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DESIGN OF AN INERT FLUID INJECTION SYSTEM

PHASE III

FINAL REPORT

Contract NAS5-11614

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by

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FOREWORD

This report presents the results of work performed by Lockheed's Huntsville Research & Engineering Center while under contract to Goddard Space Flight Center, Contract NAS5-11614. This work was accomplished under Phase III of the Work Statement of the subject contract. The NASA technical coordinator for this study was Mr. Daniel Dembrow, of the Delta Project Office.

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Section 1
INTRODUCTION AND SUMMARY

The accurate placing of unmanned payloads into specified orbits necessitates that the velocity differential imposed on the payload fall within predetermined tolerances. The ability to provide a controlled velocity trim of a known magnitude to an orbital vehicle would enhance the possibility of success of such missions. The program reported on in this document had as its goal the research, development and design of such a velocity trim system for the third stage of the Delta launch vehicle. This goal has been achieved.

A system has been designed which will accomplish the velocity trim by injecting an inert propellant into the Delta third stage motor after burnout. The heat stored in the motor case is utilized to augment the propulsive energy of the injected fluid. In such a system, the inert fluid is sprayed into the motor chamber where it either changes phase instantaneously, i.e., flashes, or contacts the heated surface of the motor case and subsequently vaporizes. The mass of inert fluid which can be vaporized by this system is dependent on the amount of heat which can be stored in the spent rocket motor case (results from Phase I of this study indicate that 33,000 Btu of heat will be stored in the case of the Delta third stage motor at burnout). The heated vapor is then expanded to ambient conditions through the converging-diverging nozzle of the rocket motor, yielding a useful thrust level. A relatively low thrust system results from this approach.

This report presents the results of work completed during Phase III (design) of the planned four-phase study. The results of Phase I, Theoretical, and Phase II, Small Scale Testing, which form the basis for this present effort are reported in Ref. 1. The Phase III study program was divided into two sections, A and B. Section A was devoted to the development of additional design information needed to complete a detailed design and included extended small-scale testing and analytical evaluation of fluid types (Ref. 2). In Section B of the study a full-scale working fluid injection velocity trim system was designed.

The work completed during Phase III has resulted in the detailed design of a full-scale working fluid injection system for use with the TE-364-3 Delta third-stage propulsion system. A set of final design drawings suitable for fabrications by any qualified source has been generated.

The description and operation of the inert fluid injection system is presented in Section 2. Sections 3 and 4 summarize the detailed design of the system and present conclusions and recommendations. Calculations made in support of the final design are presented in Appendixes A through I.

Section 2
SYSTEM PHYSICAL AND FUNCTIONAL DESCRIPTION

A system to provide a controlled velocity trim of a known magnitude for the third stage of the Delta launch vehicle has been designed. In this system the thrust necessary to provide such a velocity increment is obtained by the injection of an inert fluid into the spent Delta third stage propulsion motor (a TE-364-3 solid propellant rocket motor). The inert fluid is sprayed into the motor chamber where it either changes phase instantaneously, i.e., flashes, or contacts the hot internal surfaces of the rocket motor and subsequently flashes. Approximately 33,000 Btu of heat are available in the TE-364-3 motor case at burnout to vaporize the injected fluid. The heated vapor is then expanded to ambient conditions through the converging-diverging nozzle of the rocket motor, yielding a useful thrust level. The components which comprise the Inert Fluid Injection System (IFIS) and their functional relationships are described in the remainder of this section.

2.1 IFIS DESCRIPTION

The IFIS, as shown in Fig. 1, has three basic component groups:

- Inert fluid storage tank and support cone
- Valving, plumbing and mounting structure
- Ignition-injector assembly

The inert fluid storage tank and support cone form the nucleus of the IFIS. The fluid storage tank is torus shaped; is to be constructed from Ti-6Aℓ-4V titanium alloy; and has a volume of 1.5 cubic feet. Nominal dimensions of the tank are given in the sketch on page 5. The tank is designed for a maximum operating pressure of 150 psia, utilizing a four to one safety factor on the ultimate stress.

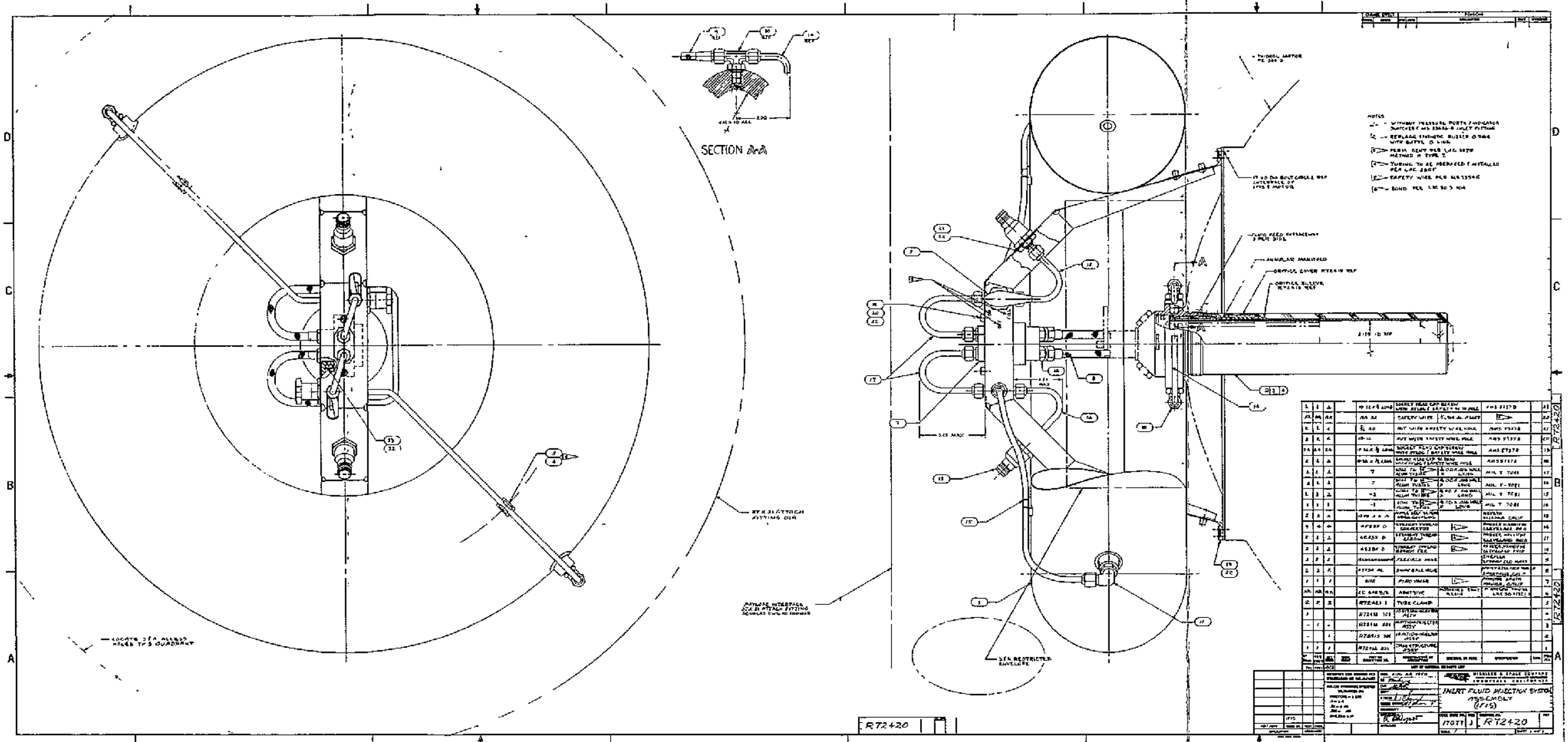
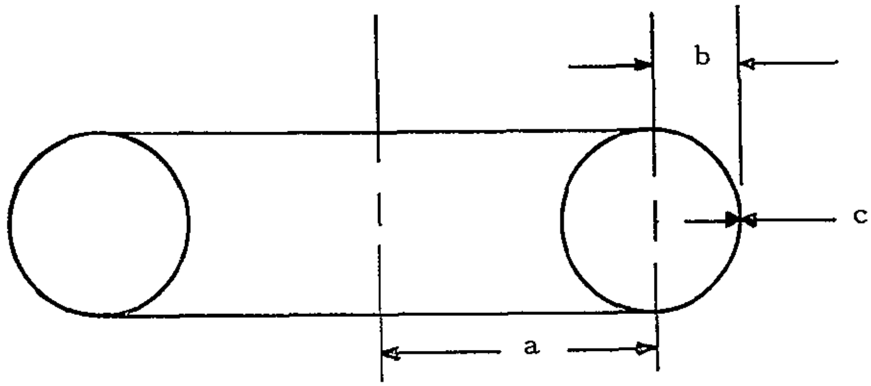


Fig. 1 - Inert Fluid Injection System Assembly

FOLDOUT FRAME 1

FOLDOUT FRAME 2



a = 10.5 in. b = 3.56 in. c = 0.022 in.

A cone frustum, also constructed of Ti-6Aℓ-4V titanium alloy, supports the tank. The base of the frustum flares to a ring which has the 17.6 in. diameter bolt hole pattern for mounting to the forward attach surface on the TE-364-3 motor. The cone frustum was designed with an allowable stress of 50,000 psi which is based on a one- and one-half design safety factor applied to the yield point stress. The forward end of the frustum is welded to the fluid storage tank so that tank and the cone frustum become one part at assembly.

To support the valves and plumbing used in the IFIS, a channel section, fabricated from 0.040 in. titanium (Ti - 6Aℓ-4F) alloy sheet is fastened to the cone frustum with blind rivet fasteners. The cone frustum is sandwiched between the valve support channel and doublers to prevent local buckling of the frustum. Holes are provided in the valve support channel for mounting the required valves and for routing of the interconnecting plumbing.

Several types of valves are utilized in the IFIS. Figure 2 presents a tabulation of the type, quantity, and basic function of the valves that are utilized, and correlates this information with a flow diagram. Two parallel flow systems are provided in the IFIS design. Each system is composed of a quick disconnect valve; a manually operated, three position, two-way valve;

and a pyrotechnically operated normally closed, normally open valve. The quick disconnect valve has self-sealing properties to prevent spillage during the fill or drain operation. It is to be noted that only the nipple portion of the quick disconnect valve is considered a part of the IFIS.

IFIS VALVING REQUIREMENTS

No.	Description	Quantity	Function
1	Manual-3 position 2-way ball valve	2	Safe and arm valve in fill and drain system
2	Normally-closed, Normally-opened, pyrotechnic valve	1	Used to initiate and terminate fluid flow to the injector
3	Self-sealing quick disconnect valves	2	Provides no-spill interface for fill and drain operations

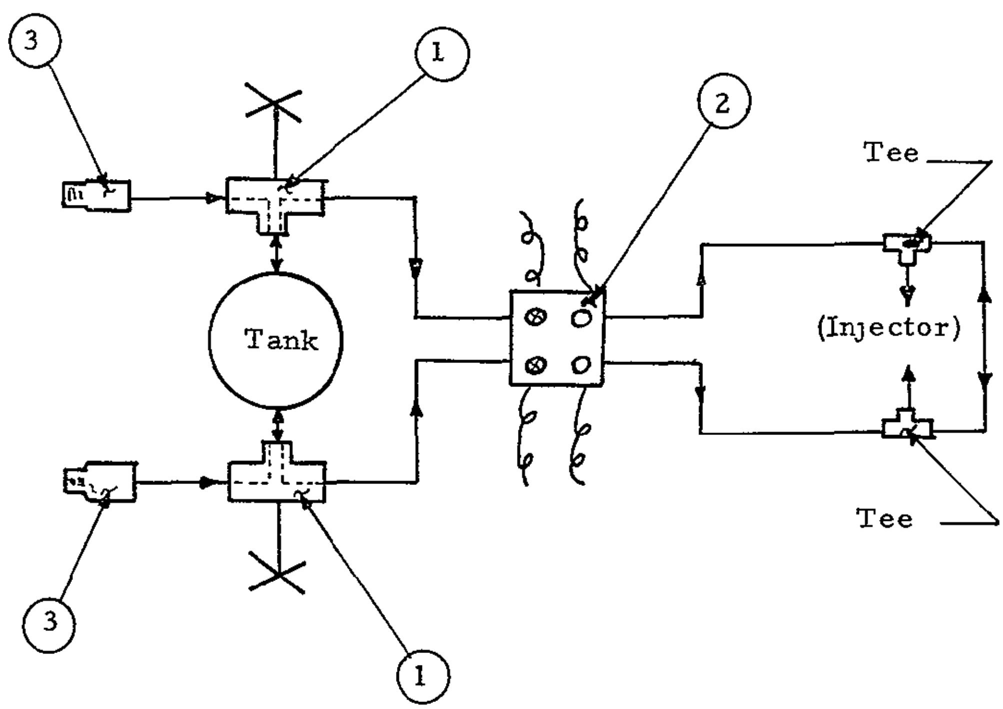


Fig. 2 - Flow Diagram for Inert Fluid Injection System (IFIS)

A manually operated, 3-position, 2-way valve is used in each flow system. By positioning this valve correctly the following functions can be performed: fluid flows through the quick disconnect valve to the storage tank during fill operation (flow is reversed during drain); fluid flows from the tank to the pyrotechnic valve (when in armed position); and there is no flow when the valve is in "safe" position.

The pyrotechnically operated valve utilized in the design is a dual-passage, four-squib, normally closed, normally open valve. Each passage in the valve contains a normally closed and a normally open squib actuated valve. During operation the normally closed valves in the passages are actuated simultaneously to initiate fluid flow to the injectors. Fluid flow is terminated by simultaneous actuation of the normally open valves.

Thin wall aluminum tubing (0.25 in. o.d.) interconnects the various valves with the exception of the pyrotechnic valve to injector path. A flexible hose, used in this location, ensures endpoint compatibility between the pyrotechnic valve and ignition-injector assembly. Standard type tube fittings accommodating 37-degree flared tubing are utilized throughout the flow system.

The remaining components of the IFIS, which comprise the ignition-injection assembly, are: a modified Thiokol E19578-02 ignition case; a porous metal orifice sleeve; and a pyrolytic graphite orifice cover sleeve. To flow the quantity of fluid required to meet performance criteria, the Thiokol case is modified to accommodate two external bosses with three-fluid feed passageways per boss (see Fig. 2). The fluid feed passageways supply an annular manifold which is created during assembly when the porous metal sleeve is fitted on the ignition case. Eight orifice (or injector) ports are located around the aft end of the porous sleeve. A "press" fit is utilized to hold the porous sleeve in place on the aluminum case. A pyrolytic graphite sleeve covers the orifice ports to prevent them from becoming clogged during the normal burn of the TE-364-3 motor. Unique properties of the pyrolytic graphite are that it has a high compressive strength and a low tensile strength, which allow the graphite to protect the orifice ports during the high temperature and pressure burn of the

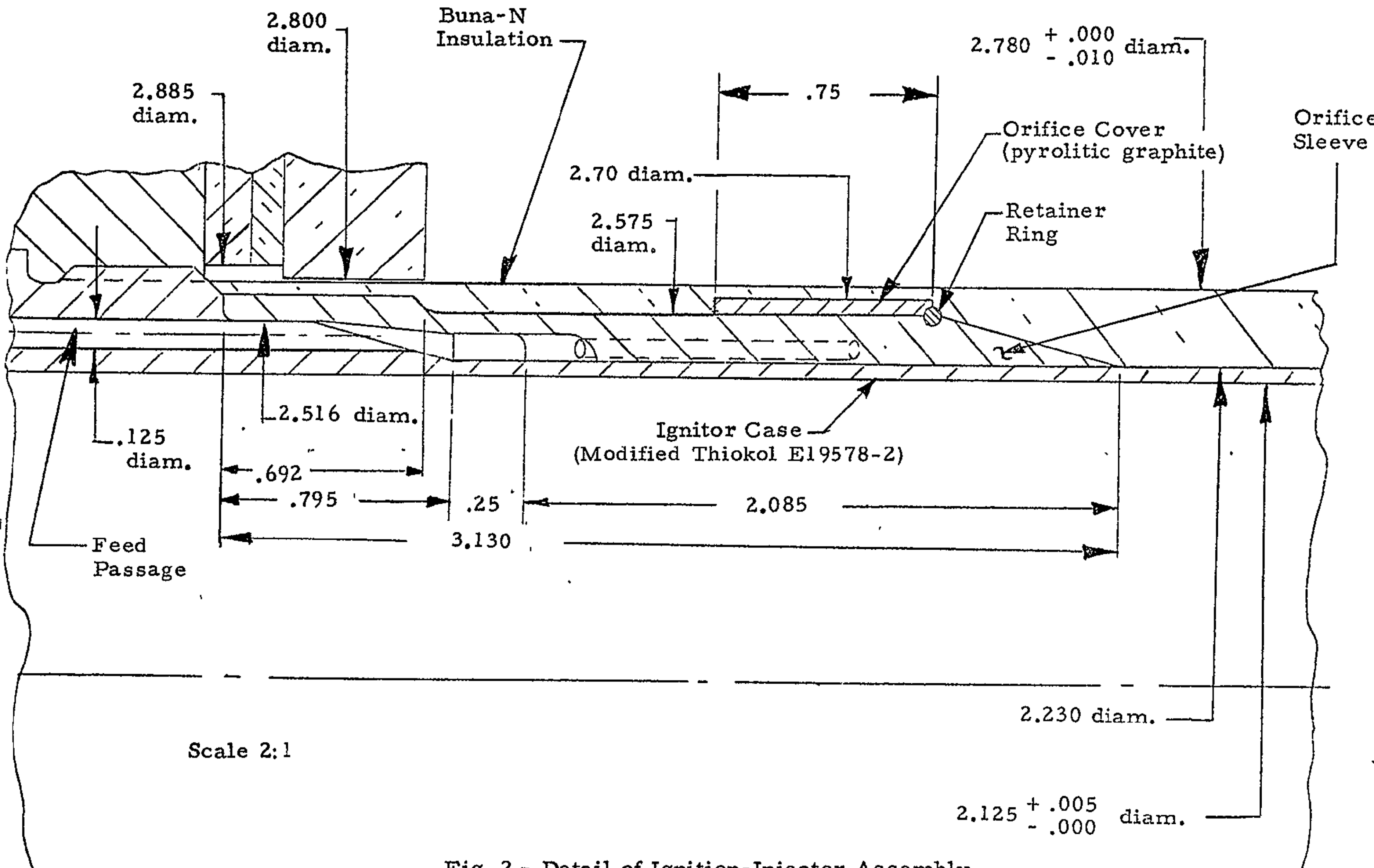


Fig. 2 - Detail of Ignition-Injector Assembly

TE-364-3 rocket motor. However, the graphite can be removed by applying relatively low fluid injection pressure. A retaining ring prevents any relative axial movement of the graphite sleeve and porous sleeve during the normal motor burn. Buna-N insulation is applied over the total length of the case of the ignition-injector assembly to provide thermal protection during TE-364-3 burn. A listing of the components of the IFIS with their applicable drawing number is given in Table 1.

2.2 IFIS OPERATIONAL SEQUENCE

The functional relationship of the various components which comprise the IFIS is most easily understood by following a typical operation sequence. First, the necessary ground support equipment (GSE) is connected to the IFIS by means of the quick disconnect (QD) valves. The manually operated three-position valve is placed in the FILL-DRAIN position and the inert fluid is loaded into the storage tank. (The fluid is either stored under its own vapor pressure or pressurized with dry N_2(G), depending on the fluid utilized.) After the tank is filled with the proper quantity of fluid, the three-position valve is turned to the SAFE position and the GSE is removed. The IFIS is then installed on the TE-364-3 rocket motor and the flexible lines attached between the pyrotechnic valve and the ignition-injector assembly. At a specified time prior to launch the four squibs are installed in the pyrotechnic valve and the 3-position valve moved to the ARM position.

If a velocity trim is required after normal burn of the third stage motor, the normally closed squib operated ports in the pyrotechnic valve are opened by a signal, and fluid flows from the tank to the ignition-injector assembly. Pressure from the fluid then causes the pyrolytic graphite orifice cover to fracture, thereby exposing the orifices. The inert fluid is injected into the motor case in a direction opposite to third-stage rotation. The fluid vaporizes and is expanded to ambient conditions, producing a useful level of thrust. Storage tank pressure and injector orifice size regulate the flow system. After the desired velocity trim has been obtained, the normally open squib-operated valves are actuated and fluid flow is terminated. The IFIS can be used once during a given mission.

Table 1

INERT FLUID INJECTION SYSTEM APPLICABLE DRAWINGS

Item	Drawing No.	Title	Type Drawing
1	R72420	Inert Fluid Injection System Assembly	Final Assembly
2	R72412	Tank Structure Assembly	Subassembly
3	R72413	Ignition-Injector Assembly	Subassembly
4	R72414	Tank-Thrust Cone	Detailed Weldment
5	R72415	Valve Support	Detailed Weldment
6	R72416	Doubler	Detail
7	R72417	Case	Detail
8	R72418	Orifice Sleeve	Detail
9	R72419	Orifice Cover	Detail
10	R72421	Tube Clamp	Detail

Section 3
TECHNICAL DISCUSSION

The underlying philosophy of the design of the inert fluid injection system was dictated by: the performance goals imposed at the inception of this study; the results obtained from Phases I and II; and the physical and environmental constraints imposed by the Delta launch vehicle. A performance goal of a total impulse correction of 1% of the total impulse of the TE-364-3 rocket motor (or about 4000 lb_f-sec) was assumed at the onset of this study. Theoretical and experimental results obtained in Phases I and II established the feasibility of the fluid injection concept but indicated that a low thrust system could be expected. This information is summarized in Appendix A. A fluid selection study, conducted in support of the conceptual design indicated that a system capable of handling multiple fluids was desirable. Results of this investigation are presented in Appendix B. The physical and environmental constraints imposed by the Delta launch vehicle imposed the configuration limitations and structural criteria on the design. A set of design criteria that reflected the constraints, limitations, boundaries and results of previously completed studies was prepared. Detailed design of the Inert Fluid Injection System was based upon these criteria, which are presented in Appendix C.

Pertinent areas in the design of the IFIS are discussed in the remainder of this section. Detailed calculations which support the design are presented in Appendixes D through I.

3.1 MAJOR COMPONENT DESIGN

3.1.1 Inert Fluid Storage Tank

The inert fluid storage tank was designed under the following basic constraints:

- Storage tank must fit within the boundaries of the 31 x 37 in. attach fitting (as defined in Ref. 3)
- Minimum empty tank weight
- Must withstand structural loads imposed with a safety factor of four applied to the yield point stress of the material
- Must have a minimum volume of 1.5 ft^3.

Various tank configurations and materials were evaluated before a final selection was made. The initial optimum shape was based on minimum weight considerations. Table 2 shows results of a study that considered three tank configurations, each having a volume of 2.085 ft^3, an operating pressure of 106.2 psia, and constructed of the same titanium material.

Table 2

TANK CONFIGURATION COMPARISON

Shape	Wall Thickness (in.)	Weight (lb)
torus	0.020	5.32
elliptical	0.072	13.22
spherical	0.0162	2.92

The spherical tank proved to be the most efficient shape, but it required the largest overall dimensions (a diameter of 19.0 inches), and thus could not be packaged inside the 31 x 37 attach fitting. Because of these considerations, the torus tank shape was selected for use in the design.

After the tank shape was selected, candidate materials were evaluated. Table 3 lists the results of a comparison of the weight of a torus tank constructed of various materials.

Table 3

TANK MATERIAL COMPARISON

Material	Density (lbm/in^3)	Allowable Stress (lb_f/in^2)	Thickness (in.)	Weight (lb_f)
17-7 PH Steel	0.273	46,500	0.0135	6.19
Modified H-11 Steel	0.281	60,250	0.0103	4.88
Ti-6Aℓ-4V Titanium	0.158	31,250	0.0200	5.32
5154 Aluminum	0.096	8,250	0.0758	12.27

This table shows that a tank constructed of Modified H-11 steel is lightest in weight. However, this advantage is overshadowed by the thin wall which imposes fabrication and handling problems. Thus, as a result of these two investigations, a torus tank constructed of Ti-6Aℓ-4V titanium appeared to be the most desirable.

An alternate method was considered to determine the optimum tank material. In this method the tank mass per internal volume ratio is expressed as a function of the material properties (density and stress) and the operating pressure. Tank materials are compared on the basis of the quantity K where K is defined by the following relation

$$\frac{\text{mass of tank material}}{\text{internal volume of tank}} = K \text{ (operating pressure)}$$

Results of this investigation, presented in Table 4, showed that for the same operating pressure and internal volume, the aluminum tank would be heaviest and a steel tank the lightest. A titanium material was selected for the tank, resulting in a tank weight slightly heavier than steel in order to keep tank wall thicknesses large enough to be fabricated easily.

The resultant tank design selected for use in the IFIS has the characteristics given in Table 5. In considering these tables, it should be kept in mind

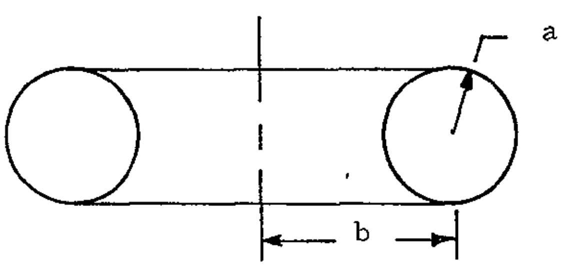
Table 4

ALTERNATE TANK MATERIAL COMPARISON TECHNIQUE

Material	Density (lbm/in.^{3})	Working Stress (lb$_f$/in.^{2})	K_1
17-7 PH Steel	0.276	92.5×10^3	4.475×10^{-6}
Modified H-11 Steel	0.281	120.5×10^3	3.497×10^{-6}
Ti-8Aℓ-1Mo-1V Titanium	0.158	62.5×10^3	3.792×10^{-6}
5154 Aluminum	0.096	16.5×10^3	8.727×10^{-6}

Table 5

IFIS TANK CHARACTERISTICS



Overall Weight	5.138 lb
Volume	1.5 ft^3
Wall Thickness, t_n	0.022 in.
Radius "a"	3.56 in.
Radius "b"	10.5 in.

that the tank fits within the 31 x 37 attach fitting and does not interfere with the spring loaded stage separation mechanism or the safe and arm envelope that surrounds the ignition-injection mechanism.

3.1.2 Cone Frustum Tank Support

The cone frustum tank support was designed to support the loads imposed by the fully loaded tank, the values and associated plumbing; and to provide an attach surface for mating the IFIS with the TE-364-3 rocket motor. Preliminary analysis, Appendix D, resulted in the selection of titanium (Ti-6Aℓ-4V) as the material for the support cone with a recommended wall thickness of 0.016 in.

3.1.3 Valving and Plumbing

Valving and plumbing for the IFIS are all commercially available items requiring no special modifications. Anticipated sources for these components are shown on Fig. 1, List of Materials.

3.1.4 Ignition-Injector Assembly

Design of the injector system and of the modifications to the Thiokol E19578-02 ignition case presented the most challenging problems of the study. The injector system design requirements included:

- Ability to flow desired flow rates for the selected working fluids and to distribute flow over maximum area
- Ability to withstand environment imposed by the TE-364-3 ignition and subsequent burn
- Existing ignition hardware must be used as a basis for the design, and it must not detract from the ability of the ignition hardware to accomplish its intended purpose.

The final configuration of the ignition-injection assembly is shown in Fig. 2. Four modifications were made to the basic E19578-02 case configuration. The number of external bosses was increased from one to two to facilitate the required flow rates. The width of the 4.00 in. diameter shoulder of the case was increased to 0.84 in. to facilitate an increased maximum boss port diameter of 0.562 in. Finally, to transfer the fluid to the injection ports, three feed passages of 0.125 in. diameter were provided to connect each boss port to the fluid distribution manifold. In incorporating these design changes to the case, the existing minimum wall thickness was maintained at all locations.

The fluid distribution manifold is formed by a sleeve constructed of porous metal. Eight injector ports are equally spaced around the periphery of the aft end of the sleeve. To determine the pore size of the porous material of the sleeve, the surface tension of the working fluids was considered along with their temperature and pressure characteristics. The minimum pore size required is 3 microns with the largest being 104 microns. Suitable materials possessing the required porosities are commercially available. Calculations for the pore sizing are to be found in Appendix D. Material pore size for butane is 3 microns; for water, 104 microns; and for ammonia, 3.78 microns.

To protect the injector ports during main motor burn, a pyrolytic graphite sleeve was fitted over the aft end of the porous metal orifice sleeve. The graphite's unique properties of high compressive strength and low tensile strength were utilized in this application. Compressive loads are imposed on the sleeve during main motor burn and tensile loading sufficient to fracture the graphite exposing the injector ports are imposed by the inert fluid. Calculations for the preliminary sizing of the graphite sleeve are presented in Appendix D.

3.2 THERMAL ANALYSIS

The thermal analysis conducted in support of the IFIS design consisted of an assessment of the effect of the general thermal environment of the tank and structure and a detailed thermal analysis of the ignition-injector assembly. A review of the third-stage environment requirements indicated that the IFIS could function normally under these conditions. To accomplish the detailed analysis of the ignition-injector assembly, a two-dimensional axisymmetric thermal model was constructed. Temperature distributions in the ignition-injector assembly were calculated as a function of time, from main motor ignition for a total elapsed time of 200 sec. Results of the analysis indicated that a minimum of 0.040 in. thick Buna-N insulation should be used over the graphite sleeve for added thermal protection, and that improved thermal protection for regions of the porous metal sleeve not covered by the graphite orifice cover was needed. Two remedies for improved thermal protection were proposed. The first involved extending the graphite cover over the entire length of the porous sleeve, while the second involved increasing the thickness of the Buna-N insulation. The latter method was selected. Results of the thermal analysis are presented in Appendix F.

3.3 STRUCTURAL ANALYSIS

To ensure structural integrity throughout the planned mission, each component of IFIS was investigated individually for its respective maximum loading conditions. The logical system breakdown is: tank, tank support cone, ignition-injector assembly and the plumbing system.

The tank and support cone were analyzed individually for their maximum load case. The tank maximum load occurs when vibrational loading and internal pressure are acting in combination. The support cone maximum load is experienced when the fully loaded tank vibrational loads act in a mode which is trying to buckle the cone. The direct axial loading of the support cone is minimal as compared to the critical axial load (critical axial load = 4800 lb; direct axial load = 900 lb). Calculations for the tank and thrust cone were performed manually, using standard stress equations. A mathematical model was constructed to evaluate the tank-thrust cone structure assembly, the purpose of which was to verify the hand calculations and to investigate further the weldment of the assembly by examining the stresses and deformations throughout the system.

The ignition-injector assembly was analyzed structurally for the following imposed conditions:

- Pressure pulse of 1254 psia applied internally to aluminum injection case caused by pyrogen ignition
- Main motor ignition pressure spike of 925 psia for 0.75 sec duration (applied externally)
- Thermal expansion caused by resulting temperature distributions.

Pyrogen ignition produces an average pressure pulse of 1254 psia, Ref. 4, internal to the ignition-injector assembly. Application of the pressure causes the aluminum case to deflect radially. To prevent the buildup of excessive hoop stresses in the porous orifice sleeve, clearance is provided between the aluminum case and porous sleeve. This clearance also attenuates stress buildup caused by the temperature distribution and difference in coefficients of thermal expansion of the aluminum and porous materials.

Applying each of the imposed conditions to the pyrolytic graphite sleeve produced the following results. The pyrogen ignition pressure pulse and associated temperature rise did not produce stresses large enough to cause premature failure of the graphite. Application of the main motor pressure transient to the sleeve did produce stresses which could cause the graphite to crack prematurely; however, results of a detailed examination of this problem indicated that if premature cracking did occur, the pressure gradient created by the main motor burn and the Buna-N insulation which overlays the graphite will hold the graphite sleeve in place. Under normal operating conditions the graphite sleeve will fail in tension when a fluid pressure of 19 psia is applied to its internal surface. To obtain these results the graphite material was assumed to have properties associated with a temperature of 1886°F. To complete the structural analysis, the valves, fitting and plumbing were evaluated for normal operating and burst conditions. Values used were obtained from manufacturer's recommended data.

A discussion of the structural analysis is presented in Appendix G. Table 6 summarizes the results.

3.4 FLOW SYSTEM ANALYSIS

The inert fluid injection system utilizes two identical and parallel fluid piping systems to provide flow from the fluid tank to the rocket motor chamber. A one-dimensional incompressible flow analysis of the piping system was conducted to calculate total head loss and to size the injector ports (or orifices) for the three possible fluid choices. In the analysis total head loss included form and shear losses. Mass flow rates predicted on the basis of performance, see Appendix B, were used in analysis. Details of the calculation of total head loss are shown in Appendix E. Table 7 presents the results for the three fluids considered.

Table 6a

STRUCTURAL ANALYSIS DESIGN RESULTS

Item	Maximum Allowable Pressures (psia)	Maximum Actual Pressures (psia)	Design Safety Factor	Margin of Safety	Condition for Basis of Margin of Safety
Pyrotechnic Valve	3300 0 (operating) 7000.0 (burst)	150.0 (operating) 925.0*	4.0 4.0	4.5 1.02	Operating Burst
Manually Operated 3-Position Valve	2000.0 (operating)	150.0 (operating)	4.0	2.33	Operating
Quick Disconnect Nipple	2800.0 (operating) 7000.0 (burst)	150.0 (operating) 925.0*	4.0 4.0	3.66 1.02	Operating Burst
Flexible Hose	1500.0 (operating) 7000 0 (burst at high temperature)	150.0 (operating) 925.0*	4.0 4.0	1.5 1.02	Operating Burst
Hard Tubing	1378.0 (operating)	150.0 (operating)	4 0	1.29	Operating

*Assumes TE-364-3 Chamber Pressure felt upstream of injector.

Table 6b

STRUCTURAL ANALYSIS DESIGN RESULTS

Item	Maximum Allowable Stress or Condition	Maximum Actual Stress or Condition	Design Safety Factor	Margin of Safety	Conditions for Basis of Margin of Safety
Toroidal Tank	150 0 (internal operating pressure)	150.0 (internal pressure)	4.0	0.102 0.288	Ultimate Stress
Thrust Cone (Tank Support)		System weight 60 lb Dynamic Load Applied 15 g vertical, 3 g lateral	1.5	2.38	
Orifice Sleeve	22,100.0 psi (Hoop Tension)	6915.0 lb_f/in^2	1.5	1.13	(yield stress)
Orifice Cover (graphite sleeve)	10,000 psi comp	Thermal expansion	1.5	0.362	Max allowable tension stress "c" direction
	500 psi tension	925.0 psia (chamber pressure)	*	-0.555	Max. allowable compressive stress "a" direction.

*No Safety Factor applied

Table 7

FLOW SYSTEM ANALYSIS RESULTS

Fluid	Mass Flow Rate	Port Diameter (in.)	Total Head Loss psia
Butane	0.564	0.090	33.54
Water	0.0474	0.021	28.676
Ammonia	0.067	0.031	16.93

3.5 SYSTEM WEIGHT

The IFIS was designed to meet a design goal of 60 lb wet weight with a fluid mass fraction of 0.80. The calculated total weight of the loaded IFIS is 59.907 lb, (see Appendix H), which includes 50 lb of inert fluid. This results in a fluid mass fraction of 0.835. The change in the fluid mass fraction with ullage is presented in Table 8.

Table 8

VARIATION IN FLUID MASS FRACTION
WITH CHANGE IN ULLAGE

Ullage Weight (lb)	Fluid Mass Fraction
0	0.8346
1	0.8316
2	0.8289
3	0.8259
4	0.8277
5	0.8195
6	0.8162

The amount of ullage required for a given fluid is dependent upon the anticipated rise of the fluid temperature above nominal loading temperature. Graphs are presented in Appendix H which show the amount of ullage (in percent of total volume and in pounds) required as a function of loading temperature.

3.6 MOMENT OF INERTIA

The mass moment of inertia of the IFIS was calculated about the longitudinal axis of the Delta vehicle for the fully loaded condition and for a series of conditions corresponding to a time history of mass remaining in the tank. The moment of inertia of the dry IFIS is invariant with time and was calculated to be 0.1604 slugs-ft^2. The change of mass moment of inertia as a function of time was calculated for three systems using butane, water and ammonia, respectively, and is presented in Fig. H-4. Details of these calculations are presented in Appendix H.

3.7 SYSTEM PERFORMANCE

The performance available from the IFIS was calculated as a function of the characteristics of the three fluids considered in this design. One-dimensional isentropic compressible flow relations were used to calculate the performance of each fluid. Each fluid was assumed to be

- Completely vaporized in the combustion chamber of the spent rocket motor
- Expanded to the same area ratio
- Treated as an ideal gas, that is, constant ratio of specific heats. The design mass flow rate associated with each fluid is limited by the rate at which fluid can be vaporized.

The vaporization rate, which is indicative of the heat transfer rate, is, in turn, a function of various fluid characteristics and wall surface conditions. Thus the performance obtainable from each fluid is a direct function of heat transfer process. A detailed discussion of the performance analysis can be found in Ref.2, and in Appendix B of this document. Figure 10 of Appendix B presents a plot of total impulse available from the IFIS as a function of injection time for butane, water and ammonia. The total mass injected as a function of injection time for each of the fluids is shown in Fig. 11 of Appendix B. An additional definition of the system performance is presented in Table 9.

3.8 CHECKOUT AND HANDLING PROCEDURES

The procedures written for the IFIS fall into three basic categories: assembly, leak checks, and fill and drain operations. Associated with the procedures is the definition of specialized servicing equipment or fixtures (GSE and GHE). In general, the procedures, presented in Appendix I, are composed of step-by-step instructions supplemented by the appropriate schematics and diagrams. The specific procedures which are provided are (1) environmental temperature constraints; (2) IFIS/TE-364-3 assembly procedure; (3) leak check and functional testing procedure; and (4) fill and drain procedure.

Only one piece of specialized hardware is specified by the procedures for handling the IFIS. A fixture to hold the tank in the proper position during fill and drain operation is needed. The remainder of the required GSE can be constructed of standard valves and plumbing. GSE requirements are specified in each procedure.

Table 9
SYSTEM PERFORMANCE PARAMETERS

Item	Ammonia (NH_3)	Butane (C_4H_{10})	Water (H_2O)
Molecular Weight	17.03	58.12	18.016
Ratio of Specific Heats	1.3	1.11	1.33
Conditions in Motor Chamber			
Initial (t_I = 1.0 sec)			
Chamber Pressure, psia	0.324	1.835	0.305
Chamber Temperature, ^oR	315.0	411.8	5.0
t_I = 160.0 sec			
Chamber Pressure, psia	0.270	1.028	0.214
Chamber Temperature, ^oR	309.5	394.5	515.0
Mass Flow Rate, lb_m/sec			
Initial, T_I = 1.0 sec	0.0673	0.564	
t_I = 160.0 sec	00.0563	0.332	0.035
Thrust			
Initial, t_I = 1.0 sec	5.397	34.4	5.013
t_I = 160.0 sec	4.50	19.17	3.51
Specific Impulse, lb_f-sec/lb_m			
Initial, t_I = 1.0 sec	80.2	61.0	100.53
t_I = 160.0 sec	80.4	57.8	99.34
Total Impulse Produced at			
t_I = 160.0 sec (lb_f-sec)	784.7	4014.3	666.9

Section 4
CONCLUSIONS AND RECOMMENDATIONS

As a result of the effort expended on this contract, a full-scale inert fluid injection system (IFIS) was designed. The IFIS, designed for use with the TE-364-3 solid propellant rocket motor, will provide a velocity trim capability for the third stage of the Delta vehicle that is independent of vehicle payload. The IFIS design is configured for use with three basic fluids, butane-n, water or ammonia, and it could be adapted with reasonable ease to use other inert or active fluids, if required. The resulting system is light weight and has a fully loaded fluid mass fraction of 0.83. Application of this concept results in a velocity trim system that requires no additional combustion chambers or expansion nozzles in order to produce a usable level of performance. In addition, with the exception of the storage tank, support cone, and ignition-injection assembly all components external to the TE-364-3 are "off-the-shelf" items, requiring no re-design. Thus the IFIS represents an effective and economical means to achieve desired velocity trim.

