gas and tank wall are determined.

After an extensive review of the literature, predictions of the transient pressurant requirements were evaluated based on an equation presented by Epstein and Anderson [8]. Their equation is based on computations from a generalized distributed parameter pressurization computer program [6, 10], for the prediction of total pressurant requirements in any axisymmetric liquid hydrogen or oxygen tanks pressurized with evaporated propellant or helium. The generalized computer program is a modified Rocketdyne tank pressurization program that can be used to predict total and transient pressurant requirements and ullage temperature gradients with an accuracy of ±5 percent. Epstein and Anderson's equation, when compared with data, has a maximum deviation of 12 percent. This deviation is acceptable for this analysis since the data will only be used for sizing pressurant flow system components, and adequate tolerances will be included in the selection process. The prediction equation developed in reference 7 was used for this analysis. This equation, including the fixed constants appropriate for hydrogen or helium pressurant, is:

$$\frac{w_p}{w_p^\circ} = \left\{\left(\frac{T_o}{T_s} - 1\right)\left[1 - \exp\left(-0.330\, C^{0.281}\right)\right]\left[1 - \exp\left(-4.26\, S^{0.857}\right)\right] + 1\right\}$$

$$\times \exp\left[-1.50 \left(\frac{1}{1 + C}\right)^{0.312} \left(\frac{S}{1 + S}\right)^{0.160} Q^{0.986}\right] \qquad (1)$$

where

$$C = \left[\frac{(\rho c_p^\circ t)_w}{(\rho c_p)^\circ_G\, D}\right]\left[\frac{T_s}{T_o}\right] \qquad (2)$$

$$S = \left[\frac{h_c\, \theta_r}{(\rho c_p)^\circ_G\, D}\right]\left[\frac{T_s}{T_o}\right] \qquad (3)$$

$$Q = \left[\frac{\dot{q}\, \theta_T}{(\rho c_p)^\circ_G\, D\, T_o}\right] \qquad (4)$$

$$w_p^\circ = \rho^\circ_G\, \Delta V \qquad (5)$$

The range of variables covered in the computer runs used in obtaining Equation (1) are shown in Table V.

TABLE V

Ranges of Variables Covered in Computer Program

Spherical tank diameter	5 - 30 ft
Ellipsoidal tank diameter	5 - 30 ft
Cylindrical tank diameter	4 - 35 ft
Wall thickness	0.1 - 1 in
Ratio of pressurant inlet temperature to propellant saturation temperature	2 - 15
Total outflow time	200 - 500 sec
Ambient heat flow	0 - 10,000 Btu/hr-ft^2

The design of HTTA falls into the range of variables covered in Table V. However, analysis was performed for time intervals below the range given to afford a best guess of the rate of mass required. This rate was needed to determine proper sizing of the flow ystem. The equivalent diameter D in Equation (1) represents the diameter of a cylindrical volume having the same wall surface area and total volume as the tank under investigation and could be considered as the hydraulic diameter. The wall thickness t_w in Equation (1) is defined as the total volume of container metal divided by the total internal wall surface area. The gas-to-wall free convection heat transfer coefficient h_c is calculated at a film temperature equal to $(T_o + T_s)/2$ and at a temperature difference of $T_o - T_s$.

Epstein and Anderson state that care should be exercised when using their estimation equation -

(1) outside the limits shown in Table V

(2) for short duration expulsion (on-off operation)

(3) where massive condensation occurs at the gas-liquid interface

(4) when the initial gas ullage volume exceeds 20% of the total tank volume

(5) when high ambient-to-tank wall heat fluxes cause appreciable evaporation of propellants at the tank walls.

A sample calculation for the total pressurant requirements is presented and proceeds as follows:

Test Conditions

Pressurant	Hydrogen
Pressurized liquid	Hydrogen
Equivalent inner tank diameter, D = 79.090 in	6.591 ft
Equivalent tank wall thickness, t_w	0.1646 in
Pressurant inlet temperature, T_o	250°R
Tank pressure, p	25.0 psia
Total outflow time, θ_t = 3.5 min	0.0583 hr
Ambient heat flux, $\dot{q}$	0
Expelled liquid volume, ΔV	383.3 ft^3

Properties

Molecular weight of pressurant	2.018 lb/lb mole
Specific heat of pressurant at p & T_o, $c_{p_G}^{\circ}$	2.96 Btu/lb_m-°R
Saturation temperature of liquid at p°, T_s	39.86 °R
Tank wall (2219 Al. Al.) density, ρ_w	0.102 lb_m/in^3
Specific heat of wall at T_o, $c_{p_w}^{\circ}$	0.140 Btu/lb_m-°R

