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SUMMARY REPORT
TASK III SPACE STORABLE PROPELLANT MODULE
ENVIRONMENTAL CONTROL TECHNOLOGY

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SUMMARY REPORT
TASK III STORABLE PROPELLANT MODULE
ENVIRONMENTAL CONTROL TECHNOLOGY

by

R. E. DeLand

O. O. Haroldsen

R. N. Porter

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Jerry T Bevans

J. T. Bevans
Mgr., Heat Transfer and Thermodynamics Department

W R Wannlund

W. R. Wannlund
Mgr., Engineering Design Laboratory

TRW Systems

One Space Park

Redondo Beach, California 90278

TABLE of CONTENTS

TABLE of CONTENTS

Continued

LIST of FIGURES

SUMMARY

The objective of Task III was to make sufficient analyses and design studies of the two thermal control systems established during Task II to specify which is the better system for an OF_2/B_2H_6 propulsion module. Areas of investigation included:

- Type of groundhold propellant coolant to be used
- Type of propellant cooling coils to be used
- Manner in which the helium tank temperature can best be controlled during flight
- Insulation configuration for groundhold and flight.

The results of this effort were evaluated and from the results the following thermal control system was chosen as the superior system to be analyzed during Task IV:

Insulation System - 3/4-inch closed cell polyurethane foam sprayed on the tanks and applied to auxiliary equipment as necessary. The foam is supplemented with multilayer aluminized Mylar to obtain flight thermal control of auxiliary equipment. The insulation design will provide openings for louver installation.

Propellant Ground Cooling - LN_2 circulating through an eight feet, half inch aluminum coil submerged inside the tanks; control of LN_2 to be accomplished by thermally controlled valves having sensors located inside the tanks.

Helium Tank - Conductively coupled to the propellant tanks via an aluminum support beam; support beams to be insulated with both foam and multilayer insulation.

1.0 INTRODUCTION

This is the Task III Summary Report of the Space Storable Propulsion Module Environmental Control Technology Project accomplished under Contract NAS 7-750.

Task II of the project had as its objective the selection of two OF_2/B_2H_6 propulsion module thermal control system concepts for continued study. The results of Task II are reported in detail in Reference 1. The two basic systems chosen for continued study during Task III are listed below.

PROPOSED COMPOSITE SYSTEM

SYSTEM 1	DUAL WRAPPED	
SYSTEM 2	SINGLE WRAPPED (INDIVIDUAL)	
VARIATIONS	REFRIGERATION COLLING LN_2/GN_2 COOLING	
	EXTERNAL COOLING COILS INTERNAL COOLING COILS	
	CONDUCTION-CONNECTED He TANK LOUVER ON He TANK	
COMMON	PROPELLANT TANKS	(2)
	HELIUM TANK	(1)
	LOWER FRAME	
	LOWER-HELIUM TANK	
	NON-POROUS FOAM	
	SEMI-PASSIVE	

The two basic systems differ principally in the insulation configuration. System 1 utilizes an insulation system which encapsulates both propellant tanks as a unit and insulates the helium tank separately. System 2, the single wrapped system, insulates both propellant tanks as well as the helium tank as individual units. For each system, there are three variations to be considered. The first two variations involve the manner of accomplishing the ground hold cooling. The third variation involves the technique to be employed in maintaining thermal control of the helium tank during flight.

It should be noted that both systems incorporate the use of semi-passive thermal control during flight. During Tasks I and II it was established that a purely passive flight thermal control system could be devised but that it could accommodate only minor deviations in the planned mission. Therefore, engineering judgement indicates that the thermal control system should include a louver assembly to aid in controlling the module temperature should it become necessary to deviate from the planned mission.

In order to logically analyze and properly select these two systems, it became necessary during Task II to perform much of the work which was originally planned for execution during Task III. In particular, the influence of mission variations, propellant and pressurant loading requirements, propulsion plumbing layout requirements and ground hold requirements were considered. Consequently, much of that which was originally scheduled for inclusion in this report has already been issued in Reference 1.

The work of this Task has been concentrated in those remaining areas in which the two proposed systems differ, the objective being to establish a single system for detailed analysis during Task IV. Sections 2, 3, and 4 of this report discuss the work done in support of this objective pertaining to ground hold thermal control, flight thermal control and propulsion system design. Section 5 is an evaluation of the results when the propulsion module is viewed as a composite system. Also, in Section 5 is listed the recommended system for detailed analysis during Task IV.

2.0 GROUND HOLD THERMAL CONTROL

The ground hold thermal control system is required to maintain the space storable propellants in a vent free mode and to prevent frost accumulation on the system during the ground hold phase of the mission. During Task II, it was established that a non-porous foam insulation system would be utilized to reduce the heat transfer rate to the tanks and that cooling coils would be used to keep the temperature of the propellants and pressurant depressed. During Task III analyses were carried out to clarify the following problem areas:

- Type and quantity of collant required
- Location and length of cooling coils
- Extent to which auxiliary equipment (valves, regulators, etc.) require ground cooling
- Advantages or disadvantages of the two competing insulation systems.

2.1 Ground Hold Cooling System

To clarify the cooling system requirements, two sets of calculations were made. The first investigated the characteristics of a cooling system which utilizes cooling coils submerged inside the fluid tanks. The second set of calculations investigated the thermal characteristics of a cooling system which utilizes cooling coils attached to the outside of the tanks.

2.1.1 Submerged Cooling Coil System

The model assumed in this analysis is as shown in Figure 2-1. Assuming negligible temperature drop across the tube wall, the heat transfer of this system is described by

$$Q/A = h_i\ (T_t - T_c) = h_o\ (T_B - T_t)$$

In general, it has been found that the principles of physical similitude and the scaling laws are valid for cryogenic application, Reference 2. Thus, after surveying applicable literature, References 2, 3 and 4, it was concluded that with the quality limitation discussed below, the internal film coefficient could be adequately approximated, ± 25%, by the equation

$$h_i = 0.029 \ \frac{k}{D} \ \left[\frac{DV\rho}{\mu}\right]^{0.8} \ \left[\frac{c\mu}{k}\right]^{0.4}$$

where h_i = internal coefficient of heat transfer, Btu/hr-ft^2-°R

D = tube diameter, ft

k = thermal conductivity, Btu/ft-hr-°R

V = coolant velocity, ft/hr

ρ = coolant density, lbs/ft^3

μ = coolant viscosity, lbs/hr-ft

c = coolant specific heat at constant pressure, Btu/lb-°R

The choice of the constants was dictated by the range of Reynolds number and the assumption as to the existence of nucleate boiling.

The film coefficient on the outside of the cooling coil has been correlated by the equation

$$h_o = 0.72 \ \frac{k}{D} \ \left[\frac{D^3\rho^2\beta g\Delta T}{\mu^2} \ \frac{c\mu}{k}\right]^{.25} \qquad \text{(Reference 5)}$$

where h_o = external coefficient of heat transfer, Btu/hr-ft^2-°R

D = tube diameter, ft

k = propellant thermal conductivity, $\frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-°R}}$

ρ = propellant density, lb/ft^3

β = propellant coefficient of volumetric expansion, 1/°R

ΔT = temperature difference between tube and propellant (T_B-T_t)

g = constant, 4.17 x 10^8 ft/hr^2

μ = propellant viscosity, lb/ft-hr

c = propellant specific heat at constant pressure, Btu/lb-°R

These equations were solved for three different fuel temperatures assuming half inch diameter cooling tube. Figure 2-2 is a graph of the calculated heat transfer rate as a function of the coolant velocity and Figure 2-3 is a plot of the cooling coil temperature as a function of coolant velocity. The main point to note from these curves is that to prevent freezing of B_2H_6 on the cooling coil, the coolant flow rate must be held below 247 lbs/hr if the bulk temperature is 220°R.

To determine, from this information, the length of cooling coil needed, it is first necessary to estimate the total heat transfer rate to the fuel tank. From the results of Tasks I and II the total heat transfer to a tank through 3/4 inch closed cell foam could not exceed 49 Btu/hr-ft^2. For individually insulated tanks, this results in a total heat transfer rate per tank of 2200 Btu/hr. For the sake of safety, assume the maximum heat transfer rate to each tank is 4000 Btu/hr. Combining this value with the information of Figure 2-2, it is possible to obtain a curve of cooling coil surface area required as a function of coolant flow rate. The solid line of Figure 2-4 is such a curve for the case of 220°R fuel. It can be seen from this graph that a surface area of only 1 sq. ft. (approximately 8 lineal feet of half inch tubing) will require less than 50 lbs of LN_2 per hour.

The equation listed above for h_i is valid for those conditions in which the coolant is 50% or more liquid by weight. If this condition is not met, an error exists in the above calculations. Assuming, as indicated, that 1) the heat to be removed from a single propellant tank is 2200 Btu/hr, and 2) that this heat is absorbed entirely by a phase change in the coolant, it can be shown that the quantity of fluid theoretically required is 26 lbs/hr. Thus, the 50% requirement is met for flow rates in excess of 52 lbs/hr. Eight feet of half inch tubing flowing at 52 lbs/hr would fulfill all heat transfer requirements.

If the heat to be removed is indeed 4,000 Btu/hr, the coolant quality restriction is not met. The result would be that the coolant flow rate would have to be increased or the propellant temperature would rise above 220°R to about 262°R if the flow is maintained at 50 lbs/hr. This, of course, is still within the acceptable temperature range.

However, if the coolant flow rate is increased by a factor of 5 (approximately 5 ft^3/hr.) in a half inch tube, the predicted heat transfer rate would increase to in excess of 10,000 Btu/hr per tank. Thus, it can be seen that there is ample cooling capability in an 8 foot, half inch cooling coil.

The actual problem in such a coil will probably be that of preventing over cooling. A flow rate of 50 lbs/hr of LN_2 through a half inch tube is an extremely low flow rate. Rather than trying to dribble through such a low flow it would be best to use a coolant flow system which is controlled by two temperature sensors, similar to the systems commonly used in cold traps of vacuum facilities. One sensor, located near the bottom edge of the coil, would stop the flow before freezing on the tube occurs. The other sensor, located at the top of the tank and away from the coil, would initiate coolant flow. The problem of initial transients due to warm gas in the coolant line being circulated through the tank is of no concern. Seven pounds of room temperature nitrogen circulated through the fuel tank will change the fuel temperature by only 1°F.

Figure 2-4 also shows the relation between coolant flow rate and required cooling coil surface area for different size tubing. However, it must be clearly understood that the curves are applicable only if the heat transfer does not result in more than 50% of the coolant being boiled. The curves for the smaller tubing indicate that some weight savings could be realized by using smaller tubing. This potential weight saving (approximately 1/4-pound for the 1/4-inch tubing) is offset by less temperature control capability particularly if it suddenly became necessary to accommodate high heat transfer rates. Considering the potential cooling capability of a half inch cooling coil and the minor weight increase it is felt prudent to use 8 feet of half inch tubing as the coil.

A question may be raised as to the possibility of using cold gaseous nitrogen as the coolant. As will be indicated below, the coolant must be below 200°R to be capable of maintaining the propellant temperature at 220°R. From 140°R to 200°R gaseous nitrogen has a heat capacitance of only 15 Btu/lb or about 18% of the heat of vaporization. Thus, the savings in coolant realized by utilizing the specific heat of the gas is comparatively small and the penalty in weight of cooling coil is large. For these reasons, attempts to use gaseous coolant is strongly discouraged.

The analyses described above was repeated for the case of the OF_2 tank and also the helium tank. The major results are shown in Figures 2-5, 2-6, and 2-7. In all cases, the required length of cooling coil is relatively modest.

The above calculations were also repeated except for the case of a coolant having a temperature of 200°R. The purpose was to establish whether or not a closed loop refrigeration system might not be made to accomplish the cooling. As expected, extremely long cooling coils would be required, of the order of 200 feet to reduce the bulk temperature to 220°R. Obviously, from a weight standpoint alone, this is unacceptable.

2.1.2 External Cooling Coil Analysis

The model assumed in this analysis was basically that of a cooling coil attached to the outside of a vertical plate, Figure 2-8 In order to make the analysis ameanable to simple calculations, several simplifying assumptions were made:

1. No vertical heat conduction in tank wall
2. Negligible temperature drop across the aluminum liner and tube wall
3. Natural convection within the tank
4. Average thickness of epoxy holding tube to tank of 0.05-inch
5. Effective width over which heat transfer through tube and tank wall occurs equals tube diameter.

With these assumptions the equations for analyses are

$$Q/A = h_i \ (T_i - T_c) = U \ (T_o - T_i) = h_o \ (T_B - T_o)$$

where Q/A is the heat transfer rate per unit area and the temperatures are as indicated in Figure 2-8.

The solution of the internal film coefficient is the same as given above in Section 2.1.1. The transmittance U was calculated in the usual manner

$$U = \frac{1}{L_B/K_B + L_E/K_E}$$

where L_B and L_E are the thickness of the boron filament tank and epoxy and K_B and K_E are the thermal conductivity of those two materials.

The film coefficient on the tank wall was calculated by

$$h_o = 0.55 \frac{k}{D} \left[\frac{D^3 \rho^2 \beta \Delta T g}{\mu^2} \frac{c\mu}{k}\right]^{0.25} \qquad \text{(Reference 6)}$$

where h_o = tank wall coefficient of heat transfer, Btu/hr-ft^2-°R

k = thermal conductivity of propellant, $\frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-°R}}$

D = effective width over which the heat transfer occurs, ft

ρ = propellant density, lb/ft^3

β = propellant coefficient of volumetric expansion, 1/°R

ΔT = temperature difference between wall and propellant (T_B-T_o), °R

g = constant, 4.17×10^8 ft/hr^2

μ = propellant viscosity, lb/ft-hr

c = propellant specific heat, Btu/lf-°R

The above equations were solved for the case of half inch diameter tubing placed on the OF_2 tank. The resulting heat transfer rate per unit area, Q/A, was then used to establish the length of tube as described. The resulting curve of cooling coil length as a function of coolant flow rate is given in Figure 2-9. This curve shows that external coils must be approximately 12 times longer than internal coils. Unless overriding reasons present themselves, thermal considerations would dictate internal coils using LN_2 as the coolant as the means of ground cooling.

2.2 Auxiliary Cooling Requirements

The above discussion establishes the ground cooling requirement for the one helium and two propellant tanks, but it does not indicate the cooling and insulation requirements imposed by auxiliary equipment. By viewing the drawings of Section 4, it may be seen that, in general, there are three distinct problems in this area:

1. Gas filled lines such as those leading from the helium tank, the top of the propellant tanks and those leading away from hardware which come into contact with cooled liquid.
2. Liquid filled lines such as those leading away from the bottom of the propellant tanks.
3. Structural hardware which, because of its proximity to the fluid tanks, will become cold during ground hold.

All other equipment (engine, main propellant valves, regulators, etc.) need not drop in temperature during the ground hold phase. In analyzing these situations, the following assumptions were made:

- Passivation would be done with warm gas
- At no time during tanking or ground hold would the propellant be dropped below the main isolation valves
- At no time during tanking or ground hold would the helium be dropped below the first set of squib valves.

2.2.1 Gas Filled Lines

Gas filled lines will become cold for appreciable distances away from their final point of contact with the fluid tanks by conduction through the tube wall and gas and possibly by convection of the gas within the tube. Figure 2-10 indicates those lines which fall within this class. Calculations of the required length of insulation were made based on the assumption that all gas lines are filled with helium and that no heat is gained through the insulation. These assumptions are conservative in that they indicate the need for more insulated line than is actually required. Results show that for the thick walled tubing (0.050 inches) leading from the helium tank, the insulation must be carried a distance of 1.4 feet. For all other gas filled tubing the insulation need extend only 0.75-feet. In both cases, the insulation is assumed to be 3/4-inch thick.

2.2.2 Liquid Filled Lines

The entire length of all liquid filled lines must be insulated with 3/4 inch thick insulation. Also, the assemblies at the end of the liquid filled lines and the mounting fixtures of the assemblies must be similarly insulated.

2.2.3 Structural Hardware

Structural hardware which comes in contact with the tanks will obviously be cold and will require insulating. The required amount of insulation is dependent upon the thickness of the structural member and the type of material from which it is made. Aluminum members must be insulated completely. Titanium and stainless steel members must be insulated for approximately 1-1/2 feet if they are 0.06 inches thick but only 3/4-feet if they are 0.04-inch thick. In all cases, the insulation should be 3/4-inch closed-cell foam.