It is therefore recommended that a full scale IFIS be constructed and evaluated. The IFIS could be evaluated as a non-critical part of a Delta mission, or suitable facilities exist at the Arnold Engineering Development Center for ground tests of the system.

CITED REFERENCES

1. Baker, L. R., "Research and Development of an Inert Fluid Injection System for a Solid Propellant Rocket (Phases I and II)," LMSC/HREC D148939, Lockheed Missiles & Space Company, Huntsville, Ala., 1969.

2. Baker, L. R., "Preliminary Results of the Fluid Selection Study of an Inert Fluid Injection Propulsion System," LMSC/HREC D162182, Lockheed Missiles & Space Company, Huntsville, Ala., 17 March 1970.

3. Delta Spacecraft Design Restraint, Douglas Report DAC-61687, October 1968.

4. White, D. W., and J. E. Harris, "Qualification Tests of Thiokol Chemical Corporation TE-M-364-3 Solid Propellant Rocket Motors Tested in the Spin and No-Spin Modes of Simulated Altitude Conditions (Part II – Final Phase)," AEDC TR 67-256, ARO, Inc., Arnold Air Force Station, Tenn., January 1968.

UNCITED REFERENCES

Archibald, R. C., et al., "Catalytic Hydrocracking of Aliphatic Hydrocarbons," Indus. Eng. Chem., Vol. 52, No. 9, September 1960.

Bergles, Arthur E., "Survey and Evaluation of Techniques to Augment Convective Heat and Mass Transfer," Vol. I, Progress in Heat and Mass Transfer, Pergamon Press, New York, 1969.

Gambill, W. R., R. D. Brundt, and R. W. Wansbrough, "Heat Transfer, Burnout and Pressure Drop for Water in Swirl Flow Through Tubes with Internal Twisted Tapes," ONR1-2911, 11 April 1960.

Kreith, Frank, "Convection Heat Transfer in Rotating Systems," Vol. 5, Advances in Heat Transfer, Academic Press, New York, 1968.

Kuo, C. Y., et al., "Heat Transfer in Flow Through Rotating Ducts," J. Heat Trans., May 1960.

Patterden, R. F., "Heat Transfer from a Rotating Tube with Controlled Fluid Flow," J. Mech. Eng. Sci., Vol. 6, No. 2, 1964.

Sandler, Samuel, and M. Ali Lanewala, "Pyrolysis of n-Butane in a Differential Flow Reactor," J. Chem. Eng. Data, Vol. 8, No. 2, April 1963.

Appendix A

RESULTS OF EXPERIMENTAL INVESTIGATION CONDUCTED WITH SCALED SIMULATED ROCKET MOTORS

Appendix A

The experimental phase of this study (Phase II) was conducted to confirm the concepts of an inert fluid injection system that were evolved from theoretical considerations. To accomplish this task, a set of experimental hardware was developed and a test program conducted. Two test model configurations were designed and fabricated for these tests. The baseline model (Fig. A-1) was spherical, and was dimensionally similar (one-fourth dimensional scale) to the TE-364-3 rocket motor now being used as the propulsion unit on the third stage of the Delta vehicle. No attempt was made, however, to design the model to be a dimensionally or thermally "scaled" model of the TE-364-3 rocket motor. The second configuration of the model was created to determine the effect of length-to-diameter ratio on system efficiency. This configuration consisted of a cylindrical insert placed between the forward and aft hemispherical domes of the baseline model. Both model configurations had provisions for varying and measuring the required test parameters. Details of the model design and fabrication and test stand hardware can be found in Ref. A-1.

The test program conducted during this study was primarily concerned with demonstrating the feasibility of generating a usable level of propulsive work by the injection of water into a heated chamber. To accomplish this objective a series of tests was conducted to evaluate variations in inert fluid flow rates, injector spray distribution and drop size, mode of fluid injection, model length-to/diameter ratio and initial amount of residual heat stored in the test model. Inert fluid flow rates were varied by controlling the pressure differential on the injector. Spray distribution and drop size were varied by utilizing injector nozzles of different diameters and arrangements for a specified range of fluid injector pressure drop. Injection was controlled manually, and consisted of continuous fluid injection and pulsed injection. The amount of residual heat stored in the model was controlled by the length of time the

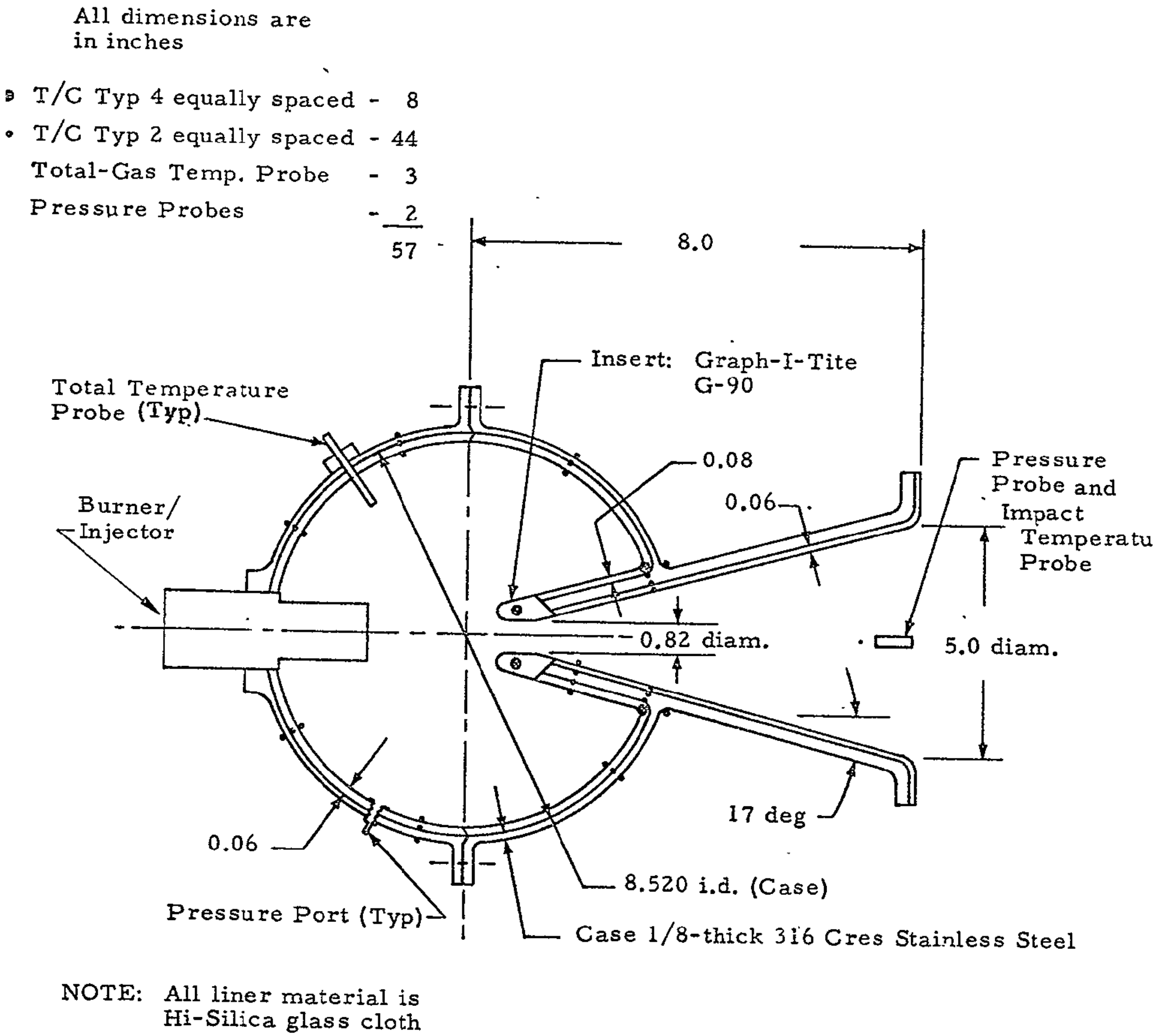


Fig. A-1 - Basic Dimensions of Spherical Subscale Motor Used in Experimental Test pre-heat burner was permitted to operate. The heating process was limited by the burner flame temperature and the heating value of the fuel-oxidizer combination that was used. The effect of changes in model length-to-diameter ratio was evaluated using the cylindrical model configuration. Test data recorded on each run included: detailed temperature distribution time histories, model chamber pressure, water mass-flow-rate into model, and total temperature at model exit plane. A discussion of utilization of the temperature data to evaluate the analytical heat transfer results is presented in Ref. A-1.

Representative performance results from tests conducted with the spherical and cylindrical test models are shown in Figs. A-2 and A-3. Data from runs 1 through 6 of Test 12 conducted with the spherical model are presented in conjunction with data from test runs 3A-3, 7B-1, 7D-1 and 9B-1 conducted with the cylindrical configuration.

Sonic specific impulse as a function of measured mass flow rate is presented in Fig. A-2. The specific impulse values were calculated using the following equation and corrected experimental values of total temperature.

$$I_{sp} = 2.45 \sqrt{T_c}$$

In calculating the specific impulse by this method, it is implied that mass-flow-in is equal to mass-flow-out, but this is not necessarily true for these tests. When mass is not conserved ($\dot{m}_{in} > \dot{m}_{out}$), the problem becomes much more complex in that mass is accumulating within the model chamber, i.e., "puddling" occurs. In this case specific impulse calculated using the above equation represents an upper limit for a given chamber temperature.

Thus, to interpret the data plotted in Fig. A-2 properly, it must be known if mass is conserved for the test condition. Figure A-3 presents a plot of test model chamber pressure as a function of measured mass-flow-rate-in that aids in determining if $\dot{m}_{in}$ does equal $\dot{m}_{out}$. Data presented in Fig. A-3, are shown relative to a curve corresponding to the vapor pressure

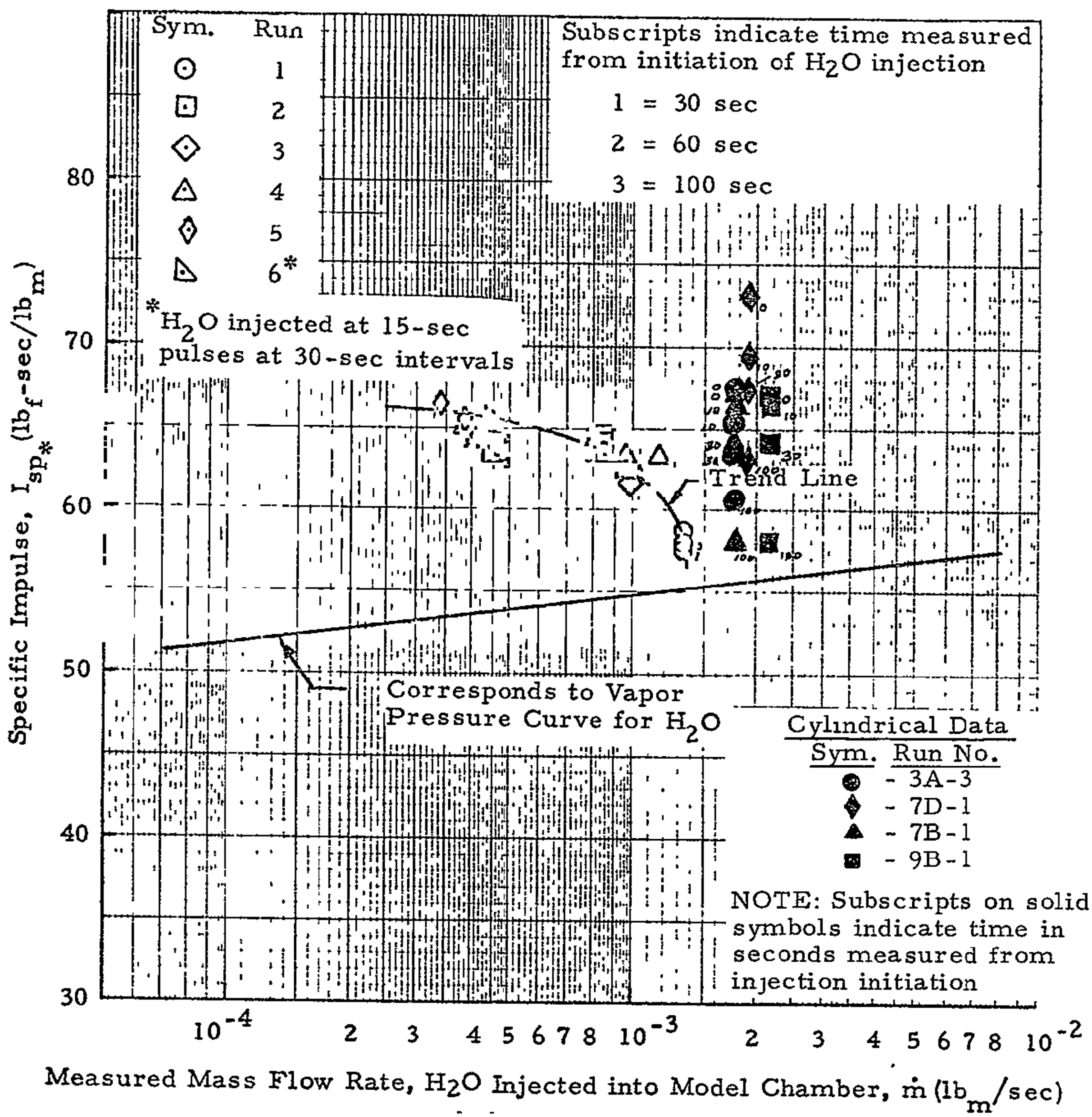


Fig. A-2 - Specific Impulse as a Function of Mass Flow Rate from Experimental Data (Test 12) Using Subscale Spherical and Cylindrical Models

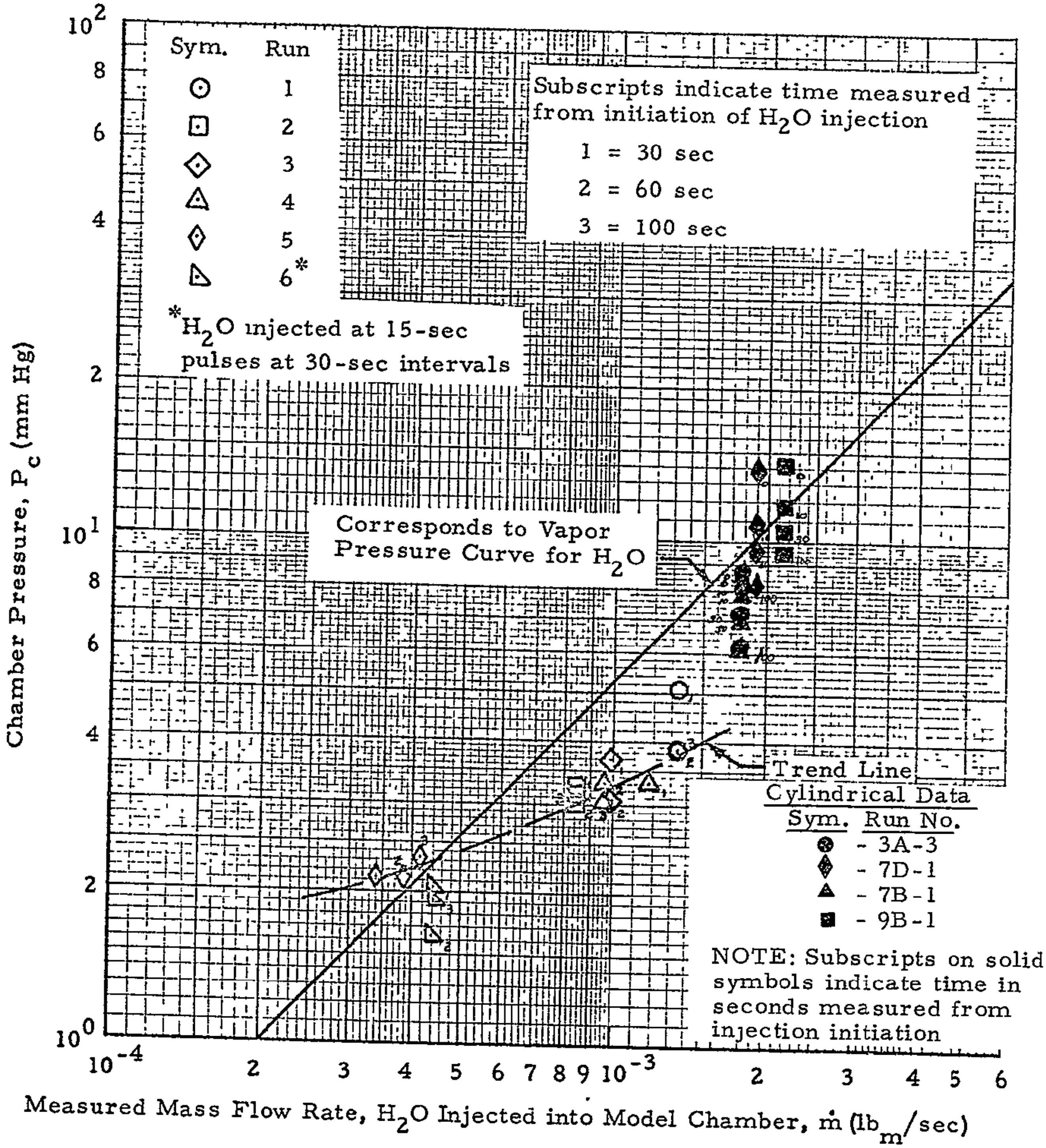


Fig. A-3 - Chamber Pressure as a Function of Mass Flow Rate from Experimental Data (Test 12) Using Subscale Spherical and Cylindrical Models curve for water. Points lying on the "vapor pressure" curve represent conditions where the indicated mass flowing into the system is being totally vaporized at the associated pressure and corresponding vaporization temperature and expelled through a specified throat. When puddling occurs, all of the mass flowing into a system is not being vaporized and expelled and it therefore does not contribute to the chamber pressure. Points corresponding to these conditions will fall to the right of the "vapor pressure" curve. When superheating of the vapor occurs, the chamber pressure corresponding to a given mass flow rate increases. Data points representative of these conditions fall to the left of the vapor pressure curve.

It was concluded from these test results and the associated analytical study that the concept of trimming the velocity of an orbital vehicle by producing a usable level of propulsive work by the recovery of the residual heat stored in a spent solid rocket motor is feasible provided that sufficient heat is available. Using a 70°F reference temperature, it was determined that approximately 33,000 Btu are available in the TE-364-3 motor case at burnout for conversion into propulsion energy.

Appendix A
REFERENCE

A-1. Baker, L. R., "Research & Development of an Inert Fluid Injection System for a Solid Propellant Rocket — Phases I and II," LMSC/HREC D148938, Lockheed Missiles & Space Company, Huntsville, Ala., 1969.

Appendix B*

FLUID SELECTION AND PERFORMANCE CALCULATIONS

*Work accomplished under Task 2 of the Work Statement of Contract NAS5-11614. The report is included here as Appendix B as a convenience to the reader.

HREC 1164-3
LMSC/HREC D162373

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FLUID SELECTION STUDY FOR AN INERT FLUID INJECTION PROPULSION SYSTEM

June 1970

Contract NAS5-11614

Prepared for NASA-Goddard Space Flight Center
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FOREWORD

This report presents the results of work performed by Lockheed's Huntsville Research & Engineering Center while under contract to Goddard Space Flight Center, Contract NAS5-11614. This work was accomplished under Task 2 of the Work Statement of the subject contract. The NASA technical coordinator for this study is Mr. Daniel Dembrow, of the Delta Project Office.

CONTENTS

INTRODUCTION AND SUMMARY

A study is being performed to design a propulsion system which will provide an orbital velocity trim capability for the Delta rocket launch vehicle. A system is being designed which will accomplish the velocity trim by injecting an inert propellant into the Delta third-stage motor after burnout and using the heat stored in the motor case to obtain or augment the propulsive energy of the injected fluid. A relatively low thrust system results from this approach

This report presents the results from an evaluation of several candidate fluids for use in the inert fluid injection system. The need for this study became apparent after analytical and experimental results for water revealed that, using water, the desired total impulse could not be produced in a time interval commensurate with the intended application. The inert fluid selection criteria presented in Ref. 1 was utilized with the boundary conditions presented in this report to evaluate the candidate fluids.

The results of the present study show that there are fluids which have properties consistent with the required objectives of the problem. Several potentially acceptable fluids were found using screening criteria involving: low latent heat of formation; low molecular weight; low specific heats; high vapor pressure; and high heat transfer coefficient between the wall and the fluid. Six of these fluids were studied in detail to evaluate performance characteristics of the system. Of the six — ammonia, butane, Freon 12, propane, ethane and sulfur dioxide — butane and Freon 12 were found to provide good performance. The remaining fluids were eliminated because the desired total impulse could not be generated in a time span consistent with application requirements.

Using butane as a working fluid, the nominal characteristics of the system were calculated to be:

Thrust		
$t_I = 1.0$ sec	$\approx$	$34.4\ lb_f$
$t_I = 160$ sec	$\approx$	$19.17\ lb_f$
Installed specific impulse	$\approx$	$56.07\ lb_f\text{-sec}/lb_m$
Fluid mass fraction	$\approx$	0.97
Amount of fluid for		
4000 lb_f-sec total impulse	$\approx$	$68.0\ lb_m$
Time increment for achieving		
4000 lb_f-sec impulse	$\approx$	160.0 sec

In the study, the rate at which heat was transferred from the motor case to the fluid was assumed to be limited by the heat transfer coefficient of the fluid. A detailed analysis was made of the conduction of heat through the motor case to the internal surface. This analysis indicates that the heat conduction rate to the surface is approximately equal to the heat transfer rate needed to support the vaporization rates associated with the heat transfer coefficients used in this study.

DISCUSSION

Candidate fluids for use in the fluid injection velocity trim system were evaluated using criteria presented in Ref. 1 and a prescribed set of boundary conditions. The boundary conditions applied to the selection criteria reflect limitations imposed by the system application and the physical phenomena being considered. These boundary conditions are:

1. A minimum of 4000 lb_f-sec total impulse is required.

2. A maximum fluid injection time of 200 sec can be used to obtain the total impulse.

3. A fluid mass fraction of 0.8 or larger is desired.

4. The injection mass flow rate must not exceed the flow rate that can be supported by the heat transfer process.

5. The fluid must be storable under its own vapor pressure at launch pad conditions.

After an initial screening, the following 13 fluids were considered for use in the fluid injection velocity trim system:

Ammonia
Butane
Ethane
Ethylmethyl Ether
Freon 11
Freon 12
Freon 13
Freon 22

Hydrogen Cyanide
Hydrogen Sulfide
Methylamine
Propane
Sulfur Dioxide

Further evaluation of the fluids on this list resulted in the elimination of seven fluids prior to the detailed study. Hydrogen sulfide (H_2S) and hydrogen cyanide (HC) were eliminated from consideration because of high melting points. Ethylmethyl ether and melthylamine were dropped from contention due to lack of adequate property data on which to base a detailed study. Fluids with similar properties were studied. Freon 11, Freon 13, and Freon 22 were not considered in the detailed study because their properties were quite similar to those of Freon 12 which was studied.

The candidate fluids considered in detail in this study are: ammonia, NH_3; butane (n), C_4H_{10}; ethane, C_2H_6; Freon 12, CCl_2F_2; propane, C_3H_8; and sulfur dioxide, SO_2. The thermodynamic properties of these fluids as a function of fluid state (vapor pressure and temperature) are presented in Table 1. References 2 through 6 were consulted to obtain the data presented in this table.

To determine if the candidate fluids satisfied the system boundary conditions, performance and heat transfer data for each of the fluids were calculated. In order to simplify the analysis and provide a realistic basis for evaluation of the fluids, the rocket motor was assumed to have a bulk temperature of 1340.0°F at the time fluid injection was initiated. The TE-364-3 rocket motor was utilized in this study and is briefly described by the information presented in Table 2. The effect of vehicle stabilization spin on the performance of the system was neglected in this analysis.

Heat transfer coefficients, h, were calculated at various states on the vapor pressure curve of each of the candidate fluids. The equation used for h is a complex relation, involving the dimensions of the heated surface and properties of the fluid. This relation was used in determining heat transfer coefficients on the forward and aft shells of the spherical test model (Ref. 1, page 9, Eq. (2.4)). Figure 1 shows h for each of the fluids plotted as a function of the temperature of the fluid. Values of h were utilized to calculate representative heat transfer rates to the fluid for each of the fluid states using the following relation:

$$\dot{q} = h A \Delta T \text{ (Btu/sec)}$$

where

A is the heat transfer surface area ($A = 3225 \text{ in}^2$)

ΔT is the temperature differential between the rocket case and the fluid.

An estimate of the rate at which a fluid could be vaporized was then obtained from the following equation:

$$\dot{m}_{HT} = \frac{\dot{q}}{\Delta h_v} \text{ (lb}_m\text{/sec)}$$

where

Δh_v is the latent heat of vaporization of the fluid at the fluid state being considered.

Since it is desirable to vaporize all of the fluid being injected, the vaporization rate can be taken as the maximum acceptable mass flow rate for system operation. The mass flow rate required to obtain choked flow in the rocket motor throat for each of the fluid states was calculated by the relation

$$\dot{m}_c = \frac{P_c A_t g}{C^*} \text{ (lb}_m\text{/sec)}$$

where

P_c is the operating chamber pressure (fluid vapor pressure)

A_t is the area of rocket throat

C^* is the characteristic velocity and is a function of temperature.

Values of $\dot{m}_{HT}$ and $\dot{m}_c$ were calculated for a series of states on the vapor pressure curves of the candidate fluids for each value of the bulk temperature of the rocket motor case. Results of these calculations for the initial fluid injection condition ($T_{wall} = 1340^{\circ}F$) are presented in Figs. 2 through 8. The point on each graph where $\dot{m}_{HT}$ crosses $\dot{m}_c$ represents the maximum choking mass flow rate that the heat transfer rate can support at that wall temperature. The motor chamber operating conditions as a function of time are determined from the mass flow rate pertaining to each of these points. Figure 9 shows the variation in maximum choking mass flow rate as a function of wall temperature for each of the candidate fluids.

The performance of each of the fluids was calculated using one-dimensional isentropic compressible flow relations. Each fluid was assumed to be expanded to the same area ratio and was treated as an ideal gas, that is, constant ratio of specific heats. A summary of the results of the performance calculations is presented in Table 3. The predicted total impulse generated as a function of injection time for each of the candidate fluids is shown in Fig. 10. An associated plot of weight of fluid required as a function of injection time for the candidate fluids is presented in Fig. 11.

In order to apply the selection criteria, an estimate of the system weight was obtained. For the storage tank weight the fluids were considered to be stored under their own vapor pressure at $70^{\circ}F$. Estimates of tank weights were made for a system design that would accommodate the total amount of each candidate fluid that could be utilized in 160 sec. Two possible tank materials were considered (titanium and Vascomax). The method used to estimate tank weight essentially follows the technique used in Ref. 7. Tank weight was obtained from the relation

$$\omega_T = v\,p\,K_1$$

where

- v is the volume required to store mass of fluid to be used.
- p is the storage pressure
- K_1 is the constant determined from tank material properties

$$\left(K_1 = \frac{3}{2} \; \frac{(\text{material density})}{(\text{working stress})}\right)$$

Estimates of the tank weight for the conditions considered are presented in Table 5.

In order to evaluate the candidate fluids in terms of the velocity differential imparted to the vehicle, representative values were assumed for the payload and system hardware weights (Table 4). The velocity differential which could be imparted to the vehicle by each candidate fluid and the velocity differential penalty for carrying the inert fluid system onboard were calculated and are presented in Table 5.

The following relations (Ref. 8) were used to calculate the velocity differential values considered in the study:

Third-Stage Velocity Increment Due to Main Motor (TE-364-3)

without fluid system ~ $\Delta V_m = I_{sp}\, g \ln \left(\frac{\omega_n + \omega_p}{\omega_{b.o.} + \omega_p}\right)$

with fluid system on board ~ $\Delta V'_m = I_{sp}\, g \ln \left(\frac{\omega_n + \omega_p + \omega_H + \omega_T + \omega_{fld}}{\omega_{b.o.} + \omega_p + \omega_H + \omega_T + \omega_{fld}}\right)$

Velocity Increment Due to Trim System

$$\Delta V_{Ts} = I_{sp}\, g \ln \left(\frac{\omega_{b.o.} + \omega_p + \omega_H + \omega_T + \omega_{fld}}{\omega_{b.o.} + \omega_p + \omega_H + \omega_T}\right)$$

Velocity Differential Penalty

$$\Delta V_p = \Delta V_m - \Delta V'_m + \Delta V_{Ts} \; .$$

Definition of the parameters used in the above relations can be found in Tables 2 through 4 along with the values utilized in the calculations.

RESULTS

Utilizing the data presented in the attached tables and figures, the boundary conditions and selection criteria can be applied to the candidate fluids. Considering the boundary conditions (page 3) first, examination of Figs. 10 and 11 and Table 3 reveals that of the candidate fluids considered only two, butane and Freon 12, satisfy all boundary conditions. Ammonia, ethane, propane, sulfur dioxide, and water were eliminated on the basis of boundary conditions 1 and 2.

Considering the maximization of the installed specific impulse, that is:

(installed specific impulse) = (specific impulse) (fluid mass fraction)

butane emerges as the better of the two systems (Table 3, Item 15). If maximization of the velocity differential imparted to the representative vehicle by the inert fluid system (Item 12) is considered, the butane has an edge over the Freon 12. Extension of the ΔV criteria to include the velocity differential penalty imposed on the stage propulsion system by carrying the inert fluid injection system onboard and ultimately using all the fluid indicates that butane is the obvious choice of the two fluids. Thus, based on the boundary conditions and criteria imposed, butane is most suitable for use as the working fluid in the fluid injection system.

Applying the selection criteria with boundary condition 2 removed makes ammonia and water more attractive as possible working fluids because of their relatively high specific impulse.

The hardware concepts considered during this study lend themselves to the development of a versatile system capable of handling serveral different types of fluids. Thus, even though butane best satisfies the applied boundary conditions and criteria, ammonia or water could also be utilized in the same system when alternate constraints are applied. A "growth" version of the system utilizing hydrazine or some other monopropellant is also well within the realm of possibility with this system.

CONCLUSIONS

The conclusions obtained from this study are:

1. Based on the boundary conditions and selection criteria applied to the candidate fluids, butane is the optimum choice of a working fluid for a fluid injection velocity trim system.

2. The hardware concepts utilized in the study lend themselves to the utilization of any of several fluids without system modification.

3. "Growth" versions of the system using an active propellant are within the realm of possibility.

REFERENCES

1. Baker, L. R., "Research and Development of an Inert Fluid Injection System for a Solid Propellant Rocket — Phases I and II," LMSC/HREC D148938, Lockheed Missiles & Space Co., Huntsville, Ala., 1969.

2. Perry, John H. (editor), Chemical Engineers Handbook, Fourth Edition, McGraw-Hill, New York, 1963.

3. "ASARAE Thermodynamic Properties of Refrigerants," American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1969.

4. "Selected Values of Properties of Hydrocarbons," Circular of the National Bureau of Standards C461, U.S. Dept. of Commerce, United States Government Printing Office, Washington, D.C., 1947.

5. International Critical Tables of Numerical Data, Physics, Chemistry and Technology, Vols. I, III, IV, V and VII, National Research Council of the United States of America, McGraw-Hill, New York.

6. Reid, Robert C., and T. K. Sherwood, The Properties of Gases and Liquids, McGraw-Hill, New York, 1966.

7. Briscoe, H. M., "The Choice of Propellant for a Cold Gas Propulsion System for a Satellite," British Interplanetary Soc., Vol. 20, 1965-1966, pp. 72-78.

8. White, D. W., and J. E. Harris, "Qualification Tests of Thiokol Chemical Corporation TE-M-364-3 Solid Propellant Rocket Motors Tested in the Spin and No-Spin Mode at Simulated Altitude Conditions (Part II — Final Phase) AEDC-TR-67-256, Rocket Test Facility, Arnold Engineering Development Center, Arnold Air Force Station, Tenn., January 1968.

FIGURES AND TABLES

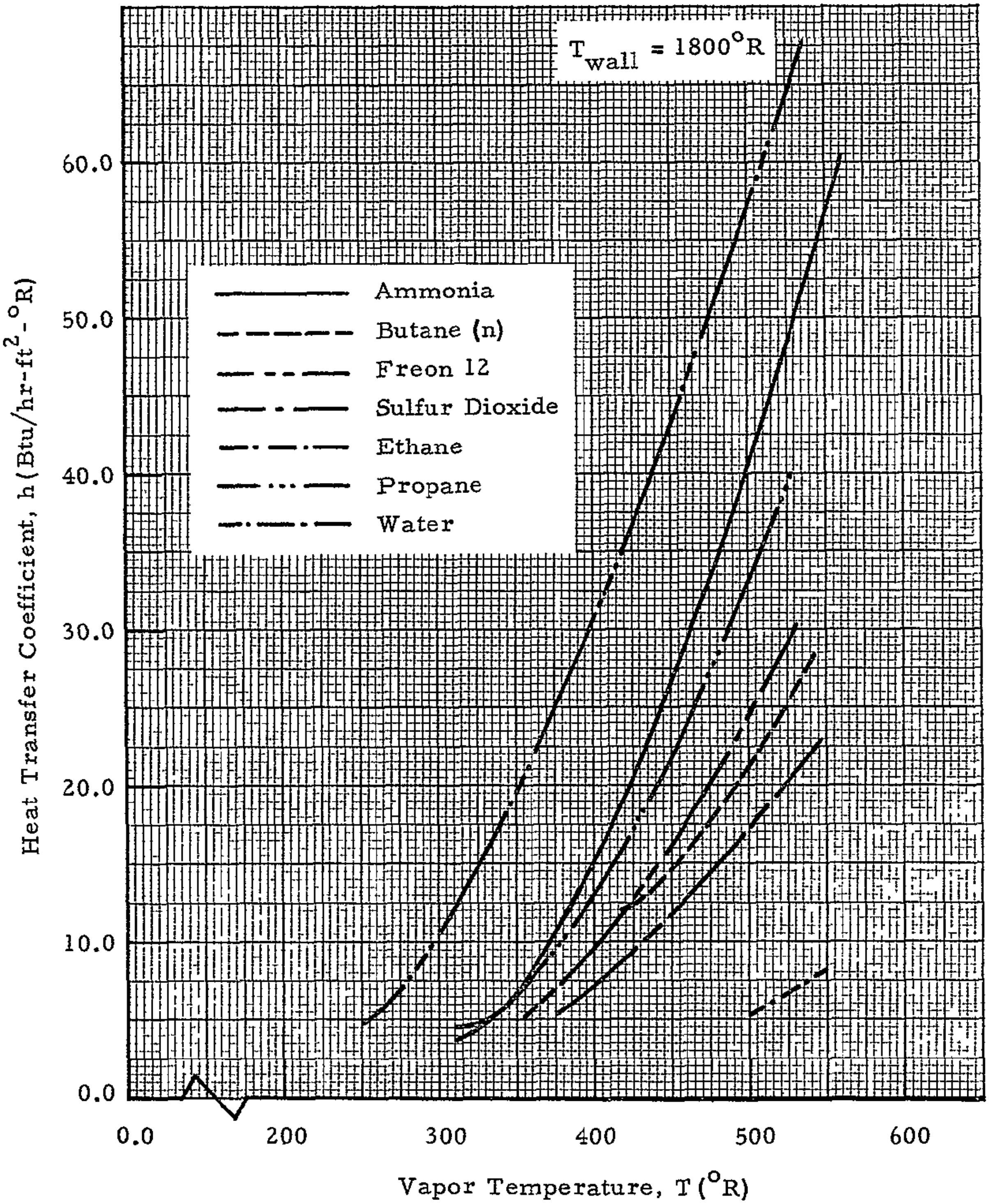

Fig. 1 - Heat Transfer Coefficient as a Function of Fluid Vapor State for the Candidate Fluids