Calculations

Film Temperature, $(T_o + T_s)/2$	144.93°R
Temperature difference, $T_o - T_s$	210.14°R
Heat transfer coefficient, He [16]	7.48 Btu/hr/ft^2°R
Pressurant density at p & T_o, ρ_G°	0.0198 lb_m/ft^3

Substituting into Equations (2), (3), (4), and (5) gives

$$C = \left[\frac{(\rho c_p{}^{\circ} t)_w}{(\rho c_p)_G^{\circ} D}\right] \left[\frac{T_s}{T_o}\right] = \frac{(.102)\ (1728)\ (.140)\ (.1646)}{(.0198)\ (2.96)\ (79.090)} \ \frac{39.86}{250} = .13971$$

$$S = \frac{h_c \quad \Theta_T}{(\rho\, c_p)^o_G D} \quad \frac{T_s}{T_o} = \frac{(7.48)}{(0.0198)} \frac{(.058\bar{3})}{(2.96)\ (6.591)} \quad \frac{39.86}{250} = .18010$$

$$Q = \frac{\dot{q} \quad \Theta_T}{(\rho\, c_p)^o_G\ D\ T_o} = 0$$

$$w_p{}^o = \rho^o_G \quad \Delta V = (.0198)\ (383.3) = 7.589$$

$$\frac{T_o}{T_s} - 1 = \frac{250}{39.86} - 1 = 5.272$$

Substituting into Equation (1)

$$\frac{w_p}{w_p{}^o} = \left\{(5.272) \left\{1 - \exp\left[-.330\ (.13971)^{.281}\right]\right\} \left\{1 - \exp\left[-4.26\ (.1801)^{.857}\right]\right\} + 1\right\}$$

$$= (5.272)\ (.17288)\ (.62483) + 1$$

$$\frac{w_p}{w_p{}^o} = 1.5695$$

Then

$$w_p = w_p{}^o \left(\frac{w_p}{w_p{}^o}\right) = (7.589)\ (1.5695) = 11.911\ lb_m\ H_2$$

In Figure 7, predicted pressurant requirements are shown as a function of outflow time for both helium and hydrogen pressurants at tank pressures of 25.0 and 50.0 psia.

3.3 Interfacial Phenomena

Interfacial transfer of heat and mass is intimately associated with both pressurization and stratification phenomena Knowledge of interfacial phenomena is very incomplete due to the coupled nature of the simultaneous transport processes in the liquid and gas phase at the liquid-vapor interface.

Past experience leads to three generalizations [5] : (1) the interfacial temperature is essentially that of equilibrium (saturation) conditions corresponding to system pressure; (2) during pressurized discharge, both condensation and evaporation of the cryogenic propellants at the interface are possible, but usually are not significant factors: and (3) during self-pressurization of liquid containers, interfacial evaporation occurs and the system pressure is governed by the vapor-pressure characteristics of the phases at the interfacial temperature.

Mass transfer by condensation or evaporation at a vapor-liquid interface depends on the relative rates of heat transfer from each phase at the interface. When heat transfer from the vapor to the liquid dominates, evaporation will occur at the interface; when the opposite is true, the vapor will condense; if the respective heat transfer rates are the same, neither evaporation nor condensation occurs and the interface remains stationary. These circumstances will exist generally. For physical systems having convective action in both phases adjacent to the interface, there is no known formulation for predicting the interfacial transport of heat and mass.

Epstein, Georgius, and Anderson [6] in their mathematical model of a pressurized propellant tank that is the basis of a computer simulation program [10] make the following assumptions concerning the interfacial phenomena.

(1) Evaporation or condensation may occur at the gas-liquid interface. Which of these takes place and at what rate depends upon the heat transfer rates in the gas and in the liquid near the interface. Evaporation which is due to heat flux from the tank wall to the liquid is neglected, and bulk boiling of the liquid is assumed absent.

(2) At the gas-liquid interface the vapor is assumed to be in thermodynamic equilibrium with the liquid. Hence, the temperature of the interface is the boiling point at the local partial pressure of the vapor, which must be below the critical pressure.