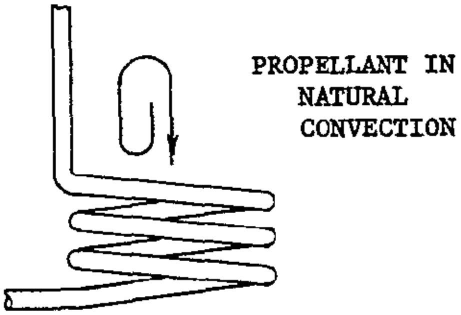
2.3 Insulation Configuration

From the standpoint of ground hold thermal control, there is little reason for choosing either the single wrapped or the double wrapped system over the other. From the standpoint of reliability a cooling coil in each tank would be required and consequently three sets of coolant control values will be required regardless of the insulation configuration.

The idea of insulating the entire module in a canister appears attractive upon a first glance. The problem of insulating individua structural members could be eliminated. All the assemblies could be included inside the insulation and thus insulation for individual assemblies could be eliminated. However, this insulation concept has four serious faults:

1. It is highly susceptable to breakage by workman. Parts of the insulation would be unsupported unless a heavy back-up structure were used. Work done around the module, particularly the installation of the RTG, would expose the insulation to harm.
2. It would be more susceptable to damage due to structural and vibration loads during launch.
3. It does not provide ready access to the equipment located inside the insulation without exposing the tanks and other cooled equipment to the ambient air.
4. It does not lend itself to leak detection checks as does the individually insulated tank system.

For these reasons, ground hold thermal control considerations would dictate the use of the individually insulated tank system.

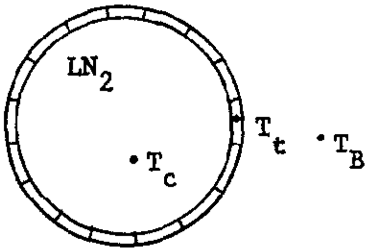


COOLING COIL

T_B = PROPELLANT TEMPERATURE

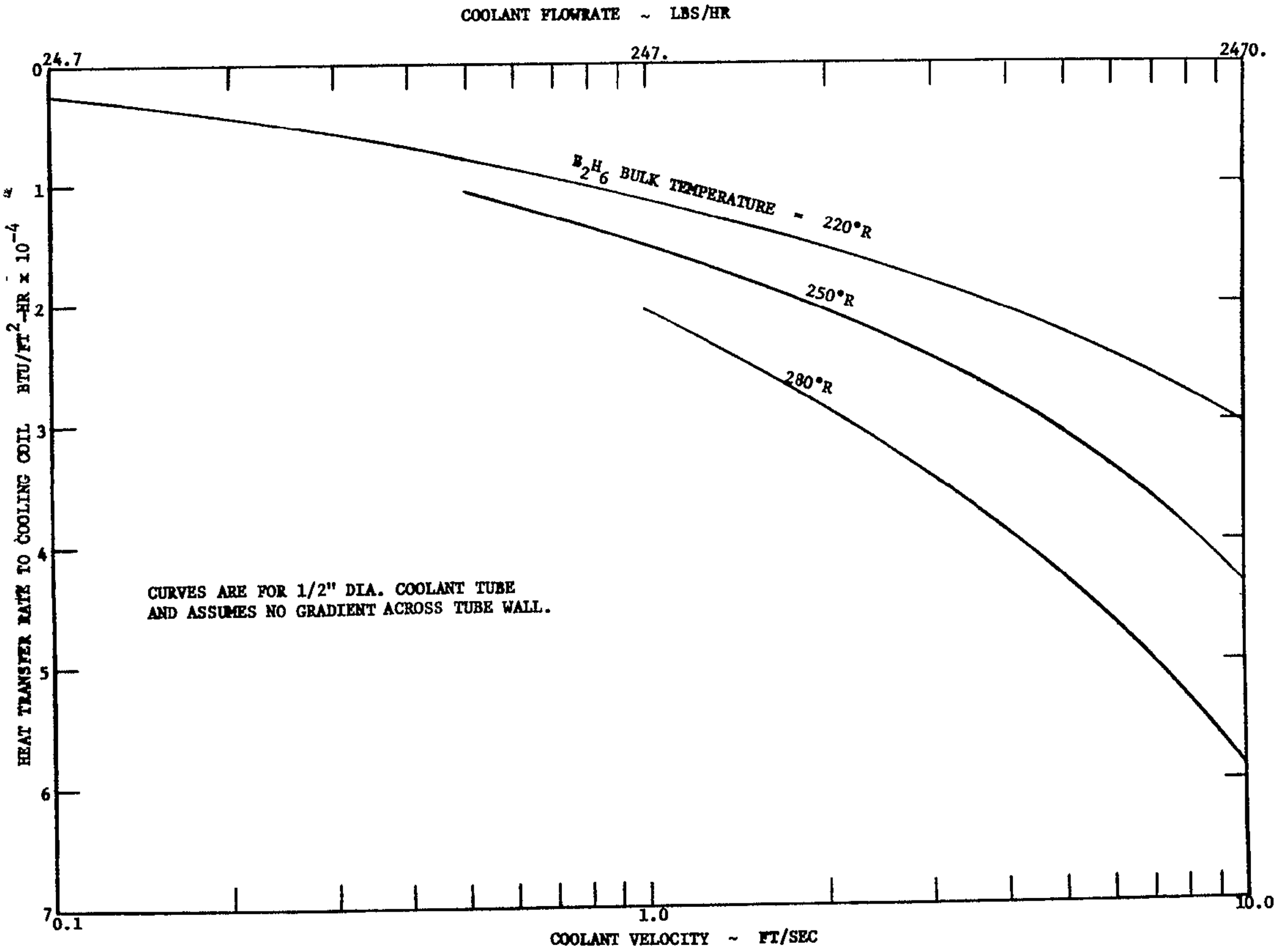
T_t = COIL TEMPERATURE

T_c = COOLANT TEMPERATURE



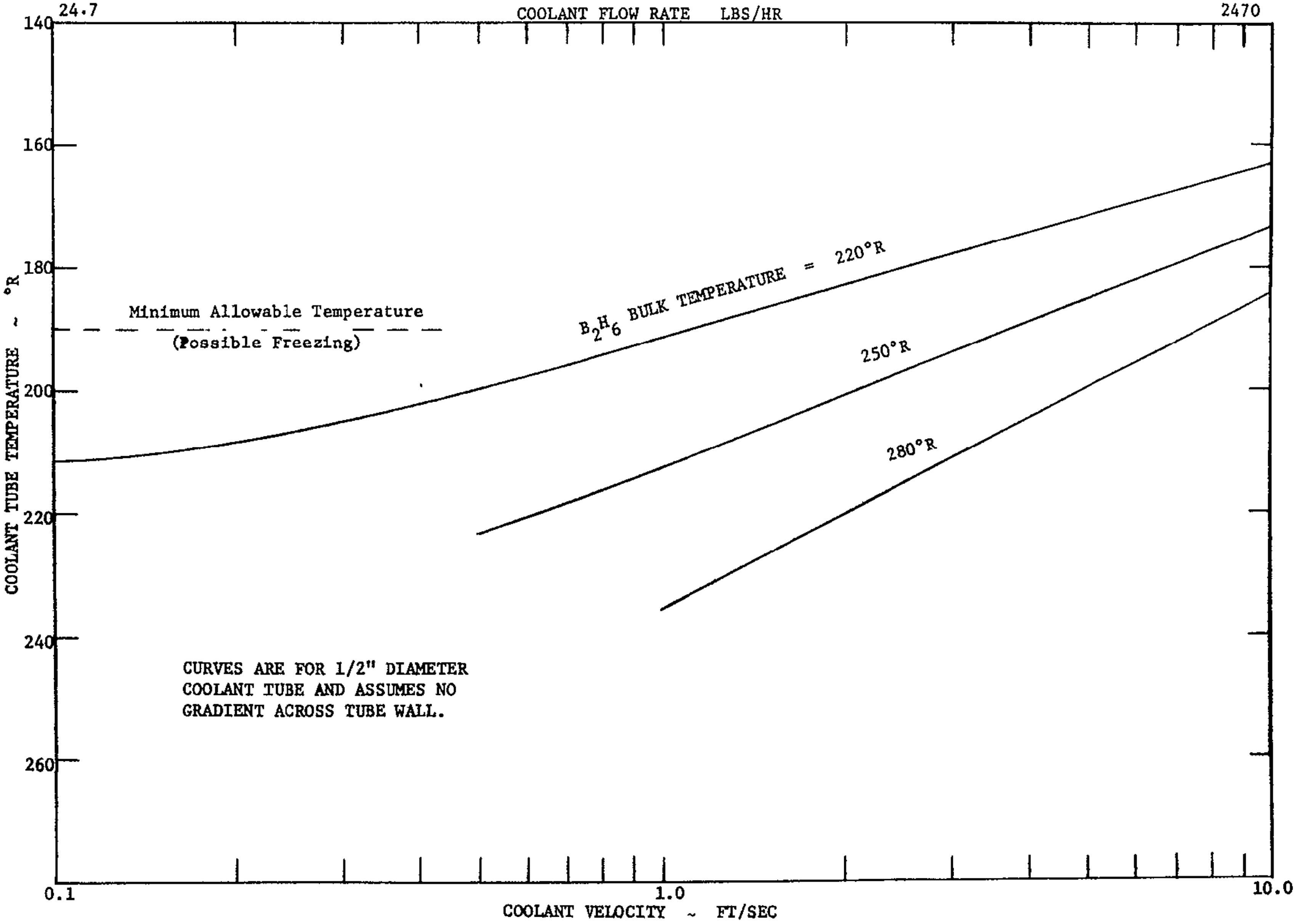
CROSS SECTION OF
COOLING COIL

FIGURE 2-1 SCHEMATIC OF SUBMERGED COOLING COIL



CURVES ARE FOR 1/2" DIA. COOLANT TUBE AND ASSUMES NO GRADIENT ACROSS TUBE WALL.

FIGURE 2-2 HEAT TRANSFER RATE TO BOILING LN_2 COOLING COIL SUBMERGED IN B_2H_6



CURVES ARE FOR 1/2" DIAMETER COOLANT TUBE AND ASSUMES NO GRADIENT ACROSS TUBE WALL.