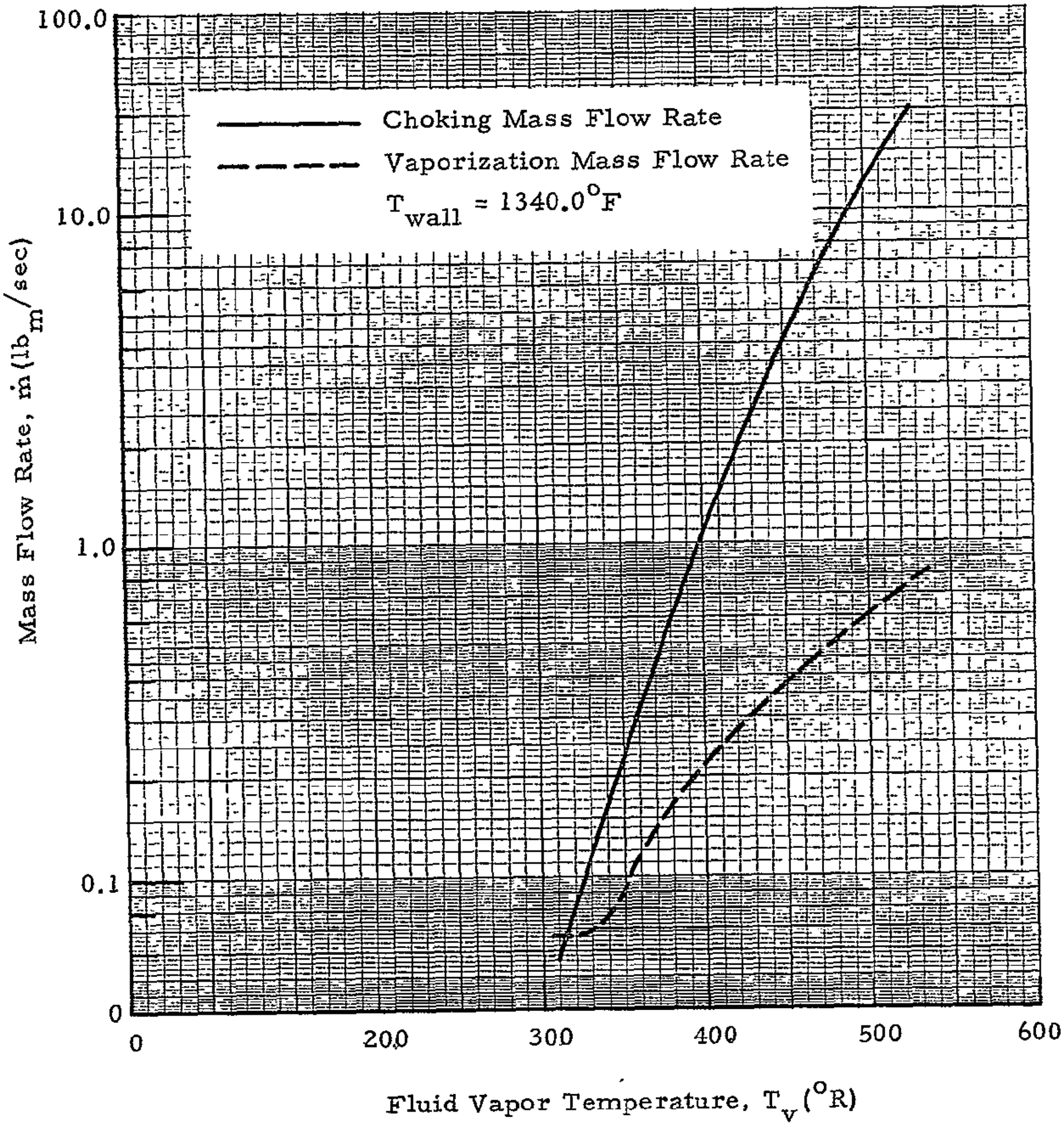

Fig. 2 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Ammonia

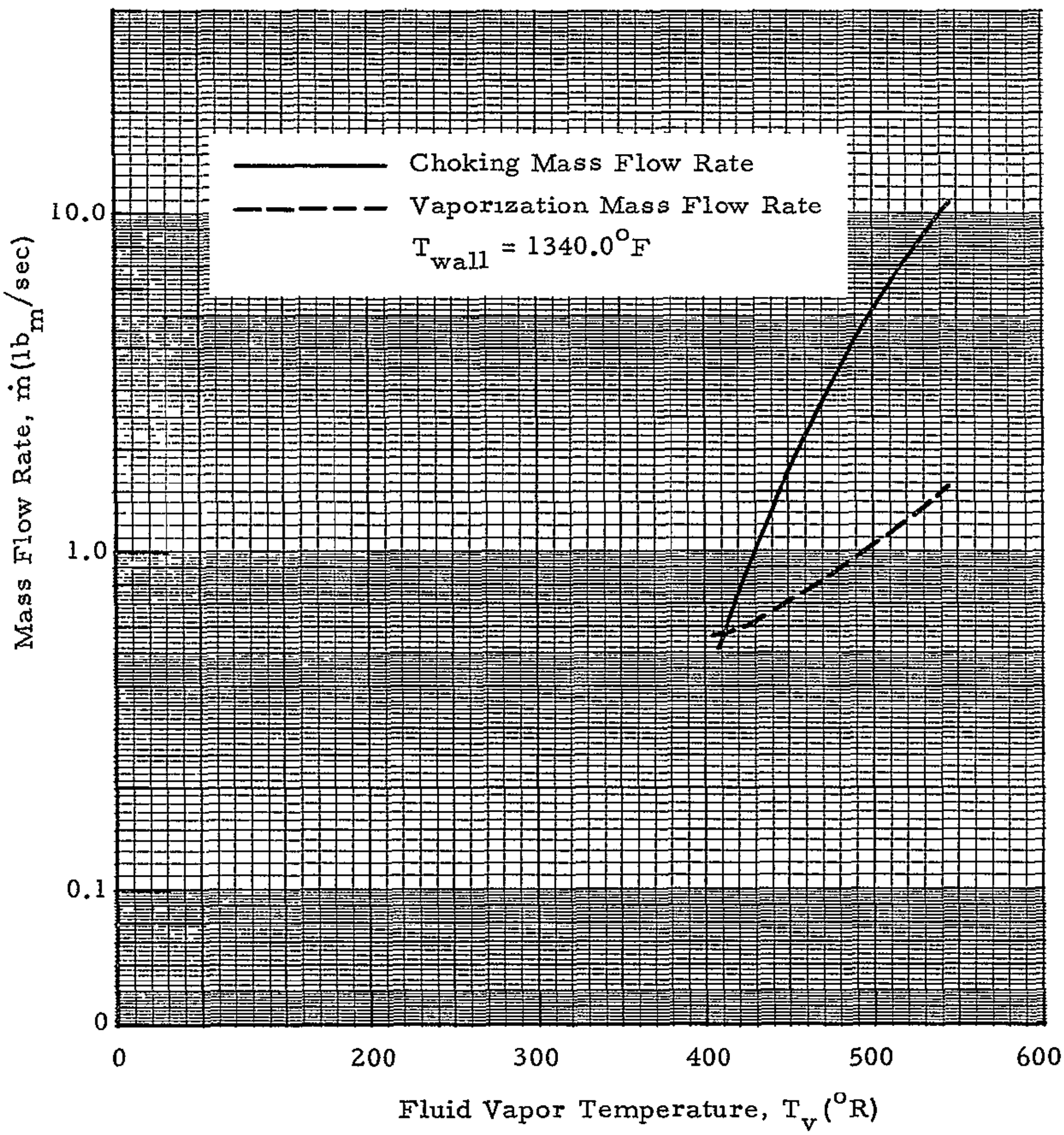

Fig. 3 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Butane (n)

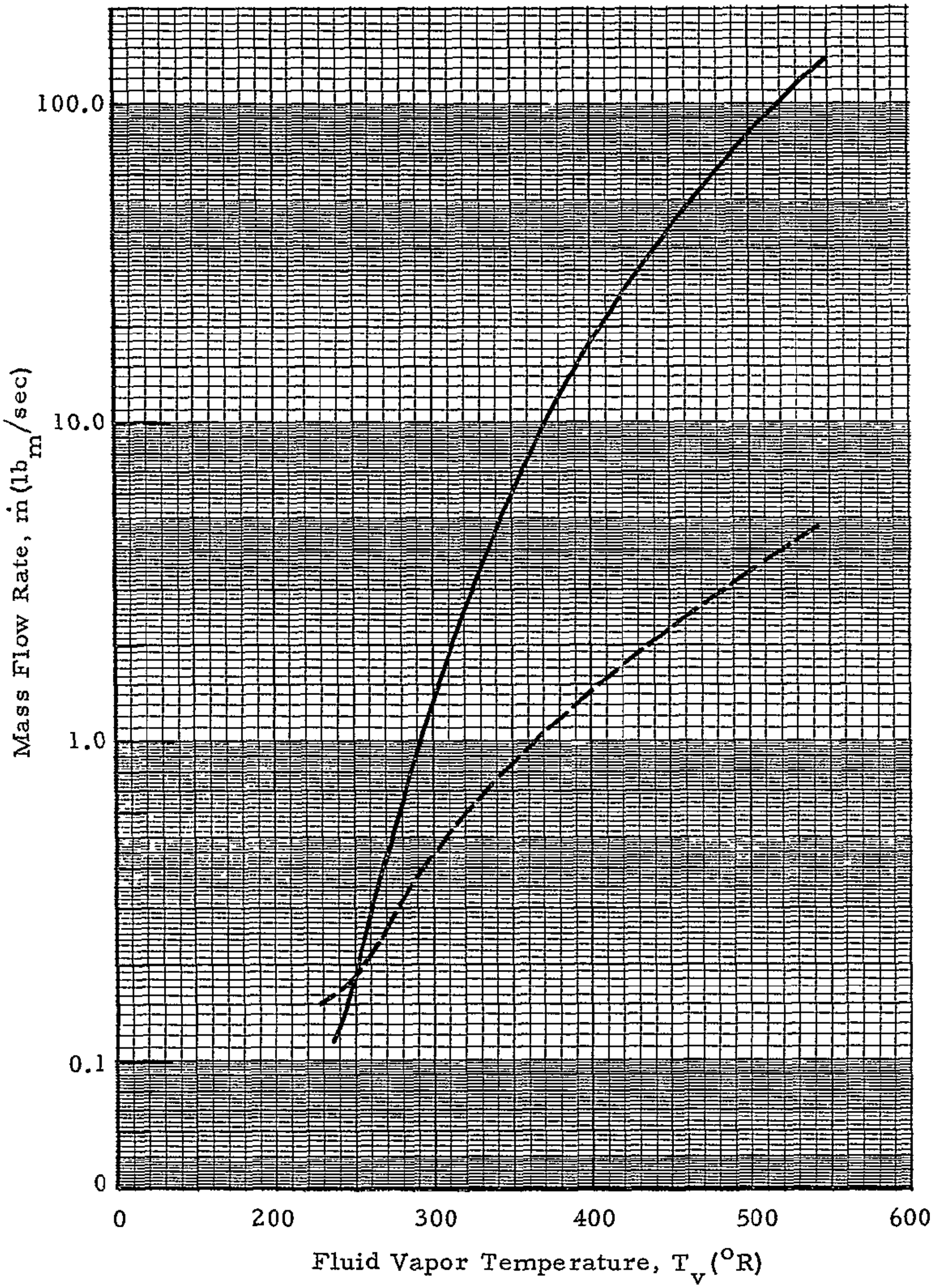

Fig. 4 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Ethane

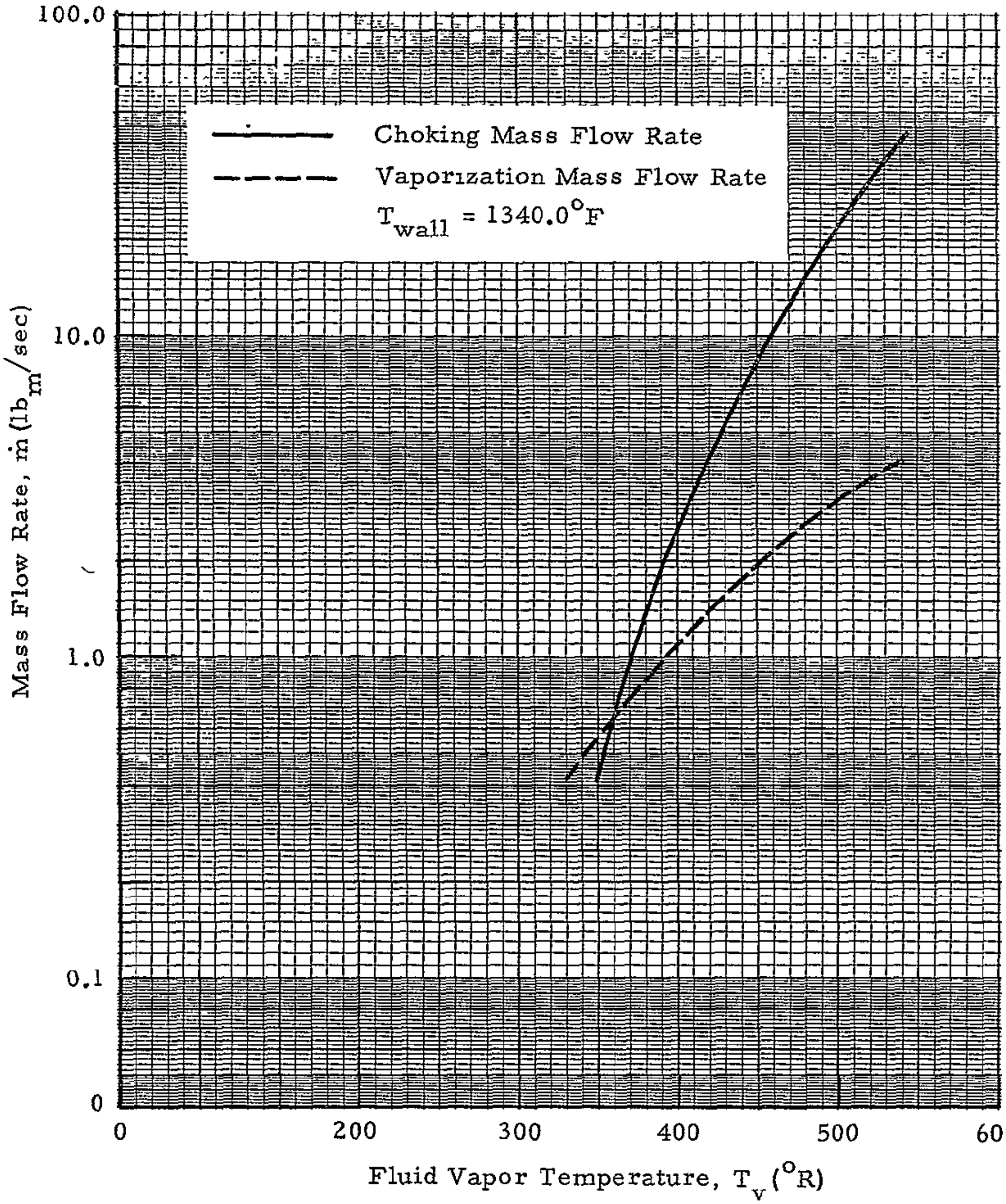

Fig. 5 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Freon-12

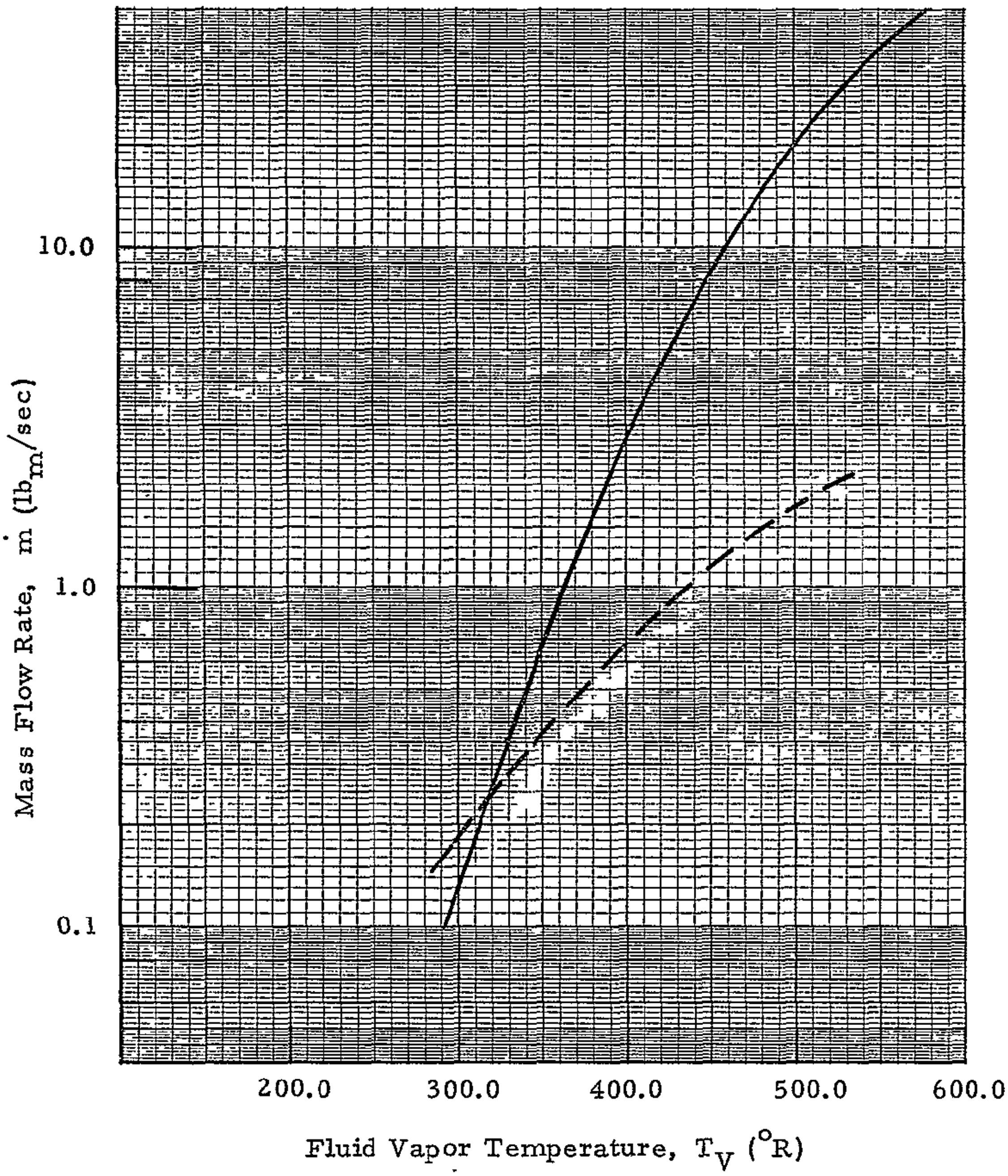

Fig. 6 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Propane

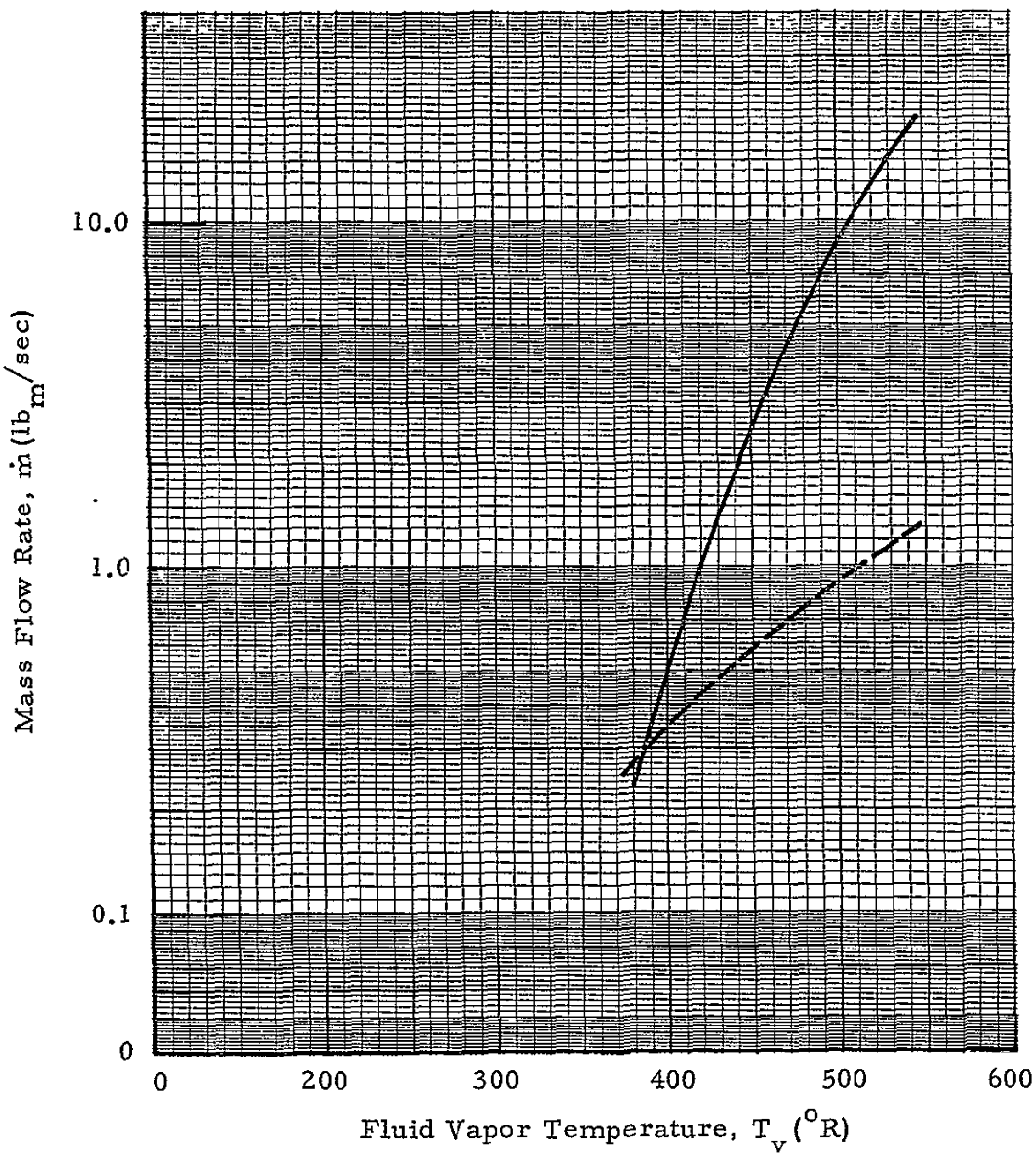

Fig. 7 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Sulfur Dioxide, SO_2

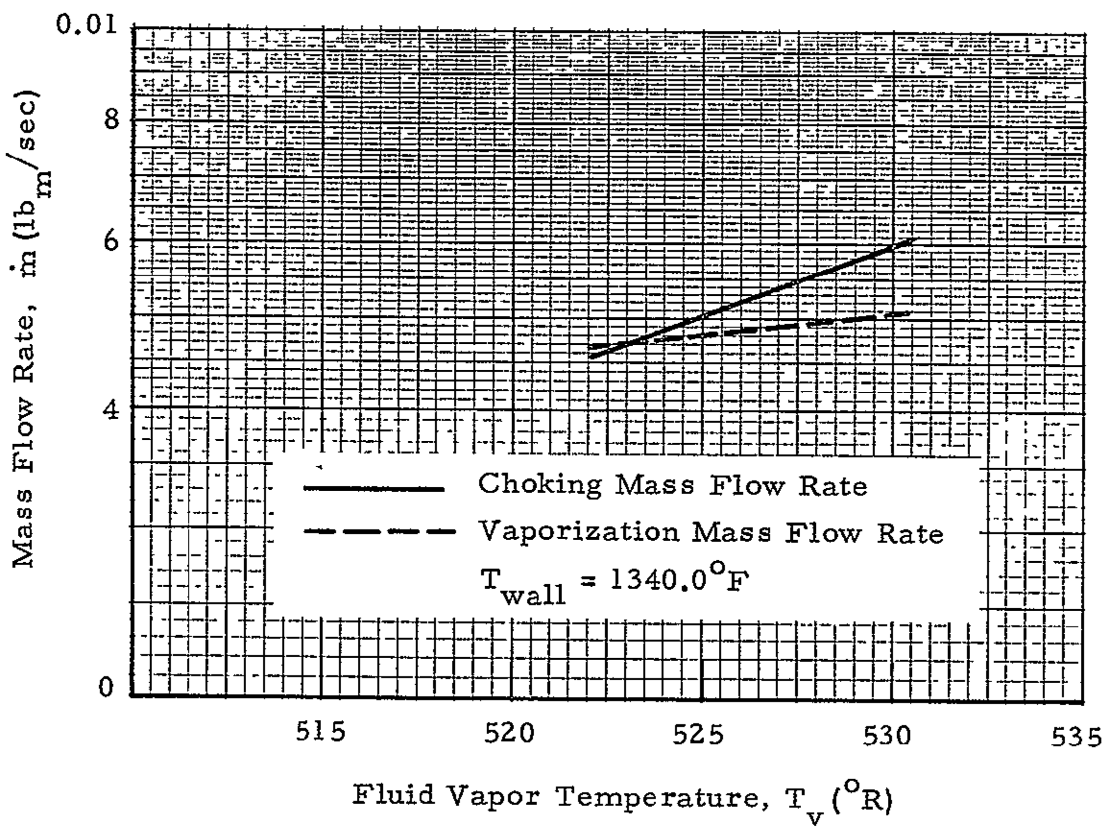

Fig. 8 - Vaporization Rate and Choking Mass Flow Rate as a Function of Vapor Temperature for Water, H_2O

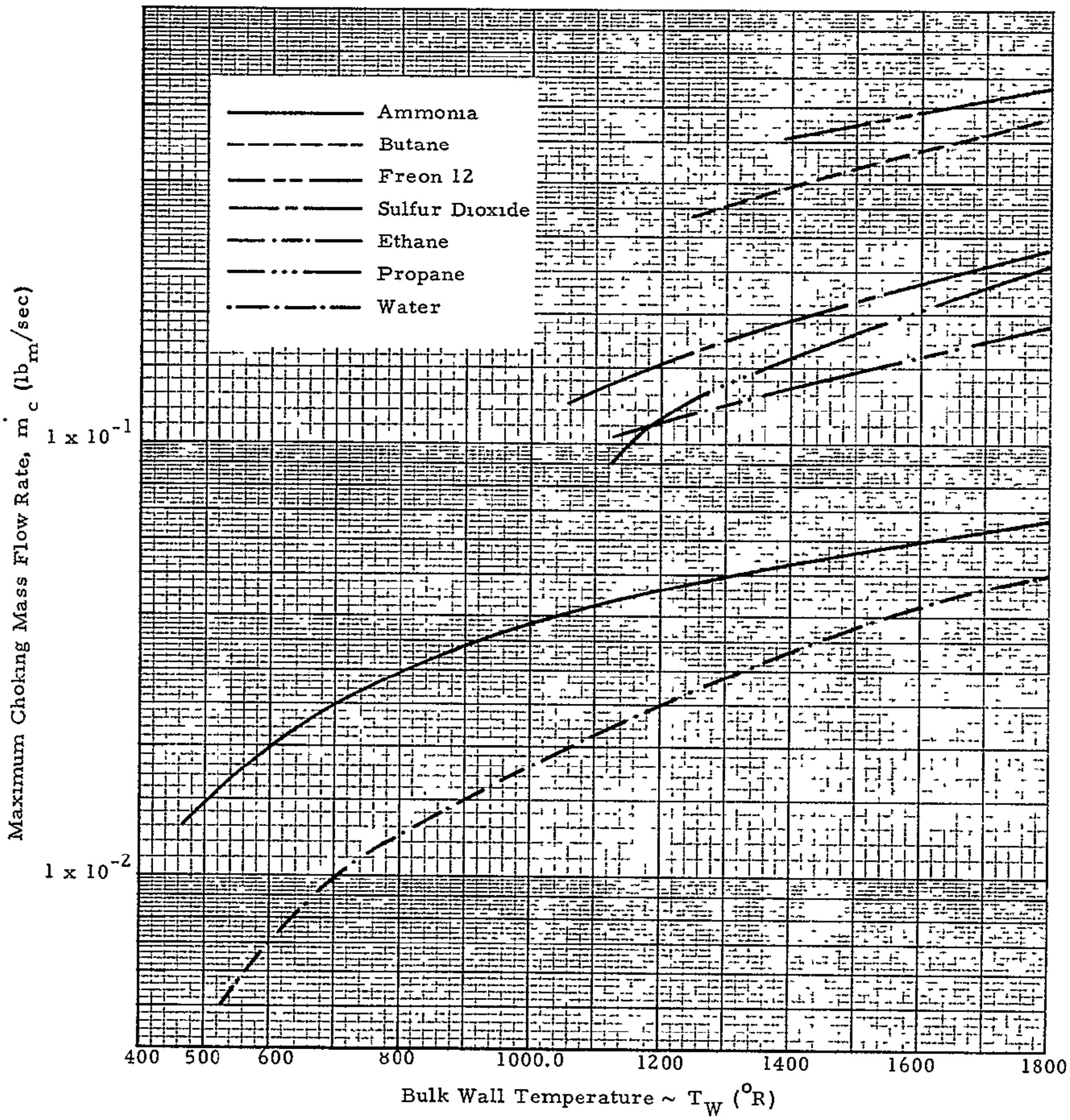

Fig. 9 - Maximum Choking Mass Flow Rate Versus Bulk Motor Wall Temperature for the Candidate Fluids

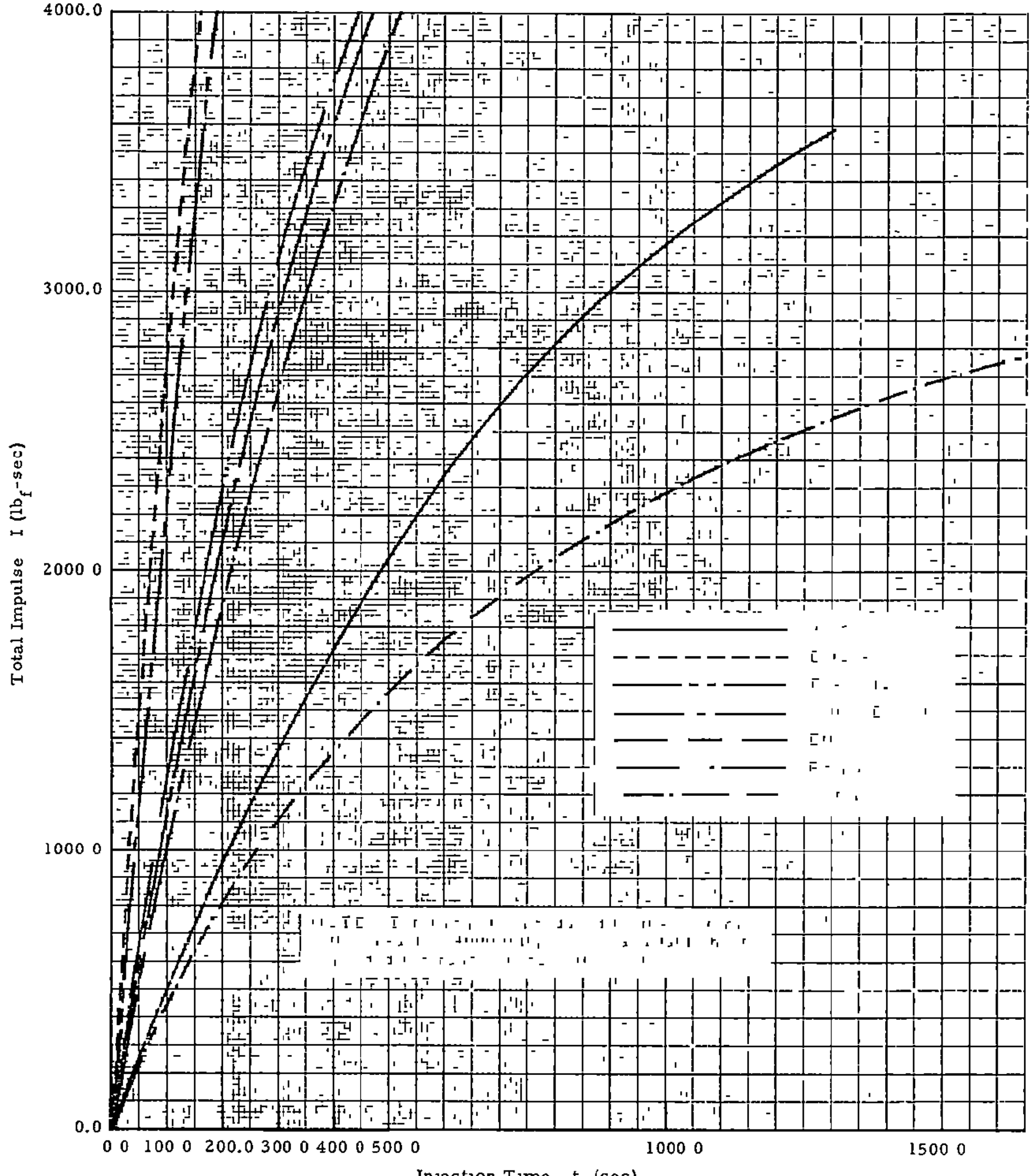

Fig. 10 - Total Impulse Produced by System as a Function of Injection Time for the Candidate Fluids

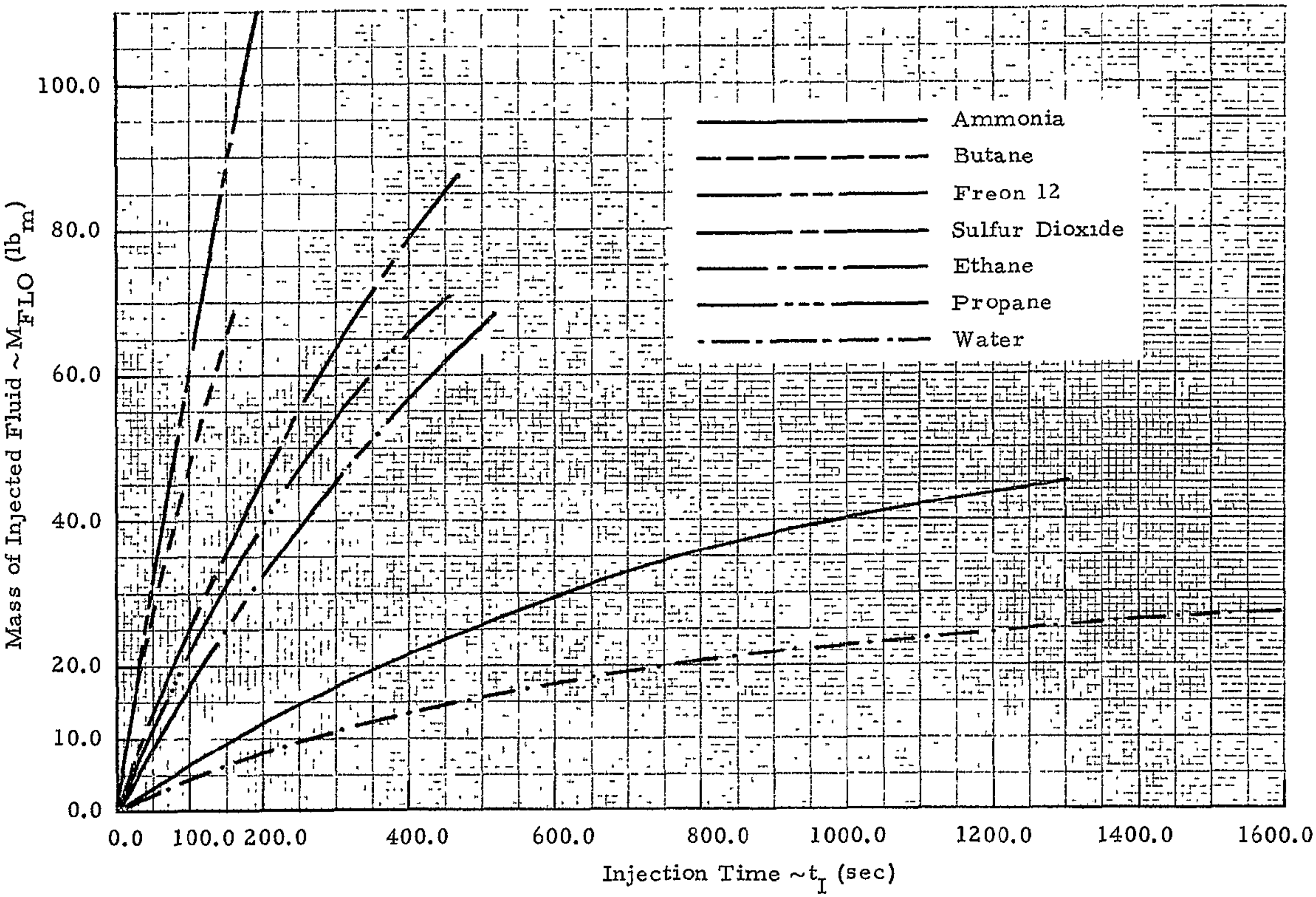

Fig. 11 - Total Mass Injected as a Function of Injection Time for the Candidate Fluids

Table 1

THERMODYNAMIC PROPERTIES OF THE CANDIDATE FLUIDS

Fluid	Vapor Temperature (^oR)	Vapor Pressure (psia)	Thermal Conductivity $\left(\frac{Btu}{hr\text{-}ft\text{-}^oR}\right)$	Specific Heat, C_p $\left(\frac{Btu}{lb_m\text{-}^oR}\right)$	Latent Heat of Vaporization (Btu/lb_m)	Density Liquid Phase (lb_m/ft^3)	Density Vapor Phase (lb_m/ft^3)	Viscosity (lb_m/ft-sec)
Ammonia	538.3	146.9	0.0142	0.7575	501.2	37.65	0.4827	6.7869 x 10^{-6}
	500.2	73.48	0.0129	0.665	536.2	39.49	0.2518	6.2493 x 10^{-6}
	458 4	29.392	0 01135	0 5865	570.0	41 40	0.1060	5 7789 x 10^{-6}
	431 5	14.696	0 0103	0 5425	589.3	42 56	0.05555	5.5102 x 10^{-6}
	409.68	7 736	0.0094	0.510	604.0	43.47	0.03066	5 1742 x 10^{-6}
	368.28	1.934	0.00775	0 445	629.0	45 08	0 00836	4.7709 x 10^{-6}
	353.0	0.912	0.0071	0.425	640.0	45.80	0.00413	4.5694 x 10^{-6}
Butane	590.0	80.83	0.01	0.43	141.5	33.52	0 8598	5 5438 x 10^{-6}
	560.0	51.37	0.0092	0.425	150.5	34.83	0.5531	5 2078 x 10^{-6}
	530.0	31.2	0.0085	0 405	157.5	36 05	0.3415	4.9389 x 10^{-6}
	491.1	14.696	0.00775	0.380	165 5	37 57	0 1690	4.603 x 10^{-6}
	470 0	9.21	0.0074	0.365	169.5	38.26	0.1105	4 4014 x 10^{-6}
	435.8	3.868	0.0069	0 340	175.5	39.40	0.0600	4.3133 x 10^{-6}
	412.4	1.934	0 0066	0.325	129.5	40.20	0.0400	3.9646 x 10^{-6}
	385.6	0 7736	0.00625	0.305	183.0	41.00	0.0250	3.763 x 10^{-6}
	351.96	0.1934	0 0059	0.280	188.5	42.00	0.01250	3.5278 x 10^{-6}
	337.7	0.0967	0.00575	0.270	190.0	42.50	0.0050	3 427 x 10^{-6}
Ethane	530.0	563.3	0.0119	0.700	87.00	21.62	5.571	6 13 x 10^{-6}
	500.0	388 10	0.01085	0.6875	123.3	25 30	3.306	5.8 x 10^{-6}
	460.0	220.80	0.0096	0.6710	153.9	28 01	1.746	5.36 x 10^{-6}
	400.0	77.37	0.00765	0.6465	184 3	31.26	0.612	4.74 x 10^{-6}
	332.44	14.696	0 00552	0.6190	209.4	34.12	0.128	4.10 x 10^{-6}
	310.0	7.14	0.0049	0.6100	217.1	34.95	0.06623	3.91 x 10^{-6}
	280.0	2.20	0.00395	0.5975	225.6	36.05	0.0227	3 675 x 10^{-6}
	260.0	0.85	0.00335	0.5890	231 0	36.76	0.09276	3 54 x 10^{-6}
Freon 12	530.0	84 80	0.00547	0.1732	60.309	82 717	0 0451	8.17 x 10^{-6}
	500.0	51.667	0.00495	0.1729	64 163	86.296	0 0632	7 9628 x 10^{-6}
	460.0	23.849	0.00425	0.1721	68 75	90.659	0.2581	7.56 x 10^{-6}
	438.4	14.696	0.00387	0.1718	71.00	92.80	0.394	7.33 x 10^{-6}
	420.0	9.3076	0.00355	0.1715	72 913	94 66	0.622	7.0893 x 10^{-6}
	370.0	2.0509	0.00268	0.1707	77 764	99.274	1.2927	6.48 x 10^{-6}
	360.0	1.428	0.0025	0 1705	78.714	100.15	2.0913	6.3165 x 10^{-6}
Propane	530.0	124.68	0.01005	0.395	145.71	31.2351	1.1716	5.4 x 10^{-6}
	500.0	78.521	0.0087	0 377	156.743	32.734	0.74168	5.08 x 10^{-6}
	460.0	38.3443	0.0076	0.355	169 607	34.7671	0.33977	4.675 x 10^{-6}
	416.27	14.696	0 0060	0 327	179.97	36.36	0.15181	4.17 x 10^{-6}
	360.0	2.8814	0.0040	0.291	196 202	38.4634	0.03339	3.675 x 10^{-6}
	340.0	1.444	0.0033	0.280	201.3	39.10	0.0185	3.48 x 10^{-6}
	300.0	0.3472	0.0029	0.255	211.2	40.50	0.0053	3.08 x 10^{-6}
	280.0	0.1701	0.0012	0.243	216.0	41.50	0.00285	2.88 x 10^{-6}
	260.0	0.08333	0.0005	0.230	221.0	42.10	0.0015	2.70 x 10^{-6}
Sulfur Dioxide	560.0	84.10	0.0057	0.15	148.2	83 0565	0.9804	8.601 x 10^{-6}
	520.0	40.30	0 0053	0.1475	157 8	87.03219	0.4878	8 064 x 10^{-6}
	500.0	26.60	0.0051	0.146	162.2	88.8888	0 3311	7.795 x 10^{-6}
	460 0	10.26	0.00475	0.1435	170.3	92.4214	0.1360	7 324 x 10^{-6}
	420.0	3.120	0.0044	0.1405	178.4	95.7854	0.04504	6.653 x 10^{-6}
	400.0	1.550	0.00425	0.1395	182.3	97.5609	0.02347	6.384 x 10^{-6}
	360.0	0.294	0.00395	0.135	190.1	101.461	0.004885	5.879 x 10^{-6}
Water	672.0	14.696	0.0139	0.4515	920.33	59.8	0.0373	8.399 x 10^{-6}
	660 0	11.526	0.0135	0.4510	977.91	60.132	0.0297	8 131 x 10^{-6}
	620.0	4.741	0.0122	0.4495	1002.31	61.0128	0.01293	7.593 x 10^{-6}
	560.0	0.9492	0.01055	0.4465	1037.23	61 996	0.00285	6 787 x 10^{-6}
	540.0	0.5069	0.0101	0.4460	1048.58	62 189	0.00158	6.585 x 10^{-6}
	520.0	0.2563	0.0097	0.4451	1059.94	62 344	0.00083	6 317 x 10^{-6}
	500.0	0.12170	0.0093	0.4445	1071 25	62.421	0 000409	6 048 x 10^{-6}
	492.0	0.08854	0 0092	0.4441	1075.80	62.421	0.000302	5.913 x 10^{-6}

Table 2

CHARACTERISTICS OF TE-364-3 ROCKET MOTOR*

Prefire Weight of Motor (ω_n)	1575.0 lb_m
Post-fire Weight of Motor ($\omega_{b.o.}$)	122.0 lb_m
Nozzle Throat Area (post-fire)	9.24 in^2
Area Ratio (post-fire)	49.43
Specific Impulse (experimental)	288.0 $\frac{lb_f\text{-sec}}{lb_m}$
Motor Case Diameter	36.8 in.