The resulting studies involving the use of the pressurization computer program [10] indicated that the heat transfer from the pressurant to the container walls is of prime importance. Only in systems involving

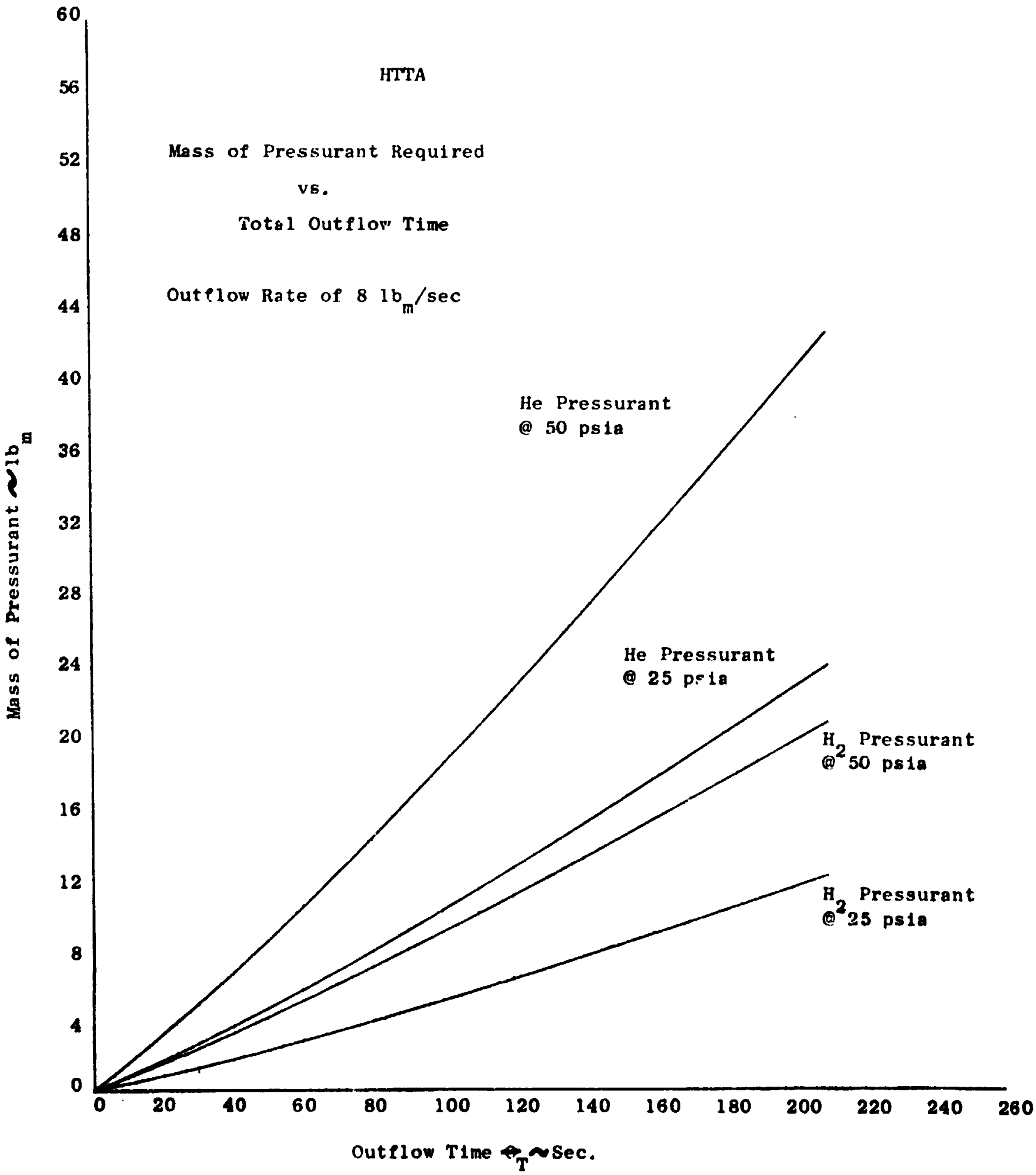

HTTA
Mass of Pressurant Required
vs.
Total Outflow Time
Outflow Rate of 8 lb_m/sec
He Pressurant
@ 50 psia
He Pressurant
@ 25 psia
H_2 Pressurant
@ 50 psia
H_2 Pressurant
@ 25 psia
Mass of Pressurant ~ lb_m
Outflow Time θ_T ~ Sec.
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
0
20
40
60
80
100
120
140
160
180
200
220
240
260

Figure 7

high pressurant inlet temperatures and small tank size should gas-to-liquid heat and mass transfer have an appreciable effect during a fast transfer process.

Gluck and Kline [7] used a gas-phase enventory method to determine the quantity of interfacial mass transfer from experimental evidence. The effect of mass transfer on gas requirements was found to be negligibly small for the conditions studied; i.e., a quiescent gas-liquid interface and low heat leak from the ambient.