FIGURE 2-3 TEMPERATURE OF COOLANT COIL IN B_2H_6 TANK

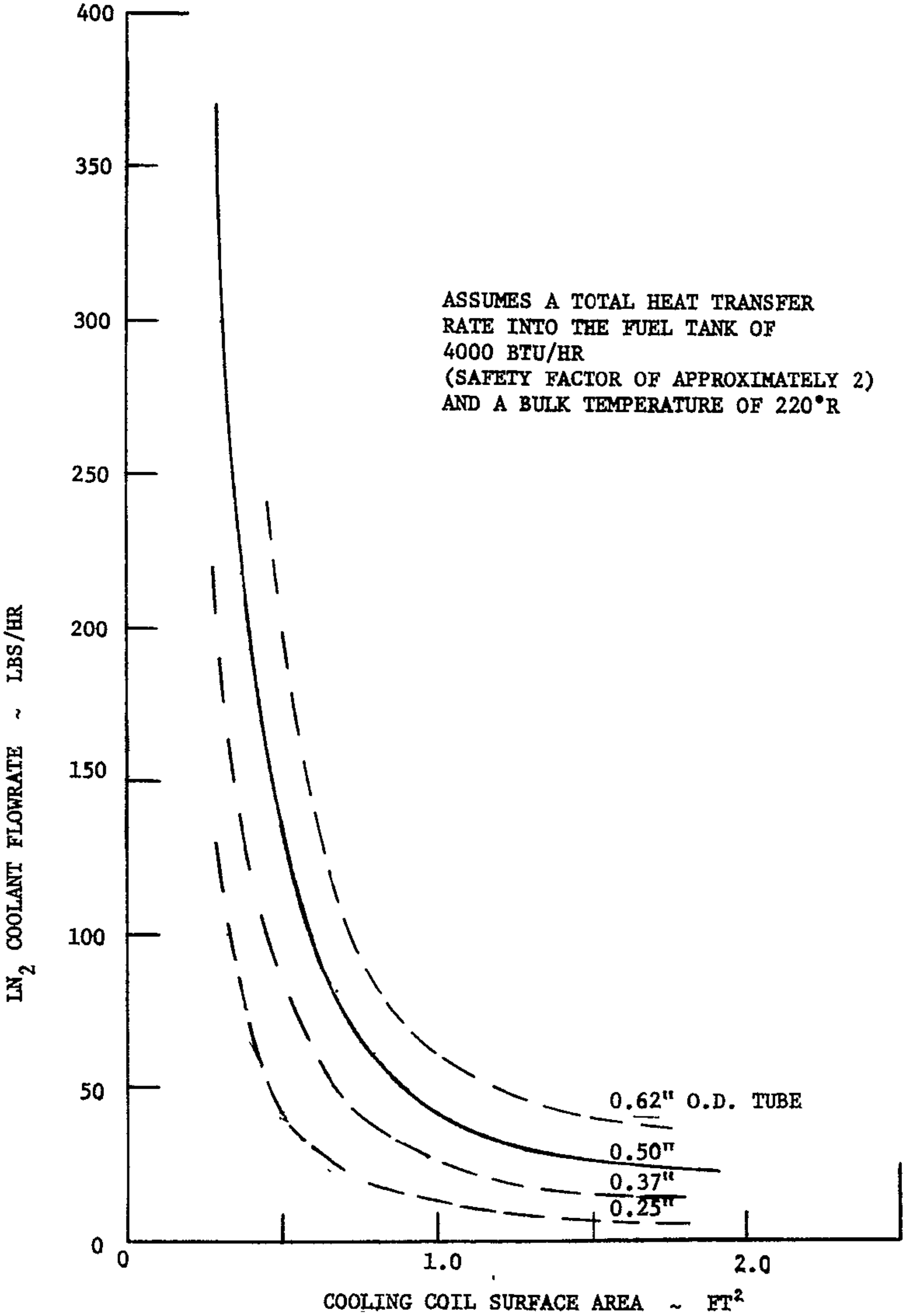


FIGURE 2-4 REQUIRED COOLANT FLOWRATE FOR COIL SUBMERGED IN B_2H_6

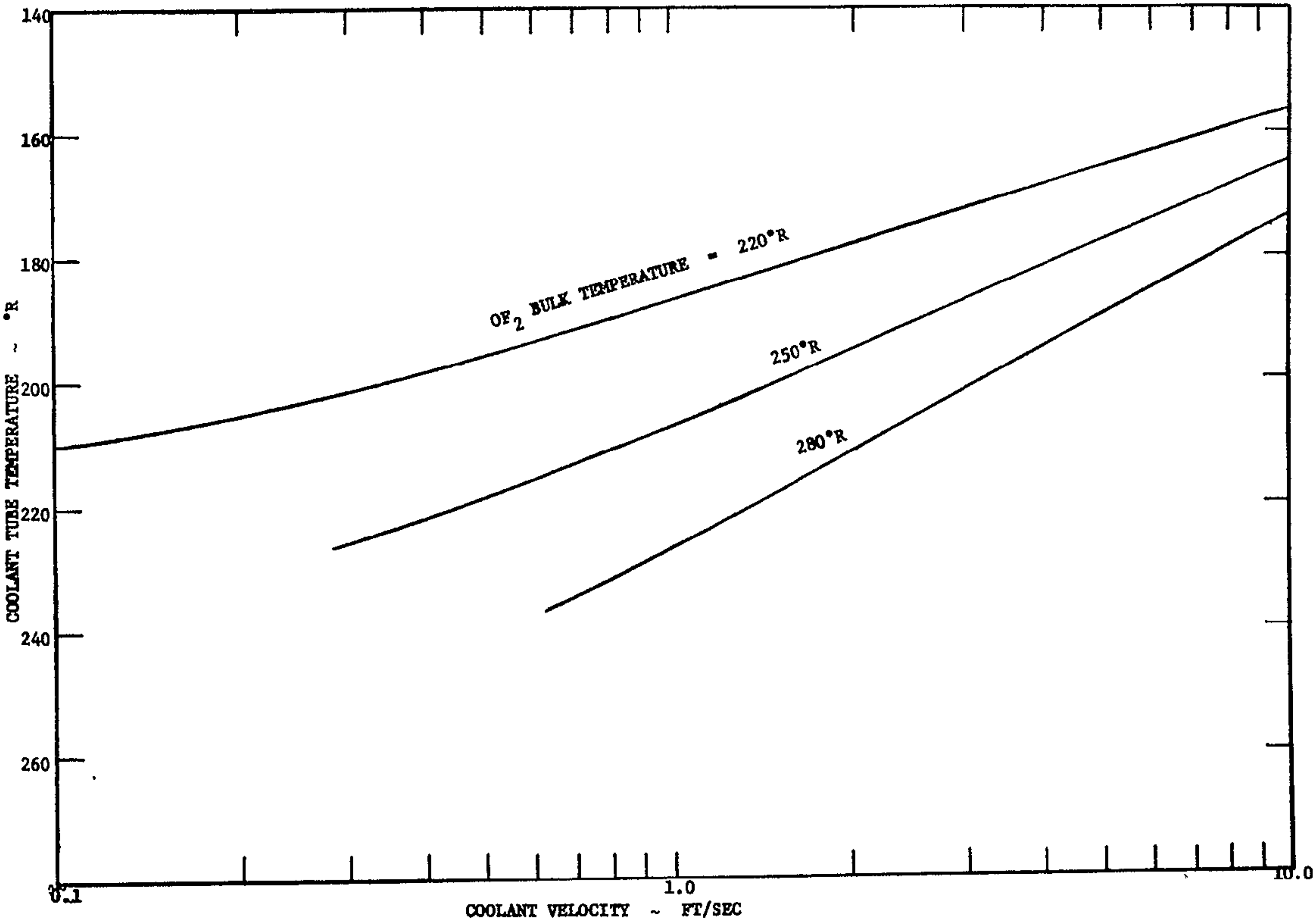


FIGURE 2-5 TEMPERATURE OF COOLANT COIL IN OF_2 TANK, HALF INCH DIAMETER TUBING

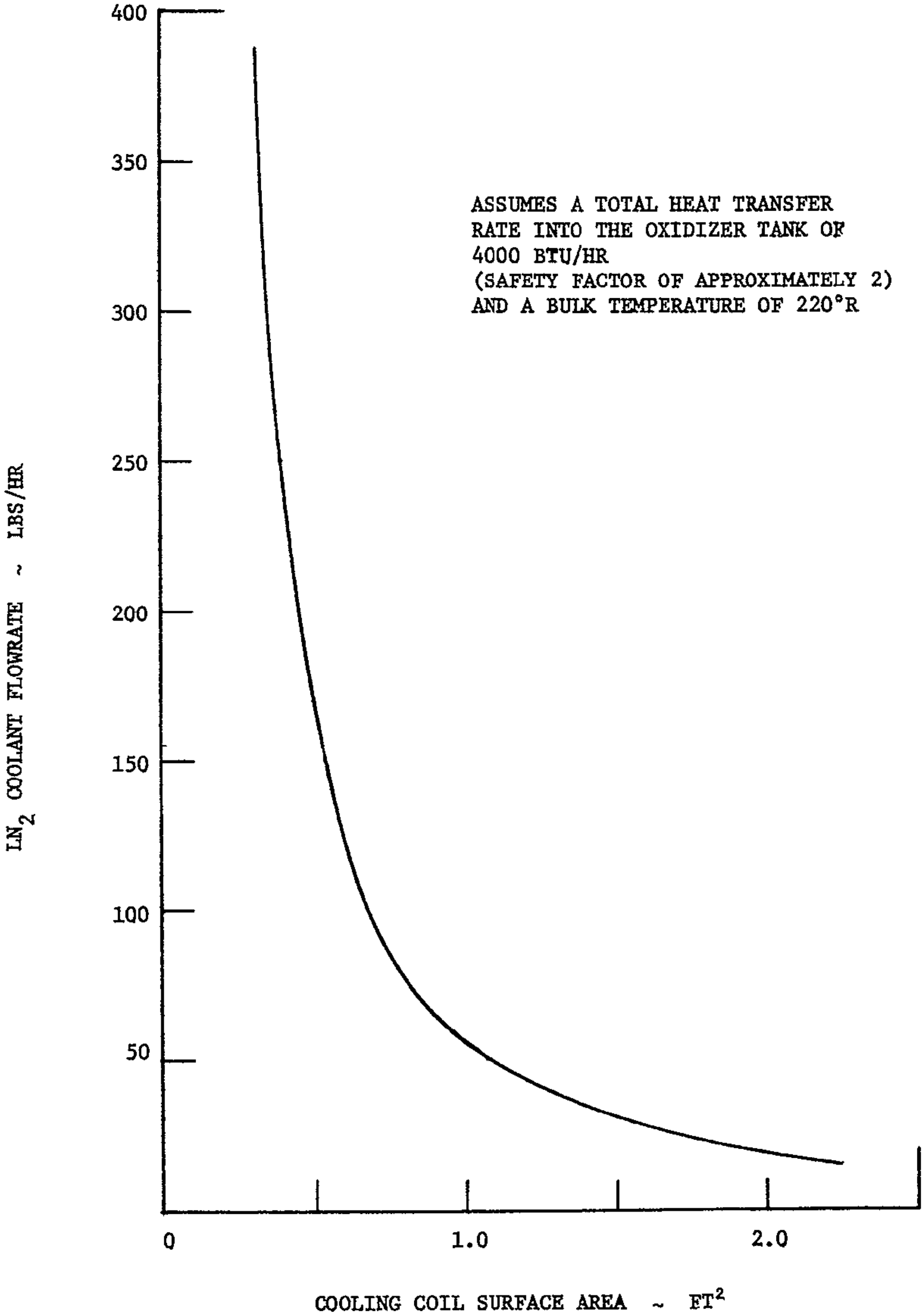


FIGURE 2-6 REQUIRED COOLANT FLOWRATE FOR COIL SUBMERGED IN OF_2, HALF INCH DIAMETER TUBING

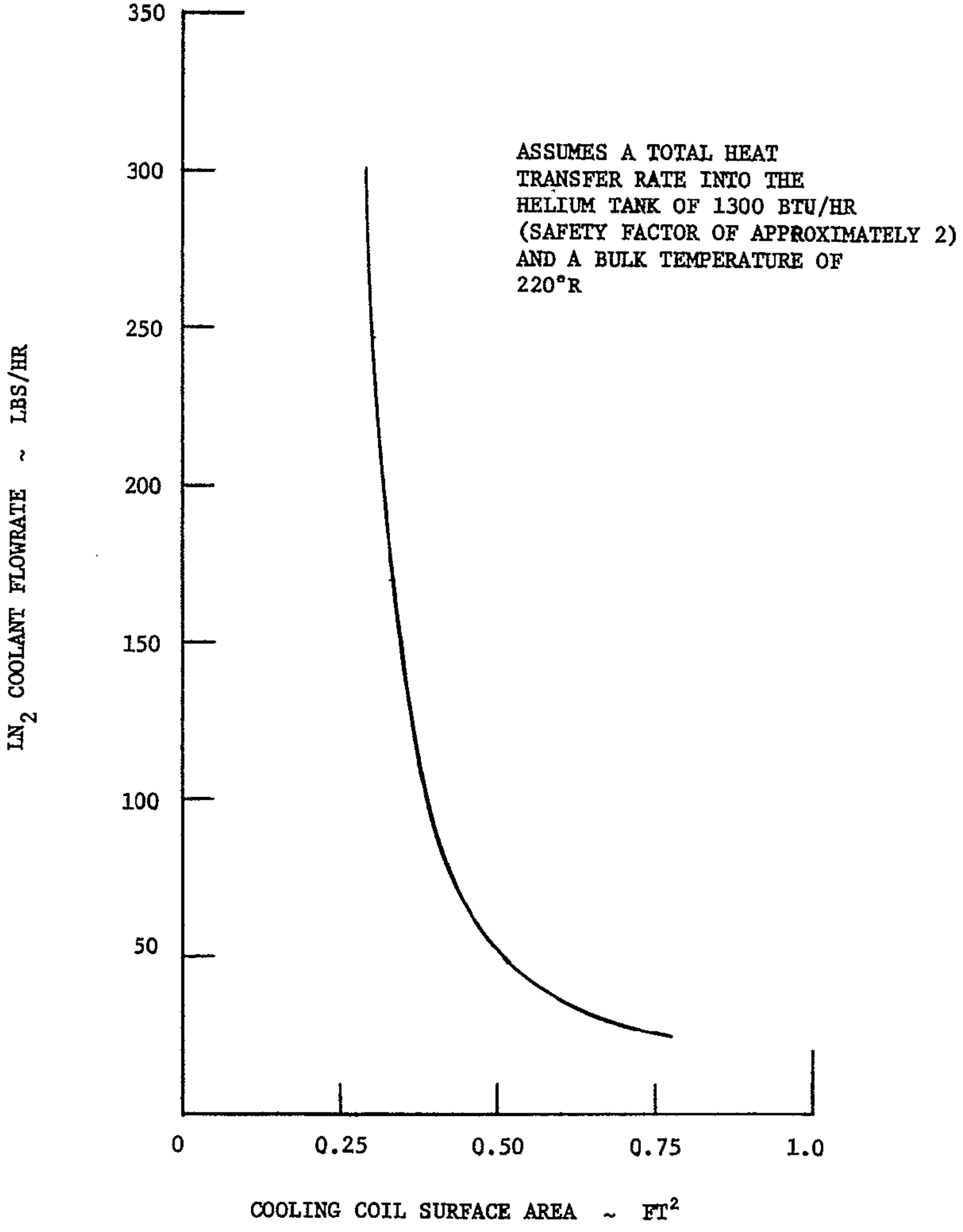
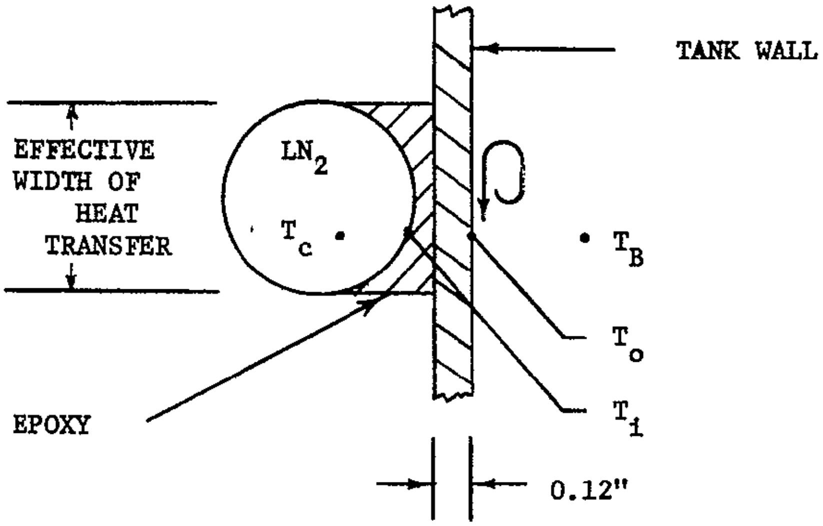


FIGURE 2-7 REQUIRED COOLANT FLOWRATE FOR COIL SUBMERGED IN HELIUM TANK, HALF INCH DIAMETER TUBING.



BORON FILAMENT TANK WALL, $k = 0.42 \frac{\text{Btu-ft}}{\text{ft}^2\ \text{hr-}^\circ\text{R}}$