*Motor data taken from Ref. 3

Table 3

COMPARISON OF CANDIDATE FLUIDS

Item	Ammonia NH_3	Butane (R) C_4H_{10}	Ethane C_2H_6	Freon 12 CCl_2F_2	Propane C_3H_8	Sulfur Dioxide SO_2	Water H_2O
Molecular Weight	17.03	58.12	30 07	120 0	44.0	64.06	18.016
Ratio of Specific Heats	1 3	1 11		1.139	1.14	1.29	1 33
Conditions in Motor Chamber Initial (t_I = 1 0 sec)							
Chamber Pressure psia	0 324	1 835	0 631	1 344	0 492	0.773	0 305
Chamber Temperature °R	315.0	411.8	250.0	358 5	305.5	383 3	525 0
t_I = 160 0 sec							
Chamber Pressure psia	0.270	1 028	0 489	1.064	0 387	0.560	0 214
Chamber Temperature °R	309 5	394 5	243.5	351.8	298.0	375.5	515 0
Mass Flow Rate (lb_m/sec)							
Initial (t_I = 1.0 sec)	0 06732	0 564	0.188	0.662	0 159	0 280	
t_I = 160.0 sec	0 0563	0.332	0.148	0 530	0.126	0.205	0.035
Thrust							
Initial (t_I = 1 0 sec)	5.397	34 4	11.16	24.55	8.98	12.93	5 013
t_I = 160.0 sec	4.50	19.17	8 64	19.44	7 06	9.37	3 51
Specific Impulse - lb_f-sec/lb_m							
Initial (t_I = 1.0 sec)	80.177	61 0	59.29	37 06	56 5	46.22	100.53
t_I = 160.0 sec	80.43	57 8	58 64	36.71	56 0	45.6	99.34
Total Impulse Produced at t_I = 160 0 sec (lb_f - sec)	784.7	4014 3	1548.06	3456.0	1264 5	1741.4	666.9
Total Impulse Produced at t_I = 200.0 sec (lb_f - sec)	921.26	4580 5	1809.7	4048 38	1479.56	2026.8	772 8
Amount of Fluid Utilized at t_I = 160 0 sec	9.75	68 65	26 31	93 66	22 42	37.92	6 7
Fluid Storage Conditions							
Storage Pressure psia	121 63	30 47	540 8	82 05	121 83	49 34	0 363
Storage Temperature °R	528.0	530.0	528.0	528.0	528.0	530.0	530.0
Ideal Tank Weight Using Vascomax Material for Fluid at t_I = 160 sec (lb_m)	0.1354	0 254	2.810	0 397	0.342	0.092	0.17×10^{-3}
Velocity Increment (ΔV) Available from the Trim System (ft/sec)	58 87	278 39	112.88	235 6	97 71	125 77	50.14
Velocity Penalty Imposed by Carrying Trim System on Primary Vehicle and Using All the Fluid (ft/sec)	137 6	826 2	389.3	1192.3	309 58	513.7	91 32
System Mass Fraction	0 83	0 97	0 85	0.977	0.913	0.953	0 79
Installed Specific Impulse (lb_f-sec)	66 76	56 07	49 84	35 86	51 13	36.14	78.300

Table 4

REPRESENTATIVE SYSTEM WEIGHTS

Payload and Vehicle Structual Weight ~ ω_p		=	300 lb_m
Weight of Fluid Injection System Hardware, ω_H			
	Fluid Vent Valve (1)	=	0.12 lb_m
	Fluid Charging Valve (1)	=	0.12 lb_m
	Squib Valves (2)	=	0.70 lb_m
	Check Valve (1)	=	0.11 lb_m
	Lines and Brackets	=	0.75 lb_m
		ω_H =	1.8 lb_m

Appendix C*

DESIGN CRITERIA FOR INERT FLUID INJECTION SYSTEM FOR VELOCITY TRIM APPLICATIONS

*Work accomplished under Task 3 of the Work Statement of Contract NAS5-11614. The report is included here as Appendix C as a convenience to the reader.

TM 54/20-269
LMSC/HREC D162476

LOCKHEED MISSILES & SPACE COMPANY
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DESIGN CRITERIA FOR INERT FLUID INJECTION SYSTEM FOR VELOCITY TRIM APPLICATIONS

July 1970

Contract NAS5-11614

Prepared for NASA-Goddard Space Flight Center
Greenbelt, Maryland

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FOREWORD

This report presents the results of work performed by Lockheed's Huntsville Research & Engineering Center while under contract to Goddard Space Flight Center, Contract NAS5-11614. This work was accomplished under Task 3 of the Work Statement of the subject contract. The NASA technical coordinator for this study is Mr. Daniel Dembrow of the Delta Project Office.

Section 1
SUMMARY AND INTRODUCTION

An Inert Fluid Injection System (IFIS) is being designed for use with the Delta rocket launch vehicle. The IFIS will provide an orbital velocity trim capability for the third stage of the Delta vehicle.

To ensure capability of the IFIS and the Delta vehicle, a Design Criteria for the Inert Fluid Injection System, Section 2, has been prepared. These criteria, which establish the requirements for the design of the IFIS, include consideration of: IFIS concepts, operation and performance; IFIS design constraints imposed by the Delta vehicle configuration and environment; and IFIS design constraints imposed by safety requirements. These criteria, together with the layout of the Inert Fluid Injection System (Lockheed Drawing No. R72411), constitute the results of Task 3 (Conceptual Design) of the Work Statement.

Section 2
TECHNICAL DISCUSSION

2.1 SCOPE

These criteria establish the requirements for the design of an Inert Fluid Injection System (IFIS). The IFIS is to be used as a velocity trim control by utilizing the latent heat in the expended Delta third-stage motor (Thiokol TE-364-3) to vaporize the injected inert fluid. This vaporization with subsequent expulsion through the rocket nozzle results in a relatively low thrust augmentation. The IFIS will consist of three major components: the tankage for inert fluid storage; the valving and plumbing for on-off control; and the injector for spraying the fluid into the spent rocket chamber.

2.2 APPLICABLE DOCUMENTS

The documents listed below form a part of this design criteria to the extent specified herein. In the event of conflict between documents here and other detailed content of Section 2.5, the detailed requirements of Section 2.5 will be considered a superseding requirement.

<u>Specifications</u>

NASA S-320-G-1	General Environmental Test for Spacecraft and Components using Launch Environments Dictated by Delta, Centaur, Agena, and Scout Launch Vehicles (Preliminary supersedes Delta Specification S-320-D-2)
MIL-D-9412D	Data for Aerospace Ground Equipment
MSFC Spec 279	Electromagnetic Compatibility, dated June 1, 1964

<u>Standards</u>

MIL-STD-803	Human Engineering Design Criteria for Aerospace Systems and Equipment. Part I, Aerospace Systems Ground Equipment
MIL-STD-810B	Environmental Test Methods
MS 3540	General Practices for Safety Wiring and Cotter Pinning

Reports

AFETRM 127-1	Safety ... Range Safety Manual, 1 November 1966, USAF
DAC-61687	Delta Spacecraft Design Restraint, October 1968, Douglas Report
LMSC/HREC D162373	"Fluid Selection Study for an Inert Fluid Injection Propulsion System," June 1970

2.3 SYSTEM REQUIREMENTS

- Concept

The Inert Fluid Injection System as shown in Fig. 1 shall consist of three major items: inert fluid storage tank; valving and plumbing; and the injector. Flow regulation of the system will be provided by the vapor pressure of the inert fluids and sizing of the injector orifices. The tank shall have a volume of 1.5 ft^3 and will be designed for a 150 psia maximum operating pressure. Sequence valves for the system are to be redundant pyrotechnic on-off normally open, normally closed type. Fill and drain valves for the tank and system mounting brackets shall be provided. The operating fluid shall be one of the following: ammonia (NH_3), butane (C_4H_{10}), or water (H_2O) as determined by mission requirements (refer LMSC/HREC D162373).

- Operation

Upon command, the normally closed pyrotechnic valve will be opened, allowing the pressurized inert fluid to inject into the rocket chamber. Again, upon command, the normally open pyrotechnic valve will be closed to shut off the system.

- Performance

The IFIS will provide usable propulsive energy for the trimming of the third stage velocity or a suitable means for quenching of the TE-364-3 rocket motor. Flow rate control shall be provided by means of the vapor pressure of the inert fluid and the injector orifice size. The nominal mass flow rate for the inert fluids is listed in the chart below.

Fluid	Tank Pressure (psia)	Fluid Temp. (^oF)	Mass Flow, $\dot{m}$ (lb_m/sec)
Butane (C_4H_{10})	30.47	70	0.564
Ammonia (N_3H)	121.63	68	0.0673
Water (H_2O)	14.70	70	0.0475

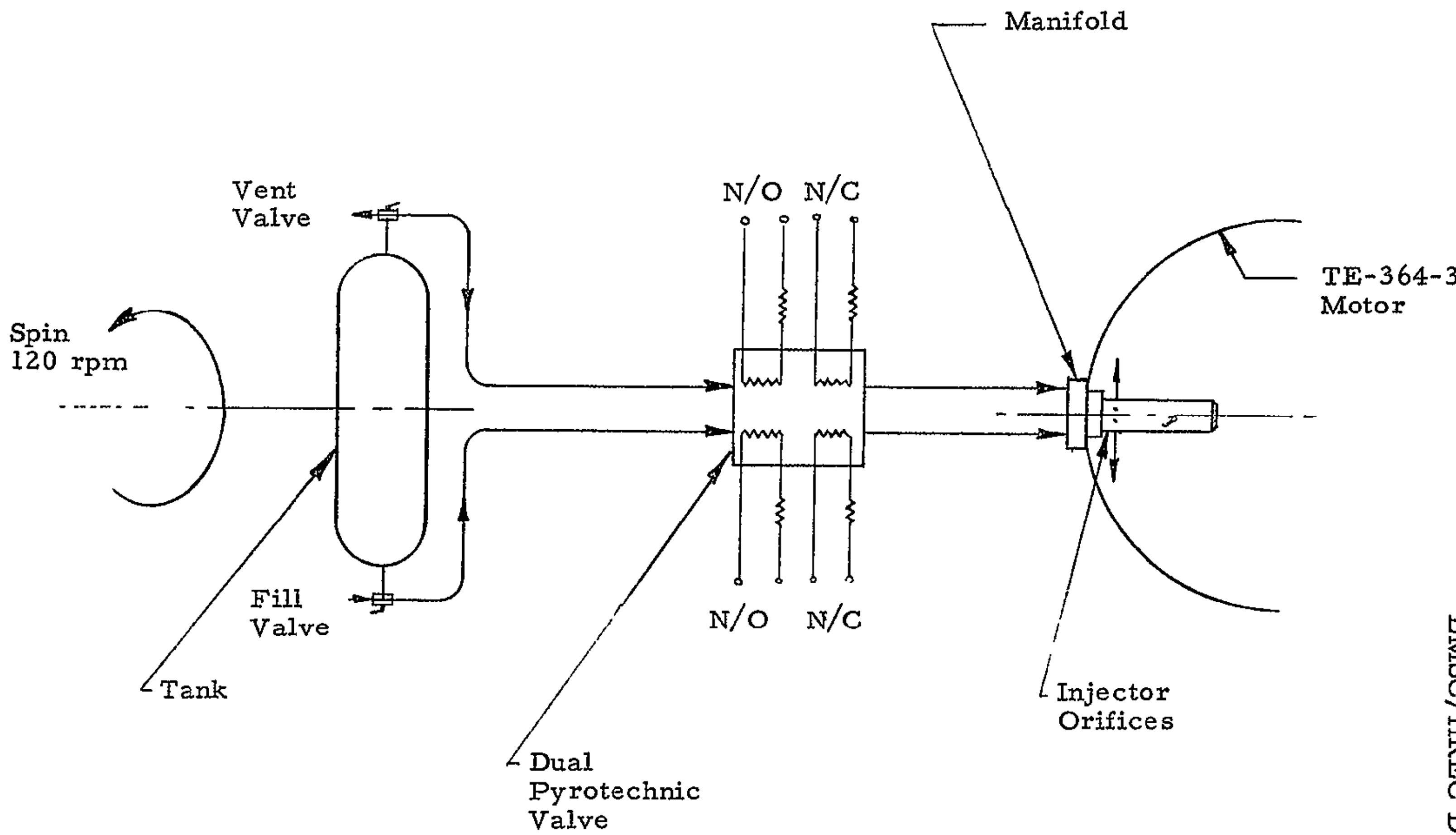


Fig. 1 - Inert Fluid Injection System Concept

Maximum operating time shall be the time required for total depletion of all the fluid in the IFIS tank. Minimum time will depend upon flight program requirements, with an absolute minimum being a function of the pyrotechnic valves. Time between command to operate and actual flow conditions shall be accountable.

2.4 SYSTEM DESIGN

- Weight

The IFIS shall maintain as low a weight as practicable and still maintain structural integrity. As a design goal the weight (loaded) shall not exceed 60 lb, with a ratio of inert fluid to total system weight of 0.80.

Balance

The static unbalance for the system, with reference to the vehicle longitudinal axis, shall be within ± 0.03 W (gm-in.), where W is system weight in grams. Dynamic unbalance shall not exceed 800 I (gm-in^2), where I is the IFIS moment of inertia about the spacecraft spin axis (slugs-ft^2), per NASA specification S-320-G-1. The values are for the prototype configurations with the final balance of flight hardware being one-half these values. In addition, the change in moment-of-inertia due to fluid depletion shall be provided.

Flight Hardware

Wherever possible, hardware for the IFIS shall be flight-qualified hardware. Flight-qualified hardware is defined as those equipment having proved their capabilities while being subjected to actual or simulated Delta flight conditions and deemed acceptable for use in launch hardware. Proof of qualified flight hardware shall be provided.

Interface

Lockwire shall be used where threaded fasteners are utilized per MS 3540.

Vehicle (Launch)

The IFIS is to be used on the Delta M launch vehicle. The payload attach fitting to be used is the 37 x 31-in. fitting, Douglas Aircraft Company Drawing No. 1D01068; Fitting, Spacecraft. Those areas designated as restricted for spring separation shall be avoided (Fig. 2). Other interference areas arising from a particular flight shall be provided by the Delta Project Manager; i.e., each flight has its own particular third-stage instrumentation and tracking system modifications. No cognizance for this task is assumed by LMSC. Relocation of existing access holes shall be performed so that access to the Safe and Arm mechanism of the initiator can be made per Mil-Std-803 requirements.

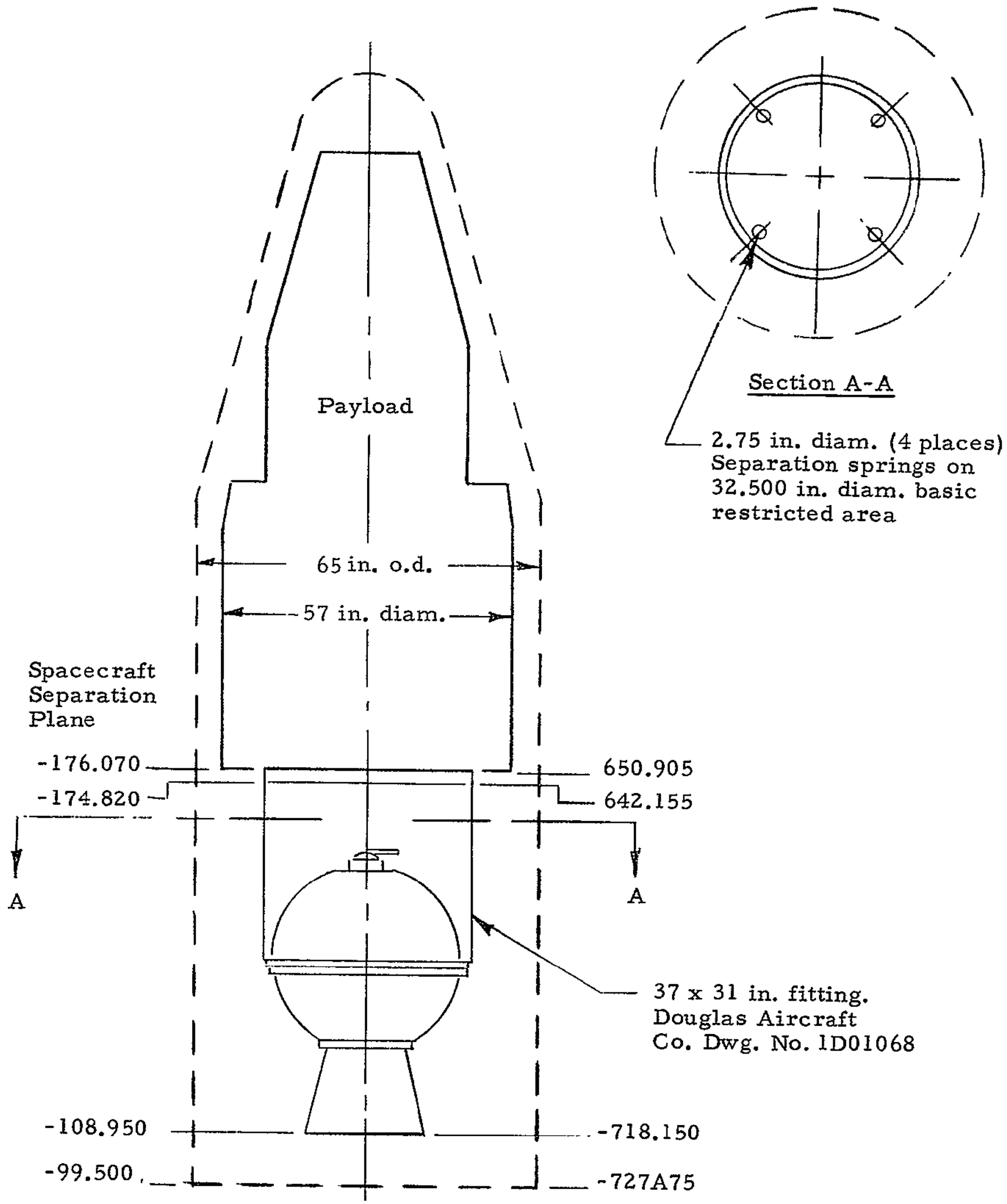


Fig. 2 - Payload Envelope, TE-364-3, 37 x 31-Inch Fitting

Motor

The motor to be used is the Thiokol solid propellant motor designated TE-364-3, per Douglas Delta Spacecraft Design Restraints DAC-61687. The forward sholder of the TE-364-3 rocket motor (17.60-in. diameter bolt circle) shall be used for mounting the IFIS hardware. No modifications are to be performed on the motor casing. Maximum steady-state loads on the forward sholder are shown in Fig. 3.

Ignition Assembly

The Ignition Assembly for the motor shall utilize the Thiokol E19578-02 case. Modifications to this case shall be such that neither the structural integrity nor function are diminished so as to require qualification firing tests.

Electrical

The electrical interface between the IFIS and third stage shall be at the connectors on the valve. The electrical firing circuit shall be under the cognizance of NASA-GSFC Delta Projects Office.

Pyrotechnics

All pyrotechnics shall be in a disarmed condition at all times except while undergoing tests, checks or flight. Circuit continuity checks shall be made by use of currents and voltages as specified by the pyrotechnic manufacturer. Nominal initiator resistance shall be 1.0 ohms, with a 1.0 amp, 1 watt no fire. The entire pyrotechnic valve shall be conductive and any connecting or surrounding metal parts shall be permanently grounded together and to the TE-364-3 motor. Any electrical firing circuit interruption point shall be accessible so that connection can be made on or later than flight minus one day. Ordnance and arm techniques shall be as specified by NASA-Goddard Delta Projects Office

Safe-Arm Valve

The safe-arm valves shall provide for mechanical disruption of fluid flow and shall be accessible for arming on or later than flight minus one day.

- Loads Criteria

All structural support members shall maintain structural integrity when the largest loadings are applied. Any system pressure vessel must have a ratio of burst-to-operating pressure of 4 to 1 and undergo proof tests of 1.5 times operating pressure. Maximum operating pressure shall be 150 psia. The more stringent safety requirements for a pressure vessel with a safety factor of less than 4 to 1 shall be met if needed per DAC-61687.

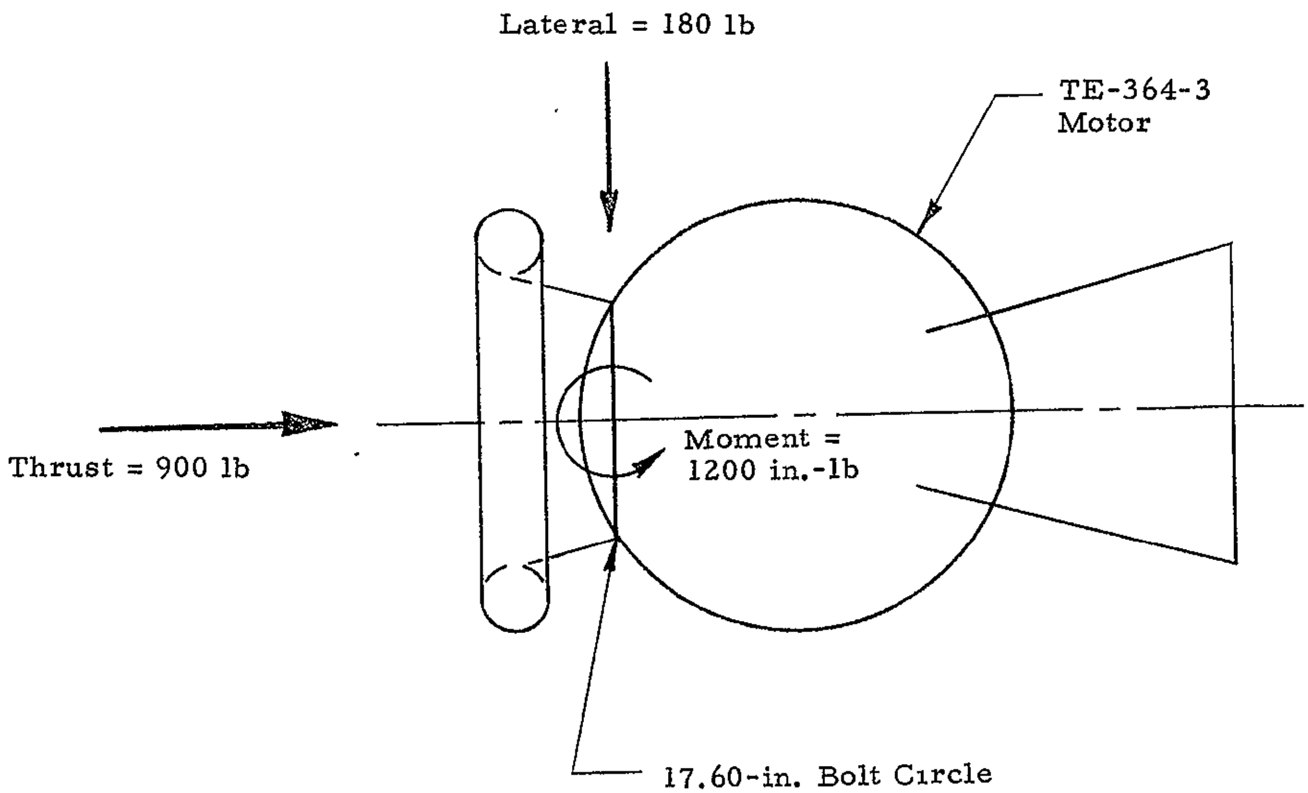


Fig. 3 - Maximum Loading on Motor from IFIS

Steady State

The IFIS structure (less pressure vessels) shall be capable of withstanding the following steady-state loads. Safety factor shall be 1.15, based on yield strength, and 1.50, based on ultimate strength (applied simultaneously).

Thrust	$\pm$15 g (based on minimum Delta payload wt. = 700 lb)
Lateral	$\pm$3 g

Dynamic

The IFIS shall be capable of withstanding the design qualification tests as set out in Section 2.5. These tests are more stringent than flight acceptance.

Spin

The IFIS shall be capable of withstanding a spin rate of 120 rpm, which is the maximum launch or orbital rate, for a minimum of 10 minutes without any material yield. The IFIS shall also withstand the angular acceleration caused by spin-up (120 rpm in one sec).

Installation

The IFIS shall become part of the TE-364-3 rocket motor once assembled; i.e., the IFIS must be assembled to the motor prior to payload attach fitting.

2.5 ENVIRONMENT

The following environmental conditions shall apply for the design of the IFIS. The environmental test methods of MIL-STD-810, where applicable, shall be specified.

Temperature and Humidity

The temperature design criteria, with no fluid in the tank, fall into two categories: storage and operational. For storage the IFIS shall be capable of withstanding six hours at -30°C and 60°C. Under operational temperature the time duration is again six hours, but the temperatures are $\pm$10°C of the predicted flight temperatures. The IFIS shall be capable of withstanding 24 hours at a relative humidity of 95% (+0, -5%) at a temperature of 30°C. Electrical circuit continuity checks before and after each condition shall be possible without system failure.

Oscillation

The main requirements is that failure does not result from launch operations. The effects of oscillations may arise from shock, sinusoidal and random vibration, and acoustic noise; and are interrelated.

Vibration

The IFIS shall be capable of withstanding the sinusoidal and random vibrations as set out in Table 1 (applied at forward shoulder surface).

Table 1

Type	Axis	Frequency Range (Hz)	g Level (0-to-Peak)	Sweep (Octaves/min)	
Sinusoidal	Thrust	5-11	0.48 in. double amplitude	2.0	
		11-17	$\pm$3.0	2.0	
		17-23	$\pm$6.0	1.5	
		23-200	$\pm$2.3	2.0	
Sinusoidal	Lateral	5-7.5	0.8 in. double amplitude	2.0	
		7.5-13	$\pm$2.3 g	2.0	
		13-200	$\pm$1.5 g	2.0	
			PSD Level (g^2/Hz)	Acceleration (g-rms)	Duration
Random	Thrust & Lateral	20-300	0.0029 to 0.045 increasing from 20 Hz at 3 dB/ octave	9.1	4 min each axis
		300-2000	0.45		

Shock

The IFIS shall withstand shock loading applied per Fig. 4, once per axis, for the Delta M3 stages.

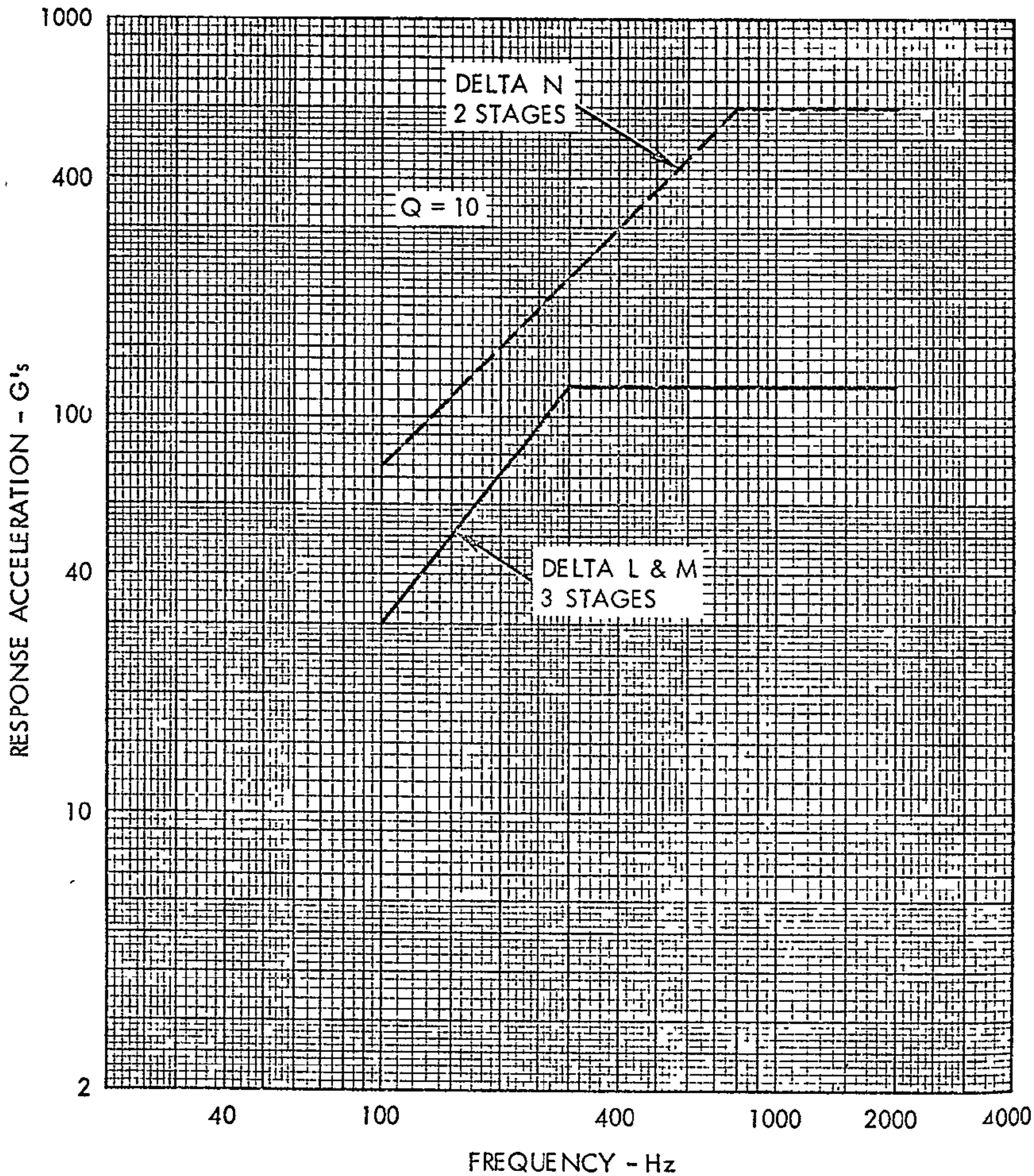


Fig. 4 - Delta Shock Spectra Input - Spacecraft Flight Acceptance

2.6 POWER REQUIREMENTS

No additional power for initiation or operation of the IFIS shall be required.

2.7 GROUND SUPPORT AND CHECKOUT

Equipment and procedures required for the checkout and maintainability of the system during test and launch operations will be specified for the IFIS and the AGE. These are to include:

1. Systems design description: including schematics, component description, physical characteristics of the pressurant fluid, etc.
2. Design and test data on pressure vessels and subsystem parts.
3. Detail description of servicing equipment.
4. Detailed operating procedures: including schedules, personnel requirements, facility requirements, and safety precautions.

(Ref. DAC-61687 and AFETRM 127-1)

For a system with a burst-to-operating pressure ratio of less than 4 to 1, the following additional information shall be supplied:

1. Quality control criteria
2. Qualification and acceptance test criteria
3. Test criteria for all flight units.

Appendix D
CONCEPTUAL DESIGN CALCULATIONS

Appendix D

TANK SIZING (INITIAL WORK)

Under the initial work the following items were the boundary conditions for the tank:

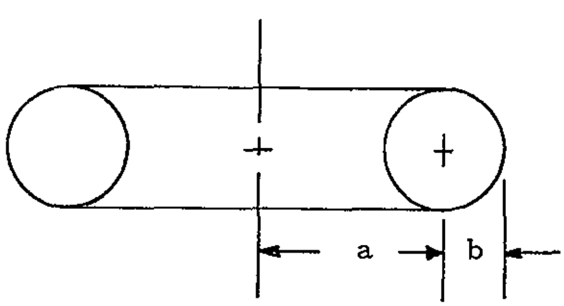
1. Working fluid - butane
2. Fluid weight - 68 lb
3. Must hold fluid volume
4. Must reside inside 37 x 31 attach fitting and not overlap access ports, and remain clear of S&A restricted envelop and spring separators.

The required volume is a function of temperature or liquid density. Using 150^{o}F as the maximum temperature the volume is:

$$W = \rho V$$

$$V = \frac{W}{\rho} = \frac{68\ \text{lb}}{32.61\ \text{lb/ft}^3} = 2.0852\ \text{ft}^3$$

For the torus tank the volume is:



$$V = 2\pi^2 b^2 a$$

Now since a general envelope shape is defined by the attach fitting, radius "a" was made the independent variable and varied as follows:

$$V = 2\pi^2 b^2 a$$

$$b^2 = \frac{V}{2\pi^2 a}$$

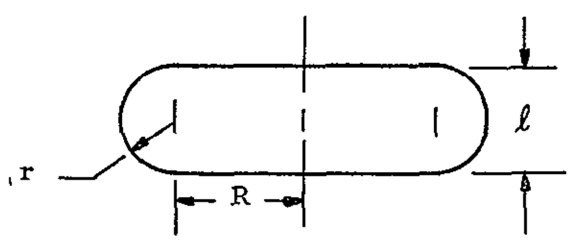
$$b = \frac{1}{\pi}\sqrt{\frac{V}{2a}}$$

6 + a = 9 inches, then b is

$$b = \frac{1}{\pi}\sqrt{\frac{2.0852\ \text{ft}^3}{2\,(9\ \text{in})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)}} = .3755\ \text{ft} = 4.506\ \text{in}$$

for a	=	10 inches	b	=	4.275 inches
a	=	11 inches	b	=	4.07 inches

Laying these tanks out on the motor-attach fitting assembly showed that the 10 inch by 4.275 inch cross-sectional tank would fit. To ensure that the torus was the optimum shape other configurations were investigated. A "pancake" tank as depicted below showed that filling the hole in the torus was not too efficient from a volume and dimension standpoint.

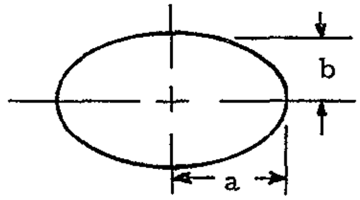


$$V = \pi R^2 \ell + \frac{2\pi^2 \alpha^2 R}{2}$$

for r = 4.32 in. R = 8.94 in.

Although these dimensions are slightly smaller than a torus, this shape is not as good a pressure vessel and would require a greater wall thickness resulting in greater weight

The next shape examined was an elliptical shape as shown below.