The consensus in the literature is that the gas-to-liquid heat and mass transfer will be small if:

(1) the incoming gas does not impinge upon the liquid surface,

(2) the pressurant gas has a low inlet temperature, or

(3) the system embodies a relatively large tank.

Considering the 7-day duty cycle, Figure 6, no time effects will be introduced providing the system is depressurized after flow has occurred. The 180-day profile, having not been defined, was assumed to be 180-day storage, then flow, and therefore, will not introduce interfacial problems. The proposed design of the HTTA has all of the above characteristics. Therefore, it is assumed that the heat and mass transfer at the gas-liquid interface will not introduce interfacial problems.

4.0 SYSTEM DESIGN FOR HTTA

4.1 Pressurization Hardware Description

The hardware required for control of the pressurization system was incorporated into a valve module assembly. Several preliminary designs of the valve module were considered. Designs investigated were attached, detachable and floor mounted systems. The advantages and disadvantages of a detachable vs. attached module are shown in Table VI.

The detachable module was selected because of the increase in valve performance, fewer components, and ease of transportation and handling. A small increase in pressure drop and additional coupling costs were minor disadvantages. The floor mounted system was eliminated because of increased cost, longer feed lines, and the resulting higher pressure drop.

Components and line sizes for each type of system are shown in Figures 8 and 9. All valve module components were selected with consideration being given to dependability, reuseability, maintainability, and thermal performance. The valve module was designed such that critical parts, i.e., valve seats, can be replaced without removal of the component from the lines.

The valve module is supported from the HTTA girth rings. Exterior coupling interfaces are symmetrical about the HTTA horizontal centerline to facilitate connection of service lines when testing the tank in the inverted position. The feed/fill, vent flow and vapor cooled shield lines exit through the tank's outer shell perpendicular to the tank surface. The ullage pressure relief system is protected by relief valves and rupture discs on the outlet side of the pressurant valve. Pressurant flow is console-controlled by a direct acting dome-loaded regulator in series with a solenoid shutoff valve. All materials in contact with fluids are compatible with GHe, LH_2, and GH_2. LH_2 transfer lines are stainless steel tubing with weld ends on all components. Valve module electrical accessories are designed for safe operation in a hydrogen environment. Test facility (100 psi) gas supply is utilized to pressurize the cylinders which operate remote control feed/fill and vent flow valves. Bayonet coupling provide test facility interface for the feed/fill vacuum jacketed line. The balance of the interface connections are AN 37° type fittings