EPOXY, 0.05" THICK (AVERAGE), $k = 0.15$

COPPER COOLANT TUBE

LN_2 COOLANT BOILING AT 140°R

FIGURE 2-8 SCHEMATIC OF TUBE ATTACHED TO OUTSIDE OF TANK WALL

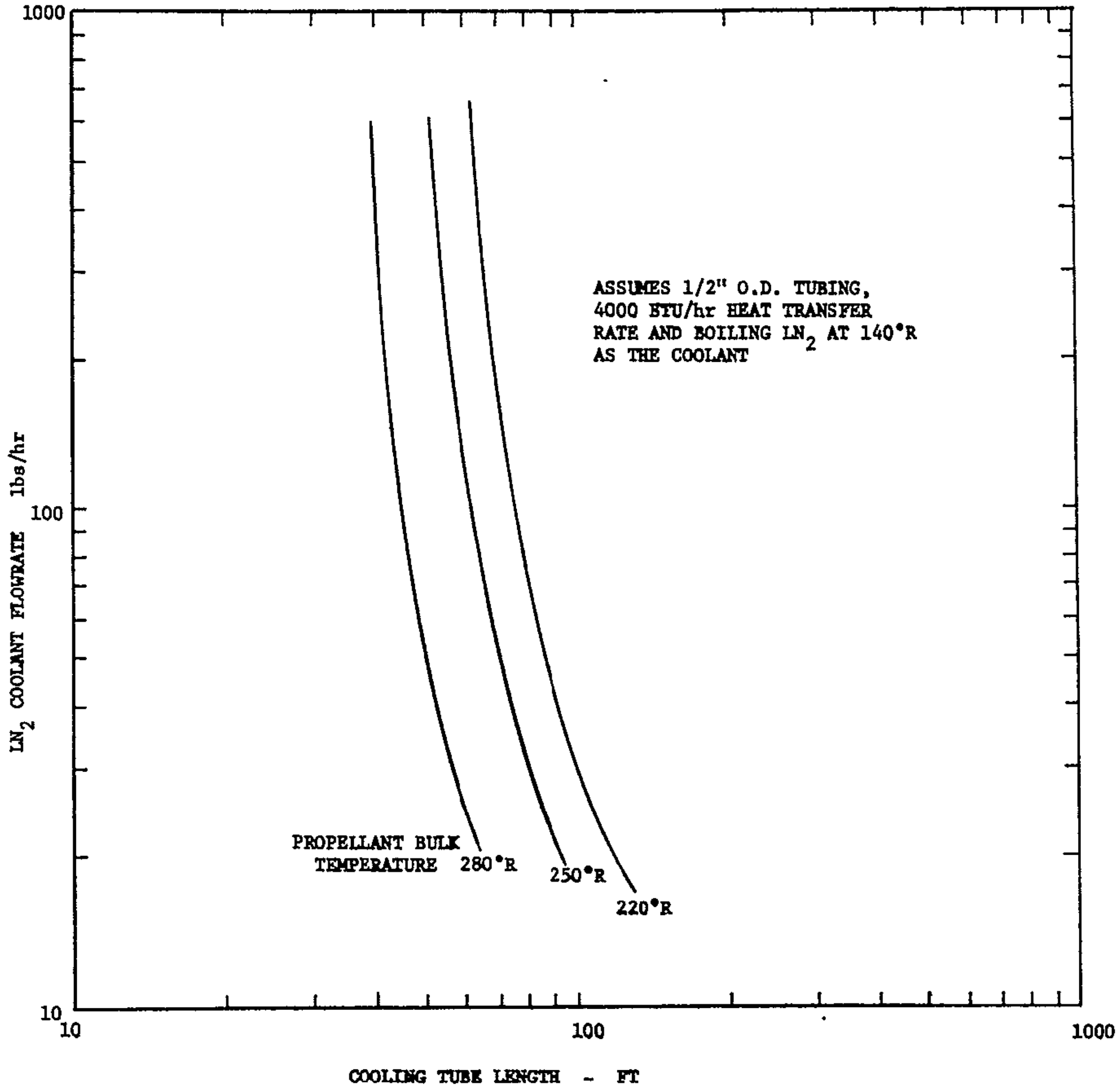


FIGURE 2-9 REQUIRE LENGTH OF EXTERNAL COOLING TUBE FOR OF$_2$ PROPELLANT TANK

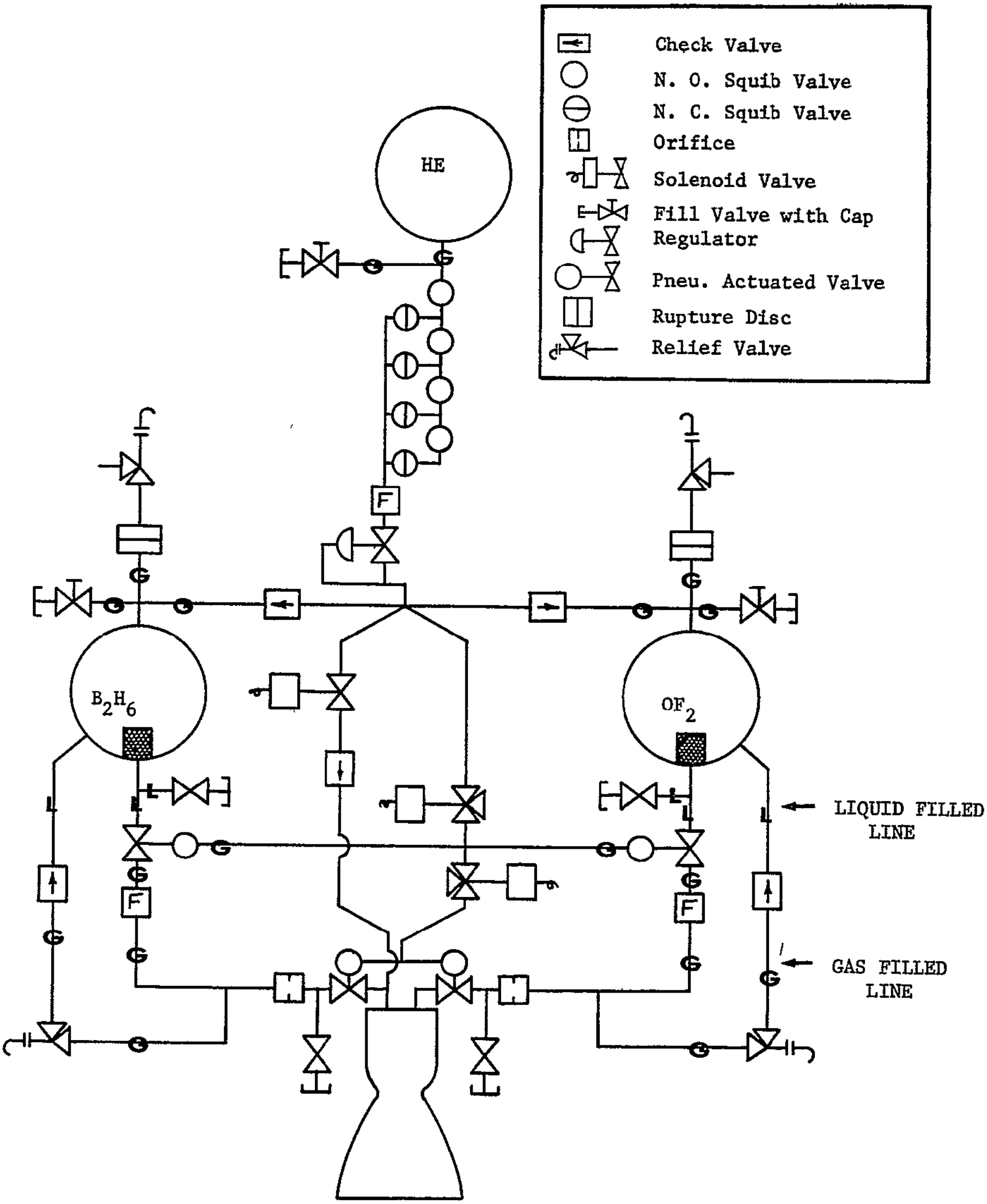


FIGURE 2-10 SCHEMATIC DIAGRAM OF OF_2/B_2H_6 SYSTEM

3.0 FLIGHT THERMAL CONTROL

During Task III Flight Thermal Control considered the following problem areas:

1. Means of controlling the helium tank temperature during flight.
2. The extent to which auxiliary equipment must be thermally controlled.
3. The advantages and/or disadvantages of the dual and single wrapped insulation systems.

3.1 Helium Tank Thermal Control

From work performed in Tasks I and II there is no doubt that the helium tank temperature can be maintained within the proper limits by insulating it within the propellant tank insulation or by providing it with a louver system of its own. In order to eliminate the louver requirement and also to allow the helium tank to be insulated separately, an analysis was made to establish whether the helium tank could be conductively coupled to the propellant tanks. If so, the helium temperature could be made to follow the temperature of the propellants. A schematic of the system analyzed is given in Figure 3-1. It consists of a propellant tank attached to the helium tank by way of an aluminum beam. The aluminum beam was assumed to be a 4-inch by 2-inch by 0.04 inch channel. Conductivity was assumed to be 90 Btu-ft/hr-ft^2-°F. The thermal resistance between the bottom of the propellant tank and the beam was assumed to be 7.2 hr-°F/Btu and the resistance between the helium tank and the beam was assumed to be 1.9 hr-°F/Btu. These values correspond with the system as shown in the drawings of Section 4.

For the case of 3/4-inch foam on the helium tank and beam, a constant heat addition to the insulation from the RTG of 90 Btu/hr and no sun heating, the results are as given in Figure 3-2.

It will be noticed that the response of the helium tank is not ideal in that a 10°F change in the propellant temperature results in approximately a 5°F change in the helium tank. The extent to which this moderating effect influences the helium tank temperature is readily discernable, however, by considering the following Table:

	HELIUM TANK TEMPERATURE	
	Without Conduction	With Conduction
No Heat From RTG or Sun	90°R	206°R
Nominal Heat From RTG RTG and 50 Btu/ From Sun	302°R	280°R

From this, it can be seen that the effectiveness of the moderation is fairly good.

The weak point of this design becomes apparent considering a case where the RTG surface temperature drops sufficiently or its surface emittance changes such that the module receives less than 50% of its normal RTG heating. In this case, the helium temperature would be of little consequence. However, if the propellant tanks were then pressurized with the colder helium, an overpressure situation would develop as the helium warms to the propellant temperature. It is impossible to know with a high degree of accuracy the extent of this problem without having a highly sophisticated model of the system. This analysis will be done during Task IV. Estimates at this time indicate that the maximum differential will not exceed 12°F. This differential would develop at about the time the RTG heat output drops sufficiently to allow fuel freezing. Such a gradient would present no danger.

As indicated above, these results are based on the assumption that 3/4-inch foam insulation is used. If the beam and those portions of the helium tank which do not see the RTG are insulated with 10 layers of aluminized Mylar in addition to the foam, the helium tank will follow the propellant temperatures more closely. Considering the light weight of multilayer insulation and the ease with which it may be applied, it appears wise to use it as well as the foam insulation. It can be seen that the conductively coupled helium tank is capable of accommodating sizable variations in the mission. The use of two louvers on the helium tank would allow for somewhat larger mission variations, but, as indicated, it would take a substantial mission variation to result in a mission failure originating in the helium system if the conductively coupled tank is used. For these reasons, there is little or no justification, thermally speaking, to prefer a louver controlled helium system over a conduction controlled system. As will be indicated later, however, consideration of simplicity points strongl to eliminating the louvers on the helium tank.

3.2 Thermal Control of Auxiliary Equipment

Section 2 pointed out that much of the propulsion plumbing and support hardware does not require thermal control prior to launch. However, it was pointed out in the Task II Summary Report, Reference 1, that most of this hardware must be thermally controlled just prior to an engine burn. This flight thermal control can be realized in two basic ways: first, the auxiliary components can be insulated directly with the propellant tanks, or second, they may be insulated separately from the tanks but still controlled in temperature by the tanks by providing proper thermal paths.

The first method, has disadvantages in that the accessibility of auxiliary hardware during ground hold is severely limited. There are parts of the support plumbing which do not need to be easily accessible because they could not be replaced or reworked once the system is loaded even if they were accessible. (These parts, as will be shown later, have been placed directly against the tanks and insulated with the tanks). To allow for maximum accessibility to the other parts during ground hold requires that the second method of thermal control be utilized, i.e., the assemblies, where possible, are separately insulated. Task II established that separately insulated components can be controlled in temperature by connecting them to the support frame and utilizing the thermal characteristics of the frame. This, by itself, is nothing more than a passive system and it has all the disadvantages of a passive system.

Upon careful study, it has been established that by properly insulating components and lines it is possible to make them follow the tank temperatures fairly closely and yet be insulated separately from the tanks. Consider the generalized arrangement shown in Figure 3-3. This consists of a typical component mounted near the foam insulation of a tank with multilayer aluminized Mylar insulation covering it. Leading from the valve is shown a typical stainless steel tube, assumed to be 3/8-inch diameter, 0.20-inch thick wall in this case, which is also insulated with multilayer insulation. Using the thermal model shown on Figure 3-3, this configuration was analyzed for a variety of tank temperatures, variations in heat addition to the multilayer insulation (variations in exposure to the RTG and/or sun), and variations in the number of tubes leading to the component. For this particular configuration, the results can be summarized as follows:

- Depending on the exposure of the component insulation to radiation from the RTG and/or sun, the component may vary ± 10°R from the propellant temperature.
- For the case of no radiation to the component insulation, a 30°R variation in the propellant temperature will cause a 24°R temperature change in the component.
- For no radiation heat addition to the tubing, the tube temperature 6 inches away from the component will be approximately 30°R colder than the component and at two feet it will be 75°R colder than the component.

The configuration of Figure 3-3 was chosen because it represents the worst condition from the standpoint of the component. With the connecting tube standing away from the tank, there is a tendency for the tube temperature to drop drastically and thus pull down the component temperature. A more realistic approach would be to route all tubing adjacent to the tank insulations or adjacent to the foam insulation which covers the conductive paths between the propellant tanks and the helium tank and then to cover it with multilayer insulation. In this manner, all tubing except for one section will inherently follow the propellant or helium temperature.

The tubing which would have to be controlled by other means would be the flexible propellant tubing that is just upstream of the bipropellant valve. Regardless of the insulation configuration, this tubing will have to be separately insulated and positioned away from the helium tank by at least one foot. To establish that this section of line will not get too cold or hot, the configuration of Figure 3-3 was again analyzed except node 9 was held constant at 250°R. This gives a fair simulation of a constant temperature bipropellant valve with 2 feet of free standing line. With this arrangement, the minimum tube temperature was 220°R and the maximum was 275°R. If the span of free standing line is reduced to one foot, the maximum differential between the tube and valve will be 3°R. Thus, it is possible to maintain all components and propellant feed lines within the correct limits even though they may be separately insulated.

This analysis was based on an assumed k/ℓ of 0.02 and 0.008 for the foam and multilayer insulation respectively. From available data, the k/ℓ for foam will not be smaller than this value and could be as large as 0.1. However, from the standpoint of maintaining a component temperature near the propellant temperature, the higher the conductivity of the foam, the better will be the component thermal control. In addition, recent work at TRW shows that the k/ℓ for the multilayer at these temperatures will be near 0.0015, Reference 7.

3.3 Comparison of Single and Dual Wrapped Insulation Systems

Considering only flight thermal control problems and interface requirements aside, there is an advantage gained by insulating the entire module as a unit, but the advantage is minor. Thermal gradients are small even when the tanks and components are insulated separately, Reference 2. In addition, when it is realized that the engine, bipropellant valve and some of the lead plumbing must be outside the main insulation regardless of its configuration, part of the reason for desiring a single insulation system disappears.

There is one very distinct advantage in choosing a single wrapped system. It forces the design to use a micrometeoroid shield which stands away from the tank insulations. This has the effect of providing a very effective sun shield for the propellants in the event the craft is oriented with the engine pointing towards the sun.

Thermally speaking, the insulation configuration chosen is of little importance so long as the proper multilayer insulation is provided for the various components which must be thermally controlled.