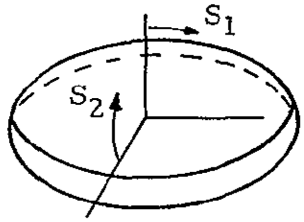


$$V = \frac{4}{3}\pi a^2 b$$

for b = 4 inches which is dictated by available space

$$a = \sqrt{\frac{3V}{4\pi b}} = \sqrt{\frac{3 \times 1728 \frac{in^3}{ft^3} \times 2.085\ ft^3}{4\pi \times 4\ in.}} = 14.7\ in.$$

This shape fits into the available space nicely but upon viewing stress and weight the ellipsoid would be costly.



$$S_1 = \frac{PR_2}{2t} \qquad S_2 = \frac{PR_2}{2t}\left(2 - \frac{R_2}{R_1}\right)$$

Using a maximum internal pressure of 106.2 psi and maximum working stress of 1/4 yield stress and 17-7 PH steel, the material thickness and weight are

$$S_1 = \frac{PR_2}{2t} \qquad t = \frac{PR_2}{2S_1} = \frac{106.2\ lb/in^2\ (14.7)\ in.}{2\ (46,500)\ lb/in.^2} = .01368\ in.$$

$$S^2 = \frac{PR_2}{2t}\left(2 - \frac{R_2}{R_1}\right)\ t = \frac{PR_2}{2S_2}\left(2 - \frac{R_2}{R_1}\right) = .01368\left(2 - \frac{A.7}{4}\right) = -.0502\ in.$$

The minus indicates that the stress is not a tensile stress but rather a compressive stress. The weight is

$$W = \rho V_{surface}\ t$$

$$W = \rho\left[2\pi a^2 + \frac{\pi b^2}{\epsilon}\ \log_e \frac{1+\epsilon}{1-\epsilon}\right] t \qquad \epsilon = \sqrt{\frac{a^2 - b^2}{a}}$$

$$\epsilon = \frac{\sqrt{(14.7)^2 - (4)^2}}{14.7} = .783 \qquad t = \text{thickness}$$

$$W = \rho t \left[2\pi (r)^2 + \frac{\pi (14.7)^2}{.783} \log_e \frac{1 + .783}{1 - .783}\right]$$

$$W = 1164 \rho t$$

for 17-7PH steel $\rho = .273$ lb/in ^{3}

$$W = 1164 (.273) (.0502) = 15.96 \text{ lb}$$

Now that the basic shape has been chosen (a torus) a comparison of material is necessary. The steps used to calculate the required wall thickness from the stress equation using a conservative value for the allowable stress are outlined below

$$S_{1max} = \frac{Pb}{t} \left(\frac{2a - b}{2a - 2b}\right)$$

$$S_{1max} = S_{allowable} = \frac{S_{yield\ point}}{4}$$

for 17-7PH $S_{all} = \frac{185,000}{4} = 46,500$ psi

$$t = \frac{Pb}{S_{all}}\left(\frac{2a - b}{2a - ab}\right) = \frac{106.2 (4.275)}{46,500} \left(\frac{2 \times 10 - 4.275}{2 \times 10 - 2 \times 4.275}\right)$$

$$t = .0134 \text{ in.}$$

$$W = \rho V = \rho (4\pi^2 abt) = (.273) (4\pi^2 \times 10 \times 4.275) \times .01345$$

$$W = 6.19 \text{ lb}$$

Substituting in various materials yields the following results for the same tank (volume):

Material	Density (ρ)lb/in.^{3}	Stress Allowable (psi)	Thickness (in.)	Weight (lb)
17-7PH Steel	0.273	46,500	.0135	6.19
Modified H-11 Steel	0.281	60,250	.0103	4.879
Titanium Ti-8AL-1Mo-IV	0.158	31,250	.0200	5.32
Aluminum 5154	0.096	8,250	.0758	12.268

Summary:

Boundary Conditions - Butane
Volume = 2.0852 ft^3
Pressure = 106.2 psi
Allowable Stress = Yield point stress/4

Tank Shape	17-7PH Steel Thickness (in.)	17-7PH Steel Weight (lb)	Titanium Thickness (in.)	Titanium Weight (lb)
torus	.0135	6.13	.020	5.32
elliptical	.0502	15.96	.072	13.22
spherical	.0109	3.415	.0162	2.92

Conclusions:

1. Spherical shape best if it would fit
2. Elliptical shape worst - too heavy
3. Steel best material from weight standpoint, but becomes too thin to fabricate and handle; hence —
4. Choice of titanium material and torus shape

TANK SIZING (INTERMEDIATE WORK)

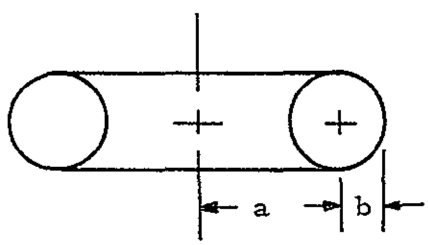
Conditions or restrictions:

1. Stay out of S & A envelope
2. Volume shall be 1 1/4 ft^3 approximate
3. Maximum internal pressure shall be 106.2 psia
4. Maximum allowable stress shall be 1/4 yield stress

From previous study the material and shape were seen to be titanium and torus.

$$\text{density } \rho = .158 \text{ lb/in.}^3$$

$$S_{max\text{-}allowable} = \frac{125{,}000}{4} = 31{,}250 \text{ psi}$$



$$\text{tank volume } V = 2\pi^2 b^2 a \qquad (1)$$

$$\text{tank stress } S = \frac{Pb}{t}\left(\frac{2a - b}{2a - 2b}\right) \qquad (2)$$

$$\text{tank weight } W = \rho 4\pi^2 abt \qquad (3)$$

item (1) restriction means $a\text{-}b \geq 6.54$ in. using equation

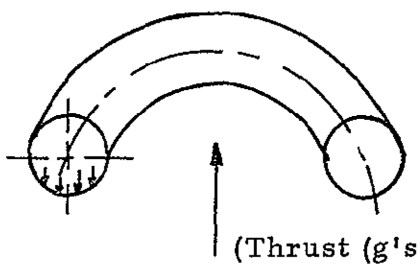
$$(1) \quad b = \frac{1}{\pi}\sqrt{\frac{V}{2a}} = \frac{1}{\pi}\sqrt{\frac{2160}{2a}} = \frac{109.5379}{a}$$

$$(2) \quad t = \frac{Pb}{S}\left(\frac{2a-b}{2a-2b}\right) = \frac{106.2b}{31{,}250}\left(\frac{2a-b}{2a-2b}\right)$$

$$(3) \quad W = \rho 4\pi abt = (.158)\,(4)\,\pi abt = 6.231\ abt$$

a (in.)	b (in.)	a - b	t (in.)	W (lb)
8.0	3.700	4.300	.01798	3.316
8.5	3.589	4.911	.01665	3.165
9.0	3.489	5.511	.01561	3.054
9.5	3.396	6.104	.01475	2.965
9.75	3.352	6.398	.01437	2.926
10.0	3.310	6.690	.0140	2.887
10.5	3.230	7.270	.0134	2.832
11.0	3.156	7.844	.01288	2.786
11.5	3.086	8.414	.01241	2.744
12.0	3.021	8.979	.01199	2.709

Stress in tank due to 15 g loading



$$S = \frac{PR}{t}$$

where $P = \frac{W(g)}{\frac{1}{2}A}$

W = fluid weight
g = 15
A = $\frac{1}{2}$ internal surface area

The fluid is to represent 80% of the total system weight which is to be approximately 50 lb, i.e.,

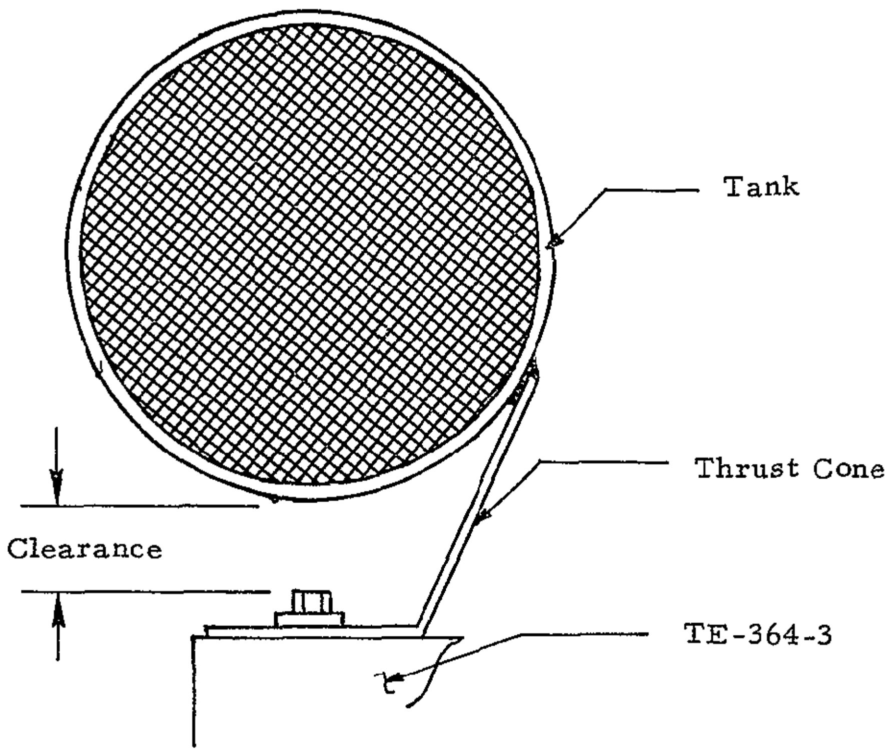
$$W = .8(50) = 40 \text{ lb}$$

assume we do slightly better than .8 or 45 lb = W

$$\text{then } S = \frac{45\ (15)\ (3.31)}{\frac{1}{2}\ (4\pi^2 \times 10 \times 3.31)\ (.014)} = 446 \text{ psi}$$

This stress along with the stress due to internal pressure amounts to 31,250 + 446 = 31,696 psi; which is very low, when compared to the yield stress (125,000 psi)

The tank location relative to the 17 in. mounting ring was decided upon by leaving room for a socket head torque wrench to be used to install the 24 mounting screws.



TANK SIZING (Universal Tank Concept)

Determination of tank sizing for "universal" tank. Nominal design factors are:

1. Torus tank - titanium
2. Nominal volume - 1.25 cu. ft
3. Nominal operating pressure - 150 psia

Refering to Eqs. 1 through 3, page D-6:

1 $b = \frac{1}{\pi}\sqrt{\frac{V}{2a}}$

2. $t = \frac{Pb}{S}\left(\frac{2a-b}{2a-2b}\right) = \frac{150b}{31,250}\left(\frac{2a-b}{2a-2b}\right)$

3. $W = \rho\, 4\pi^2 abt = 6.231\ abt$

V ft^3	a (in.)	b (in.)	a - b	t (in.)	W (lb)
1.25	10.0	3.310	6.690	.0198	4.09
1.00	10.0	2.986	7.014	.0174	3.233
1.10	10.0	3.131	6.869	.0184	3.600
1.40	10.5	3.447	7.053	.0206	4.650
→ 1.50	10.5	3.568	6.932	.0215	5.011
1.60	10.5	3.686	6.814	.0224	5.403
1.75	10.5	3.854	6.646	.0236	5.954
1.90	10.75	3.962	6.788	.0245	6.494
2.00	10.75	4.071	6.679	.0254	6.920

ALTERNATE MATERIAL SELECTION TECHNIQUE

Calculation of the ratio of tank mass to tank volume:

1. Stress in sphere: $S = \frac{PR}{2t}$
2. Sphere internal volume: $V = 4/3\ \pi R^3$
3. Sphere surface area: $A = 4\pi R^2$
4. Sphere mass: $M = \rho V = \rho 4\pi R^2 t$

S = stress - psi
P = pressure - psi
R = mean radius - in.
t = shell thickness - in.

rearranging 4. $t = \frac{M}{\rho 4\pi R^2}$ 5.

substitute 5 in 1 $S = \frac{PR}{2M}\ \rho 4\pi R^2$ 6.

$M = \frac{\rho P}{2S}\ 4\pi R^3$ 7.

$\frac{M}{V} = 3/2\ \rho \frac{P}{S}$ 8.

or

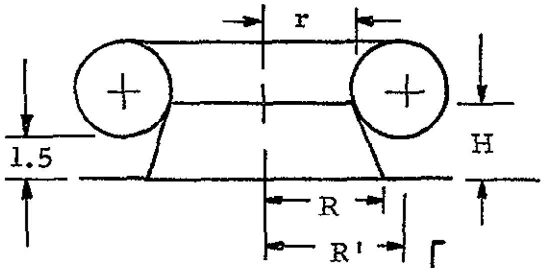
$$\frac{M}{V} = K_1 P \quad \text{where } K_1 \equiv \frac{3}{2}\frac{\rho}{S}$$

Material	ρ-Density (lb/in.^{3})	Working Stress psi x 10^3	$K_1 \times 10^{-6}$
17-7PH steel	0.276	92.5	4.475
Modified H-11 steel	0.281	120.5	3.497
MX-2 steel	0.276	119.5	3.464
Vascomax 350 steel	0.292	177.5	2.467
Ti-8Al-1Mo-IV titanium	0.158	62.5	3.792
5154 aluminum	0.096	16.5	8.727

This shows that for the same pressure and internal volume, the aluminum tank would be heaviest, with some steel materials lighter than titanium. The titanium was chosen so as to keep an acceptable fabrication thickness.

THRUST CONE

For a 1.5 in. clearance:



H = 3.68

R = 8.68

r = 7.0

$$W_{\text{cone}} = \rho t \left[\pi (R + r) \sqrt{H^2 + (R-r)^2} \right]$$

$$W = (.158)(t) \left[\pi (8.68 + 7.0) \sqrt{(3.68)^2 + (1.68)^2} \right]$$

$$W = 31.19\ (t)$$

$$W_{ring} = \rho \pi (R^2 - R'^2) t = .158 \pi (9.07^2 - 8.68^2) t$$

$$= 3.43\ t$$

t	W_{cone}	+	W_{ring}		W_{total}
.010	.3119		.0343	=	.3462
.012	.3739		.0411		.4150
.014	.4355		.0479		.4834
→.016	.4972		.0547		.5519
.018	.5599		.0616		.6215
.020	.6238		.0686		.6924

For a 2 in. clearance:

H = 4.44

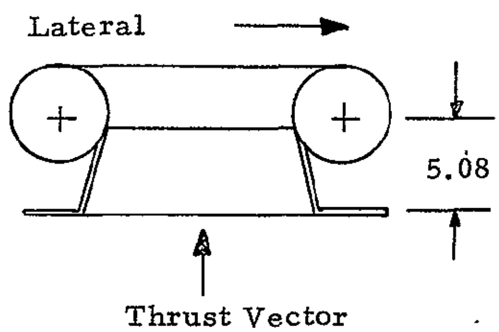
R = 8.68

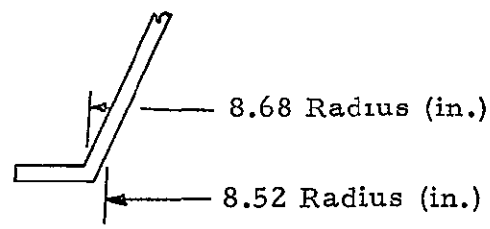
r = 6.9

t	W_{cone}	W_{total}
.010	.3697	.4040
.012	.4437	.4848
.014	.5176	.5655
.016	.5916	.6463
.018	.6655	.7271
.020	.7395	.8081

THRUST CONE (INITIAL WORK)

The thrust cone will be loaded by thrust and lateral g forces:





Static loads: Tank weight = 2.887

Fluid weight = 50.000

52.887

for the lateral case:

$$S = \frac{Mc}{I} = \frac{(52.887 \times 5.08)\ (3g)\ (8.68)}{\frac{\pi}{64}\ (8.68^4 - 8.52^4)} = 350.260 \text{ psi}$$

for the thrust case:

The problem here is a short column loading; using Rankine formula for buckling of short columns.

$$S = \frac{P}{A}\left[1 + \phi\left(\frac{L}{R}\right)^2\right]$$

$$\phi = \frac{S}{C\pi^2 E} = \frac{170{,}000}{2\pi^2 16.5 \times 10^6} = 5.23 \times 10^{-4}$$

$$p = \sqrt{\frac{(R^2 + \alpha^2)}{4} + \frac{H^2}{1B}\left(1 + \frac{2R_r}{(R+\alpha)^2}\right)}$$

$$p = \sqrt{\frac{(8.68^2 + 7^2)}{4} + \frac{3.68^2}{18}\left(1 + \frac{2 \times 8.68 \times 7}{(8.68 + 7)^2}\right)}$$

$$p = \sqrt{31.085 + 1.1242} = 5.675$$

P = load at failure

A = cross sectional area

L = length

p = least radius of gyration

$\phi = \frac{S}{C\pi^2 E}$ -ultimate

C = coefficient of constraint

E = Youngs Modulus

r = 7.0

R = 8.68

H = 3.68

$$S = \frac{(52.887)\,(15)}{\pi(7^2 - 6.984^2)} \left[1 + 5.23 \times 10^{-2} \left(\frac{3.68}{5.675}\right)^2\right]$$

$$S = \frac{793.305}{0.7025} \left[1 + .0242\right]$$

S = 1156.57 psi

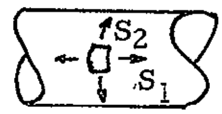
Summary of Conditions Used in Analysis

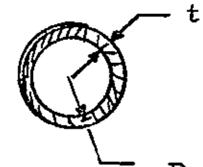
Tank -	volume	-	1 1/4 ft^3
	size	-	10.0 x 3.31
	weight	-	2.887 lb for .014 thick
Thrust cone -	weight	-	0.5519 lb for .016 thick

Similar calculations were made for a tank of 1.5 cubic feet volume and tank weight of 5.1387 pounds.

STRESS ON GRAPHITE RING (INTERNAL PRESSURE)

Deflection of the porous ring due to internal pressure - assuming porous metal sees entire 1500 psi pressure.





Radial displacement $D_K = \frac{R}{E} (S_2 \nu S)$

$$S_1 = \frac{pR}{2t} = \frac{1500\ (1.178)}{2\ (.125)} = 7{,}050 \text{ psi}$$

$$S^2 = \frac{pR}{t} = 14{,}100 \text{ psi}$$

$$D_R = \frac{1.178}{10 \times 10^6} (14{,}100 - .27 \times 7{,}050) = \frac{1.178}{10 \times 10^6} (12.195 \times 10^3)$$

$$D_R = 1.431 \times 10^{-3} = .001431 \text{ in.}$$

Allowance for this growth can be made by allowing a clearance between the graphite and the porous metal.

Graphite loads: Assume shock pressure taken by insulation sleeve and graphite sees only the 600 psi steady state chamber pressure.

Then the compressive hoop stress is:

$$S = \frac{Pr}{t} = \frac{600 \text{ psi} \times 1.278 \text{ in.}}{.094} = 8{,}150 \text{ psi}$$

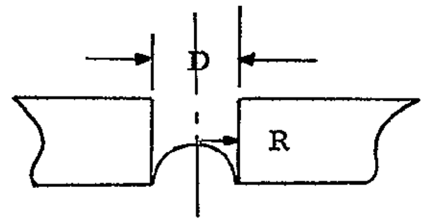
This valve is well below the maximum attainable compressive strength for pyrolytic graphite (60,000 psi).

The internal pressure required to fracture the graphite ring is:

$$S = \frac{Pr}{t} \qquad P = \frac{St}{r} = \frac{500\ (.094)}{1.278} = 36.9 \text{ psi}$$

$$P = \frac{St}{\alpha} = \frac{500\ (.0525)}{1.313} = 19.99 \text{ psi}$$

MATERIAL PORE SIZE



$$\left(\frac{\sigma}{\rho}\right) \frac{2}{Rg} = \frac{\Delta P}{eg}$$

$$\therefore \ \Delta P = \frac{2\sigma}{R}$$

σ = surface tension, dynes/cm

ΔP = differential pressure, dynes/cm^2

$$\text{psi} \times \frac{10^6}{14.7} = \text{dynes/cm}^2$$

R = pore radius, cm

D = pore diameter, cm = 2R

For Butane; σ = 9.25 dyne/cm at 120°F

$$\Delta P = 70 \text{ psia} = \frac{70 \times 10^6}{14.7} \text{ dynes/cm}^2$$

$$\therefore D = \frac{4\sigma}{\Delta P} = \frac{4 \times 9.25 \times 14.7 \times 10^{-6}}{70} = 7.75 \times 10^{-6} \text{cm}$$

$$= 3.059 \times 10^{-6} \text{in.}$$

$$= 3 \text{ micron}$$

For Water; σ = 66.2 dyne/cm at 60°C

ΔP = 14.7 psia

$$D = \frac{4 \times 66.2 \times 14.7 \times 10^{-6}}{14.7} = 264.8 \times 10^{-6} \text{cm} = 104 \times 10^{-6} \text{in.}$$

D = 104 micron

For Ammonia; σ = 19.95 at 80°F

ΔP = 122

D = 3.78 micron

Appendix E

FLUID PIPING SYSTEM ANALYSIS

Appendix E

FINAL CALCULATION OF REQUIRED ORIFICE SIZES

The inert fluid injection system (IFIS) utilizes two identical and parallel piping systems to provide flow from the fluid tank to the rocket motor chamber. The following analysis is concerned with one of the "legs" of the piping system. A one-dimensional analysis is presented with the fluid assumed to be incompressible. Total head loss is calculated for the systems to include pressure form losses and shear losses. The orifices in the injector assembly are sized to give desired mass flow rate for an available pressure drop to the rocket motor conditions. Tank pressure requirements can then be determined.

The piping system considered initially has the following physical characteristics:

Supply Tube:

O. D.	0.25 in.
Wall Thickness	0.16 in.
I. D.	0.218 in.

Injector Supply Passages:

$$d_s = 0.125 \text{ in.}$$

Mass Rate of Flow (for Butane):

$$\dot{m} = 0.564 \ \text{lb}_m/\text{sec}$$

$$\dot{m}_{line} = \frac{0.564}{2.0} = 0.282 \ \text{lb}_m/\text{sec} \quad \text{(flow in single leg)}$$

The piping system was divided into the segments described in Table E-1. Piping lengths or loss coefficients are shown for each of the segments.

Table E-1
PIPING SYSTEM CHARACTERISTICS

Station No.	Item	Section Length	Loss Coefficient
1.0	Tank		----
2.0	Tank fitting		$C_L = 0.05$
3.0	Elbow at tank		$C_L = 0.90$
4.0	Straight section	2.5 in.	
5.0	90^{o} bend		$C_L = 0.09$
6.0	Straight section	11.5 in.	
7.0	45^{o} bend		$C_L = 0.08$
8.0	Straight section	1.0 in.	
9.0	Fill value		$C_L = 0.75$
10.0	Straight section	1.5 in.	
11.0	180^{o} bend		$C_L = C_{L_{90^o}}(1.5) = (1.5)(0.09)$
12.0	Straight section	1.0 in.	
13.0	Pyrotechnic valve		$C_L = 0.5$
14.0	Straight section	4.0 in.	
15.0	68^{o} bend		$C_L = 0.08$
16.0	180^{o} bend		$C_L = 0.135$
17.0	Straight section	1.0 in.	
18.0	"Tee" at injector		$C_L = 0.90$
19.0	Three supply passages (in injector) pressure form loss	3.0 in	$C_L = 1.0$
20.0	Injector ports:		
	Entrance		$C_L = 0.05$
	Straight section	0.75 in.	
	Exit		$C_L = C_L = 1.0$

Calculate flow velocity in supply tube for Butane fluid:

$$\vec{V} = \frac{\dot{m}}{\rho A} = \frac{0.282}{(36.05)\left(\frac{3.14159}{4.0}\left(\frac{0.218}{12.0}\right)^2\right)}$$

$$\vec{V} = \frac{0.282}{(36.05)(2.591 \times 10^{-4})}$$

$$\vec{V} = 30.1911032 \text{ ft/sec}$$

Now calculate Reynolds number, N_{rey}:

$$N_{rey} = \frac{\vec{V}\rho D}{\mu}$$

$$N_{rey} = \frac{(36.05)\left(\frac{0.218}{12.0}\right)}{1.06843 \times 10^{-4}}$$

where for Butane:

$$\rho = 36.05 \text{ lb}_m/\text{ft}^3 \text{ at } T = 70.0^\circ F$$

$$\mu = 1.06843 \times 10^{-4} \text{ lb}_m/\text{ft-sec}$$

Thus

$$N_{rey} = 18.506 \times 10^4 \text{ and } f = 0.016$$

from Fig. 7-3 of Ref. E-1*.

The total head loss in the system can then be expressed as (excluding the injector losses):

$$H_L = \sum_{i=1}^{n} (C_{L_i} + f_i \, L/D) \left(\rho \frac{V^2}{2g}\right)$$

*Albertson, M. L., et al., Fluid Mechanics for Engineers, Prentice-Hall, Englewood Cliffs, N. J., 1960.

or combining terms

$$H_L = \left[3.62 + (0.016)\frac{22.5}{0.218}\right]\left[\frac{36.05 \ (30.1911)^2}{2.0 \ (32.174)}\right]$$

$$H_L = (5.2713761)\ (510.6556) = 2691.857 \text{ psf}$$

$$H_L = 18.6934 \text{ psia}$$

Head loss in injector supply ports can then be calculated in the following manner.

$$\dot{m}_{insp} = \frac{0.282}{3.0} = 0.094 \ lb_m/sec$$ (mass flow in each of supply passages)

$$\vec{V} = \frac{0.094}{(36.05)\left(\frac{3.14159}{4.0} \quad \left(\frac{0.125}{12.0}\right)^2\right)}$$

$$\vec{V} = \frac{0.094}{(36.05)\ (0.852 \times 10^{-4})}$$

$$\vec{V} = 30.60 \text{ ft/sec}$$

Then the Reynolds number is

$$N_{rey} = \frac{(30.60)\ (36.05)\ (\frac{0.125}{12.0})}{1.06843 \times 10^{-4}} = 10.756 \times 10^4$$

Thus f = 0.018.

The head loss in the supply passages is

$$H_{L_{insp}} = \left(1.0 + (0.018)\ \frac{3.0}{0.125}\right)\left(\frac{36.05\ (30.60)^2}{(2.0)\ (32.174)}\right)$$

$$H_{L_{insp}} = (1.432)\ (0.5602349\ (30.60)^2\ )$$

$$H_{L_{insp}} = (1.432)\ (524.731) = 751.4431 \text{ psf}$$

$$H_{L_{insp}} = 5.218 \text{ psia}$$

The head loss in the injector ports (for d_{port} = 0.073 in.) can then be calculated as follows:

$$\dot{m}_{inj} = \frac{0.282}{4.0} = 0.0705\ lb_m/sec \quad \text{(for single injector port)}$$

$$\vec{V} = \frac{0.0705}{(36.05)\left(\frac{3.14159}{4.0}\ \left(\frac{0.073}{12.0}\right)^2\right)}$$

$$\vec{V} = \frac{0.0705}{(36.05)\ (0.2906 \times 10^{-4})}$$

$$\vec{V} = 67.28659$$

Then

$$N_{rey} = \frac{(67.28659)\ (36.05)\ (\frac{0.073}{12.0})}{1.06843 \times 10^{-4}}$$

$$N_{rey} = 13.811 \times 10^4$$

Note: Assume rough tube wall. $f = 0.028$

Then

$$H_L = \left(1.05 + (0.028)\left(\frac{.75}{0.073}\right)\right)\left(\frac{36.05\ (67.28659)^2}{(2.0)\ (32.174)}\right)$$

$$H_L = (1.33767)\ (2536.4552) = 3392.943$$

$$H_L = 23.562 \text{ psia}$$

The total head loss in the Piping system is:

$$\text{Head Loss} = 18.6934 + 5.218 + 23.562$$
$$= 47.4735 \text{ psia}$$

To reduce head loss in the system the injector port diameters were increased to 0.090 in. and the calculations repeated.

$$\dot{m}_{inj} = 0.0705\ lb_m/sec$$

$$\vec{V} = \frac{0.0705}{(36.05)\left(\frac{3.14159}{4.0}\left(\frac{0.090}{12.0}\right)^2\right)}$$

$$\vec{V} = \frac{0.0705}{(36.05)\ (0.441 \times 10^{-4})}$$

$$\vec{V} = 44.3452 \text{ ft/sec}$$

Then

$$N_{rey} = \frac{(44.3452)\ (36.05)\ (\frac{0.090}{12.0})}{1.06843 \times 10^{-4}}$$

$$N_{rey} = 11.2219 \times 10^{4} \qquad f = 0.025$$

Then

$$H_L = \left(1.05 + (0.025)\ (\frac{0.75}{0.090})\right) \left(\frac{36.05\ (44.3452)^2}{(2.0)\ (32.174)}\right)$$

$$H_L = (1.25834)\ (1101.700) = 1386.305 \text{ psf}$$

$$H_L = 9.627 \text{ psia}$$

The total head loss for the system is then calculated to be

$$H_{L_{total}} = 33.538 \text{ psia}$$

Now consider similar systems using water as the working fluid:

$$\rho = 62.189 \text{ at } T = 80^{\circ}F$$

$$\mu = 0.8545 \text{ centipoises}$$

$$u = (0.8545)\ (6.7197 \times 10^{-4})\ lb_m/\text{ft-sec} = 5.74198 \times 10^{-4}$$

$$\dot{m} = 0.0474$$

$$\dot{m}_{line} = 0.0237 \text{ lb}_m/\text{sec}$$

Calculate velocity:

$$\vec{V} = \frac{0.0237}{(62.189)\ (2.591 \times 10^{-4})}$$

$$\vec{V} = 1.47085 \text{ ft/sec}$$

Then

$$N_{rey} = \frac{(1.47085)\ (62.189)\ (\frac{0.218}{12.0})}{5.74198 \times 10^{-4}}$$

$$N_{rey} = 0.289 \times 10^4 \text{ (transition region)} \qquad f = 0.035$$

Then total head loss

$$H_L = \left[3.62 + (0.35)\ (\frac{22.5}{.218})\right] \left[\frac{62.189\ (1.47085)^2}{(2.0)\ (32.174)}\right]$$

$$H_L = (7.23238)\ (2.0908) = 15.121 \text{ psf} = 0.105 \text{ psia}$$

or

$$H_L = 0.105 \text{ psia}$$

Now calculate head loss in the injector supply passages

$$\dot{m}_{insp} = \frac{0.0237}{3.0} = 0.0076 \ lb_m/sec$$

$$\vec{V} = \frac{0.0076}{(62.189)\ (0.852 \times 10^{-4}}$$

$$\vec{V} = 1.434367$$

Then

$$N_{rey} = \frac{(14.3436)\ (62.189)\ (\frac{0.125}{12.0})}{5.74198 \times 10^{-4}}$$

$$N_{rey} = 1.618 \times 10^{3} \quad \text{and} \quad f = 0.043$$

Then

$$H_L = \left(1.0 + (0.043)\ (\frac{3.0}{0.125})\right) \left(\frac{62.189\ (1.43437)^2}{(2.0)\ (32.174)}\right)$$

$$H_L = (2.032)\ (1.988386) = 4.0404 \ \text{psf}$$

$$H_L = 0.28 \ \text{psi}$$

Head loss in injector ports:

Assume d_{inj} = 0.021 in. (number 75 drill). Then

$$\vec{V} = \frac{0.0059}{(62.189)\left(\frac{3.14159}{4.0}\ \left(\frac{0.021}{12.0}\right)^2\right)}$$

$$\vec{V} = \frac{0.0059}{(62.189)\,(0.23 \times 10^{-5})} = 41.248 \text{ ft/sec}$$

Then

$$N_{rey} = \frac{(41.248)\,(62.189)\,\left(\frac{0.021}{12.0}\right)}{5.74198 \times 10^{-4}}$$

or

$$N_{rey} = 0.78179 \times 10^{4} \quad \text{and} \quad f = 0.035$$

So

$$H_{L_{inj}} = \left(1.05 + (0.035)\left(\frac{.75}{.021}\right)\right)\left(\frac{62.189\,(41.248)^2}{(2.0)\,(32.174)}\right)$$

$$H_{L_{inj}} = (2.299)\,(1644.312) = 3781.917 \text{ psf}$$

$$H_{L_{inj}} = 26.26 \text{ psia}$$

Total head loss in system is

$$H_{L_{total}} = 28.676 \text{ psia}$$

Consider the third option of using Ammonia as the working fluid:

$$\rho = 37.65 \text{ lb}_m/\text{ft}^3 \text{ at } 78.3^{\circ}\text{F}$$

$$\mu = 0.207 \text{ centipoises}$$

$$= (0.207)\,(6.7197 \times 10^{-4}) = 1.3909779 \times 10^{-4}$$

$$\dot{m} = 0.067 \ lb_m/sec$$

$$\dot{m}_{line} = 0.0335 \ lb_m/sec$$

Calculate velocity in supply line:

$$\vec{V} = \frac{0.0335}{(37.65)\ (2.591 \times 10^{-4})} = 3.434 \ ft/sec$$

Then

$$N_{rey} = \frac{(3.434)\ (37.65)\ (\frac{0.218}{12.0})}{1.3909779 \times 10^{-4}}$$

$$N_{rey} = 1.688 \times 10^4 \qquad f = 0.027$$

Then total head loss in the supply line:

$$H_L = \left[3.62 + (0.027)\ \left(\frac{22.5}{0.218}\right)\right] \left[\frac{(37.65)\ (3.434)^2}{(2.0)\ (32.174)}\right]$$

$$H_L = (6.406697)\ (6.8997) = 44.204 \ psf$$

$$H_L = 0.30697 \ psi$$

Now calculate head loss in the injector supply passages:

$$\dot{m} = \frac{0.0335}{3.0} = 0.01116$$

$$\vec{V} = \frac{0.01116}{(37.65)\ (0.852 \times 10^{-4})} = 3.479 \text{ ft/sec}$$

$$\vec{V} = 3.479 \text{ ft/sec}$$

Then

$$N_{rey} = \frac{(3.479)\ (37.65)\ (\frac{0.125}{12.0})}{1.3909779 \times 10^{-4}}$$

$$N_{rey} = 0.9809 \times 10^{4} \qquad f = 0.032$$

Then

$$H_L = \left(1.0 + (0.032)\ (\frac{3.0}{0.125})\right)\left(\frac{37.65\ (3.479)^2}{(2.0)\ (32.174)}\right)$$

$$H_L = (1.768)\ (7.0817) = 12.52 \text{ psf}$$

$$H_L = 0.08694 \text{ psia}$$

Calculate loss in injector parts:

$$\dot{m} = \frac{0.0335}{4.0} = 0.0084: \quad d_{inj} = 0.031 \text{ (No. 68 drill)}$$

Then

$$\vec{V} = \frac{0.0084}{(36.75)\left(\frac{3.14159}{4.0}\ \left(\frac{0.031}{12.0}\right)^2\right)}$$

$$N_{rey} = 2.9772 \times 10^4 \qquad f = 0.045$$

Thus

$$H_{L_{injp}} = \left(1.05 + (0.045)\left(\frac{.75}{0.031}\right)\right)\left(\frac{37.65\ (43.62)^2}{(2.0)\ (32.174)}\right)$$

$$H_{L_{injp}} = (2.1387)\ (1113.2719)$$

$$H_{L_{injp}} = 2380.965 \text{ psf} = 16.535 \text{ psia}$$

Total system loss = 16.92839 psia

PIPING SYSTEM ANALYSIS SUMMARY

The results of the piping system analysis are summarized in the following table.

Fluid	Mass Flow Required (lb_m/sec)	Injector Port Diameter (in.)	Total Head Loss (psia)
Butane-n	0.574	0.090	33.538
Water	0.0474	0.021	28.676
Ammonia	0.067	0.031	16.93

Appendix F
THERMAL ANALYSIS

Appendix F

LAUNCH TEMPERATURES FOR IFIS (Including Pad)

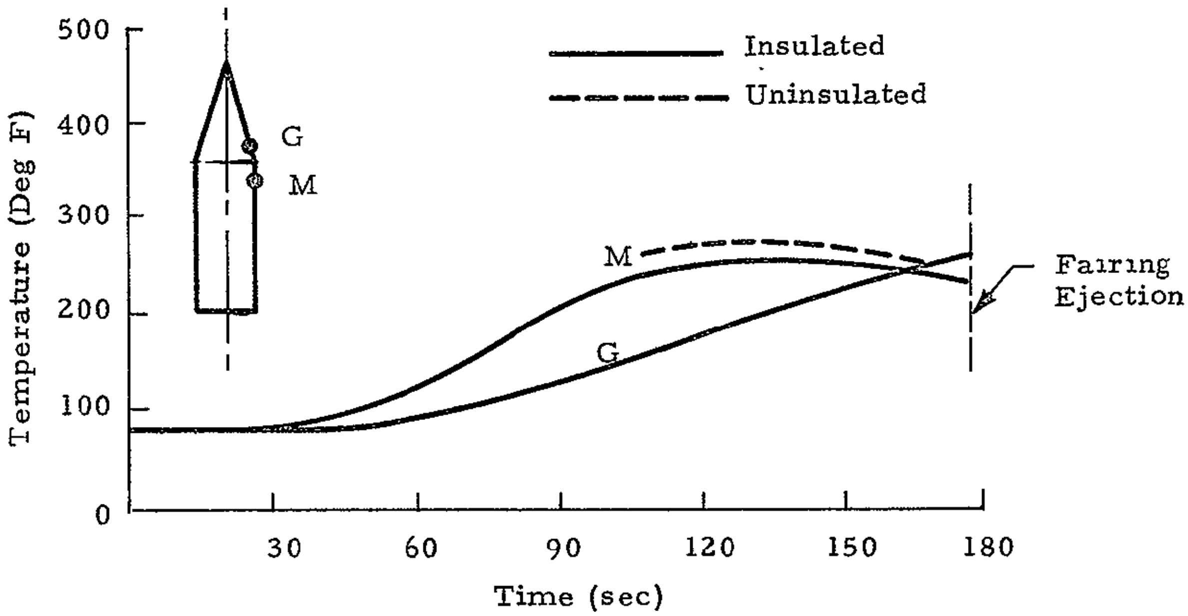
This section documents the anticipated launch temperatures for the IFIS to set a maximum operating temperature.

Data to substantiate the maximum operating temperatures are listed below.

1. AEDC — TR-67-256 Qualification Test of Thiokol Chemical Corporation. TE-M-364-3 Solid-Propellant Rocket Motors....
   Test temperatures with 46 hr soak: 50°, 55°, 75°, and $95^\circ \pm 5^\circ$ F.
2. Delta Spacecraft Design Restraints, Douglas Report DAC-61687.

Allowable fairing inside surface temperature, specified by the spacecraft agency, is maintained by applying insulation, if necessary to the fairing exterior*. For every mission a Fairing Thermal Profile Analysis is made when the powered flight has been established. A typical time history of this analysis is presented in the figure on the following page.

*Emissivity of the fairing interior surface is approximately 0.9). In any case, the inside surface temperature will not be allowed to exceed 500 degrees F, above which temperature outgassing of the fairing material (phenolic resin) may occur.



The temperatures for pad operations are:

for Eastern Test Range —

Location	Temperature
Spacecraft Labs	75 ± 5°F
Hanger AF	75 ± 3°F
Spin Test Facility	75 ± 5°F
Handling Can	Not controlled
Gantry Greenhouse	70 ±5°F
Gantry Fairing	75 - 90°F ± 5°

for Western Test Range —

Location	Temperature
Building 836 Areas	70 ± 5°F
	75 ± 2°F
Spin Test Facility	77 ± 5°F
Handling Can	Not controlled
Gantry Greenhouse	70 + 5°F
Gantry Fairing	75 - 90 ± 5°F

3. Accordingly, the IFIS may be subjected to a maximum temperature of ~100°F during the pad and launch operations. For the fluids used, the following tank pressures may be expected:

	Temp.	Vapor Pressure
A. Butane	100°F	51.37 psia
B. Ammonia	100°F	211.9 psia
C. Water	100°F	0.9492 psia

DETAIL THERMAL ANALYSIS

To ensure that modifications to the ignition-injector assembly do not produce a thermal environment that cannot be tolerated, a detailed thermal analysis was conducted. A mathematical thermal model of the ignition-injector assembly was constructed for this purpose. Various pieces of the assembly were partitioned into nodes and assigned the proper material characteristics. Material properties used in this analysis are presented in Table F-1. The thermal model was used as input to Lockheed's thermal analyzer program described in Ref. F-1.

All portions of the ignition-injector assembly were assumed to be at 95°F prior to ignition. Motor burn was then simulated for 48 seconds by a constant level heat source with an average temperature of 5500°F. From motor ignition, the temperature time histories for the various nodes were calculated for a total elapsed time of 200 seconds. Results of these calculations are presented in Table F-2.

The conclusion was reached from this analysis that the ignition-injection assembly could withstand the imposed thermal environment. Temperature information generated in this analysis was utilized in the detailed structural analysis.