TABLE VI

Detachable Module Evaluation

DISADVANTAGES

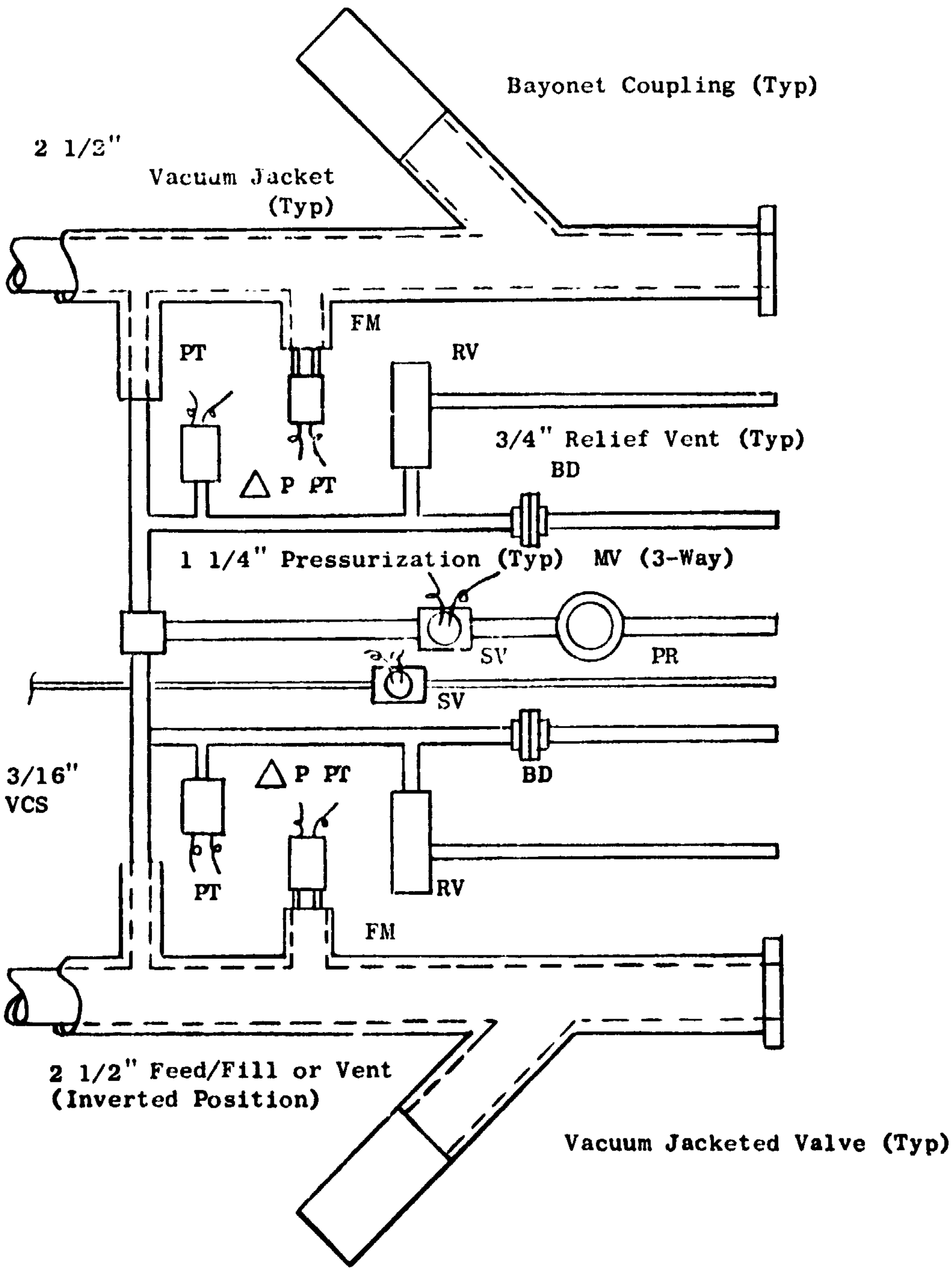
1. Extra set of bayonet fittings
2. Slightly larger line loss
3. Install module before test
4. Need hoist for attachment
5. Extra cleanliness precautions
6. More expensive mounting brackets
7. Separate vacuum pumpout ports
8. Bayonet coupling mating