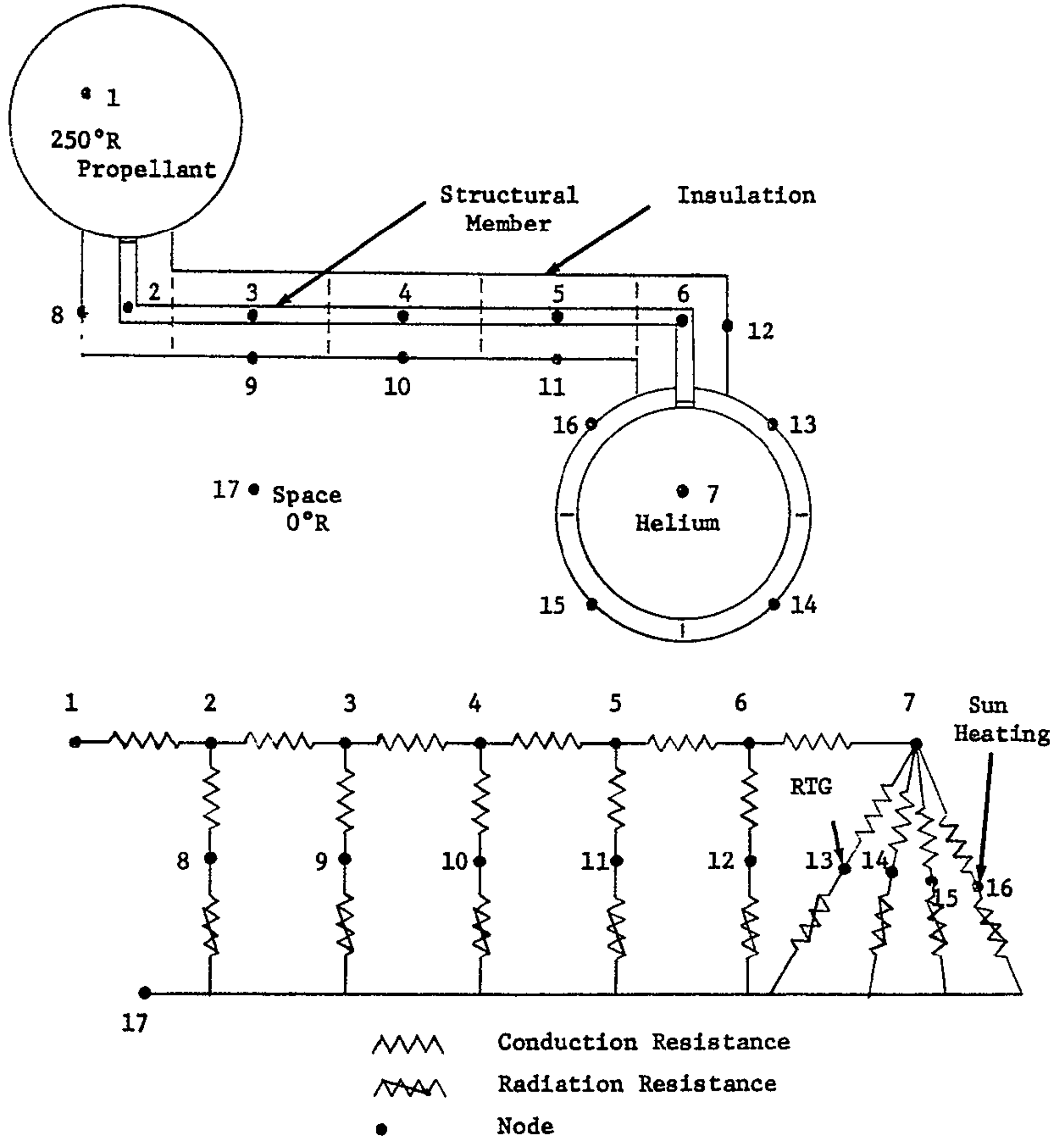


FIGURE 3-1 SCHEMATIC AND NODAL ARRANGEMENT FOR HELIUM TANK ANALYSIS

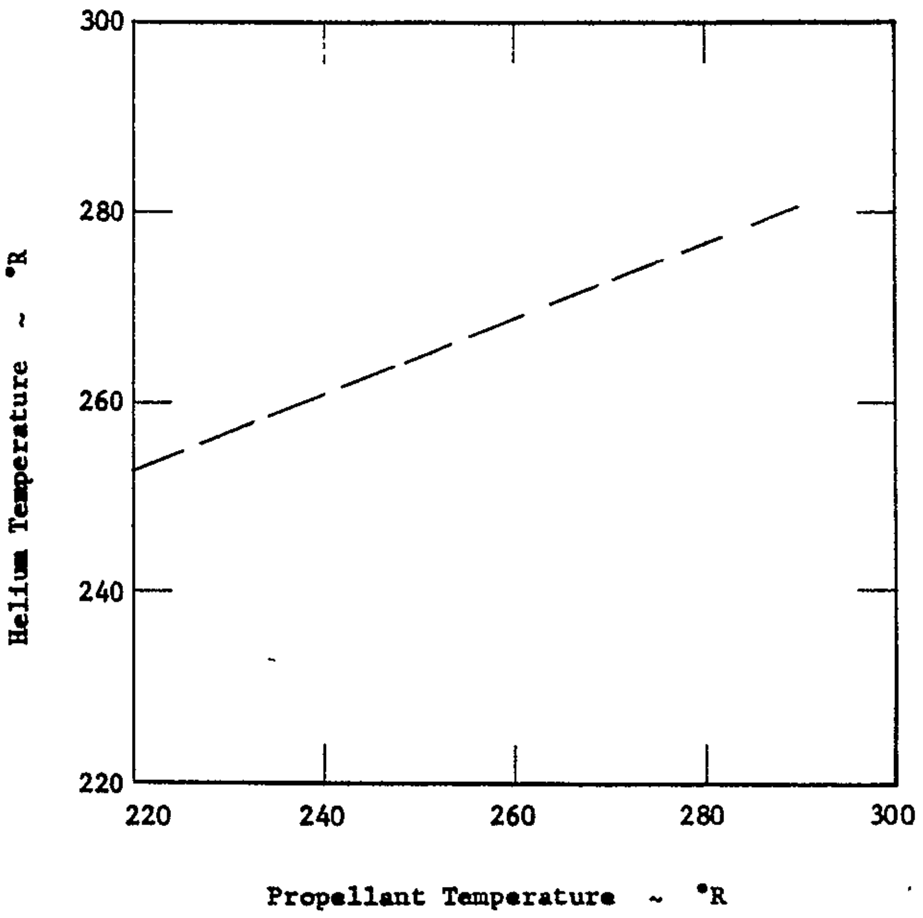


FIGURE 3-2 THERMAL CONTROL OF CONDUCTIVELY COUPLED HELIUM TANK

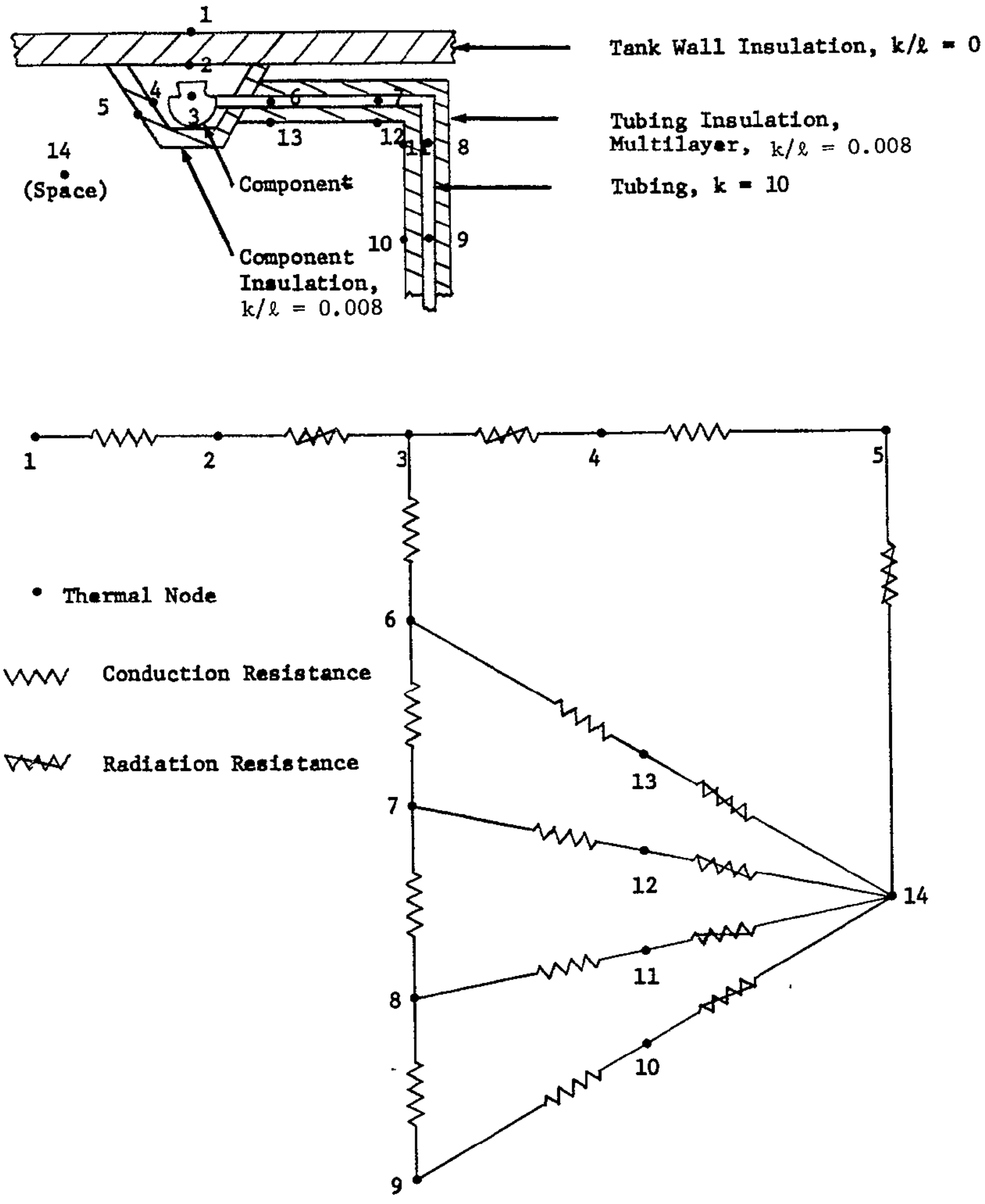


FIGURE 3-3 SCHEMATIC FOR COMPONENT ANALYSIS

4.0 MODULE LAYOUT AND DESIGN

The layout and design effort during Task III included making minor modifications in equipment layout but primarily it was directed towards clarifying the design of the thermal control system as contrasted to designing the module structure or propulsion system. The objective was to establish a basis for deciding which of the two systems listed in Section 1 should be retained analyses in Task IV.

4.1 Propulsion Equipment Modification

The following changes were made in the propulsion equipment layout.

1. A separate helium filter was added upstream of the regulator; previously it was assumed that the filter was small enough to be integral with the regulator inlet fitting.
2. Lines are sloped to allow drainage.
3. The propellant valve solenoid pilot valve was moved closer to the actuation port to improve response. It is now a part of the gimballing portion of the engine assembly.
4. Feedline isolation and relief return valving was moved closer to the tank outlet ports to minimize the lengths of liquid filled lines.
5. Injector purge solenoid and check valves were added.
6. Gas supply lines to the pilot and purge valves were looped to provide flexibility; in practice it may be possible to use flex hose instead since these lines are only pressurized briefly.
7. Bellows-type expansion joints were added to the feed lines below the isolation valves to avoid thermal stresses.

These changes are reflected in the drawing included at the end of this section.

4.2 Insulation Characteristics

Regardless of the insulation configuration to be used, the Task II work concluded that those areas which will experience reduced temperatures during ground hold would be insulated with a closed cell polyurethane foam. Since that time, the following characteristics of that foam have been accumulated.

The foam to be used is a rigid, closed-cell, polyurethane foam as specified by Reference 8. It can be obtained in precast shapes or it may be applied directly to a surface by spraying in place or foaming (pouring) in place. The material may be cut or machined but cut surfaces powder from vibration and mechanical contact. Such a raw surface would have to be sealed to prevent possible contamination of adjacent hardware by the powder. Sprayed and poured foam form a skin on the outside and the skin of the sprayed foam is non-porous.

When sprayed or foamed in place, the foam forms a tenacious bond to the substrate material, particularly to such materials as epoxies. This foam has a high coefficient of thermal expansion, but the sprayed-on material will nevertheless remain attached to substrates (if applied according to Reference 8) under severe conditions. It is used on the Saturn SII stage tank where it has successfully demonstrated its ability to comply with the strains imposed by the aluminum structure when at liquid hydrogen temperature as well as strains resulting from tank pressurization and flight loading. When it is applied to metal surfaces, a primer is used to provide better adherence and also to protect the metal from corrosion. One general point about spray-on foam should be noted. The state-of-the-art is such that only persons who have demonstrated an ability in this area should be trusted with this phase of the work.

Exposure to ultra-violet radiation will cause the solar absorptivity to increase measurably. For this reason, precautions would be required to degrade the material prior to flight or to coat it with a constant absorptivity material. The emissivity will change very little since it is already of the order of 0.8.

Exposure to the level of radiation expected from the RTG will produce no degradation other than increasing the solar absorptivity. From data supplied by JPL, the worst radiation level expected would not exceed 127 mrads/hr (4 ft distance at 15° angle). For a 10-year period, this would amount to about 10^4 rads. At the Arco Idaho Nuclear Test Site, Argonne National Laboratories subjected polyethylene, Teflon, and polyurethane to 10^6 rads/hr and 10^{10} neutrons/sec. At the end of 14 days the materials were structurally sound but totally discolored. At the end of 28 days, the material was structurally decomposed, Reference 9. This corresponds with estimates of Reference 10 in which the radiation required to harm polyurethane was listed as 10^8 to 10^9 rads. Thus, foam exposed the radiation levels of the RTG for 10 years will have a safety factor of 10^4.

Some question has been raised as to the water absorption characteristics of the foam. Reference 11 reports an experiment in which 3/4-inch of foam was used as the insulation on a liquid hydrogen container. The ambient condition was 120°F and 100% relative humidity. At no time during the test (200 days) was there any indication of insulation degradation or water absorption. If the foam is not mixed or applied correctly, water absorption can be a problem, however.

4.3 Thermal Control System Design

The design of the two basic systems described in Section 1 was carried out in sufficient detail to establish their basic advantages and disadvantages. In doing this work, the following guidelines were observed:

- A conductively connected helium tank as described in Section 3.0 was assumed.
- Foam is to cover all parts which are cold during ground hold. Where only flight insulation is required, aluminized Mylar is used.

- Foam is to extend out from "cold points" 12 inches on metal parts and 3 inches on non-metalic parts. This is dictated by heat transfer requirements.

The propulsion hardware was the same in both cases.

4.3.1 Single Wrapped Insulation System

This system utilizes sprayed on insulation applied directly to both propellant tanks and the helium tanks. Since the foam is supported by the tanks, the thickness, 3/4 inch nominal, is dictated only by the desired thermal properties and can easily be controlled by machining the entire surface in a lathe. At this time there is no reason to suppose that such an operation is necessary. An opening is left in the insulation to accept each thermal louver assembly. Flanges on the frame of this assembly are bonded to the tank wall and then foam is installed to insulate both the outside of the frame and the tank surface that is exposed outside the frame.

There are four louver operating requirements which necessitate mechanical design solutions to the several problems thus created. Requirements are as follows:

1. Insulation on top of the louvers is required after propellant tank filling and during ground hold.
2. The volume between louver and tank must be sealed against air flow during this period to prevent frosting.
3. Pressure differentials across the louver insulation must be kept low to avoid structural weight penalty and to avoid possible louver damage when the pressure is released.
4. The insulation covering must be removed during or soon after launch to expose the louvers.

Several cover design concepts were considered which would, in theory, accommodate these requirements. Most notable were the ideas of 1) attaching a line between the insulation and the shroud so that upon shroud ejection, the cover would be removed and

2) allowing the pressure differential to blow off the cover. The cover which does accomplish all the objectives reliably is shown in the drawing included at the end of this section. It consists of a 1-1/2 inch thick, low-porosity, rigid foam insulating panel that has a flexible plastic sealing diaphragm attached to and sealed around the periphery. The panel is sealed to the fixed insulation around the louvers by a soft elastomeric seal that is compressed and held by latches located on two opposite sides of the panel. The diaphragm is loose fitting to provide a volume between it and the foam panel that is slightly greater than the volume enclosed by the louver assembly. When the tank is filled and the air between the tank and louver insulation cools, the diaphragm can tolerate no pressure differential and thus collapses to the extent dictated by this condition. The requirement to maintain a low pressure differential during ascent is met by providing a pressure relief valve on the fixed portion of the assembly to allow air to escape as the external pressure lowers. It is planned to utilize a collapsed rubber or plastic tube for this purpose, sometimes referred to as a 'raspberry valve'. The resulting air flow after cover removal is so low that no louver damage is possible. To remove the cover, as required by Item 4, the energy of two negator, constant force spring are utilized. These springs are mounted on the frame of the module support structure and one is attached to each of the cover latches previously mentioned. Upon release of the spring by an ordnance type pin puller, the springs first release the latches and then slide the cover assembly through guides until the louvers are uncovered. The two springs are coupled by a torque shaft to synchronize motion.

Both propellant tanks, with their louvers, and the helium tank are installed in the module structure after they have been insulated The aluminum alloy beam which supports all three tanks also serves as a thermal conductor. It is attached to each tank by a flexible thermally conductive strap in addition to the regular structural attachment. This entire beam is insulated as shown on sheet two of drawing SK 406876. In addition to the aluminum beam, there are other structural members which are connected either to the tanks or to the structure immediately adjacent to the tanks. These members are either titanium alloy shapes or boron epoxy tubes with end fittings. In these areas, the members are insulated for a distance of twelve inches from the tank when the material is titanium. When the member is boron epoxy, the end fitting plus three inches of the tube is insulated. After installation of the tanks, either precast or foamed in place insulation is used to complete the insulation in the area between the insulated tank and the insulated structure. To provide compliance for motion at hinged joints, the insulation surrounding each joint is slotted and then covered by a flexible boot to prevent air flow into the slot.

The fluid control components associated with the helium pressurization tank are mounted on an aluminum bracket that is supported by truss members and is located on the -X side (away from the RTG). The arrangement is shown by View A-A of Drawing SK 406876. The components consist of the squib valves, fill valve, filter, pressure regulator, and the solenoid valve for tank isolation valve actuation. The line connecting these components to the helium tank is foam insulated for 18 inches adjacent to the tank and the remainder of the line to the components is insulated by an aluminized Mylar blanket. This insulation is primarily designed to minimize heat conduction into the tank to the extent that no frost will form during ground hold. An aluminized Mylar blanket covers the outer area of the component assembly and extends to the tank surface in order to provide radiative coupling to the tank and thus thermally control the assembly during space operation. A detachable flap is provided in this blanket to afford access to the components during ground operations.

The pressurization system control components associated with each propellant tank are mounted on aluminum brackets that are supported by truss members and located near the upper end of each tank, as shown in Zone B, sheet 1 of Drawing SK 406876. The components mounted on the B_2H_6 tank bracket consist of the burst disc, relief valve, and vent valve while those on the OF_2 tank bracket comprise the same components.

In each case the assembly is insulated by aluminized Mylar in the same manner as previously described for the helium tank components.

The fill valve, pneumatic isolation valve, filter, check valve, and relief valve associated with each propellant system are mounted below and adjacent to each tank. Foam insulation is used to enclose the components and is also used to insulate the line to the engine for an additional length of six inches. The entire line, including that which is covered with foam, is insulated with aluminized Mylar and as it passes around the helium tank, it is laying against the helium tank insulation. This is to accomplish thermal control as indicated in Section 3. A removable door is provided in the insulation and in the meteoroid shield to permit access to the fill valve. The configuration is shown in Zone 6, sheet 1 of Drawing SK 406987.

Each structural fitting that attaches to the electronics compartment of the spacecraft is covered with aluminized Mylar insulation. This insulation also covers the end fitting of each attaching structural member and three inches of the boron-epoxy tube. Zone 9 of sheet 1 on Drawing SK 406876 shows the general insulation method. For clarity, the aluminized Mylar is not shown in several areas.

4.3.2 Dual Wrapped Insulation System

This second insulation system is the same as described above except the two propellant tanks are insulated together in canister arrangement. In utilizing this concept, the simplest approach, if it would function properly, would be to foam insulate the outer half of each propellant tank and then provide a machined band around the meridian to accept the insulation forming the cannister volume between the tanks.

The configuration and thickness of the insulation and supporting structure in this area was investigated by considering structural requirements associated with launch conditions. The acoustic environment of the Titan III D and an assumed amplification factor of five was used to determine an equivalent pressure loading. Although the amplification factors are probably conservative for this material, the resulting pressure of 1/4-psi appears to be a realistic minimum for the pressure differential that must be controlled during chilling of the tanks and for venting during ascent.

Three structural methods of supporting this pressure differential were studies in sufficient depth to obtain a reasonable estimate of weight and complexity. These three methods were:

1. Provide sufficient foam thickness to carry the loads.
2. Utilize an internal structural frame to reduce panel size.
3. Incorporate glass reinforced plastic face sheets on the foam to form sandwich panels.