Table F-1

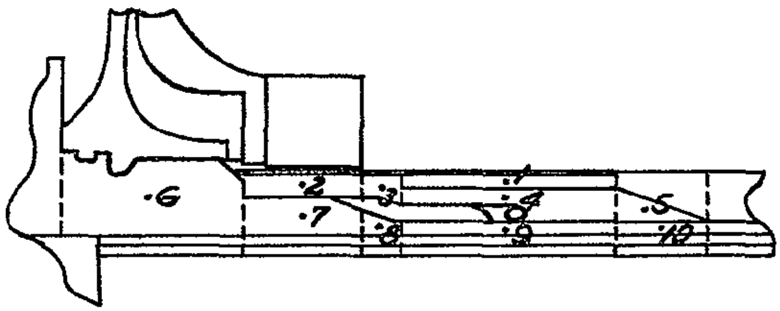
THERMAL PROPERTIES OF MATERIALS USED IN THERMAL MODEL OF IGNITION-INJECTOR ASSEMBLY

Temperature (^oF)	k (Btu/hr-ft-^oF)	C_p (Btu/lb_m - ^oR)	ρ^* (lb_m/ft^3)
Stainless Steel - Ladish DGAC			
0.0	29.173	0.114	490.0
1300.0	↓	0.114	↓
2600.0		0.114	
4000.0		0.114	
Aluminum - 7075 - T6			
0.0	90.680	0.192	174.0
200.0	101.695	0.214	↓
400.0	105.882	0.229	
600.0	101.695	0.250	
800.0	96.774	0.280	
1000.0	92.307	0.318	
1200.0	88.235	0.360	
2600.0	88.235	0.360	
GENGARD - BUNA-N			
0.0	0.0499	0.42	70.0
2750.0	↓	0.42	↓
5500.0		0.42	
Pyrolytic Graphite			
0.0	108.434	0.125	119.0
500.0	72.000	0.320	↓
1000.0	50.139	0.390	
1500.0	37.815	0.435	
2000.0	30.875	0.460	
3000.0	24.390	0.490	
4000.0	21.583	0.510	
5000.0	19.780	0.530	
430 FM			
0.0	0.3801	0.11	194.0
1300.0	↓	0.11	↓
2600.0		0.11	
4000.0		0.11	

*NOTE: Density values assumed constant over temperature range of the analysis.

Table F-2

IGNITER TEMPERATURES



Position	Temperatures, °F									
	1	2	3	4	5	6	7	8	9	10
Time, sec.										
48*	1862	168	1968	1250	384	123	129	132	274	308
50	1886	171	1986	1291	399	126	131	134	282	316
100	1781	236	1789	1497	614	189	196	201	397	458
150	1614	287	1614	1397	683	245	252	257	454	541
200	1452	328	1450	1276	711	291	298	302	491	592

*Motor Burnout

Recommended Pyrolytic Graphite Insulation

- Buna N
- 0.040 in. thick

REFERENCES

F-1 Bible, A. E., et al., "Thermal Analyzer Control System for IBM 709-7090-7094 Computer Engineering Utilization Manual," LMSC 3-56-65-8, Lockheed Missiles & Space Company, Sunnyvale, Calif., 1 September 1965.

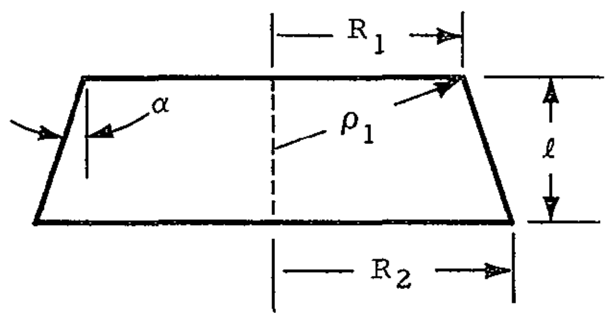
Appendix G

DETAILED STRUCTURAL ANALYSIS

Appendix G

THRUST CONE

The thrust cone is a welded titanium structure. The toroidal tank is welded to the upper outside edge.



Material: Ti - 6Aℓ - 4V (Annealed)

F_{ty} = 126,000 lb/in.^{2} (Ref. G-1)

F_{cy} = 132,000 lb/in.^{2}

$E = 16 \times 10^6$ lb/in.^{2}

t = .016 in.

$\alpha = 15^\circ$

R_1 = 7.05 in.

R_2 = 8.27 in.

ℓ = 4.5 in.

$\rho_1 = R_1/\cos\alpha$ = 7.3 in.

Compute Critical Axial Load

General instability

$$P_c = 2\pi C E t^2 \cos^2 \alpha$$

$c = 0.20$ (Ref. G-2)

$$P_c = 2\pi(.2)\ 16 \times 10^6\ (.016 \cos 15^\circ)^2$$

$$P_c = 20.1 \times 10^6\ (2.39 \times 10^{-4})$$

$$P_c = \underline{4{,}800}\ \text{-lb}$$

$$F_a = \frac{P_c}{2\pi \rho_1 t \cos^2 \alpha}$$

$$= \frac{4800}{2\pi\ (7.3)\ (.016)(.966)^2}$$

$$F_a = \underline{7030}\ \text{lb/in.}^2$$

Compute Critical Torsional Load

$$R_2/R_1 = 8.27/7.05 = 1.172$$

$$\frac{\rho^*}{R_1 \cos \alpha} = 1 + \sqrt{.5\ (1 + R_2/R_1)} - \frac{1}{\sqrt{.5\ (1 + R_2/R_1)}}$$ (Ref. G-2)

$$= 1 + \sqrt{.5\ (1 + 1.172)} - \frac{1}{\sqrt{.5(1 + 1.172)}}$$

$$= 1 + 1.042 - .958$$

$$\frac{\rho^*}{R_1 \cos\alpha} = 1.084$$

$\therefore \rho^* = 1.084\ (7.05) \cos 15 = 7.38$ in equivalent cylinder radius

$$Z_L = \frac{\ell^2}{\rho^* t}\sqrt{1-\mu^2}$$

$$= \frac{4.5^2}{7.38(.016)} \sqrt{1-.3^2}$$

$$Z_L = 163.5$$

$K_s = 33.5$ (Ref. G-2, Fig. 6.12-1)

Critical torque for general instability

$$T_a = \frac{2\pi^3 K_s}{(\ell/\rho^*)^2} \quad \frac{Et^3}{12\ (1-\mu^2)}$$ (Ref. G-2)

$$= \frac{2\pi^3 \cdot (33.5)}{(4.5/7.38)^2} \quad \frac{16 \times 10^6\ (.016)^3}{12\ (.91)}$$

$T_a = \underline{33{,}450}$ in. -lb

Critical torsion stress

$$\tau_c = \frac{T_c}{2\pi R_1^2 t}$$

$$= \frac{33{,}450}{2\pi (7.05)^2 (.016)}$$

$\tau_a = \underline{6{,}710}$ lb/in.^{2}

CRITICAL TRANSVERSE SHEAR LOAD

Increase the torsional buckling stress by 1.25 to determine the transverse shear buckling stress. (Ref. G-3, C8.12)

$$F_{s_a} = 1.25\ \tau a = 8{,}380\ \text{lb/in.}^2$$

For cylinders the maximum shear stress occurs at the neutral axis

$$F = 4/3\ \frac{V}{A}\left(1 + \frac{D_o\ D_i}{D_o^{\,2} + D_i^{\,2}}\right) \qquad \text{(Ref. G-3, A14.4)}$$

For thin wall shells

$$\left(1 + \frac{D_o\ D_i}{D_o^{\,2} + D_i^{\,2}}\right) = 1.5$$

$$\therefore V = 3/4\ \frac{f_s\ 2\pi R t}{1.5}$$

$$= \pi\ R t f_s$$

$$V_a = \pi R t F_s$$

$$= \pi(7.05)(.016)(8{,}380)$$

$$V_a = \underline{2{,}970}\ \text{- lb}$$

APPLIED LOADS

Maximum combined weight of torial tank and fluid is 60 lb. Dynamic loads of 15 g vertical and 3 g lateral will be experienced.

$$P_{axial} = 60(15) = 900 \text{ lb}$$

$$\sigma_{ax} = \frac{900}{2\pi(7.3)(.016)(.966)^2}$$

$$\sigma_{ax} = 1{,}316 \text{ lb/in.}^2$$

$$\sigma = SF \times \sigma_{ax} = 1.5(1316) = 1972 \text{ lb/in.}^2$$

$$V = 60(3) = 180 \text{ lb}$$

$$f_s = \frac{180}{\pi(7.05)(.016)}$$

$$f_s = 508 \text{ lb/in.}^2$$

$$f_s = S.F.\ (f_s) = 1.5(508) = 762 \text{ lb/in.}^2$$

Margin of safety

$$R_c = \frac{\sigma}{F_a} = \frac{1972}{7030} = .281$$

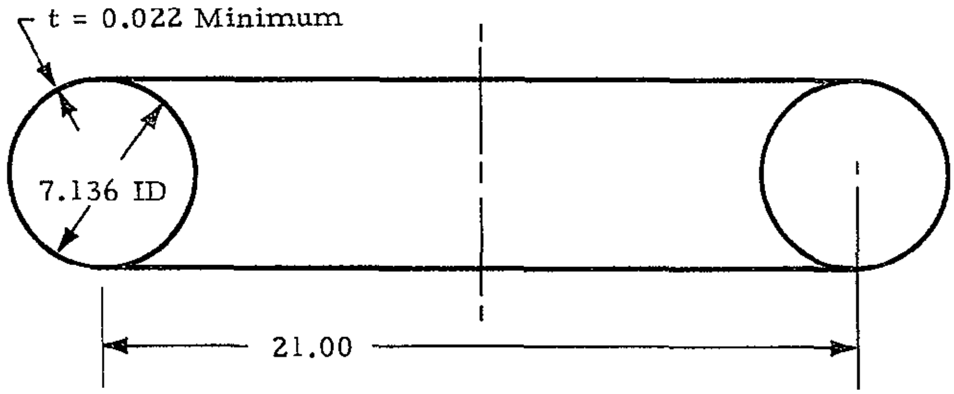
$$R_s = \frac{f_s}{F_s} = \frac{762}{8380} = .0909$$

$$MS = \frac{1}{\sqrt{R_c^2 + R_s^2}} - 1$$

$$MS = \frac{1}{\sqrt{.281^2 + .0909^2}} - 1 = 2.38$$

TOROIDAL TANK

The toroidal tank is a welded pressure vessel designed to store the inert fluid.



Load Condition - Internal pressure 150 psi

150 psi operating pressure Factor of safety (ultimate) = 4.0 $\rho_u = \rho \times F.S. = 140 \times 4.0 = 600$ psi	(Ref. G-4)

Material Properties MIL-HDBK-5 (Ref. G-5)

Titanium - 6Aℓ-4V (annealed)

F_{tu} = 134 k psi

F_{ty} = 126 k psi

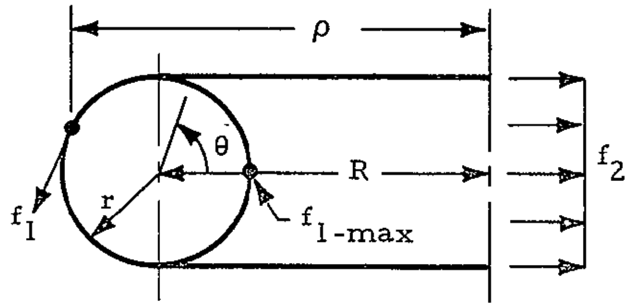
F_{cy} = 132 k psi

F_{su} = 76 k psi

e = 10%

E = $16. \times 10^3$ k psi

Membrane Stress Due to Internal Pressure



R = 10.50
r = 3.58

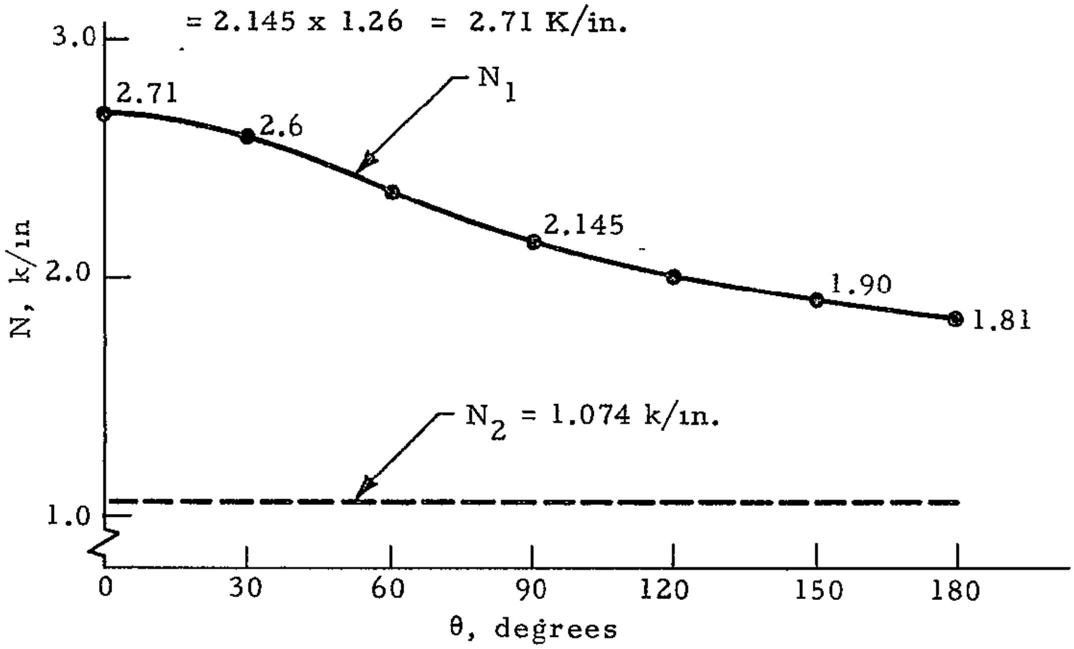
$$f_1 = \frac{\rho r}{t}\left(\frac{\rho + R}{2\rho}\right)$$

$$f_2 = \frac{\rho r}{2t}$$ (Ref. G-5)

$$f_{1\text{-max}} = \frac{\rho r}{t}\left(\frac{2R - r}{2R - 2r}\right) \text{ at } \rho = R - r$$

$$N_{1\text{-max}} = f_{1\text{-max}} \times t = 0.600 \times 3.58\left(\frac{21. - 3.58}{21 - 7.16}\right)$$

$$= 2.145 \times 1.26 = 2.71 \text{ K/in.}$$

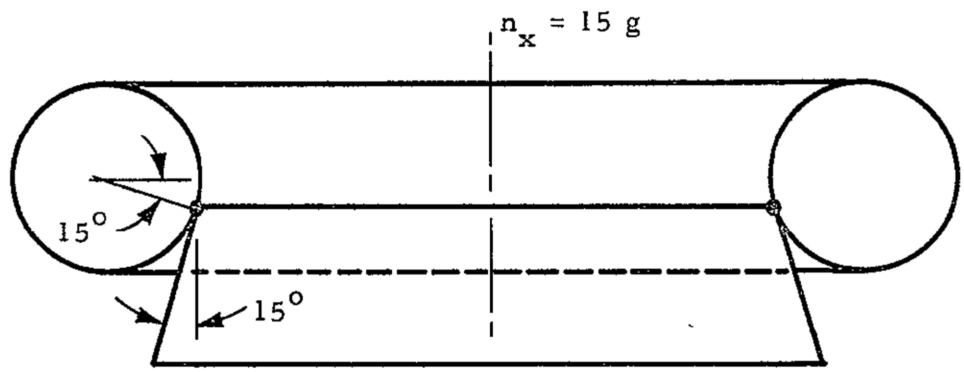


$$N_2 = f_2 \cdot t = \frac{\rho r}{2} = 0.600 \times 3.58/2 = 1.074 \text{ K/in.}$$

$$f_{1\text{-max}} = \frac{N_{1\text{-max}}}{t} = 2.71/.022 = 123. \text{ kpsi}$$

$$M.S = \frac{Ftu}{f_1} - 1 = \frac{134}{123} - 1 = +0.089$$

SHELL STRESSES DUE TO AXIAL LOAD



Wt = 60 lb max.

n_x = 15. g

$F.S._{ult.}$ = 1.5 and $F.S._{yield}$ = 1.15

$P_x = n_x \cdot Wt = 15 \times 60 = 900$ lb

It will be assumed that the inertia loads are transmitted to the tank as a membrane stress. The running loads are

$$N_1 = \frac{P_x}{2\pi\rho \cdot \cos 15^\circ} = \frac{900}{2\pi \cdot 7 \cdot \cos 15^\circ} = 21.2 \text{ lb/in.}$$

$$f_{1\text{-ult}} = \frac{1.5 \times 21.2}{0.022} = 1.500 \text{ k psi}$$

Summing the stresses due to internal pressure (F.S. = 4.0) and inertial loads (F.S. = 1.5)

$$f_{1\text{-u}} = 123. + 1.5 = 124.5 \text{ k psi}$$

$$MS = \frac{F_{tu}}{f_{1\text{-u}}} - 1 = \frac{130}{124.5} - 1 = +0.04$$

TORUS TANK/THRUST CONE – MATH MODEL

A mathematical model of a segment of the torus tank and thrust cone was constructed. This finite element model provides an accurate structural analysis of the stresses and deformations of the two structural components and a detailed look at their interface. The structure was modeled using the Lockheed SNAP/V70D, Finite Element Digital Computer Program (Ref. G-6).

The global axis system was located at the center of the tank/cone structure with the cone lower flange in the (1-2) plane. A segment of the structure was defined by rotating through an angle θ, measured in the (1-2) plane, positive about the 3-axis. A theta value of 3 degrees was used in this analysis. The orientation and location of the node points are shown in Fig. G-1.

To facilitate the description of the model and preparation of input data, local reference frames were specified at the center of the tank cross-section. The local axis system is denoted by the prime superscript (1', 2', 3', θ') in Fig. G-1. The (1'-2') planes lie in the global (R-Z) plane at both θ=0 and 3 degrees. Only the local axes at the zero degree plane is shown in Fig. G-1 for clarity. Using the local reference system, the tank node points are easily specified by cylindrical coordinates (1'=R, 2'=θ', 3'=Z), where θ' is measured positively about the 3' axis.

The cone node points are specified in rectangular coordinates since they lie on the tangent, with the local axes selected as shown. The location and orientation of each of the local reference axis systems is specified with respect to the global system. The local (1'-3') planes make an angle of $12^{o}8'$ with the global (1-2) plane. For greater accuracy, smaller angle increments (Δθ') were used in the region of the tank/cone interface. For 30 degrees either side of node 1 (31), a 10 degree increment was used in defining the node points. Twenty degree increments were used from nodes 4-19 (34-49).

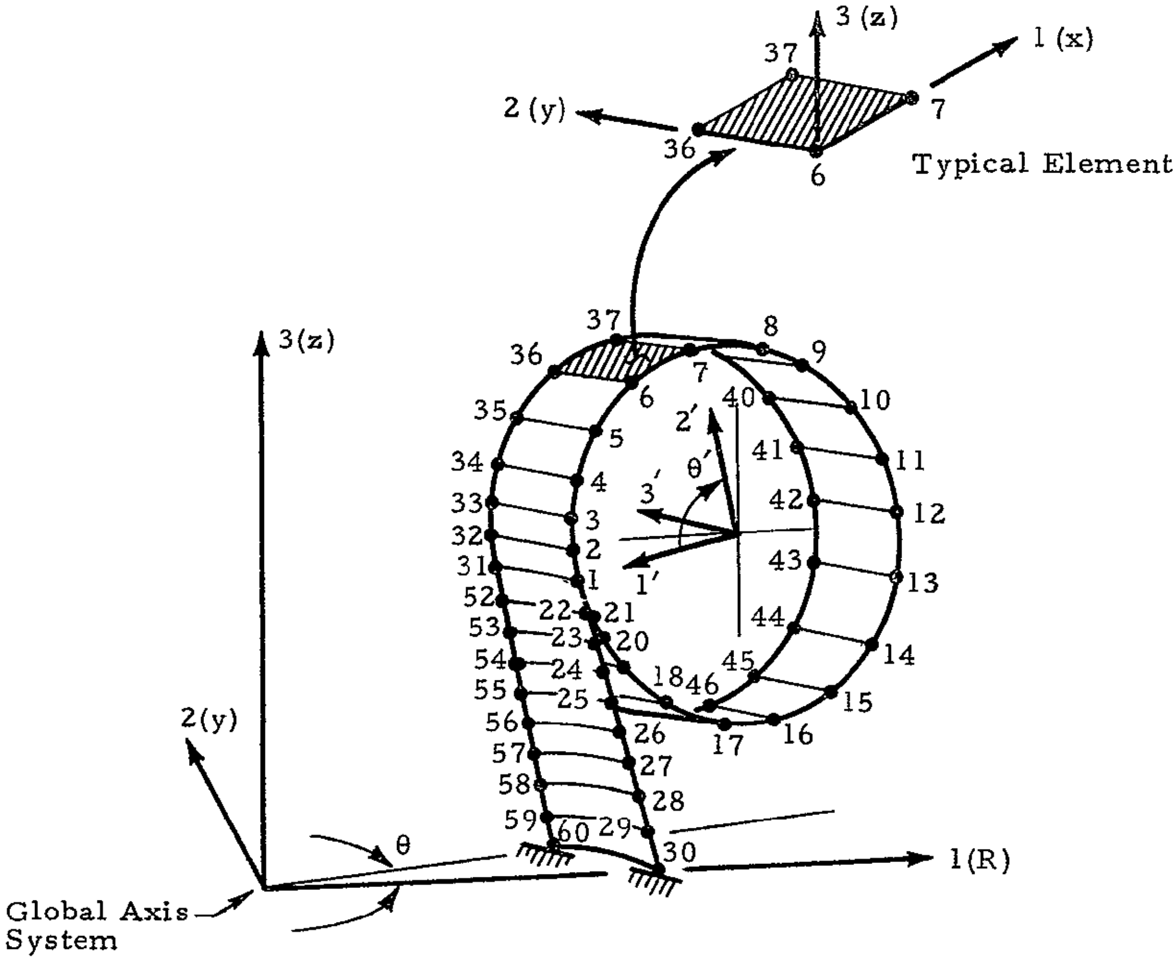


Fig. G-1 - Tank and Cone Math Model

The math model was analyzed for the condition of 150 psi internal pressure in the tank. The applied loads are specified using the local axis systems.

Table G-1 is part of the SNAP program output. The first set of data is the forces and moments at the node points of each element, the second set contains the stress values. All values are oriented in the element reference frames. Each element has a reference frame associated with it as shown in Fig. G-1. For the typical quadrilateral element shown (6, 7, 37, 36), the origin is located at the first node specified, and the second node designates the positive direction of the 1-axis. The 3-axis is always the normal or out-of-plane axis. The forces and moments acting at the nodes of this element are given on the fourth page of Table G-1. The forces are parallel to the axis designated and the moments are acting about the designated axis. Force values are in (lb), moments in (in.-lb) and stresses in (lb/in.^{2}). A negative sign denotes a load acting in the negative direction and not a compression load. For example, F1 at node 6 of the element shown is -135.076 lb. From Fig. G-1, this is seen to be a tension load acting in the (-1) direction. Likewise, M1 is a negative moment about the 1-axis resulting in compression in the top or external surface of the tank element. For the stress values, the (+) or (-) sign denotes tension or compression, respectively.

Using the computed stress values, the margin of safety for the tank at the tank/cone interface can be determined. For element (1, 2, 32, 31) the hoop tension stress (SXX) is taken from the last page of Table G-1.

$$SXX = 30{,}345.9 \text{ (lb/in.}^2\text{)}$$

The stress due to in-plane bending can be determined from M2, page G-15

$$M2 = -.0004370 \text{ in.-lb}$$

$$SM = \frac{M2c}{I}$$

$$= \frac{(.000437)(.011)}{3.27 \times 10^{-7}}$$

Table G-1

SNAP PROGRAM COMPUTER OUTPUT

LOADING CONDITION

FORCES AND MOMENTS ACTING ON ELEMENT BOUNDARY NODES.

COMPONENTS ARE GIVEN IN LOCAL (ELEMENT) REFERENCE FRAMES.

THERMAL EFFECTS ARE EXCLUDED

CONNECTED JOINTS	F1	F2	F3	M1	M2	M3
29	-.16248301+00	-.24535194-01	-.46903232-03	-.35675817-04	.84298235-04	.0
30	.16283779+00	-.42270381-01	.46908321-03	.59254827-04	.15037122-03	.0
60	.16241339+00	.44070441-01	.46909613-03	-.60901006-04	.14971013-03	.0
59	-.16276818+00	.22735135-01	-.46914702-03	.34762433-04	.84695977-04	.0
28	-.16250177+00	.13178416-02	.16853631-03	.58680052-06	-.18852732-06	.0
29	.16248300+00	-.37949661-03	-.16857361-03	-.33217790-04	-.84298237-04	.0
59	.16249405+00	.21785370-02	-.16871082-03	.34151920-04	-.83937702-04	.0
58	-.16247528+00	-.31168819-02	.16874812-03	-.60802497-06	-.21273233-06	.0
27	-.16251723+00	-.19635042-03	.40558109-04	.82930353-05	-.20416054-04	.0
28	.16250180+00	.36804023-02	-.40627171-04	.94145460-07	.18851038-06	.0
58	.16253047+00	-.18952980-02	-.40426038-04	-.12265562-06	.20468078-06	.0
57	-.16251503+00	-.15887539-02	.40495101-04	-.80599000-05	-.20502567-04	.0
26	-.16257665+00	.70645795-02	-.49022861-04	-.17828575-05	.42231675-05	.0
27	.16251727+00	.37049533-02	.49237158-04	.80322374-05	.20416022-04	.0
57	.16255363+00	-.19164754-02	.49253788-04	-.82050377-05	.20323581-04	.0
56	-.16249424+00	-.88530574-02	-.49468084-04	.17997368-05	.42816818-05	.0
25	-.16261110+00	-.85491324-02	-.31363017-03	-.64780714-04	.16019661-03	.0
26	.16257568+00	.32437453-02	.31280685-03	-.21353875-05	-.42232223-05	.0
56	.16260716+00	-.14050346-02	.31208245-03	.21335259-05	-.42384010-05	.0
55	-.16257274+00	.57104218-02	-.31125912-03	.62713815-04	.16069843-03	.0
24	-.16167170+00	-.83083756-01	.11701193-02	.17250086-03	-.42398934-03	.0
25	.16261115+00	-.49445366-01	-.11705119-02	-.59898088-04	-.16019552-03	.0
55	.16193708+00	.51067827-01	-.11680260-02	.61387210-04	-.15933300-03	.0
54	-.16287554+00	.81451294-01	.11684186-02	-.16771583-03	-.42571554-03	.0

Table G-1 (Continued)

	F1	F2	F3	M1	M2	M3
23	-.16371059+00	.30565959+00	.86007011-03	.34698807-03	-.84691842-03	.0
24	.15157181+00	.95577572-01	-.85038784-03	.17572496-03	.42398945-03	.0
54	.16301373+00	-.93917493-01	-.84950656-03	-.17949735-03	.42189512-03	.0
53	-.15397495+00	-.30731967+00	.83982429-03	-.33486796-03	-.84886733-03	.0
22	-.16903082+00	.20811698+00	-.16303636-01	-.29857478-02	.72952136-02	.0
23	.15371062+00	.36582082+00	.16324046-01	.23203204-03	.84691898-03	.0
53	.16834367+00	-.36237008+00	.16306445-01	-.23776584-03	.84256703-03	.0
52	-.15332346+00	-.21156772+00	-.16326855-01	.29393710-02	.73300951-02	.0
1	-.13606270+00	-.43690996+01	.33334734-01	.37956901-02	-.93343942-02	.0
22	.15933092+00	-.21446921+01	-.33255913-01	-.27222425-02	-.72952140-02	.0
52	.14171159+00	.21484913+01	-.33264842-01	.28106476-02	-.72671587-02	.0
31	-.17467982+00	.43553004+01	.33186022-01	-.36720135-02	-.93624413-02	.0
20	-.12574135+03	-.78299643+02	.16921395-01	.13394912-02	-.42445028-02	.0
21	.12385531+03	-.80643216+02	-.16745394-01	-.26351261-02	-.60728122-02	.0
51	.12574745+03	.77656709+02	-.16226150-01	.24509609-02	-.60910920-02	.0
50	-.12386141+03	.81286149+02	.16050149-01	-.13277124-02	-.41591839-02	.0
21	-.12384840+03	-.77925701+02	-.25625753-01	-.20164620-02	.60730670-02	.0
1	.12263518+03	-.78906954+02	.25210461-01	.39768699-02	.97713453-02	.0
31	.12384682+03	.77008271+02	.25646066-01	-.39043136-02	.98818401-02	.0
51	-.12263453+03	.79824385+02	-.25230774-01	.20333838-02	.60004570-02	.0
19	-.12835038+03	-.79822809+02	-.22524485-01	-.37119939-02	.80741998-02	.0
20	.12575795+03	-.82301621+02	.19927490-01	.12711519-02	.42442799-02	.0
50	.12831437+03	.78311779+02	.18454541-01	-.12301139-02	.42304568-02	.0
49	-.12571493+03	.83812652+02	-.15857546-01	.29616446-02	.74073240-02	.0
18	-.13594278+03	-.15251637+03	.76645642-02	-.71957617-02	.60505613-02	.0
19	.12952761+03	-.16078905+03	-.44157495-02	-.90113565-02	-.80734913-02	.0
49	.13600900+03	.15528057+03	.28001209-02	.78709382-02	-.78283780-02	.0
48	-.12959382+03	.15802485+03	-.60489356-02	.99890945-02	.78089730-02	.0
17	-.14409634+03	-.16140180+03	.72848149-01	.43568782-01	-.75379393-01	.0
18	.13613848+03	-.15865310+03	-.59412537-01	.93778527-02	-.60499997-02	.0
48	.14394089+03	.15166548+03	-.68705763-01	-.77576347-02	-.78375371-02	.0
47	-.13598303+03	.16838942+03	.55270151-01	-.42970155-01	-.70050950-01	.0

Table G-1 (Continued)

	F1	F2	F3	M1	M2	M3
16	-.15355380+03	-.17292783+03	-.10476451+00	-.66669025-02	.54133899-01	.0
17	.14435739+03	-.17627817+03	.11318722+00	.45167375-01	.75377032-01	.0
47	.15348829+03	.16850941+03	.94294775-01	-.37239552-01	.74150627-01	.0
46	-.14429587+03	.18069658+03	-.10271749+00	.98486832-02	.53942437-01	.0
15	-.16196620+03	-.15977803+03	.33587631-01	-.11031300-01	.12464881-01	.0
16	.15387318+03	-.17353570+03	-.34222580-01	-.26707554-01	-.54136488-01	.0
46	.16210432+03	.16587548+03	-.34718702-01	.24048609-01	-.55617351-01	.0
45	-.15401733+03	.16743824+03	.35353651-01	.11184654-01	.11657524-01	.0
14	-.16836241+03	-.15814336+03	.14795222-01	.11662478-02	-.49458042-02	.0
15	.15217793+03	-.16092566+03	-.14887873-01	-.57190139-02	-.12466212-01	.0
45	.16828767+03	.15450568+03	-.12802261-01	.48267677-02	-.12383934-01	.0
44	-.15210325+03	.16456334+03	.12894913-01	-.95644350-03	-.46089128-02	.0
13	-.17255076+03	-.16177438+03	-.62307449-02	-.78951847-03	.30601108-02	.0
14	.15854547+03	-.16527846+03	.72221665-02	.23463153-02	.49463894-02	.0
44	.17254416+03	.16110805+03	.55237613-02	-.17356877-02	.46869745-02	.0
43	-.15853887+03	.16594479+03	-.55151828-02	.10713297-02	.31384522-02	.0
12	-.17382331+03	-.16418696+03	.18196757-02	-.66391015-03	.96526367-03	.0
13	.17264457+03	-.16474913+03	-.14954662-02	-.14466362-02	-.30603248-02	.0
43	.17381787+03	.16350844+03	-.19220878-02	.15637762-02	-.31752039-02	.0
42	-.17263914+03	.16542765+03	.15978784-02	.76937088-03	.10215386-02	.0
11	-.17198988+03	-.16690140+03	.24173164-02	.80073843-03	-.17132800-02	.0
12	.17381594+03	-.16482691+03	-.20301411-02	-.23885342-03	-.96523381-03	.0
42	.17198848+03	.16672853+03	-.22391054-02	.35390204-03	-.10231588-02	.0
41	-.17381454+03	.16499978+03	.19519302-02	-.60469381-03	-.16031741-02	.0
10	-.16728111+03	-.16665992+03	-.64091709-02	-.27391270-02	.62092225-02	.0
11	.17187554+03	-.16352186+03	.66728287-02	.32098142-03	.17131925-02	.0
41	.16725631+03	.16824394+03	.60846535-02	-.20060483-03	.15912989-02	.0
40	-.17185175+03	.16193785+03	-.63483113-02	.25903982-02	.63431044-02	.0
9	-.16013846+03	-.17249009+03	-.14726392-02	-.43028812-02	.95103940-02	.0
10	.15739562+03	-.16376932+03	.29227899-02	-.32415861-02	-.62086130-02	.0
40	.16018288+03	.17052831+03	.31664628-02	.36335988-02	-.61229058-02	.0
39	-.15714004+03	.16573111+03	-.46166135-02	.46757899-02	.10405711-01	.0

Table G-1 (Continued)

	F1	F2	F3	M1	M2	M3
8	-.15147707+03	-.16946834+03	.63490902-01	.33093923-01	-.62035196-01	.0
9	.15987521+03	-.16653483+03	-.56785953-01	.51410397-02	-.95094303-02	.0
39	.15139609+03	.17427857+03	-.58646039-01	-.35472419-02	-.10392337-01	.0
38	-.15979523+03	.16172460+03	.51941089-01	-.27184002-01	-.61354985-01	.0
7	-.14305214+03	-.15700598+03	-.75694280-01	-.16963884-01	.33566251-01	.0
8	.15121353+03	-.15592629+03	.82148792-01	.21392628-01	.62033453-01	.0
38	.14291763+03	.16363367+03	.70400081-01	-.21693830-01	.58869136-01	.0
37	-.15107901+03	.14929860+03	-.76854593-01	.15998106-01	.35112207-01	.0
6	-.13507651+03	-.16533864+03	.20038411-01	-.15460122-01	.85854830-02	.0
7	.14292122+03	-.15417365+03	-.17903037-01	-.25592506-01	-.33567822-01	.0
37	.13519279+03	.16091695+03	-.20867423-01	.27889281-01	-.32916026-01	.0
36	-.14293753+03	.15859533+03	.18732048-01	.15386673-01	.97616135-02	.0
5	-.12840036+03	-.16441322+03	.15756243-01	.97774743-03	-.45101549-02	.0
6	.13484559+03	-.16572127+03	-.10153127-01	-.52301123-02	-.85863470-02	.0
36	.12831830+03	.17081786+03	-.95498464-02	.57791911-02	-.87876061-02	.0
35	-.13476353+03	.15931663+03	.39467303-02	.11386808-02	-.25532541-02	.0
4	-.12436073+03	-.16237731+03	-.79502943-02	-.24624387-02	.39591700-02	.0
5	.12825541+03	-.15988957+03	.12448166-01	.20701246-02	.45106270-02	.0
35	.12438415+03	.16299529+03	-.42825089-03	.20925545-05	.25990004-02	.0
34	-.12827984+03	.15927159+03	-.40696205-02	.20847427-02	.38923571-02	.0
3	-.12245596+03	-.81678335+02	.83864904-02	.25749244-03	-.13795428-02	.0
4	.12341437+03	-.80710035+02	-.94768001-02	-.18368705-02	-.39593834-02	.0
34	.12244930+03	.82135704+02	-.74978498-02	.15806912-02	-.38222675-02	.0
33	-.12340772+03	.80252667+02	.85881595-02	-.34649169-03	-.14306375-02	.0
2	-.12224557+03	-.81265510+02	-.10291275-01	-.21453050-02	.47819134-02	.0
3	.12245346+03	-.80889154+02	.95833959-02	.20253791-03	.13795591-02	.0
33	.12224928+03	.81210947+02	.10003872-01	-.28742816-03	.14257841-02	.0
32	-.12245715+03	.80942816+02	-.93959928-02	.19919035-02	.46945459-02	.0
1	-.12276554+03	-.78509169+02	.81174369-02	-.27562183-03	-.43704158-03	.0
2	.12224903+03	-.80360632+02	-.87940572-02	-.22556667-02	-.47818783-02	.0
32	.12276809+03	.79564432+02	-.79131923-02	.20897537-02	-.47029736-02	.0
31	-.12225158+03	.79305369+02	.85898127-02	.16375803-03	-.50018739-03	.0

Table G-1 (Continued)

CONDITION 1 — STRESSES IN PLANE-STRESS QUADRILATERAL ELEMENTS

CONNECTED JOINTS				NBETA		NODE 1	NODE 2	NODE 3	NODE 4
29	30	60	59	5	SXX=	.48922333+02	.48922333+02	.48859131+02	.48859962+02
					SYY=	.10593787+01	.15712010+02	.15644549+02	.99280385+00
					SXY=	.22455831+00	.22455831+00	.22455831+00	.22455831+00
28	29	59	58	5	SXX=	.49507997+02	.49507997+02	.49500904+02	.49500998+02
					SYY=	-.14211200+01	.12013845+01	.11894691+01	-.14328767+01
					SXY=	.27467944+00	.27467944+00	.27467944+00	.27467944+00
27	28	58	57	5	SXX=	.50179672+02	.50179672+02	.50192020+02	.50191853+02
					SYY=	.34694932+00	-.12219156+01	-.12148823+01	.35388761+00
					SXY=	.27803055+00	.27803055+00	.27803055+00	.27803055+00
26	27	57	56	5	SXX=	.50894095+02	.50894095+02	.50872314+02	.50872512+02
					SYY=	-.32668625+01	.59451892+00	.57744214+00	-.32837058+01
					SXY=	.28733149+00	.28733149+00	.28733149+00	.28733149+00
25	26	56	55	5	SXX=	.51613965+02	.51613965+02	.51610188+02	.51610240+02
					SYY=	.43817171+01	-.30845006+01	-.30519331+01	.44138324+01
					SXY=	.28823436+00	.28823436+00	.28823436+00	.28823436+00
24	25	55	54	5	SXX=	.52113542+02	.52113542+02	.52371685+02	.52368053+02
					SYY=	.28523209+02	.45093796+01	.46126723+01	.28625050+02
					SXY=	.17019741+00	.17019741+00	.17019741+00	.17019741+00
23	24	54	53	5	SXX=	.53354279+02	.53354279+02	.52666618+02	.52676431+02
					SYY=	-.12922831+03	.29590701+02	.28917165+02	-.12989223+03
					SXY=	.54587144+00	.54587144+00	.54587144+00	.54587144+00
22	23	53	52	5	SXX=	.55345916+02	.55345916+02	.54657879+02	.54667840+02
					SYY=	-.14129731+02	-.12982857+03	-.12934491+03	-.13653069+02
					SXY=	.96701835+00	.96701835+00	.96701835+00	.96701835+00
1	22	52	31	5	SXX=	.49412701+02	.49412701+02	.55153164+02	.55068844+02
					SYY=	.16436143+04	-.21970644+02	-.15108690+02	.16503755+04
					SXY=	-.38284138+01	-.38284138+01	-.38284138+01	-.38284138+01
20	21	51	50	5	SXX=	.29383322+05	.29383322+05	.29387546+05	.29387712+05
					SYY=	.11726406+05	.11445247+05	.11443210+05	.11724290+05
					SXY=	-.21335430+03	-.21335430+03	-.21335430+03	-.21335430+03
21	1	31	51	5	SXX=	.29970443+05	.29970443+05	.29969305+05	.29969276+05
					SYY=	.11630104+05	.11228983+05	.11227154+05	.11628227+05
					SXY=	-.14275875+03	-.14275875+03	-.14275875+03	-.14275875+03

Table G-1 (Continued)