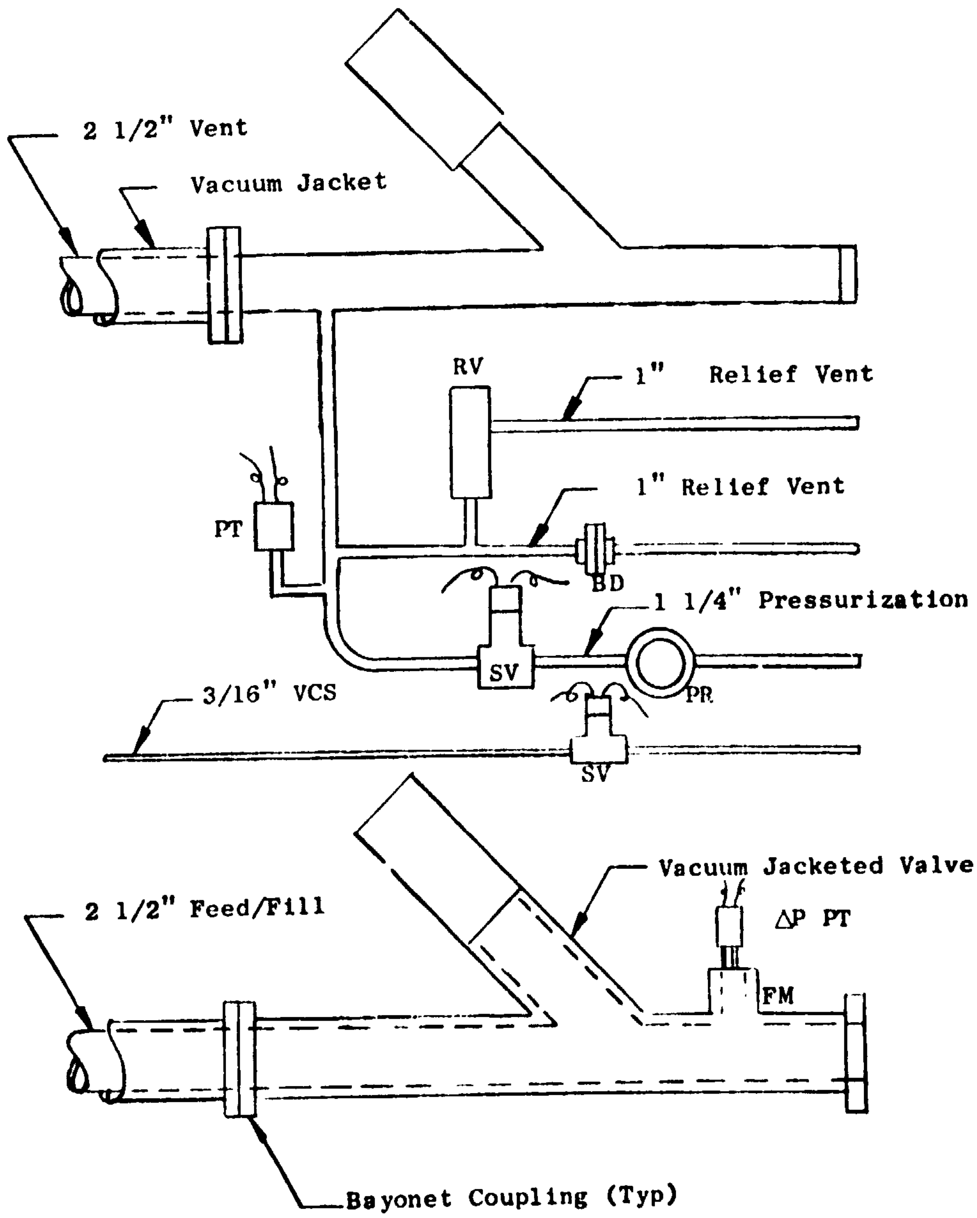
ADVANTAGES

1. Ease of transportation
2. Valves operate in upright position
3. Less components
4. Cheaper components
5. Easier handling for leakage and proof pressure tests
6. Simultaneous fabrication
7. Easier facility hook-up (more compatible for hard wiring and plumbing)

Figure 8

ATTACHED VALVE MODULE





Detachable Valve Module

Figure 9

4.2 Pressure Drops in Feed and Pressurant Lines

4.2.1 Feed Lines

For purpose of analysis, the feed lines were sized to facilitate the delivery of liquid hydrogen to the feed line outlet coupling 4 psi (+ 0 psi - 2 psi) above saturation pressure. The liquid hydrogen will be in equilibrium at 17 psia (see Section 3.1) prior to prepressurization and the flow test. Therefore, the saturation pressure was assumed to be 17 psia. The control pressure for transfer conditions was selected as 25 psia allowing a 4 to 6 psia pressure drop through the feed line and valve. A schematic of the feed line analyzed is shown in Figure 10.