Calculations and sketches are shown in Appendix A for each of these. Summarizing the results, method 1 requires a foam thickness of two inches and is 9.6 pounds heavier than the individually insulated tanks. Method 2 requires a foam thickness of 1.25 inches and 2.3 pounds of frame to give a total weight increase of 6 lbs. Method 3 incorporated 0.75 inches of foam with 0.015 inch face sheets resulting in a weight increase of 14.1 pounds.

It is probable that a detail design and evaluation would show these values to be low. In particular, it may be impossible to insulate directly on the outside half of each tank since tank vibration would probably cause insulation failure due to the tanks moving away from each other. To avoid the probability of such a failure, the use of additional framework is necessary. But, as a minimum, the weight increase is 6 pounds with the internal framing arrangement providing the lightest configuration.

To prevent excessive pressure differentials during tank chill down, some method must be provided to allow air to enter the sealed volume but any circulation that would permit cryopumping of atmospheric moisture must be avoided. The method must also enable pressures to be balanced during ground hold since a temperature change of only about 4°F causes an internal pressure change of 1/4 psi. In addition, to prevent excessive pressure differentials during ascent, a relief valve is required. As shown in Appendix B, this valve could theoretically have a flow area of 0.8 square inches However, safety considerations would dictate a vent area of about 1.6 sq. in.

To provide a mechanism which would assure no appreciable pressu differentials is not easy. The collapsible tube valve would suffice for the ascent vent valve, but no simple means of stabilizing the pressure during ground hold is presently known. A variation of the breathing membrane described above could be used but the volume enclosed by the membrane would have to be large and as such would be susceptable to damage. The best approach appears to use a pressurized nitrogen bottle with a pressure regulator as a source of gas to keep the pressure inside the insulation from dropping below atmospheric pressure and a collapsible tube valve to prevent excess internal pressure.

The thermal louver used with the dual wrapped insulation arrangement is essentially the same as that discussed for the individually insulated tank arrangement except that the pressure balancing scheme is not required since the pressure in the entire volume would be controlled. Therefore, the diaphragm and relief valve previously described is not used and the porous foam cover is replaced by non-porous foam. However, instead of the louver being supported by direct attachment to the tank, it is mounted in the flat panel of the insulation. In order to accomplish this, a structural frame is required that is a part of the frame for supporting the insulation. The additional weight required for this support was not included in the weight estimate previously discussed

4.4 Comparison of Insulation Systems

From a design and fabrication point of view, the single wrapped system is far superior for the following reasons:

1. It is lighter by at least 6 pounds (probably 10 pounds).
2. The problems of venting are substantially reduced.
3. It is more easily fabricated, installed and repaired.

4. It is less susceptible to damage.

5. It can more readily accommodate relative movements between the tanks.

Item 3 is particularly worthy of note. The dual wrapped system requires that the insulation, support frames, venting devices, and louvers be installed after the tanks are mounted in the structure. Even though the truss structure is relatively open, the access limitations cause this to be a difficult task. In performing the installation, the insulation must be fitted around the diagonal truss members that pass through the insulation and then sealed around these openings. The chances of leakage or breakage occurring at these points is large.

There is one area in which design considerations would indicate a slight advantage for the dual wrapped system, and that is louver reliability. The dual wrapped system and single wrapped system will have a reliability of 0.9975 and 0.9870, respectively, Appendix C.

A comment is in order concerning these reliability values. In the past, reported values of louver reliability have usually been 0.997 or better. In all cases, these values were based on blade cycle reliability only and did not include the time dependent reliability (10 year life) of a single blade. Had such an approach been taken here, the reliability would have been in excess of 0.99990. In addition, the reliabilities reported above include the effect of the louver cover. Without the covers the reliabilities would have been 0.99896 and 0.9898 for the dual wrapped louver and single wrapped louvers, respectively.

Though the reliability of the dual system is somewhat better, it is felt that overall, the advantages of the single wrapped system far outweigh the dual system. Only if thermal control considerations dictated a dual system, which they do not, could the dual system be justified.

4.5 Cooling Coil Design

The cooling coils used to maintain propellant temperatures during ground hold could be located either within the propellant tanks or intimately attached to the exterior surface inside the insulation. The implications of each location were investigated from mechanical design considerations.

Placing the coils internally presents no design problems and is the most simple and direct installation. Since a surface tension device is already used in the tank, it serves as a convenient means of support. The required length of tubing is wrapped around the device and attached to it by spring clips as required structural support during vibration. The inlet and outlet ports are incorporated in the existing polar fittings on the tank. The assembly of the coils and device can be installed in the tanks as a complete unit. The internal cooling coil configuration is shown on Sheet 2 of Drawing SK 406 876.

The coils, if wrapped around the exterior of the tank, would be epoxy bonded to provide both structural attachment and thermal conduction. The aluminum alloy tube is subjected to tensile stresses both from relative thermal contraction when the tank is chilled and from the induced deflection when the tank is pressurized. The magnitude of these stresses are such that either of these conditions can be imposed separately with no adverse effects but if both occur simultaneously, the tube will yield. Under normal operating conditions where the tank is cooled during ground hold and then pressurized after launch, the yielding imposes no problem. However, if such conditions are cycled, when the pressure is relieved and the temperature raised to ambient, residual compressive stresses will result in the tube that could fracture the epoxy bond from the tensile loading imposed on the attachment. While this is a potential problem, it can be solved by judicious design. Foam insulation can be applied to the tank over the coils with no problem and by keeping the coils away from the louver area, no installation problems are anticipated.

In consideration of the above factors, the internal coil location is structurally preferred because of the greater simplicity, but either location is acceptable if required for other reasons.

5.0 EVALUATION

The evaluation method devised during Task I for judging the relative merits of competing systems weighs the particular system in the light of three absolute requirements and six subjective factors as follows:

ABSOLUTE REQUIREMENTS

1. All propulsion systems components having specified temperature limits must be maintained within those limits under normal environmental conditions.
2. No frost or water (as would be discernible by weight measurements) collected on any flight hardware at time of launch.
3. The proposed design must show a weight savings when compared to an earth storable propellant system.

SUBJECTIVE FACTORS

1. Weight A rating of 0 to 15 is adopted with 0 being the rating of a system having a 50-lb. savings in module weight as compared to the standard earth storable system.
2. Reliability A rating of 0 to 10 is adopted with 0 being the rating for a system having the reliability of a totally passive system.
3. Effectiveness A rating of 0 to 10 is adopted with 0 being the effectiveness rating of a system in which all temperature sensitive components are maintained at their nominal operating temperature ± 10°F. Any uncertainty in the analytical calculations is considered as part of the deviation from nominal.
4. Adaptability A rating of 0 to 10 is adopted with 0 being the rating for a system capable of maintaining

all propulsion system components within temperature limits when any or all of the listed parameters vary as indicated:

RTG temperature, 500°F ± 200°F

electronics compartment temperature, 70°F ± 50°F

spacecraft temperature, 70°F ± 50°F, ground hold
100°F ± 150°F, flight

sun angle during transfer orbit, 20°

exposure time during mid-course corrections, 15 hrs.

5. Testability A rating of 0 to 5 is adopted with 0 rating being the ability to thermally test in a ground facility an engineering model of the propulsion module and to simulate in the test all major phases of the mission except engine firing.

6. Cost A rating of 0 to 5 is adopted with 0 rating being the rating for a thermal control system costing $40,000.00.

Two comments are in order concerning this evaluation criteria.. First, though the evaluation standards were established to evaluate a composite working system, they are just as applicable for evaluating components. Therefore, it was deemed wise to apply the evaluation criteria to the system variations under study in this task as well as basic insulation systems. Second, the subjective criteria weight was originally based on the concept of comparing total module weights. However, it is more logical to compare thermal control system weight savings. In this manner, attention is focused directly on the advantages and disadvantages of the thermal control system. With these adjustments, the evaluation may be summarized as given below.

5.1 Coolant Evaluation

5.1.1 Refrigeration Cooling

Calculations show that a refrigeration system will not suffice for a cooling system. Manufacturers of refrigeration equipment state that at this time, commercial equipment capable of supplying coolant below 200°R cannot be made. In addition, the coolant would have to be methane. Safety would preclude the use of internal methane cooling coils. External cooling coils operating at 200°R are incapable of maintaining the propellant temperatures at 220°R without more than 2400 feet of tubing. Heat gain to the coil from sources other than the propellant would prevent proper operation. Obviously 2400 feet of cooling coil would be unacceptable from a weight point of view.

5.1.2 LN_2/GN_2 Cooling

Theoretically, either LN_2 or GN_2 can function as the cooling media.

Weight LN_2, because of its colder temperature and high density, will require the minimum length of cooling tubing whether placed internally or externally. To be competitive, a GN_2 system would have to operate at a pressure sufficient to create a coolant velocity approximately 170 (liquid density divided by gas density) times higher than LN_2 coolant velocity. Rating for LN_2 is 0. Rating for GN is 5.

Reliability Experience with both LN_2 and GN_2 flow systems is sufficient to expect a high degree reliability. However, a pure LN_2 system would be less complicated since no vaporization equipment would be required. The same type of control system would be required in each case. Rating for LN_2 is 2. Rating for GN_2 is 5.

Effectiveness Calculations show that both LN_2 and GN_2 would be effective in controlling the module temperatures during ground hold. Rating for GN_2 and LN_2 is 0.

Adaptability LN_2 has great adaptability. It has the ability to accommodate sudden increases in the heat addition to the propellants. Thus, if the insulation failed or was broken, the use of LN_2 would make it possible to accommodate a 10-fold increase in heat transfer.

If a minor failure appeared in the propellant system, the cooling capability of LN_2 makes it possible to reduce the inherent danger by substantially reducing the vapor pressure of the propellants within minutes.

GN_2 at best can accommodate only a two-fold increase in heat transfer rate, and it has essentially no capability of reducing the vapor pressure of the propellants by greater sub-cooling. Rating of LN_2 is 0. Rating of GN_2 is 8.

Testability Either GN_2 or LN_2 could be tested as a possible coolant. However, GN_2 would be inherently more difficult to test since more hardware (vaporization equipment) would be in use. In essence, it would involve testing a cold gas generation system as well as a propulsion module thermal control system. LN_2 rating is 0. GN_2 rating is 2.

Cost The LN_2 system would be the least expensive. A standard supply system with a set of temperature controlled valves would be required. A GN_2 system would require the same equipment, and in addition, in would require a vaporization unit. Also, the GN_2 system would require considerably more nitrogen. LN_2 rating is 0. GN_2 rating is 4.

The total rating of LN_2 is 2. The total rating of GN_2 is 24.

5.2 Cooling Coil Evaluation

From the analysis it was determined that either internal or external coils will meet the absolute requirements.

Weight Internal tubing would weigh approximately 0.6 pounds per tank. External tubing would weigh approximately 8 pounds per tank. Thus, the use of internal coil would result in a net weight savings of about 22 pounds. Internal coil rating is 2. External coil rating is 12.

Reliability Internal coils present a possible problem of leakage. The tubing, being immersed in the propellants, is susceptible to corrosion. Leakage of nitrogen into the tanks is not of itself dangerous, but side effects such as tank pressurization could occur. It should be emphasized that though such problems are a possibility, they are low probability situations.

External coils are susceptible to breaking loose from the tanks. This would not constitute a dangerous situation since the tanks could still be sprayed with LN_2 to keep them cold. However, it would mean a system failure of sufficient magnitude to cause major rework. Internal coil rating is 6. External coil rating is 3.

Effectiveness. Both internal and external coils would be capable of maintaining the temperatures well within the required limits. Rating of both systems is 0.

Adaptability Because of the ability to bring the coolant in closer contact with the fluids to be cooled by using internal coils, it is possible to adapt to widely fluctuating heating loads with internal coils. External coils have severe limits as to the variations in external heating loads which would be handled. Internal coil rating is 0. External coil rating is 5.

Testability Either coil arrangement would lend itself to performance testing. In both cases, testing would consist of monitoring fluid flow, pressures and temperatures. Rating of both systems is 0.

Cost Internal cooling coils would be considerably cheaper to make and install. They would be made and installed as integral parts of the standpipes. The external coils must be epoxied to the outside of the tanks which would take considerably more time. Internal coil rating is 0. External coil rating is 3.

The total rating of internal cooling coils is 8.
The total rating of external coils is 23.

5.3 Helium Tank Thermal Control Evaluation

The helium tank can be thermally controlled by conductively coupling it to the propellant tanks or by using a louver. However, there are distinct advantages to a conductively coupled system

Weight A slight weight savings (approximately 1.5 pounds) is realized by eliminating the helium tank louvers and using a conductively couple helium tank. Part of this savings is off-set, however, by added requirements for foam and Mylar insulation. Rating of conductively coupled helium tank system is 2. Rating of louver controlled helium tank is 5.

Reliability From the standpoint of reliability, the conductively controlled system is as reliable as a passive system. The louver controlled system will have the reliability of the louvers. Rating of conduction coupled helium tank is 0. Rating of louver controlled helium tank is 3.

Effectiveness Both systems will sufficiently control the helium tank temperature. The rating of both systems is 0.

Adaptability The louver controlled helium tank will have the ability to accommodate a wider variation in mission parameters and RTG surface temperature. However, the conductively coupled system would be able to handle variations so large that a failure in another system (fuel freezing) would occur before a failure in the helium tank occurs. Louver controlled helium tank rating is 2. Conductively coupled system rating is 4.

Testability Both systems could be tested with ease. However, the analysis of test data from systems with louvers is more difficult since the louver is effectively a variable which can only be approximated. This is so even for steady state tests since it is difficult to know the louver blade angle. Unless they can be visually measured (which will be impossible in this system) the angle can only be estimated. Louver controlled helium tank rating is 4. Conductively coupled system rating is 1.

Cost The production cost of louvers for the helium tank would be about $7,000. The cost of added insulation for the conductively coupled tank would be approximately $2,500. The rating of the louver system is 4. The rating of the conductively coupled system is set at 2.

The total rating of the louver controlled helium tank is 18. The rating of the conductively controlled helium tank is 9.

5.4 Insulation Configuration Evaluation

As was indicated in Reference 1, there is no reason that either insulation configuration will not function acceptably. It is a question of which of the two systems is superior.

Weight The double wrapped system is heavier by at least six pounds due to insulation and substructure weight. In addition, it would require louver support structure and it may require substructure not considered in the above analysis to accommodate lateral tank movement. Total insulation weight penalty for the dual wrapped system is about 10 pounds. Dual system rating is set at 10. Single wrapped system rating is set at 0.

Reliability The mechanical reliability of the double wrapped system is slightly higher because only two louver assemblies are used. However, the dual wrapped system insulation is more susceptible to breakage since it is not fully supported as is the single wrapped system. In addition, the dual wrapped system would have to incorporate a pressure relief system to prevent damage to the insulation during ascent. This would, of course, lower the reliability of the dual wrapped system. Dual wrapped system rating is set at 6. Single wrapped system is 4.

Effectiveness Each system will control propellant and component temperatures within the specified limits. However, the dual wrapped system would keep the thermal differentials between the two propellant tanks to a minimum. During a normal mission, the maximum temperature differential for a dual wrapped system would be less than 3°R, Reference 1, whereas for a single wrapped system, the differential might reach 6°R. Both systems are equal relative to controlling the temperature of auxiliary equipment. The use of multilayer Mylar around much of the auxiliary equipment is easy to install, allows for easy access, and yet maintains the temperature of those units during flight when such control is necessary. Dual wrapped system rating is 2. Single wrapped system rating is 4.

Adaptability The adaptability of the two systems is the same except for the case in which the vehicle is oriented such that one propellant tank shades the other from the sun. In such a case the dual wrapped system would demonstrate an advantage. It would be able to hold in such a position for a longer period of time without ill effects than could a single wrapped system. For these reasons, the rating of the dual wrapped system is set at 2, and the rating of single wrapped system is 4.

Testability Both systems could be tested with ease, but the test data from the single wrapped system would be easier to analyze since the louver blade angles would be more readily estimated. Except for thermal transients, the blade angles could be estimated directly from the tank temperature. However, in a dual wrapped system this method of estimating blade angle is not as reliable since the louvers sense temperatures of components other than the tanks, e.g., the inside surface temperature of insulation. This makes analysis considerably more difficult. Dual wrapped system rating is set at 4 and the single wrapped system rating is set at 0.