CONDITION 1 — STRESSES IN PLANE-STRESS QUADRILATERAL ELEMENTS

CONNECTED JOINTS				NBETA		NODE 1	NODE 2	NODE 3	NODE 4
19	20	50	49	5	SXX=	.28639870+05	.28639870+05	.28616102+05	.28614912+05
					SYY=	.12153353+05	.11492390+05	.11485803+05	.12146437+05
					SXY=	-.26285859+03	-.26285859+03	-.26285859+03	-.26285859+03
18	19	49	48	5	SXX=	.27476570+05	.27476570+05	.27515448+05	.27520280+05
					SYY=	.11163374+05	.11770432+05	.11774601+05	.11168051+05
					SXY=	-.33370551+03	-.33370551+03	-.33370551+03	-.33370551+03
17	18	48	47	5	SXX=	.25731360+05	.25731360+05	.25650813+05	.25640077+05
					SYY=	.12800303+05	.10661141+05	.10641225+05	.12777733+05
					SXY=	-.34855363+03	-.34855363+03	-.34855363+03	-.34855363+03
16	17	47	46	5	SXX=	.24233931+05	.24233931+05	.24203717+05	.24199986+05
					SYY=	.13277871+05	.12306944+05	.12296188+05	.13265787+05
					SXY=	-.29712707+03	-.29712707+03	-.29712707+03	-.29712707+03
15	16	46	45	5	SXX=	.23072893+05	.23072893+05	.23130695+05	.23136584+05
					SYY=	.11524657+05	.12864303+05	.12879758+05	.11541687+05
					SXY=	-.26461015+03	-.26461015+03	-.26461015+03	-.26461015+03
14	15	45	44	5	SXX=	.22237590+05	.22237590+05	.22208467+05	.22206311+05
					SYY=	.12080115+05	.11281262+05	.11273132+05	.12071383+05
					SXY=	-.20505630+03	-.20505630+03	-.20505630+03	-.20505630+03
13	14	44	43	5	SXX=	.21676917+05	.21676917+05	.21674452+05	.21674345+05
					SYY=	.12036943+05	.11890691+05	.11889683+05	.12035892+05
					SXY=	-.11868733+03	-.11868733+03	-.11868733+03	-.11868733+03
12	13	43	42	5	SXX=	.21429038+05	.21429038+05	.21427034+05	.21427010+05
					SYY=	.12103804+05	.11954921+05	.11954608+05	.12103486+05
					SXY=	-.33649422+02	-.33649422+02	-.33649422+02	-.33649422+02
11	12	42	41	5	SXX=	.21457268+05	.21457268+05	.21456739+05	.21456749+05
					SYY=	.12150591+05	.12112659+05	.12112783+05	.12150712+05
					SXY=	.51262643+02	.51262643+02	.51262643+02	.51262643+02
10	11	41	40	5	SXX=	.21765111+05	.21765111+05	.21755325+05	.21755792+05
					SYY=	.11906223+05	.12253936+05	.12251110+05	.11903531+05
					SXY=	.13484929+03	.13484929+03	.13484929+03	.13484929+03
9	10	40	39	5	SXX=	.22347372+05	.22347372+05	.22365315+05	.22364907+05
					SYY=	.12519326+05	.12088462+05	.12093411+05	.12523907+05
					SXY=	.20755874+03	.20755874+03	.20755874+03	.20755874+03

Table G-1 (Concluded)

CONDITION 1 — STRESSES IN PLANE-STRESS QUADRILATERAL ELEMENTS

CONNECTED JOINTS				NBETA		NODE 1	NODE 2	NODE 3	NODE 4
8	9	39	38	5	SXX=	.23259706+05	.23259706+05	.23221472+05	.23225173+05
					SYY=	.11779755+05	.12836664+05	.12803115+05	.11767513+05
					SXY=	.27164147+03	.27164147+03	.27164147+03	.27164147+03
7	8	38	37	5	SXX=	.24550555+05	.24550656+05	.24479088+05	.24487141+05
					SYY=	.10740629+05	.12197029+05	.12179323+05	.10724916+05
					SXY=	.34248865+03	.34248865+03	.34248865+03	.34248855+03
6	7	37	36	5	SXX=	.26147760+05	.26147760+05	.26217861+05	.26209622+05
					SYY=	.12180844+05	.11209433+05	.11219148+05	.12189417+05
					SXY=	.35178927+03	.35178927+03	.35178927+03	.35178927+03
5	6	36	35	5	SXX=	.27947563+05	.27947563+05	.27892193+05	.27898097+05
					SYY=	.11384750+05	.12791147+05	.12781211+05	.11375873+05
					SXY=	.30607375+03	.30607375+03	.30607375+03	.30607375+03
4	5	35	34	5	SXX=	.29506460+05	.29506460+05	.29523551+05	.29522265+05
					SYY=	.11721921+05	.11857556+05	.11867017+05	.11721422+05
					SXY=	.21863944+03	.21863944+03	.21863944+03	.21863944+03
3	4	34	33	5	SXX=	.30187536+05	.30187536+05	.30182583+05	.30182579+05
					SYY=	.11733014+05	.11932973+05	.11932275+05	.11732329+05
					SXY=	.10608506+03	.10608506+03	.10608506+03	.10608506+03
2	3	33	32	5	SXX=	.30406958+05	.30406958+05	.30409726+05	.30409714+05
					SYY=	.11826529+05	.11802630+05	.11802649+05	.11826547+05
					SXY=	.24652795+02	.24652795+02	.24652795+02	.24652795+02
1	2	32	31	5	SXX=	.30345943+05	.30345943+05	.30347827+05	.30347848+05
					SYY=	.11344482+05	.11805812+05	.11806689+05	.11345369+05
					SXY=	-.61000807+02	-.61000807+02	-.61000807+02	-.61000807+02

$SM = 14.7 \text{ lb/in.}^2$ (tension in top surface)

$$S_{t_{max}} = 30{,}345.9 + 14.7 = 30{,}360.6 \text{ lb/in.}^2$$

Applying the specified ultimate factor of safety

$$S_{t_u} = F.S. \times S_{t_{max}}$$

$$= (4)\,(30{,}360.6)$$

$$S_{t_u} = 121{,}442.4 \text{ lb/in.}^2$$

For Ti - 6Aℓ - 4V (annealed)

$$F_{t_u} = 134{,}000 \text{ lb/in.}^2 \quad \text{(Ref. G-1)}$$

$$MS_u = \frac{F_{t_u}}{S_{t_u}} - 1$$

$$= \frac{134{,}000}{121{,}442.4} - 1$$

$$MS_u = 0.102$$

The hand calculations of the toroidal tank (page G-6) agree with these values.

By inspection of the computer stress results, 30 ksi is the maximum hoop tension stress in the tank structure. This value occurs in the region of the tank/cone interface.

By inspection of the inplane bending moments the maximum moment, M2 = .075377 in. -lb, occurs in element (16, 17, 47, 46). The margin of safety at this element is

$$SXX = 24{,}233.93$$

$$SM = \frac{(.075377)(.011)}{4.67 \times 10^{-7}} = 1774 \text{ lb/in.}^2$$

$$S_{t_{max}} = 24{,}233.93 + 1774 = 26{,}008 \text{ lb/in.}^2$$

$$S_{t_u} = (4)(26{,}008) = 104{,}032 \text{ lb/in.}^2$$

$$MS_u = \frac{134{,}000}{104{,}032} - 1 = 0.288$$

The results of this computer analysis shows that the tank structural integrity is maintained and will satisfy the safety requirements.

IGNITER CASE/POROUS SLEEVE

A math model of the igniter case and porous sleeve was constructed and used to analyze three temperature cases. The impulse pressure during igniter injection was also analyzed.

Igniter Case:

MATL: 7075-T6 Aluminum
$t = .0525$ in.
$R_{in} = 1.0625$ in.

Porous Sleeve: RIGIMESH (Ref. G-7)

MATL: 347 Stainless Steel
MESH: 12 x 64
LAYERS: 12
$t = 0.1725$ in.
$R_{in} = 1.115$ in.

The resultant radial deflections for the four cases are given in Table G-2. The values shown are the changes in radius. The temperature cases were taken from the thermal analysis. The ignition pressure was 1250 psi.

Table G-2
RADIAL DEFLECTIONS

Condition	Igniter Case Deflection (in.)	Porous Sleeve Deflection (in.)
Igniter Ignition	.00053	.00050
Temperature 50 sec	.01081	.01271
Temperature, 100 sec	.01161	.01358
Temperature 200 sec	.01215	.01408

NOTE: Values given are changes in radius.

Table G-3 gives the computer program output for the stresses in the igniter case and porous sleeve during igniter ignition. The igniter case is denoted by nodes 1, 2, 5, 6 and the porous sleeve by nodes 2, 3, 7, 6. The sketch gives the node locations and local axis system for the nodes in each plane.

From the output, the maximum hoop tension stress in the porous sleeve is

$$SYY = 6{,}915 \text{ lb/in.}^2$$

Applying the safety factor of 1.5

$$f_t = S.F. \times SYY$$

$$= (1.5)(6915)$$

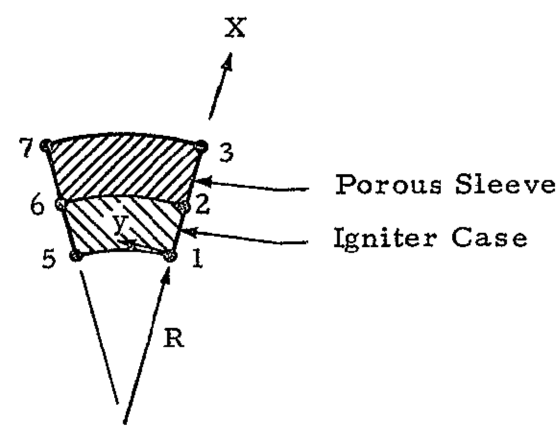
$$f_t = 10{,}380 \text{ lb/in.}^2$$

Table G-3

COMPUTER OUTPUT, IGNITER IGNITION

CONDITION 4 — STRESSES IN PLANE-STRESS QUADRILATERAL ELEMENTS

CONNECTED JOINTS				NBETA		NODE 1	NODE 2	NODE 3	NODE 4
1	2	6	5	5	SXX=	-.10796922+04	-.10736922+04	-.11336718+04	-.11311297+04
					SYY=	.48634692+04	.44906707+04	.44979734+04	.48704282+04
					SXY=	-.13385892+03	-.13385892+03	-.13385892+03	-.13385892+03
2	3	7	6	5	SXX=	-.45053544+03	-.45053544+03	-.41548425+03	-.42018112+03
					SYY=	.69148915+04	.56627437+04	.56713633+04	.69223566+04
					SXY=	-.14157651+03	-.14157651+03	-.14157651+03	-.14157651+03



The allowable stress is the tensile yield

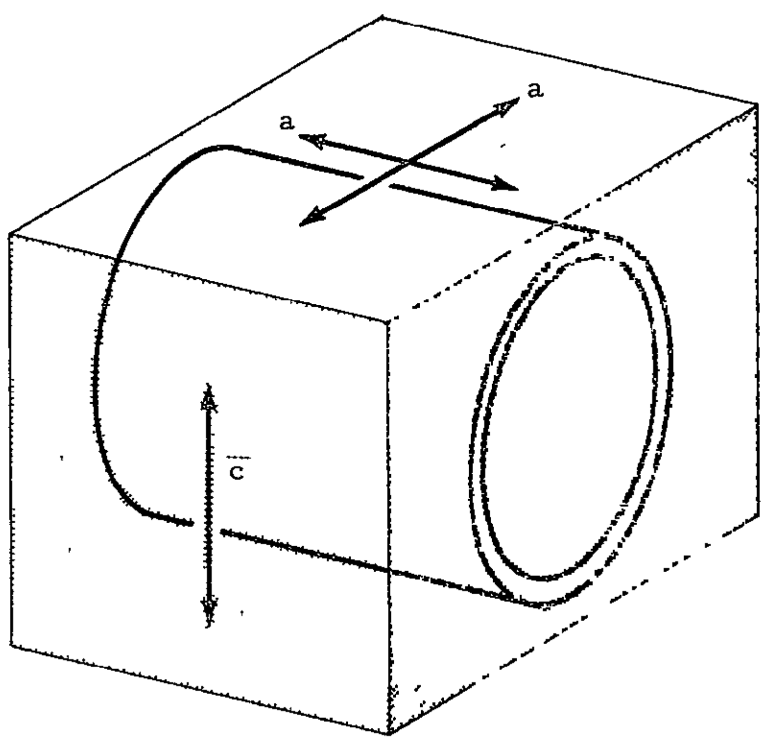
$$F_{ty} = 22,100 \text{ lb/in.}^2$$

Margin of safety

$$MS = \frac{22,100}{10,380} - 1 = 1.13$$

PYROLYTIC GRAPHITE SLEEVE

The following analysis will be applicable only if the sleeve is oriented as shown below. This arrangement takes advantage of the orthotropic properties of pyrolytic graphite.



Tolerances adequate to prevent contact with the stainless steel ring during the igniter ignition impulse pressure must be provided. Changes made in the length of the graphite sleeve will not affect this analysis.

PYROLYTIC GRAPHITE SLEEVE

$R_o = 1.35$ in.

$R_1 = 1.2935$ in.

$t = .0565$ in.

$L = 0.75$ in.

$A = .0565\ (.75) = .0424\ \text{in.}^2$

$I = \frac{1}{12}\ (.75)(.0565)^3 = 1.128 \times 10^{-5}\ \text{in.}^4$

PRESSURE DURING MOTOR BURN

$p = 925$ psi acting as an external pressure on the sleeve

$$f_c = \frac{2pR_o^2}{R_o^2 - R_1^2}$$

$$= \frac{2\ (925)\ (1.35)^2}{1.35^2 - 1.2935^2} = \frac{3370}{.15}$$

$f_c = 22{,}450\ \text{lb/in.}^2$

For the "a" direction (Ref. G-8)

$F_c = 10{,}000\ \text{lb/in.}^2$

$MS = \frac{10{,}000}{22{,}450} - 1 = -.555$ (no S. F. applied)

Sleeve will crack under motor burning pressure. Since the pressure is external and the insulation will act as a membrane around the sleeve, the sleeve should remain in position around the orifices.

INTERNAL PRESSURE REQUIRED FOR FAILURE

$$P_a = \frac{F_{t_{cr}} (R_o^2 - R_1^2)}{(R_o^2 + R_1^2)}$$

For "c" direction (Ref. G-8)

$$F_t = 500 \text{ lb/in.}^2 \text{ at RT}$$

$$F_t = 200 \text{ lb/in.}^2 \text{ at } 5{,}000^\circ F$$

At RT

$$P_{cr} = \frac{500\ (1.35^2 - 1.2935^2)}{(1.35^2 + 1.2875^2)}$$

$$= \frac{500\ (.15)}{3.495}$$

$$P_{cr} = 21.45 \text{ psi}$$

At 5000°F

$$P_{cr} = \frac{200\ (.15)}{3.495}$$

$$P_{cr} = 8.59 \text{ psi}$$

The temperature is approximately 1000°F, therefore a pressure of approximately 19 psi will probably cause failure if the sleeve did not crack during motor burn.

CONTACT OF SLEEVE WITH THERMALLY EXPANDED POROUS STAINLESS STEEL RING

For the "a" direction, change in diameter from Table 2, t = 200 sec.

$$\Delta D = 2(.0141) = 0.0282 \text{ in.}$$

$$P = \frac{\Delta D\ EI}{.149\ \bar{R}^3} \qquad \text{(Ref. G-5)}$$

$$= \frac{(.0282)(5 \times 10^6)(1.128 \times 10^{-5})}{(.149)\ (1.32175)^3}$$

$$P = \frac{1.59}{.3435} = 4.63 \text{ lb}$$

Maximum Bending Moment

$$M = 0.3183\ PR$$

$$= 0.3183\ (4.63)(1.32175)$$

$$M = 1.95 \text{ in./lb}$$

$$f = \frac{1.95\ (.02825)}{1.128 \times 10^{-5}}$$

$$f = 4890 \text{ lb/in.}^2$$

Applying the safety factor

$$f = 1.5(4890) = 7340 \text{ lb/in.}^2$$

$$F_c = 10{,}000 \text{ lb/in.}^2 \qquad \text{(Ref. G-8)}$$

$$MS_B = \frac{10{,}000}{7340} - 1 = .362$$

Maximum Shear Stress

$$f_s = \frac{1}{2} \; P/A$$

$$= \frac{1}{2} \; (4.63/.0424)$$

$$f_s = 54.7 \text{ lb/in.}^2$$

$$MS = \frac{500}{54.7} - 1 = 8.14$$

REFERENCES

G-1 "Metallic Materials and Elements for Aerospace Vehicle Structures," MIL-HDBK-5, Department of Defense, Washington, D. C.

G-2 Structural Methods Handbook, Lockheed Missiles & Space Company, Lockheed Aircraft Corp., Sunnyvale, Calif.

G-3 Bruhn, E. F., Analysis and Design of Flight Vehicle Structures, Tri-State Offset Company, Cincinnati, Ohio, 1965.

G-4 Johnson, P. T., "Design Criteria for Inert Fluid Injection System for Velocity Trim Applications," LMSC/HREC D162476, Lockheed Missiles & Space Company, Huntsville Research & Engineering Center, Huntsville, Ala., July 1970.

G-5 Roark, R. J., Formulas for Stress and Strain, Third Edition, McGraw-Hill Book Company, Inc., 1954.

G-6 Whetstone, W. D., "Structural Network Analysis Program User's Manual, Version V70D," LMSC/HREC D162471, Lockheed Missiles & Space Company, Huntsville Research & Engineering Center, Huntsville, Ala., July 1970.

G-7 "Transpiration Cooling Through RIGIMESH Sintered Woven Wire Sheet," Field Service Report No. 18C, Aircraft Porous Media, Inc., Glen Cove, L.I., New York, 1 March 1968.

G-8 Pyrolytic Graphite, Tech. Report, Pfizer and Co., Inc., Minerals, Pigments and Metals Division, New York, New York, 1970

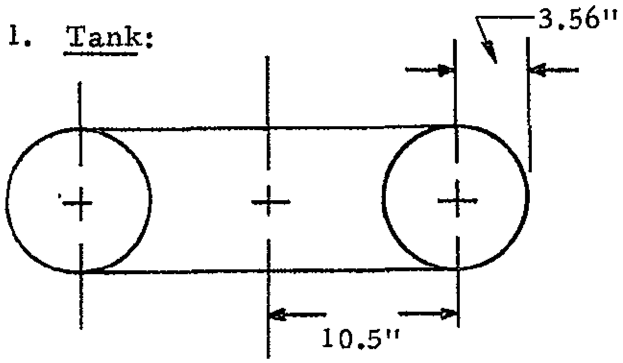
Appendix H

CALCULATION OF SYSTEM CHARACTERISTICS (WEIGHT/ULLAGE/MOMENT OF INERTIA)

Appendix H

TOTAL SYSTEM WEIGHT

1. Tank:



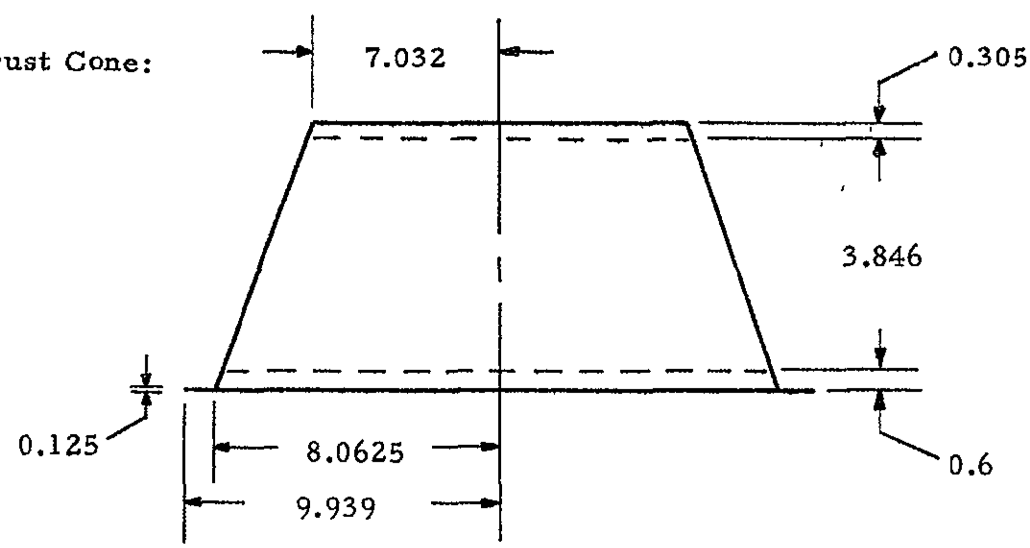
Thickness = .022 inch

$$W = \rho 4\pi^2 a\, b\, t = (.158)\, 4(\pi)^2\, (10.5)\, (3.57)\, (.022)$$

$$W = 5.1387$$

TOTAL SYSTEM WEIGHT

2. Thrust Cone:



Assume top curved section straight

Cone: $W = \rho t \left[\pi (R+r) \sqrt{H^2 + (R-r)^2} \right]$

$$W = .158(.016)\left[\pi(8.0625 + 7.032)\sqrt{(4.151)^2 + (8.0625 - 7.032)^2}\right]$$

$$W_{cone} = 0.5125$$

Ring: $W = t\rho\pi\,(R^2 - r^2) = (.094)(.158)(\pi)(9.938^2 - 8.0625^2)$

$$W_{ring} = 1.5702$$

$$W_{total} = 2.0827$$

3. Pyrovalve:

Body	0.60
Squibs and connectors	0.49
	1.09

TOTAL SYSTEM WEIGHT

4. Plumbing:

1/4" OD Tubing 0.016 Wall Wt/ft - .014 lb/ft ALUM.

Tank to ball valve — 14 in.
Ball valve to pyro valve — 8 in.
Ball valve to OD — 4 in.
Tubing total length = 26 inches/side = 52 inches total

$$W_{tubing} = \left(\frac{52\text{ in}}{12\text{ in/ft}}\right)(.014\text{ lb/ft}) = .060\text{ lb}$$

Flex Hose weight = .08 lb/ft

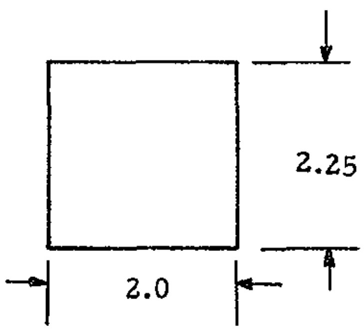
$$W_{flex\ hose} = 2\left(\frac{10\text{ in}}{12\text{ in/ft}}\right)(.08\text{ lb/ft}) = .133\text{ lb}$$

Fittings

2	- Quick Disconnects	.06 lb. ea. =	1.20
2	- Elbows at tank	.027 lb. ea.	= .054
2	- Tee's at injector	.045 lb. ea.	= .090
4	- Female conn. at valve	.0272 lb. ea. =	.109
			.393 lb

5. Ball Valves: 0.09 lb ea. = 0.18 lb

6. Doubler:



.030 thickness

W = ρV = (.158)(.030)(2)(2.25)

W = .0213 lb. ea.

2 doublers W = .0426

TOTAL SYSTEM WEIGHT

7. Valve Support:

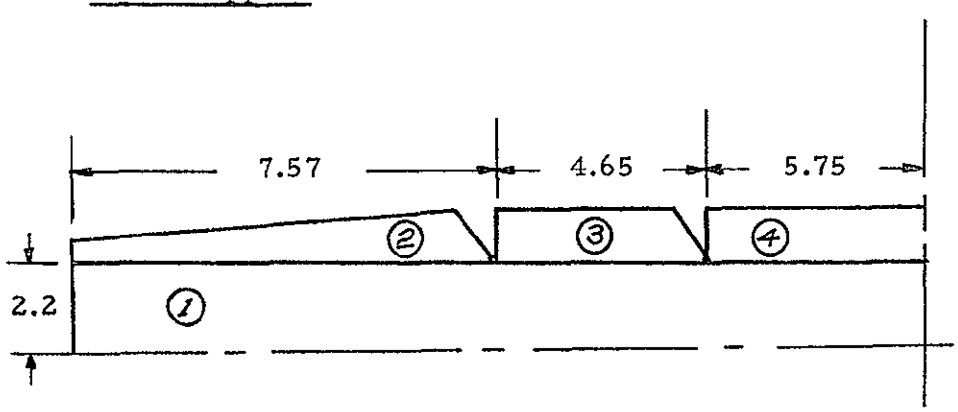


Figure flat pattern area times .04 thickness x ρ = weight

$$A_1 = (2.2)(7.57 + 4.65 + 5.75 + 4.65 + 7.57) = 66.418 \text{ in.}^2$$

$$A_2 = \tfrac{1}{2}(.569)(.985) + \tfrac{1}{2}(7.)(.725) + (7.0)(.26) = 4.6377$$

$$4A_2 = 18.5508$$

$$A_3 = \tfrac{1}{2}(.66)(1.143) + (3.99)(1.143) = 4.938$$

$$4A_3 = 19.7510$$

$$A_4 = (.688)(1.28) + (5.062)(1.28) = 7.26$$

$$2A_4 = 14.72$$

so that the flat area before cut out is:

```
  66.418
  18.551
  19.751
  14.720
 ________
119.640 in.^2
    .04  in. thick
 ________
 4.7856 in.^3
```

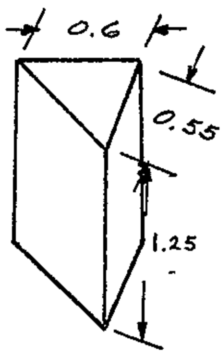
$$W = \rho V = (.158)(4.786) = .7562 \text{ lb.}$$

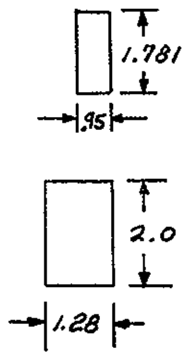
TOTAL SYSTEM WEIGHT

Now we remove all holes and cut-outs, and then add in the two corner blocks.

8 - 3/8 diameter corner bend relief holes	V =	$.00441 \text{ in.}^3$
2 - 1/2 diameter holes	=	.00785
2 - .687 diameter holes	=	.01482
2 - .781 diameter holes	=	.01915
2 - .203 diameter holes	=	.00129

Valve meeting cut outs





= .06767

= .1024

V_T = .21758

W = .034379 lb.

2W = (.6)(.55)(1.25)(.158) = .0652

W = .7562 - .0344 + .0652 = 0.787

Total System Weight:

Tank	5.1387
Thrust cone	2.0827
Pyrovalve	1.0900
Plumbing	0.5860
Ball valves	0.1800
Doublers	0.0426
Valve support	0.7870

= 9.907 Hardware
50.00 Fluid (nominal)
59.907 lb.

Ratio $\frac{\text{fluid}}{\text{total}} = \frac{50}{59.907} = 0.8346$

SYSTEM ULLAGE REQUIREMENTS

The three primary fluids; butane, ammonia, and water each have characteristics which make determination of a "universal" tank very much a tradeoff.

I. For the baseline tank previously described, using Butane as the working fluid the following is found:

V_T = 1.25 ft^3
P_{max} = 150 psia
T_{max} = 177.8 °F
$T_m exp$ = 150 °F

Due to ullage required for fluid expansion at increased temperatures, a volume less than maximum is available at normally expected temperature.

The ullage required is a varying percentage of total volume depending on the temperature (fluid) maximum design and the loading temperature.

$$\%\text{ Ullage} = \left\{ 1 - \left[\frac{V_f \text{ at loading temperature}}{V_f \text{ at maximum temperature}} \right] \right\} \times 100$$

which is the percentage extracted at loading.

a. For $T_{max} = 178^{o}$ $\quad T_{load} = 75^{o}$

$$W_F = (1.25\,ft^3)(31.3\ lb/ft^3) = 39.1\ lb$$

$$\%\text{ Ullage} = 1 - \left[\frac{V_f \text{ at } 39.1\ lb}{1.25} \right] = 1 - \frac{1.185}{1.25} = 1.0 - .869$$

$$\%\text{ Ullage} = 13.1\%$$

Weight total at $75^{o}F$

$W_f = 1.25(36.05) = 45.0$ lb.

Ullage weight = (.13)(45) = 5.9 lb

$\therefore$ W_f Final = <u>39.1 lb</u>

which is equivalent to W_f at T_{max}.

b. For maximum expected conditions $T_{max} = 150^{o}F$

$\therefore$ For loading temperature of 75^{o}

Ullage Weight = 4.4 lb or 9.8%

W_F Usable = 40.6 lb

II. In order to provide a usable fluid weight of ~ 50 lb, the tank volume must be increased.

$$T \text{ at } 150^\circ F \quad V = \frac{50 \text{ lb}}{32.6 \text{ lb/ft}^3} = 1.53 \text{ ft}^3$$

Using 1.5 ft^3

Ullage = 9.1% or 4.9 lb

W_F Usable = 49.1 lb

Tank weight for 1.5 ft^3 = 5.011 lb

Weight for fittings, tubes, and thrust cone ≅ 3.00 lb

$$\text{Mass fraction} = \frac{49.1}{57.01} = .86$$

III. Ammonia presents other problems in that at the maximum pressure, the allowable temperature is <u>79°F</u>.

Therefore three alternatives are available:

1. Normal tank (universal) equipped with pressure relief valve (150 psia)
2. Increase tank wall thickness to withstand higher pressure (1.25 ft^3)
   i.e., at 125°F = 307 psia
   $\therefore \; t_{wall} = .0388$
   Weight = 8.36 lb
   This is assuming no burst test and design to safety factor of 4.
3. Restrict maximum operating temperature to 80°F.

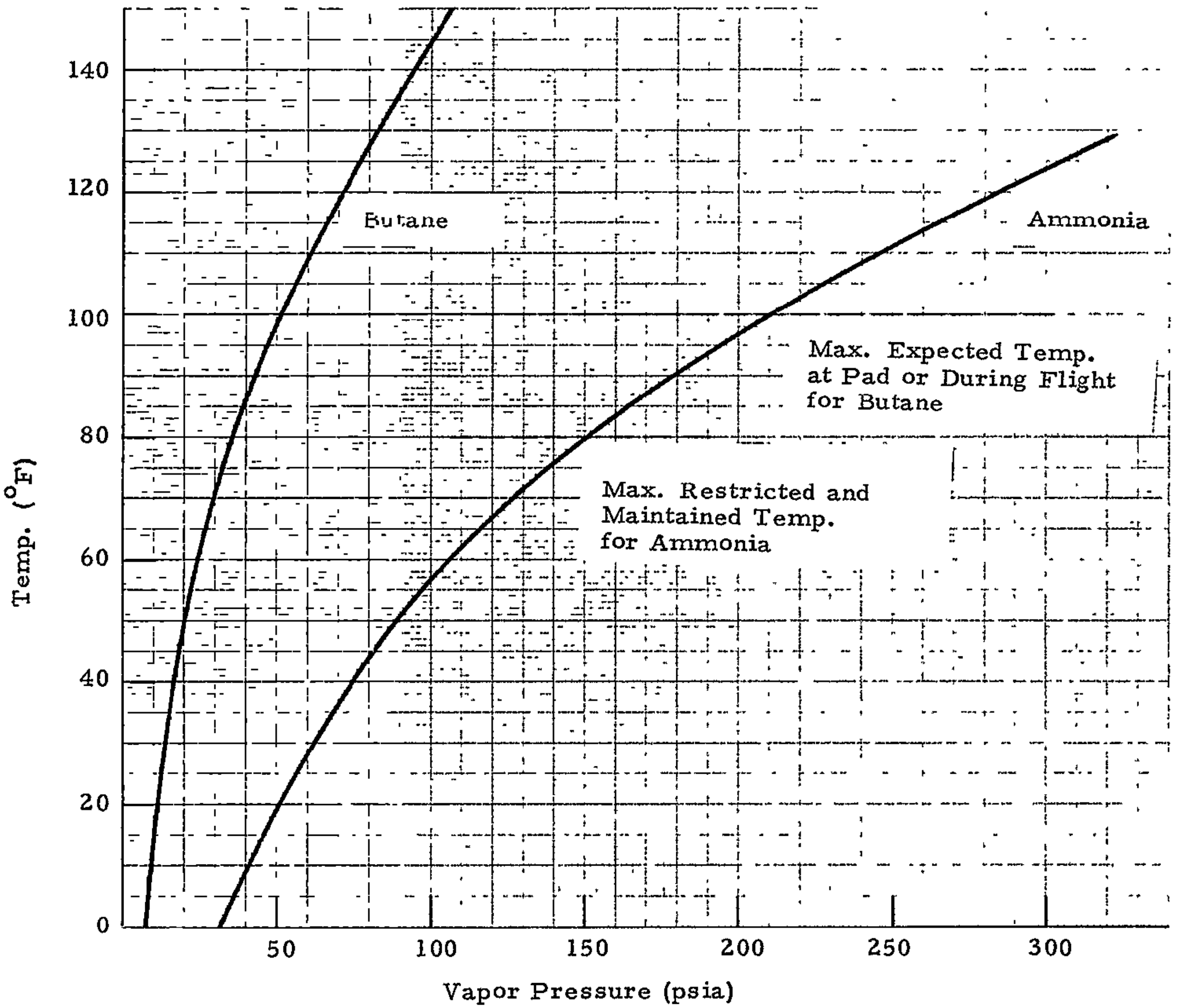


Fig. H-1 - Vapor Pressure Curves for Butane-n and Ammonia for Anticipated Pad Temperature Conditions

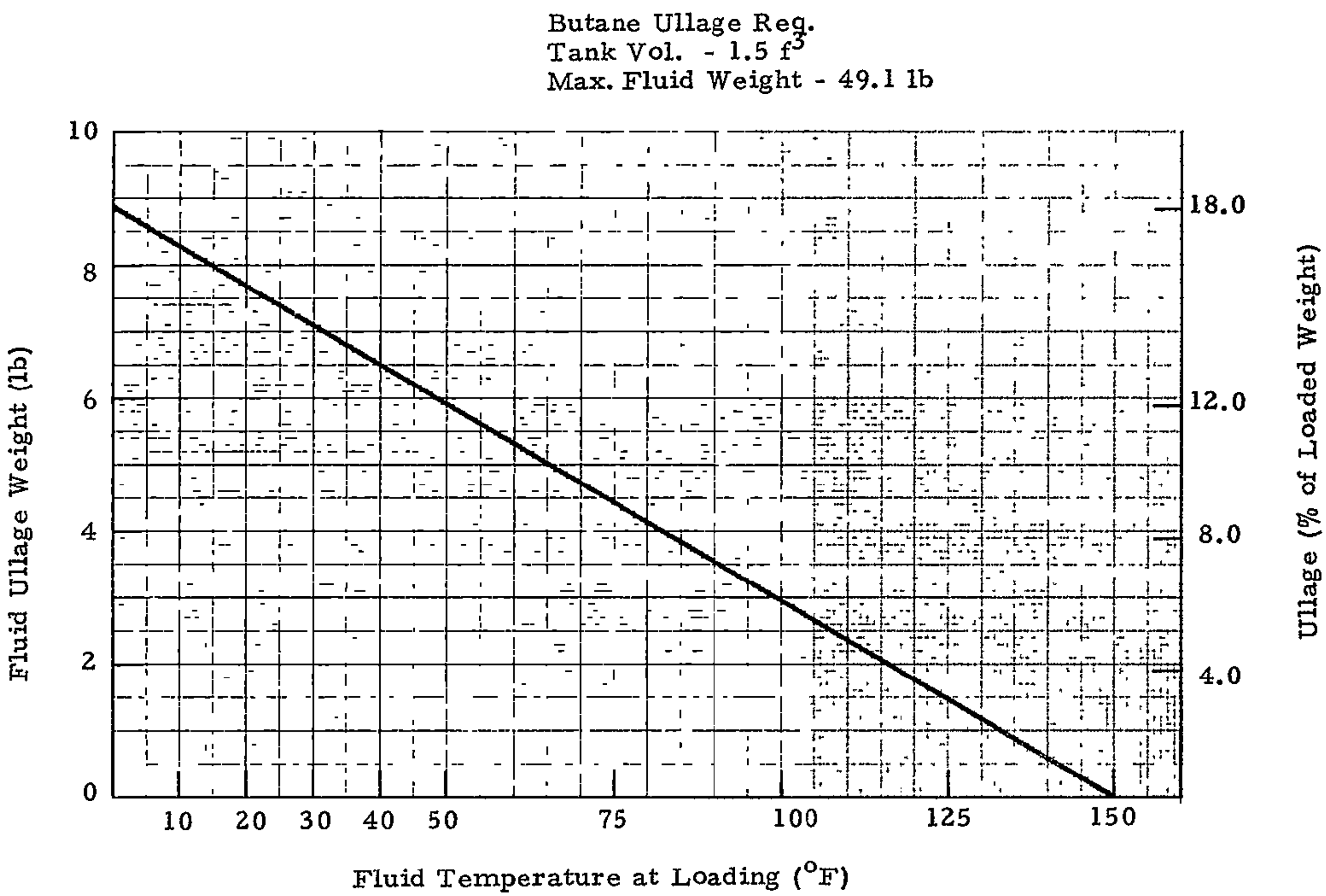


Fig. H-2 - Fluid Ullage Requirements as Function of Fluid Temperature for Butane-n