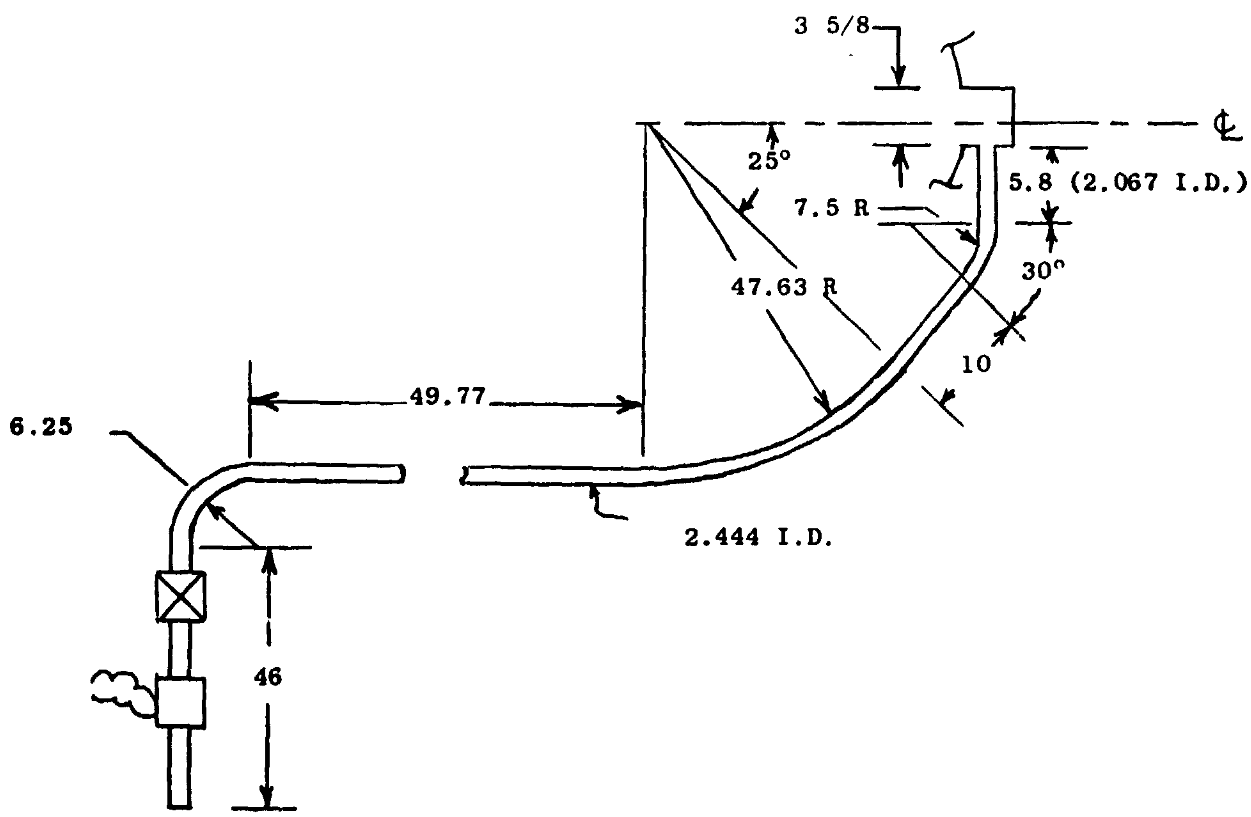


Figure 10

FEEDLINE SCHEMATIC

The resistance coefficients, friction coefficients, and equivalent lengths were taken from [9]. The pressure drop breakdown is as follows:

TABLE VII

Resistance Item	K	L/D	Equivalent L (Ft)
Entrance - Sharp Edge	0.5	50	10.18
Sharp Bend - 90°		60	12.22
Sudden Restriction	0.3	30	6.11
Line 2.067" I.D. x 8.3"			.69
Bend 7.5" R x 30°		4	.81
Bend 47.63 R x 65°		40.8	8.31
Bend 6.25" R x 90°		12	2.44
Tee - Flow Thru		20	4.07
Valve - Gate Type - Open		13	2.65
Flow Meter			2.0
Line, 2.444" I.D. x 108"			

The total pressure drop through the feed line and valve was calculated to be 4.3 psi for the nominal transfer condition of 8 lb/sec flow rate and a control pressure of 25 psia. Liquid will then be provided at a pressure of 20.7 psia at the fluid outlet coupling.

4.2.2 Pressurant Line Losses

The pressurant line losses (pressure drops) were calculated for the four pressurant mass flow rates as specified in Section 3.2. The maximum flow values (maximum slope of curves) were used for these pressure drop calculations. These flow rates are shown in Table VIII. The pressurant system lines were sized to provide an acceptable pressure drop to facilitate operation during test. The line sizes and configurations used for the analysis were as shown in Figures 9 and 10. The worst pressure drop condition for the pressurant line was found to be transfer using the GHe pressurant at 50 psia. The calculated pressure drops are as follows:

TABLE VIII

Pressurant	Pressure	Flow Rate	ΔP
GHe	50 psia	0.223 lb/sec	11.0
GHe	25 psia	0.126 lb/sec	8.0
GH_2	50 psia	0.108 lb/sec	5.1
GH_2	25 psia	0.065 lb/sec	3.8

4.3 Control and Operation

The HTTA will be designed to permit remote operation after the test facility lines have been connected. All control valves and regulators will be controlled from a remotely located test console. The flow meter and pressure transducer outputs will be transmitted to the test console for amplification and readout using standard test equipment. Limit switch indications from the pneumatically operated valves will also be transmitted to the test console.

4.3.1 Cool-Down and Fill Procedure

The tank will be filled in either the upright or the inverted vertical positions. Both feed/fill and vent flow valves (pneumatically operated) will be opened while all other valves and regulators will be closed. Liquid hydrogen will then flow into the tank through the feed/fill line and the hydrogen gas and residual purge gases will be vented through the upper transfer line. The cool-down operation will continue until all lines and the pressure vessel are cooled down and temperature stabilized. The pressure vessel will then be filled.

The remotely operated pneumatically controlled flow valves will be operated from the test control console. These console controls will regulate electrical power to the solenoid pilot valves that actuate the pneumatic operators. Limit switches on these pneumatic operators will provide feedback of the valve position (open or closed) to the test console.