Cost The cost of the single wrapped insulation is estimated at $17,500. The cost of the dual wrapped insulation could run considerably more due to the degree of difficulty. Framework is required but more important are the problems of sealing cracks in those areas in which the struts pierce the insulation. Dual wrapped insulation system rating is set at 5. Single wrapped insulation system is 1.

Total rating of the dual wrapped insulation system is 29. The rating of the single wrapped system is 13.

5.5 Recommended System

Based on the analyses performed to date, and the resulting evaluation, Table 5-1, the following thermal control system is recommended for detailed study during Task IV (alternate configuration of Drawing SK 406 876).

Insulation System - 3/4-inch closed cell polyurethane foam sprayed on the tanks and applied to auxiliary equipment as necessary with supplemental multi-layer aluminized Mylar to obtain flight thermal control of auxiliary equipment.

Propellant Ground Cooling - LN_2 circulating through an eight foot long, half inch diameter aluminum coil submerged inside the tanks; control of LN_2 to be accomplished by thermally controlled valves having sensors located inside the tanks.

Helium Tank - Conductively coupled to the propellant tanks via an aluminum support beam; support beam to be insulated with both foam and multilayer insulation.

It will be noticed that this system is composed of those individual components which were individually superior according to the evaluation. Ordinarily, it is not be possible to form a system without considering the performance of each component inconsiderate of the other system components. Most of these types of trade-off analyses were made during Tasks I and II. The serveral areas of study of this task are to a large extent independent and do not require such a trade-off study. The method chosen to control the helium tank temperature during flight has only a minor bearing on the choice of LN_2 and internal cooling coils as the means of ground hold thermal control. The choice of the single wrapped insulation system does not bear upon the decision to use internal coils. Only if the evaluation had shown external coils to be superior to internal coils and GN_2 coolant superior to LN_2 would a trade-off analysis have to be made in the present situation. Therefore, in the present situation, the superior system is established by choosing those components which are independently superior.

TABLE 5-1 EVALUATION SUMMARY

SYSTEM	RATING
COOLANT	
Refrigeration	Unacceptable
LN_2	2
GN_2	24
COOLING COIL PLACEMENT	
Internal	8
External	23
HELIUM TANK THERMAL CONTROL	
Louver	18
Conduction	9
INSULATION CONFIGURATION	
Dual Wrapped	29
Single Wrapped	13

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6. Mechanical Engineering, Vol. 54, "Free Convection" W. J. King, 1932.

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   Specification MA 0-606-050, "Spray Application of Two Pound Density Polyurethane Foam Material";
   Specification MBO 130-077, "Specification for Two Pound Density Polyurethane Spray Foam";
   Specification MBO 130-046, "Specification for Two Pound Density Polyurethane Pour Foam."

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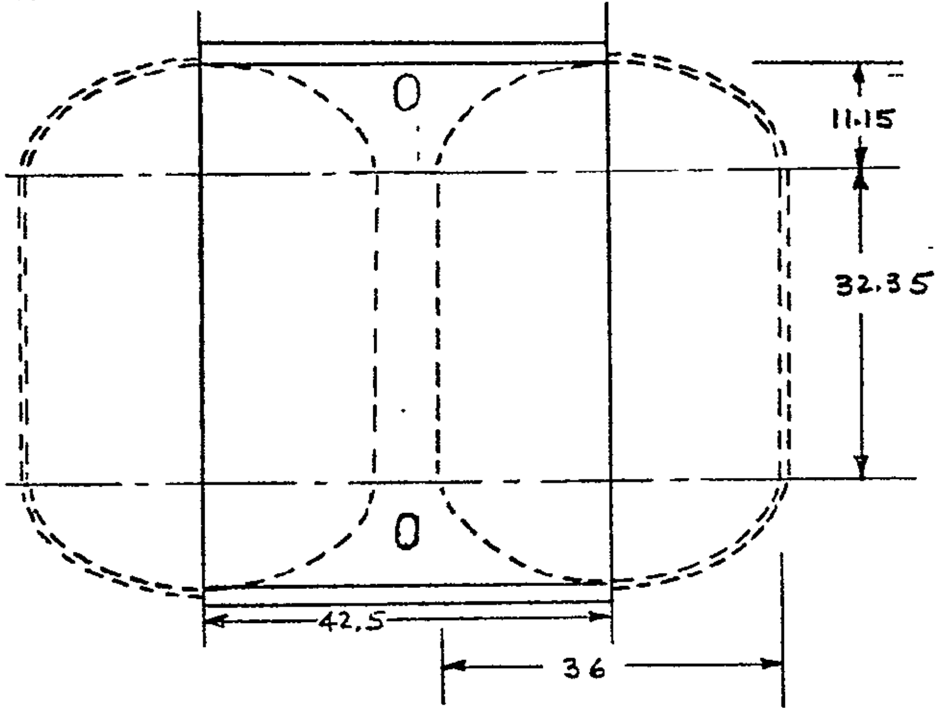
1. UNSUPPORTED FOAM



TITAN 3D ACOUSTIC SPECTRA SHOWS OVERALL SOUND PRESSURE LEVEL OF 145 db. THIS IS EQUIVALENT TO .048 PSI.

ASSUMING AMPLIFICATION = 5, EQUIV. PRESS. = .24 PSI
USING F.S. = 1.5, DESIGN PRESS. = .36 PSI

FOR A SQUARE PANEL,

$$\text{MAX } \sigma = \frac{.2208\, w\, a^2 (1+\mu)}{t^2}$$

WHERE $w = .36$
$a = 42.5$
$\mu = .3$ (ASSUMED)
ALLOW. $\sigma = 50$ PSI

$$\text{THEN } t^2 = \frac{.2208(.36)(42.5)^2(1.3)}{50}$$

$$= 3.74$$

$t = 1.94''$ ⟶ USE 2"

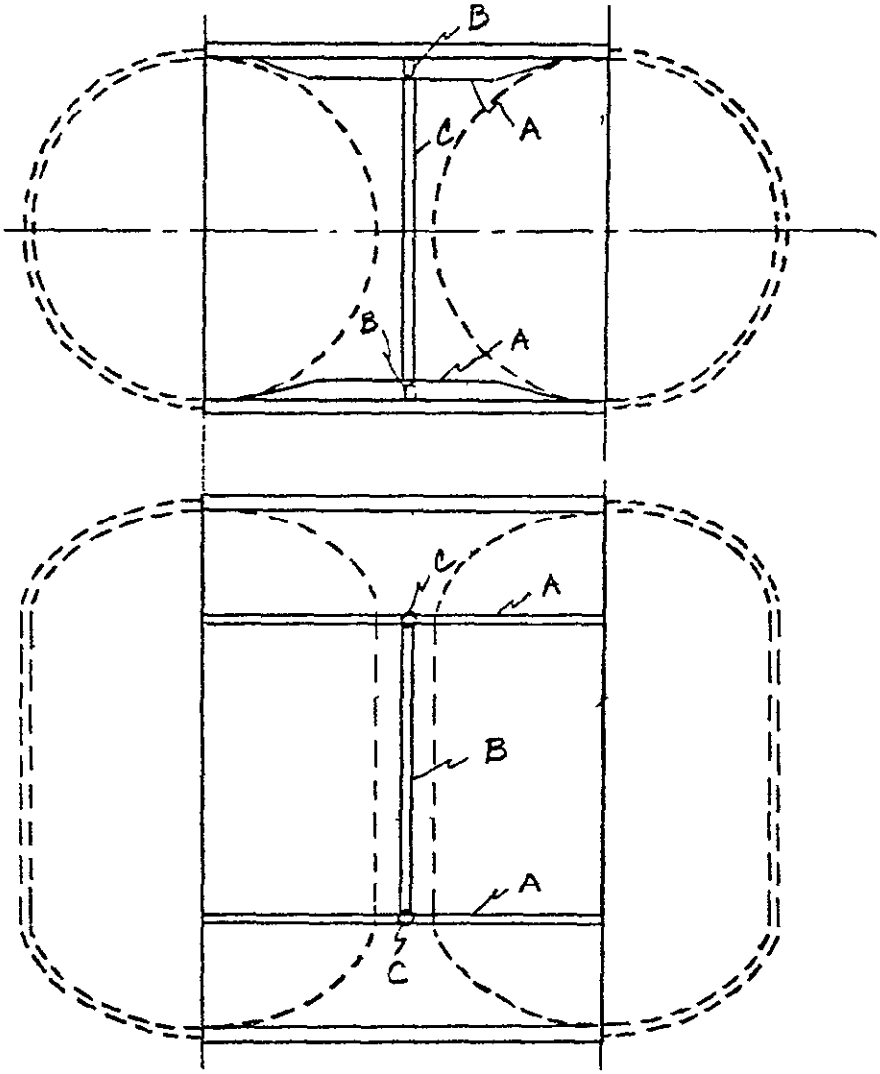
$$\text{SURFACE AREA} = 2\left[42.5(32.35) + \pi\sqrt{\frac{18^2 + 11.15^2}{2}}\,(42.5)\right]$$

$$= 2\,(1380 + 2000) = 6760 \text{ IN}^2$$

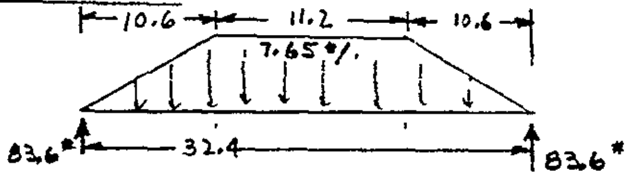
$\text{VOL.} = 6760\,(2'') = 13520 \text{ IN}^3 = 7.8 \text{ FT}^3$

$\text{WT.} = 7.8\,(2) = 15.6$ # (FOAM WT. = 2 LB./CU. FT.)

2. INTERNAL SUPPORT FRAME



MEMBER B



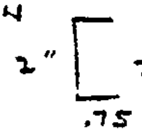
$.36 \times 1 \times \frac{42.5}{2} = 7.65\#/"$

$7.65(5.6) + 7.65\left(\frac{10.6}{2}\right)$

$= 43 + 40.6 = 83.6\#$

$M_{MAX} = 83.6(16.2) - 40.6(9.13) - 43(2.8) = 857\#"$

SECTION



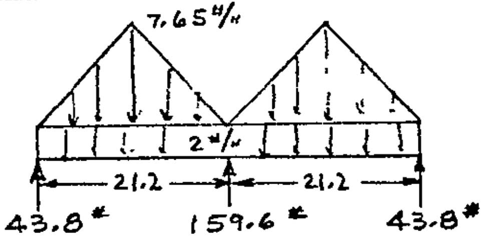
t = .025
2024-T6

$I = .054 \quad A = .087 \quad \sigma_{tc} = 1600$

$\sigma_b = \frac{857(1.0)}{.054} = 15,800$ psi σ

$WT. = .087(32.4)(2)(.10) = .56\#$

MEMBER A



ASSUMING 1/2 DOME LD.,

$q = 5.6(.36) = 2^{\#/''}$

TOTAL LD. $= 2(42.5) + 7.65(21.2)$

$= 85 + 162 = 247^{\#}$

SUPPORT REACTIONS (ASSUMING CONSTANT SECTION)

WITH PINNED CENTER JOINT

END REACTION $= \frac{247}{2}\left(\frac{1}{2}\right) = 61.8^{\#}$; CENTER $= 123.6^{\#}$

ROTATION AT CENTER $= \frac{42.5(21.2)^2}{24EI} + \frac{5}{96}(81)\frac{(21.2)^2}{EI}$

$= \frac{2690}{EI}$

FOR SLOPE = 0 AT CENTER

$\frac{M_c \ell}{3EI} = \frac{M_c(21.2)}{3EI} = \frac{2690}{EI}$

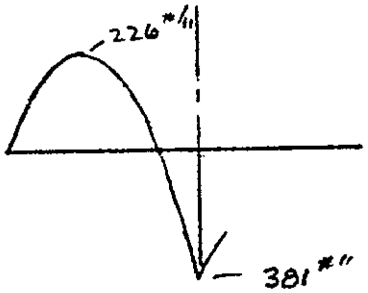
$M_c = 381^{\#''}$ END REACTIONS $= \frac{381}{21.2} = 18^{\#}$

TOTAL

END REACTIONS $= 61.8 - 18 = 43.8^{\#}$

CENTER REACTION $= 123.6 + 18 + 18 = 159.6^{\#}$

MAX. MOMENT



$M_{MAX} = 381^{\#''} < 857^{\#''}$ (MEM. B.)

∴ USE SAME SECTION AS "B"

WT. $= .087(42.5)(4)(.10) = 1.5^{\#}$

MEMBER C

MAX. LOAD $= 159.6 + 83.6 = 243.2^{\#}$ (TENS. OR COMP.)

USING ALUM. TUBE

DIA. = 1.0 $t = .010$ $L = 36$ $A = .031$ $\rho = .352$ $L/\rho = 102$

$F_c = \frac{\pi^2(10)(10^6)}{(102)^2} = 9500$ PSI $\sigma_c = \frac{243.2}{.031} = 7850$ PSI ok

WT. $= .031(36)(2)(.10) = .22^{\#}$

FOAM THICKNESS

$a = 32.4 \quad b = 21.2 \quad a/b = 1.52 \quad \beta = .466$

$$\sigma_B = \frac{.36\,(21.2)^2\,(.466)}{t^2} = 50 \text{ (MAX.)}$$

$$t_{MIN} = 1.23'' \longrightarrow \text{USE } 1.25''$$

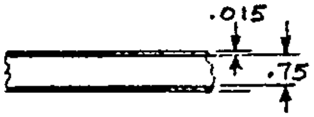
WEIGHT

$$\text{FOAM} = \frac{6760\,(1.25)}{1728}\,(2) = 9.7\,^{\#}$$

$$\text{FRAME} = .56 + 1.50 + .22 = 2.3\,^{\#}$$

$$\text{TOTAL} = 12.0\,^{\#}$$

3. SANDWICH PANEL (GRP FACE SHEETS)



$$M_{MAX} = .0479\,(.36)(42.5)^2 = 31.2\ ^{\#''}/_{''}$$

WITH $t_F = .015''$, FOAM $t = .75$

$$\sigma_F = \frac{31.2}{.75\,(.015)} = 2760 \text{ psi} \quad \text{ok.}$$

$$\text{MAX. } \delta = .0037\,\frac{(.36)(42.5)^4}{2\,(10^6)\,(.015)(2)(.375)^2} = 0.52''$$

$$\text{WT.} = 6760\,(.75)\,\frac{2}{1728} + 6760\,(2)(.015)(.07)$$

$$= 5.9 + 14.2 = 20.1\,^{\#}$$

4. WEIGHT DIFFERENTIAL SUMMARY

FOR INDIVIDUALLY INSULATED TANKS (3/4" FOAM)

$$\text{VOL./TANK} = 4/3\,\pi\left[11.90(18.75)^2 - 11.15(18.00)^2\right] + 32.35\pi\left[\overline{18.75}^2 - \overline{18}^2\right]$$

$$= 2392 + 2801 = 5193 \text{ IN.}^3$$

$$\text{WT. (2 TANKS)} = \frac{5193}{1728}\,(2)(2) = 12\,^{\#}$$

FOR 1. UNSUPPORTED FOAM

$$\Delta W = 15.6 + 6 - 12 = +9.6\,^{\#}$$

2. INTERNAL SUPPORT FRAME

$$\Delta W = 12 + 6 - 12 = +6.0\,^{\#}$$

3. SANDWICH PANEL

$$\Delta W = 20.1 + 6 - 12 = +14.1\,^{\#}$$

APPENDIX B VENTING ANALYSIS FOR INSULATION ENCLOSURE

As the launch vehicle ascends there will be a net mass flow out of the compartment as the volume of air contained originally at sea level condition escapes through the vent to the decreasing internal shroud pressures. The assumed shroud internal pressure history is presented in Figure B-1.