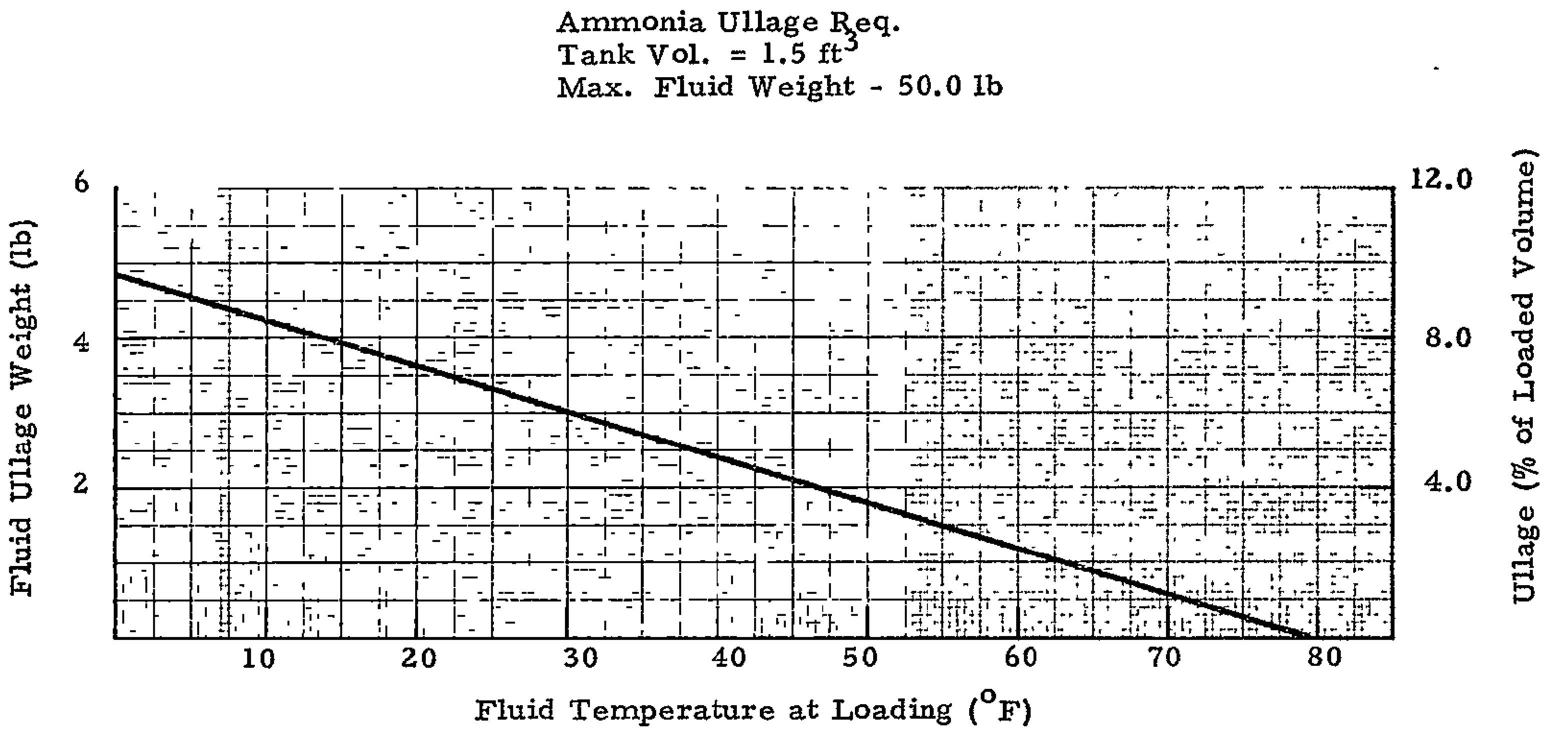


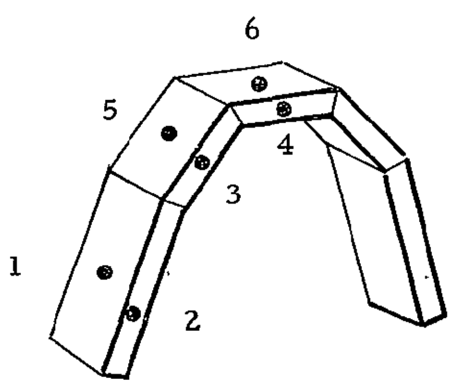
Fig. H-3 - Fluid Ullage Requirements as Function of Fluid Temperature for Ammonia

MOMENT OF INERTIA OF STRUCTURE

$I = mr^2$ $W = mg$ $I = \frac{W}{g} r^2$

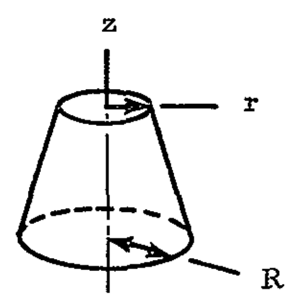
Item	Weight (lb)	r(in.)	I(lb-in.^{2})	I(in-lb-sec^2)
Tank	5.1387	10.5	566.542	1.4662
Thrust cone skin	0.5125	**	3.986	0.0103
Thrust cone ring	1.5702	9.050	128.603	0.3328
Doublers	0.0426	7.81	2.598	0.0067
Valve Support:				
Sect 1*	0.2105	7.15	10.761	0.0278
Sect 2	0.1173	6.80	5.421	0.0140
Sect 3	0.1248	4.00	1.997	0.0052
Sect 4	0.0930	1.28	0.152	0.0004
Sect 5	0.1293	4.28	2.369	0.0061
Sect 6	0.0799	1.28	0.131	0.0003
Pyrovalve	1.09	0.52	0.295	0.0008
Ball valves	0.180	2.08	0.779	0.0020
Q. D.'s	0.120	5.00	3.00	0.0078
Tank Elbows	0.054	15.06	12.247	0.0317
Tees	0.090	2.68	0.646	0.0017
Plumbing:				
Tank to Ball valve	0.0326	11.00	3.945	0.0102
Ball valve to pyrovalve	0.0186	1.25	0.029	0.00007
Flex Line	0.1330	1.625	0.351	0.0009
Ball valve to Q. D.	0.0093	3.25	0.098	0.0003
Manifold	0.0093	2.20	0.045	0.0001
				1.92537

$I_{structure} = 1.925 \text{ in.-lb-sec}^2 = 0.1604 \text{ slugs-ft}^2$



Sections of valve support

**

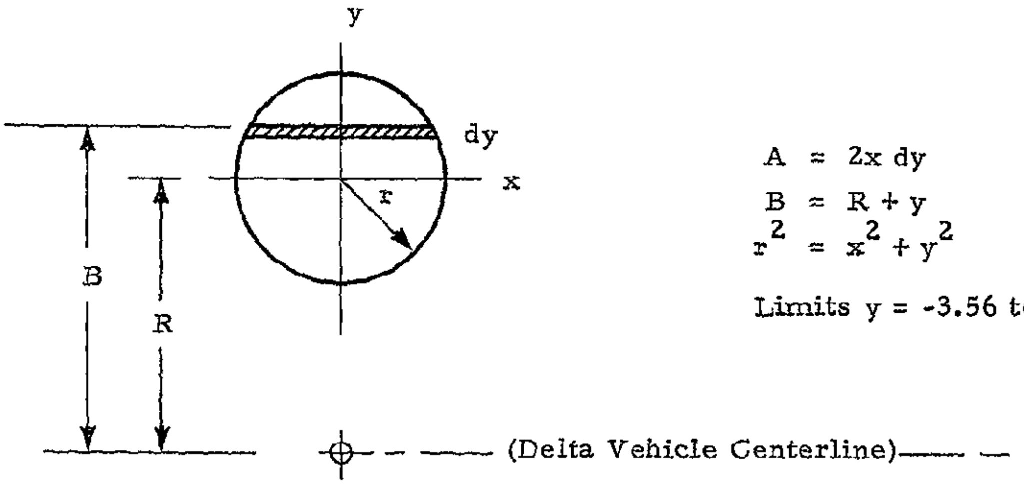


$$I_z = \frac{W}{2}(R^2 + r^2)$$

$$= \frac{.5125}{2}(8.0625^2 + 7.032^2)$$

SYSTEM MOMENT OF INERTIA AS FUNCTION OF TIME

Tank Fluid Volume



$A = 2x\,dy$ $\qquad R = 10.5$

$B = R + y$ $\qquad r = 3.568$

$r^2 = x^2 + y^2$ $\qquad V_T = 2\pi R(\pi r^2)$

Limits y = -3.56 to +3.56

$$V = 2\pi B(2x\,dy) = 2\pi(R+y)(2x\,dy)$$

$$V = \int_{y_1}^{y_2} 4\pi\ (R+y)(\sqrt{r^2-y^2})\ dy$$

$$V = \int_{y_1}^{y_2} (R\sqrt{r^2-y^2})\ dy + (y\sqrt{r^2-y^2})\ dy$$

I. $$V = 4\pi\left[R(\tfrac{1}{2}y\sqrt{r^2-y^2}) + r^2 \sin^{-1}(\tfrac{y}{r})) - \tfrac{1}{3}\sqrt{(r^2-y^2)}\right]_{y_1}^{y_2}$$

For Centroid

II. $$\overline{y_c} = \frac{4}{3}\,\frac{(r-y)}{\pi} + y$$

∴ For $y_1 = 0$ and $y_2 = 3.56$

$$V = 4\pi\left[10.5\ (\tfrac{1}{2}\,y\sqrt{r^2-y^2}) + \frac{12.7}{2}\sin^{-1}(1)) - \tfrac{1}{3}\sqrt{(r^2-y^2)^3}\right]_0^{3.56}$$

$$= -4\pi\,[0 + 0 - 14.01]$$

$$V = 1509 \text{ in.}^3$$

$$\overline{y_c} = \frac{4}{3} \frac{3.56}{\pi} = 1.51$$

Therefore from the initial volume of fluid (Butane) at 70°, $\rho = 36.05 \text{ lb/ft}^3$ and the initial weight of 49.1 lb.

$$V_{f_i} = 1.365 \text{ ft}^3 = 2355 \text{ in.}^3$$

For the first increment, then:

$$\Delta V = 846 \text{ in.}^3 \quad \text{and } \Delta W = 17.66 \text{ lb}$$

$$\Delta t = \frac{17.66 \text{ lb}}{.564 \text{ lb/sec}} = 31.9 \text{ sec.}$$

Moment of inertia at $t_1 = 31.9$ sec

$$I_m = MR^2 = \frac{31.44 \text{ lb}}{386 \text{ in/sec}^2} (12.01 \text{ in.})^2 = 11.82 \text{ in-lb-sec}^2$$

$$I_m = .987 \text{ slug-ft}^2$$

In Fluids:

I. Butane $T = 70^\circ$ $\rho = 36.05$ $\dot{m} = .564 \text{ lb}_m\text{/sec}$

V_f (in.^{3})	$\overline{y}$ (in.)	W_f (lb)	t (sec)	rg (in.)	I_m (in-lb-sec^2)	I_m (slug-ft^2)
2355	0	49.1	0	10.5	14.05	1.168
1509.2	1.51	31.4	31.9	12.01	11.82	.987
858.2	1.98	17.81	55.6	12.48	7.20	.599
153.3	2.54	3.20	81.4	13.04	1.41	.117
0	~	0	87.08	14.06	0	0

II. Water T = 70° ρ = 62.34 lb/ft^3 $\dot{m}$ = .0475 lb_m/sec

V_f (in.^{3})	$\bar{y}$ (in.)	W_f (lb)	t (sec)	rg (in.)	I_m (in-lb-sec^2)	I_m (slug-ft^2)
1409	1.55	50.0	0	11.05	15.78	1.315
858.2	1.98	31.09	419	12.48	12.55	1.045
153.3	2.54	5.52	935	13.04	2.44	.203
0	~	0	1050	14.06	0	0

III. Ammonia T = 70° ρ = 38.0 lb/ft^3 $\dot{m}$ = .067 lb/sec

V_f (in.^{3})	$\bar{y}$ (in.)	W_f (lb)	t (sec)	rg (in.)	I_m (in-lb-sec^2)	I_m (slug-ft^2)
2300	0	50	0	10.5	14.30	1.190
1509	1.51	33.2	250	12.01	12.44	1.035
853	1.98	18.82	466	12.48	7.60	.632
153	2.54	3.38	695	13.04	1.49	.124
0	~	0	746	14.06	0	0

Combining the structure and fluid moments assuming full load the moments are:

Fluid	I(slug-ft^2)
Butane	1.3284
Ammonia	1.3504
Water	1.4754

The graph on the following page shows the change in mass moment versus time of actual fluid flow. The zero corresponds to 0.1604 slug-ft^2 for the structure. The effect of any axial acceleration during this period has been assumed to be negligible, and therefore it has been neglected in this analyses.

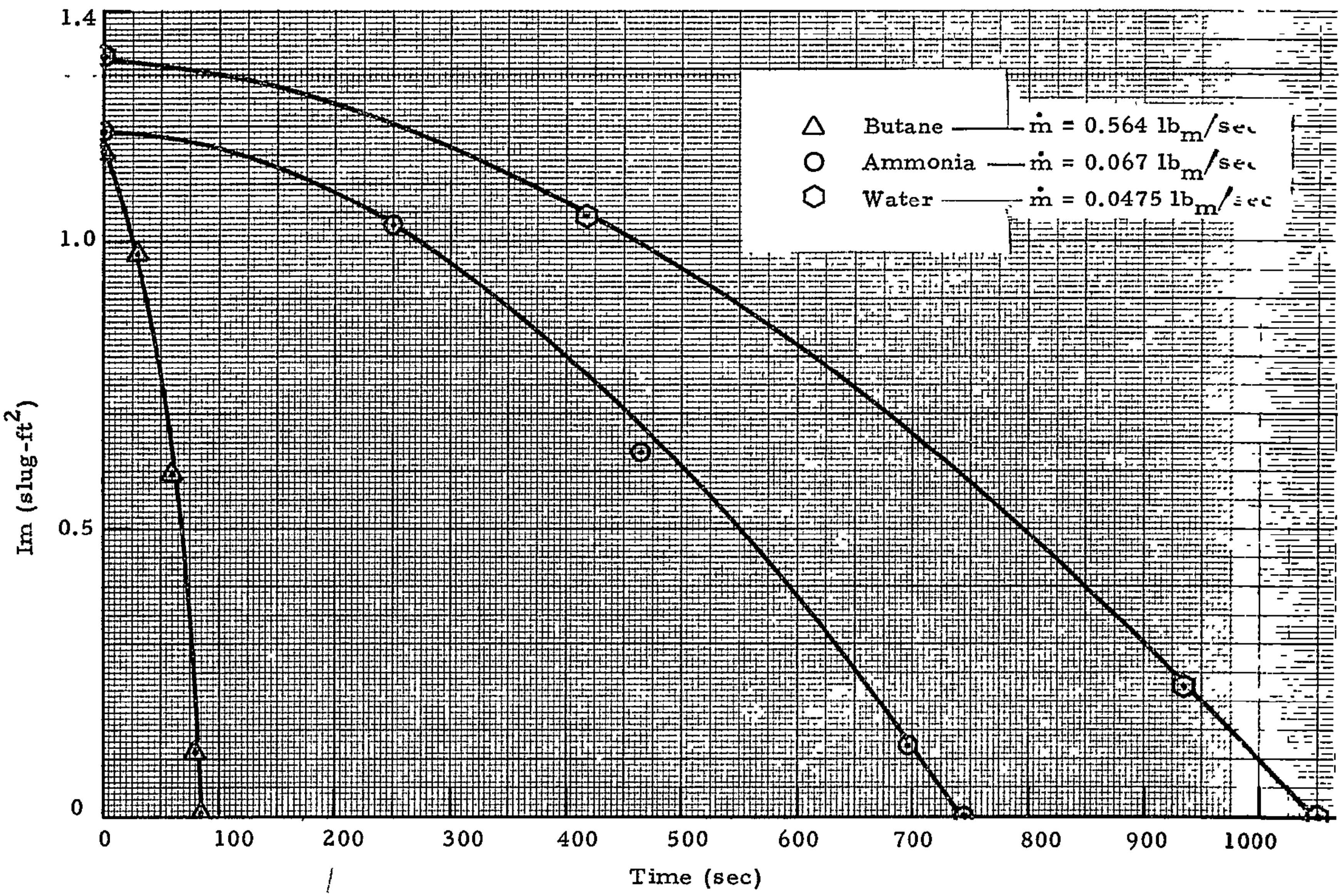


Fig. H-4 - Mass Moment of Inertia as a Function of Time for Butane, Ammonia and Water

Appendix I
FUNCTIONAL PROCEDURES

Appendix I

TEMPERATURE ENVIRONMENT CONSTRAINTS

During the ETR operations the environmental temperatures are controlled for all operations except in the "handling can" during transportation to the pad. Due to the weight considerations, a 1.50 cu ft tank with a 0.021-in. thick wall is used in the IFIS. For the three expected fluids the tank will maintain a 4:1 safety stress factor at 150°F with one exception: If ammonia is used as the working fluid, a maximum temperature of 80°F must be maintained to limit tank pressure to 1/4 design burst.

Since the tank will be loaded prior to spin tests, it is imperative that temperature control be utilized for the "handling can" if ammonia is used.

ASSEMBLY PROCEDURES

The IFIS system consists of two major subassemblies: the tank (including thrust cone, valving and most hardware) and the ignition assembly (which incorporates the ports, manifold, etc.). The final assembly and connections shall be made just prior to the third stage spin tests. Following is the final assembly and operations sequence:

A. Tank Subassembly
   1. Receiving inspection and approval.
   2. Installation of valves, support, tubing, etc., not previously installed.
   3. Leak and functional checks. (See page I-2.)
   4. Fluid loading (page I-6) accomplished approximately one day prior to final assembly.

B. Ignition Subassembly

1. Receiving inspection and approval.
2. Leak and functional check (if not previously accomplished).

C. Final Assembly

1. Install ignition subassembly R72413 in third stage motor.
2. Install motor S/A assembly in the ignition subassembly.
3. Attach tank subassembly to the third stage motor casing.
4. Connect lines from tank subassembly to ignition subassembly at the pyrotechnic valve.
5. Leak check final assembly. (See page I-5.)

The final assembly shall be performed just prior to the spin tests at the Spin Test Facility. Due to the required orientation of the tank (tank fittings in vertical plane) during loading (fluid), the tank must be filled prior to attachment to the third stage motor. Also, because of environmental control for the fluid, the loading should be accomplished just prior to third stage buildup. Extreme care should be utilized at all times when the loaded tank is being handled to prevent any damage to the fittings, etc.

The IFIS is in an operational configuration at this point, with the loading of the pyrotechnics and positioning the S/A valves at the pad the only remaining operation before flight.

LEAK AND FUNCTIONAL CHECK

Tank Assembly

1. The pressure vessel shall be proof tested to 1.50 times maximum pressure (150 psia operating – 225 psia proof) prior to installation of mating hardware (preferably at manufacture of tank).

2. Leak and functional test will be performed after assembly of the following components:

a. Tank
b. S/A valves
c. Pyrotechnic valve
d. Interconnecting lines
e. Quick-Disconnects

The following operational outline shall be followed in order to provide proper checkout of the items listed in No. 2 above. Pressures shall not exceed 1/4 design burst at any time. A relief valve shall be provided to limit supply pressure to approximately 200 psia.

3. Leak and Functional Test (Tank) (Refer to Fig. I-1.)

A. GSE

1. Assemble GSE as per Fig. I-1.
2. Adjust supply pressure to 250 psig.
3. Adjust RV1 until GA1 indicates approximately 20 psig.
4. Leak check GSE fittings (Leak-Tek Sol).
5. Close RV1 and bleed off pressure.

B. Tank – Purge

1. Connect GSE Q.D.'s to Tank Q.D.'s.
2. S/A valves to FILL position.
3. Adjust RV1 until GA1 indicates approximately 20 psig.
4. Verify flow through vent line.
5. Purge system for five minutes.

C. Tank – Leak Check

1. Close S/A valve on vent side.
2. Adjust RV1 to maintain constant approximately 20 psig.
3. Leak check all fittings on tank and S/A valves.
4. Position both S/A valves to ON position.
5. Leak check lines and fittings to pyro valve.

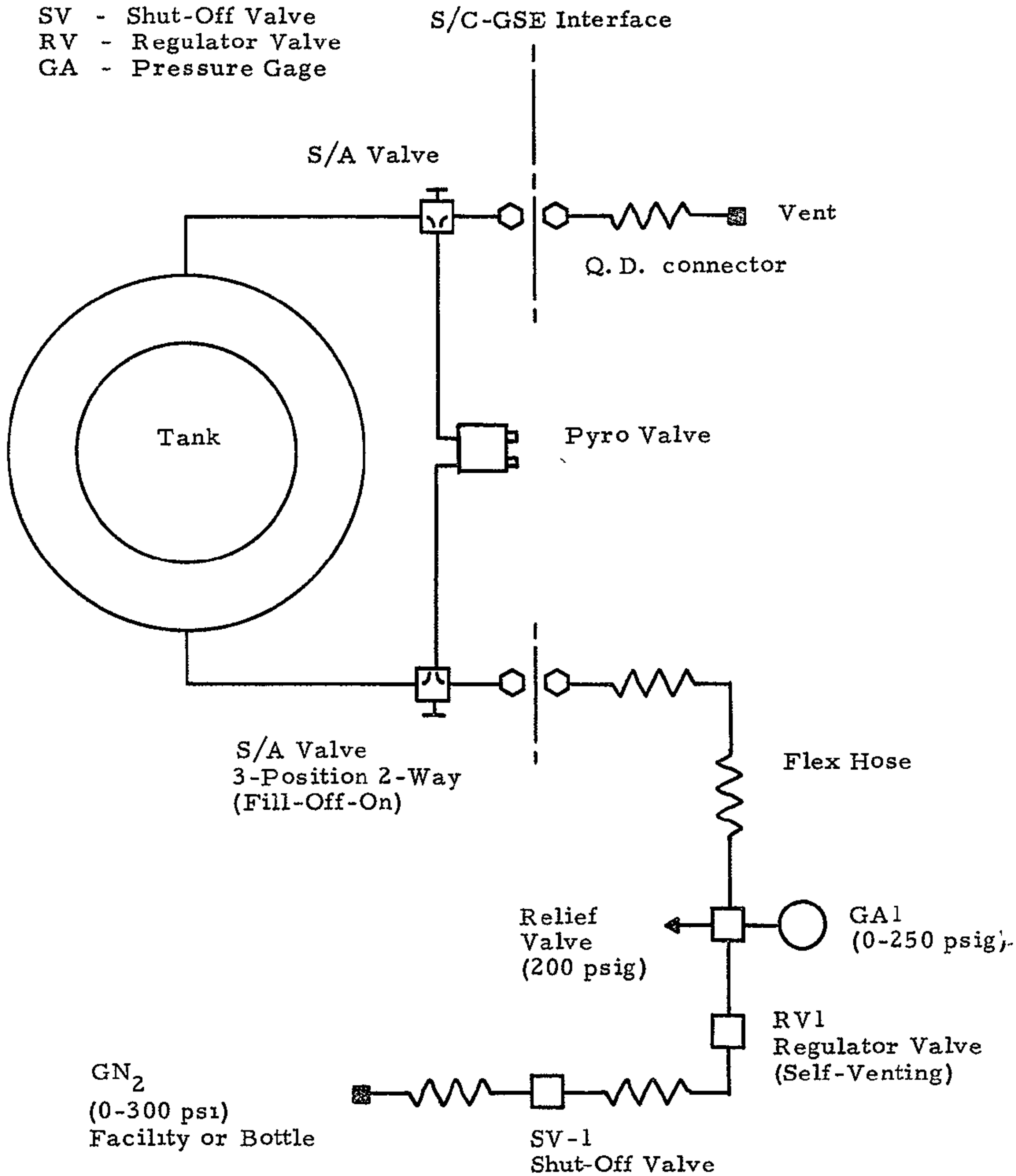


Fig. I-1 - Leak and Functional (Schematic)

D. Tank – Functional – Decay Check
   1. Position inlet S/A valve to FILL.
   2. Adjust RV1 until GA1 indicates 135 $^{+0}_{-5}$ psig.
   3. Close RV1 and observe pressure decay for 10 minutes (no leakage allowable).
   4. Adjust pressure to 5 ± 2 psig.
   5. S/A valves to OFF.
   6. Disconnect GSE.

I.3.2 Ignition Subassembly

Functional checkout of the ports, manifold and orifices shall be conducted prior to the installation of the pyrolytic graphite orifice cover.

A. Flow Rate
   1. Inlet lines connected to separate flowmeters in order to determine flow with either one or both lines operating.
   2. Water shall be used for flow check.
   3. Flow rate shall be a minimum of 0.047 lb/sec at 15.0 psig with both inlets open.

B. Drying

   After flow rate test, the ignition system must be purged with GN_2 at 20 psig until dry.

Final leak check of the ignition system shall be performed after the fittings are mounted and after the graphite orifice cover is installed. A maximum pressure of 8 psig shall not be exceeded after graphite cover is installed.

After the tank subassembly and ignition subassembly are installed, the final leak check shall be accomplished. In order to perform this check, GHe will be introduced at low pressure and leaks sensed with a Mass Spectrometer. A low flow into the motor will result because of the bleed orifice in the injector assembly. Generally:

1. Verify all connections downstream of pyrotechnic valve are correctly torqued.

2. Unplug one transducer port on pyrotechnic valve.

3. Connect low pressure GHe supply (with pressure gage and regulator valve) to transducer port.

4. Establish low flow rate of helium through system. (DO NOT EXCEED 8 PSIG SUPPLY PRESSURE.)

5. Check system (connections) with Mass Spectrometer.*

6. Disassembly and replug transducer port. Verify correct torque on plug.

I.4 TANK LOADING PROCEDURE

The tank will be fully loaded with fluid (liquid) then, and ullage will be withdrawn to allow space for expansion. The amount of ullage (by weight) shall be determined by the fluid temperature at loading. (Refer to Figs.I-2 and I-3 for ullage requirements.) The supply pressure is then used to add additional pressure to the tank. Refer to Fig. I-4 for accompanying servicing schematic.

A. Mount tank in fixture with one inlet line at the top. Place fixture with tank on scales.

B. Assembly GSE equipment as per schematic using 1/4 in. or larger flex hose and appropriate fittings.

C. Fluid supply tank should be high pressure vessel, with or without internal bladder. Maximum capacity approximately 100 lb fluid. Temperature gage should be integral with tank (0 to 200°F, $\pm$ 0.25°F).

   CAUTION: Vent line should lead to open area where Butane or Ammonia vapor will not collect.

D. Prior to connection of supply tank (fluid) to GSE lines, leak test all fittings.

   1. Tank S/A valves – FILL

   2. RV2 – CLOSE RV1 – OPEN
      RV3 – CLOSE SV2 – OPEN

   3. Adjust GN_2 ullage pressure to 200 psig.

*An alternate leak check method using soap solution can be utilized.

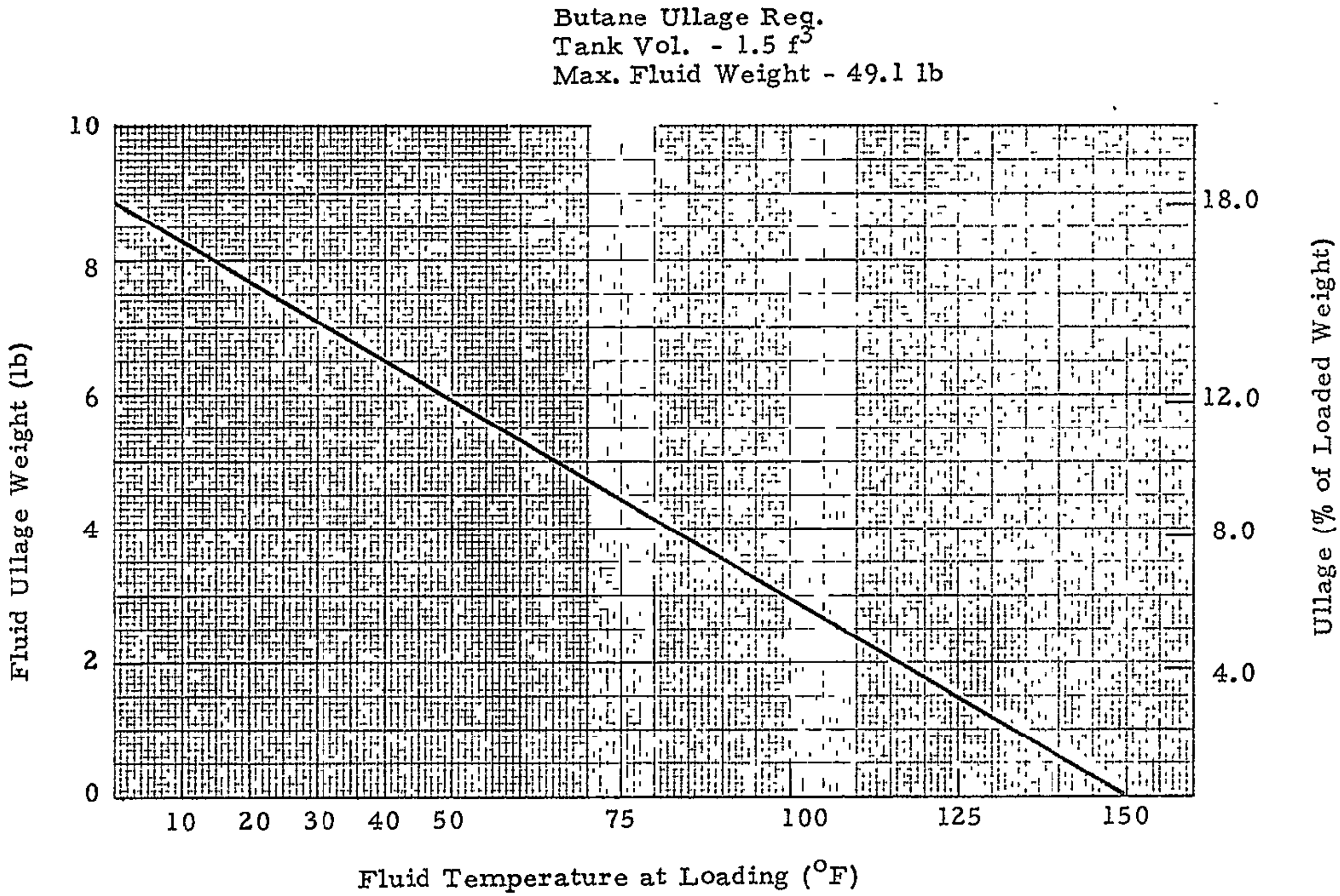


Fig.I-2 - Fluid Ullage Requirements as Function of Fluid Temperature for Butane-n

Ammonia Ullage Req.
Tank Vol. = 1.5 ft^3
Max. Fluid Weight - 50.0 lb

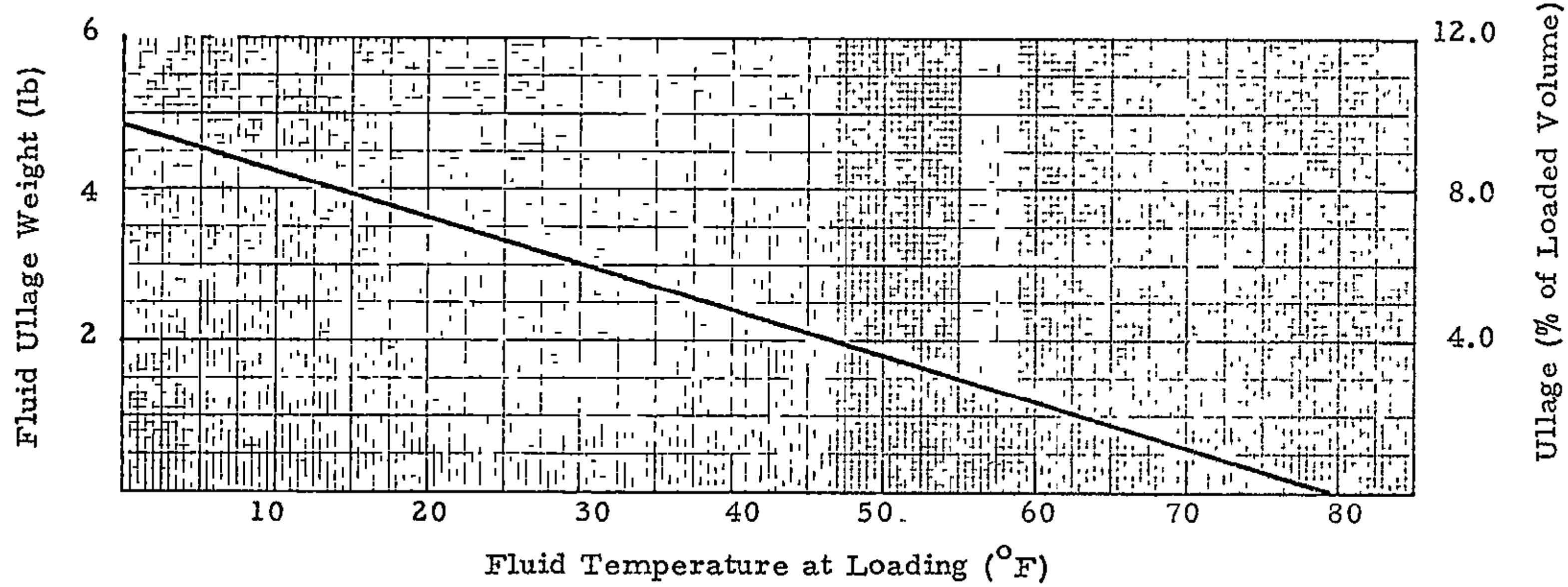
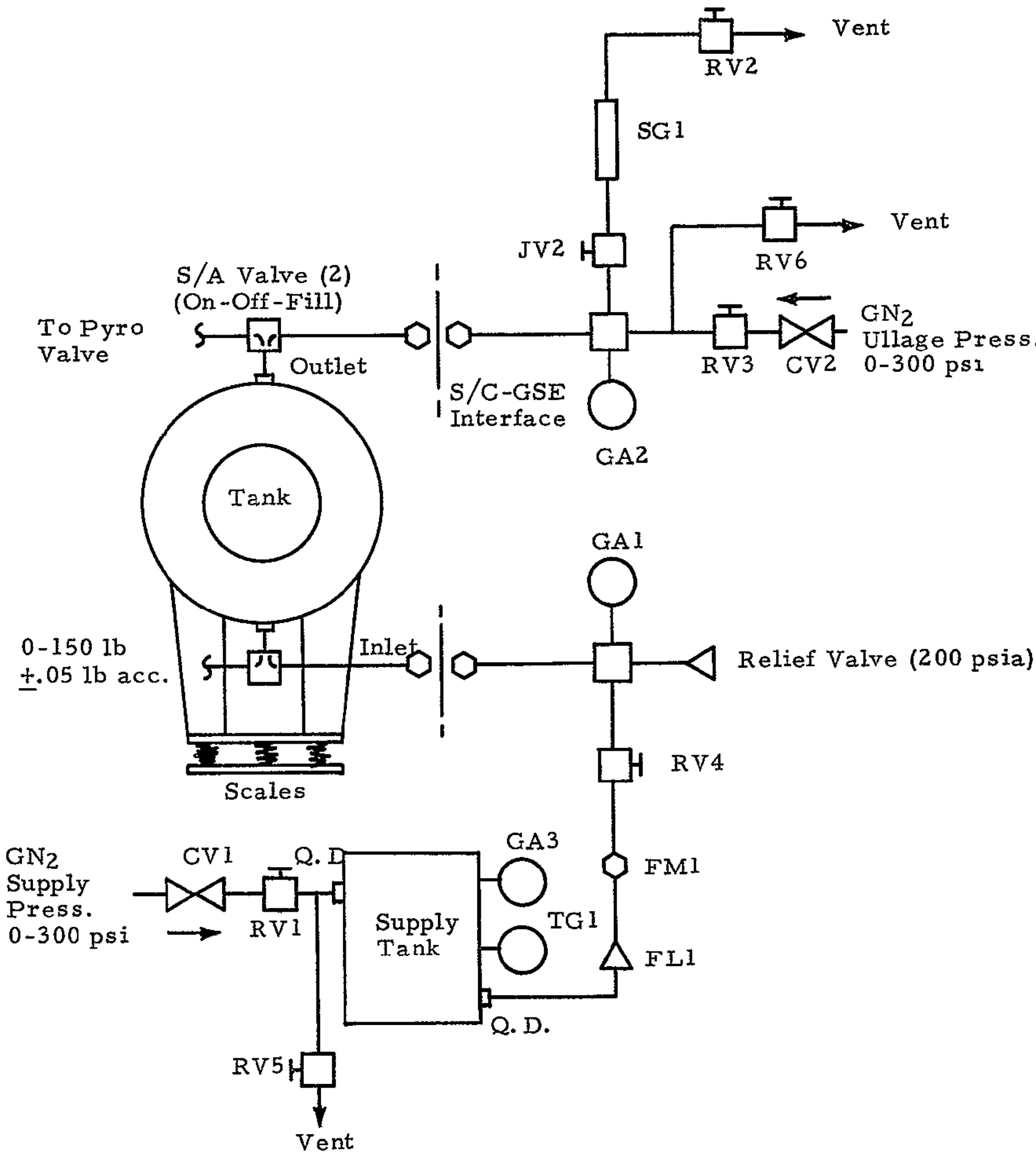


Fig.I-3 - Fluid Ullage Requirements as Function of Fluid Temperature for Ammonia



CV - Check Valve
SV - Shut-Off Valve
RV - Regulator Valve
GA - Pressure Gage (0-300 psig)
TG - Temperature Gage (0-200°F)
SG - Sight Glass
FM - Flow Meter (optional)
FL - Filter (10μ)

Fig. I-4 - IFIS Servicing Schematic

4. RV3 – OPEN
5. Use Leak-Tek on all fittings. Verify no leakage.
6. RV3 – Adjust GA2 pressure to 0 psig.

The following loading procedures are presented in basic outline form, with all major operations detailed. There are two procedures, generally similar, but with necessary changes pertinent to the specific fluid. The sections are: (I) Butane or Ammonia, (II) H_2O.

I. Butane or Ammonia

A. Valve positions (initial). Verify following:

1. RV1 – CLOSE; RV3 – CLOSE; RV4 – CLOSE; RV5 – CLOSE; SV2 – OPEN; RV2 – OPEN (slightly); S/A – FILL
2. Adjust GN_2 pressure (both bottles) to 30 psig.
3. Record tank tare weight, lb
4. Record fluid temperature (TG1), °F
5. Record pressure (tank) (GA3), psig

   NOTE: If GA3 is approximately 30 psig, GN_2 pressure not required.

B. Fill

1. RV4 – OPEN
2. Verify flow by FM1. Verify P of approximately 20 psig between GA1 and GA2.
3. Adjust RV2 as required to control above step.
4. If ΔP cannot be maintained, adjust RV1 as required.
5. With tank full, slight glass approximately all liquid (no vapor bubbles) and $\Delta_{wt} > 50$ lb as read on scales. Proceed.
6. RV2 – CLOSE; RV4 – CLOSE; RV1 – CLOSE; SV2 – CLOSE
7. Record TG1, °F
8. RV5 – OPEN-CLOSE as required until GA3 indicates approximately initial pressure (Step A-5). Record, psig

C. Ullage

1. Record tank weight, lb
2. Refer to Ullage Chart (for applicable fluid) using TG1 temperature to determine ullage required.
3. RV2 – OPEN approximately 30 psig on GN_2 outlet.
4. OPEN/CLOSE RV4 carefully to drain required ullage. When tank weight is at final weight, close RV4 and RV3.
5. Inlet S/A valve – OFF. Let stabilize.
6. OPEN/CLOSE RV3 to increase tank pressure to 60 psia (45.3 psig) for butane or 122 psia (107.3 psig) for ammonia. Record, psig
7. Outlet S/A valve – CLOSE. OPEN RV6.
8. Disconnect S/C-GSE Q.D.S.
9. Drain and disassemble GSE.

II. H_2O

A. Initial valve position.

1. RV1 – CLOSE   RV6 – CLOSE
   RV4 – CLOSE   RV2 – OPEN
   RV3 – CLOSE   SV2 – OPEN
   RV5 – CLOSE
2. Adjust GN_2 pressure (supply) to approximately 20 psig.
3. Record tank tare weight, lb
4. RV1 – OPEN
5. S/A valves – FILL

B. Fill

1. Open RV4. Verify flow by FM1 and increasing tank weight.
2. Flow until $50^{+0}_{-0.2}$ lb H_2O is in tank. Record, lb
3. Close RV4

C. Pressurization

1. RV1 – CLOSE   SV2 – CLOSE
   RV5 – OPEN

   NOTE: If fluid weight in tank is less than 50 lb, perform the following:

a. Adjust ullage pressure to 10 psig.
b. OPEN RV3
c. OPEN/CLOSE RV4 as required to obtain correct fluid weight.
d. RV3 – CLOSE
e. RV6 – OPEN

2. S/A inlet valve – OFF.
3. Adjust GN_2 ullage pressure to 10 psig.
4. RV3 adjust until GA2 indicates 35 $^{+2}_{-0}$ psig. Record, psig after stabilization.
5. S/A outlet valve – OFF.
6. RV3 – CLOSE GN_2 pressure – 0
7. Disconnect GSE-S/C Q.D.'s.
8. Stow GSE.