4.3.2 Purging Operation

The pressure vessel may be purged, prior to and after filling as required by utilizing the pressurant system. The purge gas will be introduced into the tank through the pressurant line with the solenoid valve and regulator open. The purge pressure can be controlled by the dome loaded regulator in the pressurant system. The residual gases in the tank may be vented through the lower transfer line with the valve open.

4.3.3 Flow Test Operation

The flow test will be performed by flowing LH_2 through the feed/fill line while pressurizing through the vent/pressurant line. The pressurant system connects to the vent/pressurant line, upstream of the remote pneumatically operated valve which will remain in the closed position. All other valves will be in the closed position. The tank pressure will be maintained by the dome loaded regulator which will be controlled by a hand loading regulator at the test control console. Tank pressure and flow rate data will be fed back by transducers and recorded at the test control location.

4.4 Safety and Relief Operation

4.4.1 Pressure Vessel Relief System

The pressure vessel is protected from overpressurization by a parallel mounted relief valve and rupture disc located with no valve between the vessel and vent port. The relief valve will be set at 56 psia and the rupture disc designed to burst at 61 psia. These settings were determined from the analysis which allowed a 5 percent tolerance on the relief pressure and a 2 percent tolerance on the rupture pressure.

The relief system lines were sized for a maximum pressure drop of 3 psi during the worst condition requiring relief flow (Case 2). The two following cases were considered for analysis of the relief system requirements.

CASE 1

The HTTA loses vacuum in the annulus due to a leak in the vacuum jacket with the pressure vessel being full of LH_2. Ambient air flowed into the annulus at a rate sufficient to maintain the annulus at near atmospheric pressure. Liquid air will condense on the pressure vessel surface. The calculated boiloff rate at this condition will be approximately 27 pounds per hour of gaseous hydrogen.

CASE 2

The HTTA loses vacuum in the annulus due to leak in the pressure vessel while the pressure vessel was full of LH_2, resulting in continuous hydrogen vapor flow into the annulus. The vacuum jacket pressure relief disc will relieve at approximately 20 psia. Hydrogen vapor continues flowing into the annulus, maintaining 20 psia in the annulus. The hydrogen vapor temperature was assumed to be at an average between liquid hydrogen temperature and maximum ambient temperature (140°F). The resulting boiloff rate for this case was approximately 240 pounds per hour.

The relief system was arranged to provide a low pressure drop between the pressure vessel outlet and the relief valve at the maximum relief flow conditions. The maximum pressure in the pressure vessel would be 56.2 psia since the relief valve would relieve at 53.5 psia $\pm$ 5%. The rupture disc would burst between the pressures of 57.6 and 66.0 psia at 140°F.

4.4.2 Vacuum Jacket Relief System

The vacuum jacket will also be provided with a pressure relief device for the condition discussed in Case 2 above. The relief device will be designed to relieve below the maximum pressure considered in the structural design of the vacuum jacket or the collapsing pressure of the pressure vessel, whichever is smallest. The relief device will have a tolerance of two percent or less. The vacuum jacketed lines and modules will have separate relief devices if the line vacuum jackets do not communicate with the vacuum annulus of the tank.

5.0 CONCLUSIONS

5.1 Pressurant Selection

Hydrogen gas will be used as the pressurant for HTTA because evidence exists to indicate that a recirculation-type pressurization system will be the final selection on the space shuttle and similarity in this respect is preserved. The recirculation-type pressurization system appears to be more desirable than the stored gas system. A stored gas system would weigh more and require a larger volume than the recirculation-type pressurization system.

However, a stored gas system, utilizing hydrogen, has been selected for HTTA because it will: (1) require less hardware and hardware development than a recirculation-type pressurization system; (2) the results will still be directly be applicable to a recirculation-type system.

The system is designed to also accommodate the use of helium gas as the pressurant when supplied by a stored gas system. The gas requirements are shown in Figure 7 of Section 3.2 for both hydrogen and helium pressurants at entrance pressures of 25.0 and 50.0 psia and 250°R.

The pressurization gas mass transfer analysis determined that the mass of helium gas required will be larger than the mass of hydrogen gas required for pressurization. Analysis also shows that a greater pressurant mass (helium or hydrogen) will be required for pressurization at a system pressure of 50 psia than for a system pressure of 25 psia.

5.2 Design Selection

The detachable valve module concept is recommended for the pressurization and flow control components because it provides for less components, higher operational dependability, and easier transportation.

A dome loaded pressure regulator will be used for pressure control during the high flow test. A blowdown system without a regulator was considered but without a regulator a substantial inlet gas pressure decrease would occur unless the stored gas supply was large in comparison to the pressurization gas required.

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