The following assumptions have been made for the present analysis:

1) The free volume within the tank enclosure is completely sealed everywhere except at the vent location.
2) The air remaining in the compartment expands adiabatically.
3) The mass flow from the vent is subsonic, i.e.,

$$\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} < \frac{p_e}{p} < 1 \text{ (See Page B-3 for nomenclature)}$$

The differential equation which gives the exact relation for the compartment pressure as a function of time consistent with the noted assumptions is:

$$\frac{dp}{dt} = \left(-\frac{C_d A\gamma}{V}\right)\sqrt{\frac{p_o^{1/\gamma}}{\rho_o}}\sqrt{\left(\frac{2\gamma}{\gamma-1}\right) p^{\frac{3\gamma-1}{\gamma}}\left(\frac{p_e}{p}\right)^{\frac{2}{\gamma}}\left[1-\left(\frac{p_e}{p}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad (1)$$

Since, for preliminary design purposes, we are interested only in the maximum pressure difference, Δp_{MAX}, equation (1) can be rewritten in terms of Δp_{MAX} to give

$$\Delta p_{MAX} = (p - p_e)_{MAX} = \frac{1}{2}\left(\frac{V}{AC_d\gamma}\right)^2 \frac{\rho_o}{p_o^{1/\gamma}}\left[\frac{\frac{dp_e}{dt}}{p_e^{\frac{2\gamma-1}{\gamma}}}\right]^2_{MAX} \qquad (2)$$

$$\text{for } \frac{\Delta p}{p_e} << 1$$

The rate of change of the shroud internal pressure was determined as a function of time and was used to evaluate the bracketed term f $[(p_e)]$ of Equation (2) as shown in Figure B-1 . The maximum value is found to be 0.35 and occurs at t = 60 seconds.

Using this result, together with the following values

$V = 20 \text{ ft}^3$

$C_d = 0.605$

$\gamma = 1.4$

$p_o = 2117 \text{ lbs/ft}^2$

$\rho_o = 0.002378 \text{ slugs/ft}^3$

equation (2) was evaluated to give

$$\Delta p_{MAX} \text{ (psia)} = \frac{0.14}{A^2}$$

This relationship between Δp_{MAX} and A is presented in Figure B-2. Table B-1 indicates the vent areas required to keep the maximum pressure differential, Δp_{MAX}, less than 0.25, 0.1, and 0.05 psia.

For $V = 0.5 \text{ ft}^3$, equation (2) yields

$$\Delta p_{MAX} \text{ (psia)} = \frac{.0000875}{A^2}$$

This relationship between Δp_{MAX} and A is presented in Figure B-3. Table B-1 indicates the vent area required to keep the maximum pressure differential Δp_{MAX}, less than 0.25, 0.1, and 0.05 psia.

TABLE B-1

	$V = 20 \text{ ft}^3$	$V = 0.5 \text{ ft}^3$
Δp_{MAX} (psia)	A (in^2)	A (in^2)
0.25	0.75	0.02
0.10	1.20	0.03
0.05	1.70	0.042

These vent areas should be used for preliminary design purposes only. It should be noted from Figures B-2 and B-3 that the maximum differential pressure, Δp_{MAX}, increases quite rapidly for vent areas less than 1.2 in^2 ($V = 20$ ft^3) and 0.03 in^2 ($V = 0.5$ ft^3).

NOMENCLATURE

A	area of vent, ft^2
C_d	discharge coefficient
p	compartment pressure, psia
p_e	local external pressure at vent location, psia
p_o	compartment pressure at launch, psia
p	$= p - p_e$, differential pressure, psia
t	time, seconds
V	compartment free volume, ft^3
γ	ratio of specific heat for air ($\gamma = 1.4$)
ρ_o	compartment air density at launch, $slugs/ft^3$

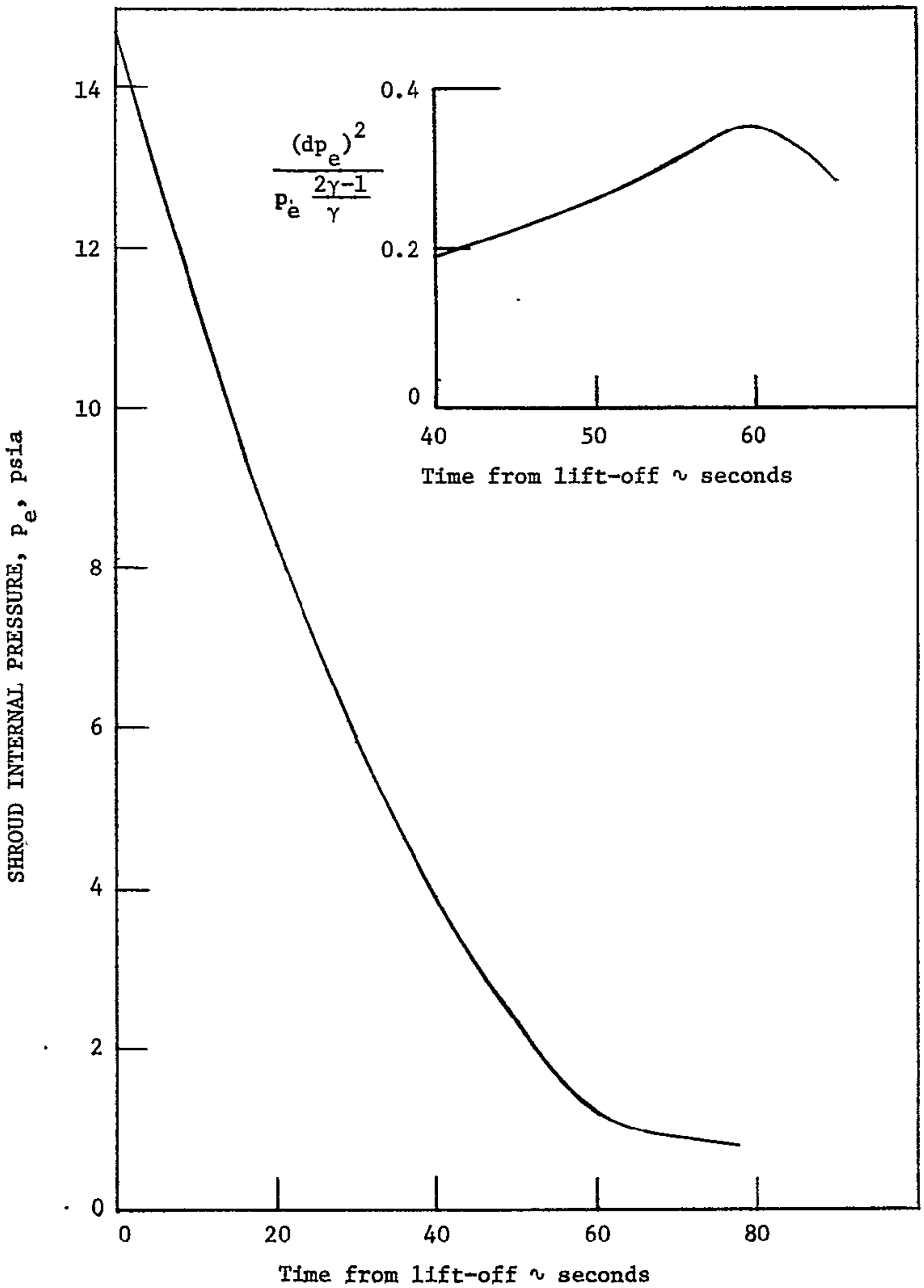


FIGURE B-1 SHROUD INTERNAL PRESSURE HISTORY

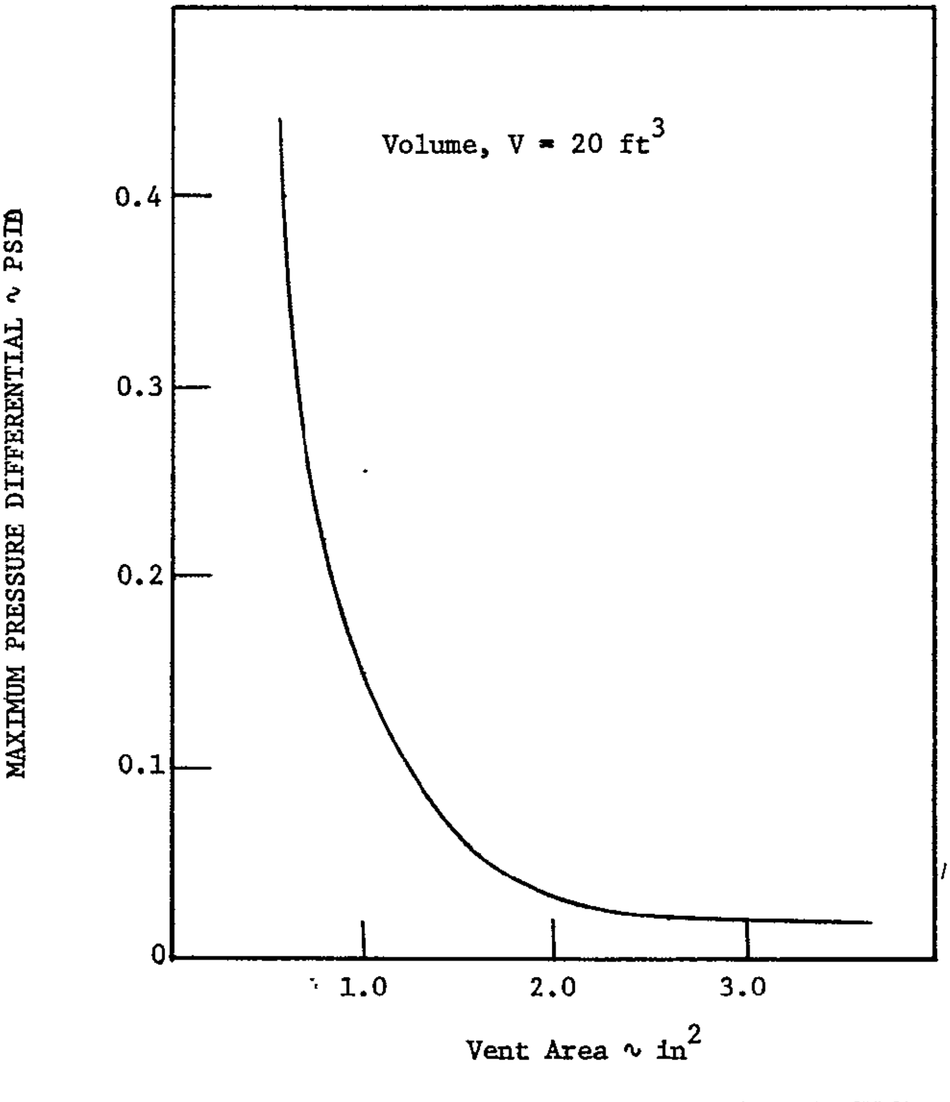


FIGURE B-2 MAXIMUM DIFFERENTIAL PRESSURE VERSUS VENT AREA, V = 20 FT^3

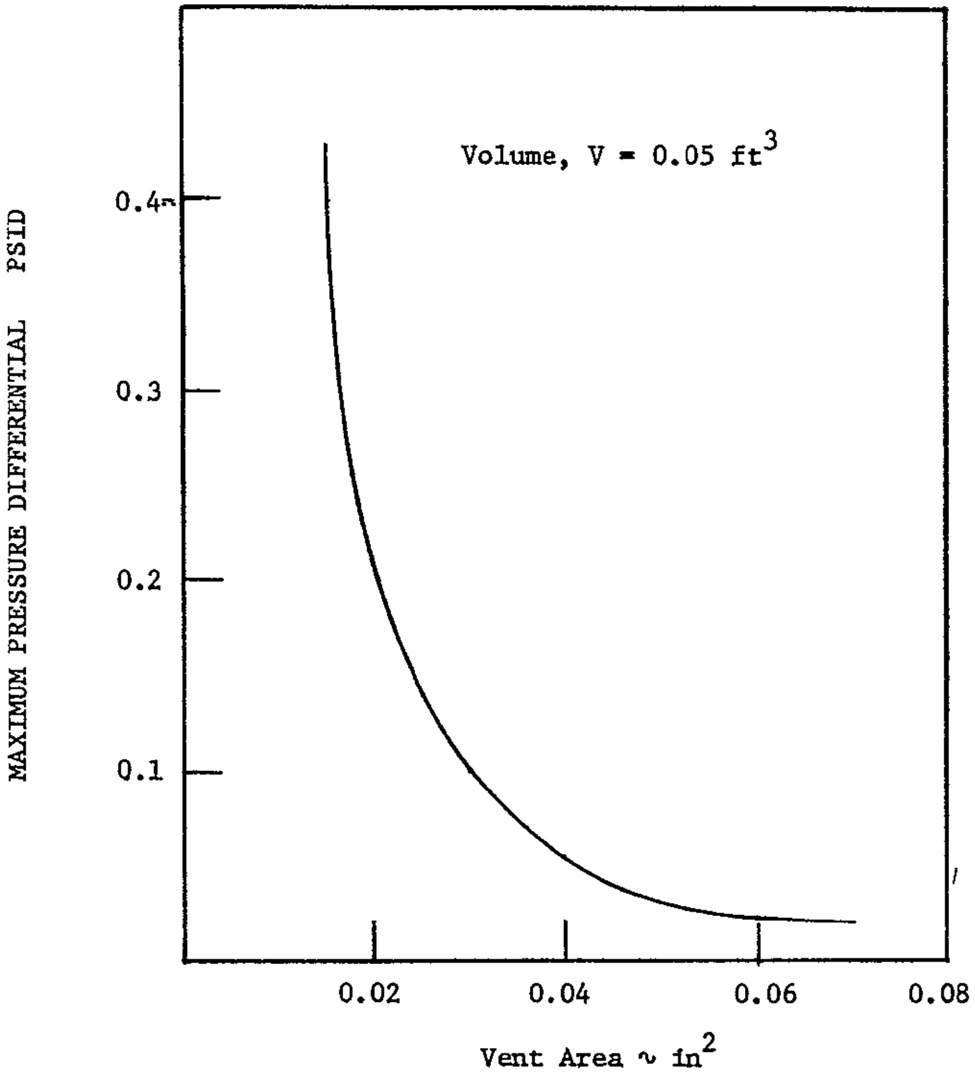


FIGURE B-3 MAXIMUM DIFFERENTIAL PRESSURE VERSUS VENT AREA, V = 0.05 FT^3

APPENDIX C - RELIABILITY OF LOUVER ASSEMBLIES

ASSUMPTIONS AND GROUND RULES

Assumptions and ground rules necessary to perform the reliability assessment included:

1. An assembly would function successfully provided that:

   Configuration 1 (see Figure C-1):

   At least six out of eight blades were operable in each of two positions.

   Configuration 2:

   At least 3 of 4 blades were operable in each of four positions.
2. Each louver would experience 25 cycles in the ten year mission.
3. The reliability of a louver per cycle was taken to be 0.9_5869 (about 50% Confidence Level) based on 527,280 cycles without failure from OGO life test data.
4. The active elements of a louver were considered to consist of two teflon bearings with failure rates of 11×10^{-9} each, Reference C-1, and a bimetallic spring with a failure rate of 220×10^{-9}.

MATHEMATICAL ANALYSIS

The reliability of the Thermal Controller for the boost and deployment phase was determined from the exponential equations as follows:

$$R = e^{-\lambda t \div K \cdot 10^{-9}}$$

$$= .9_5758$$

where

t = (.10) hour

K = 100 (environmental factor)

$\lambda = 242 \cdot 10^{-9}$

R = Reliability of one louver = $1-Q$

For Configuration (1)

$$R_{B_1} = [P(6 \text{ of } 8)]^2 = [R^8 + 8R^7Q + 28\,R^6Q^2]^2 = .9_{10}$$

For Configuration (2)

$$R_{B_2} = [P(3 \text{ of } 4)]^4 = [R^4 + 4R^3Q]^4 = .9_9$$

The time-dependent reliability of a single louver for the mission was determined as follows:

$$R^1 = e^{-\lambda t}$$

where

λ is the failure rate of a louver (independent of cycles)
$= 242 \cdot 10^{-9}$

$t = 87{,}610$ hrs. (ten years + boost)
$R^1 = .97902155$

The total reliability of a single louver subjected to X cycles was determined as follows:

$$R_T = R_L^x \cdot R^1$$

where

R_L = louver reliability per cycle
= $.9_5869$ about 50% Confidence Level

X = number of cycles
= 25

$R_L^x = (.9_5869)^{25} = .9_4672$

R^1 = louver reliability for mission

$$= .97902155$$

$$R_T = (.97902155)\ (.9_4672) = .979$$

The general equation for determining the reliability of each louver configuration is again:

Configuration (1) - 6 of 8 louvers in each of two positions

$$R_1 = [R_A{}^8 + 8\ R_A{}^7\ Q_A + 28\ R_A{}^6\ Q_A{}^2]^2$$

$$R_1 = [.999482]^2 = .99896$$

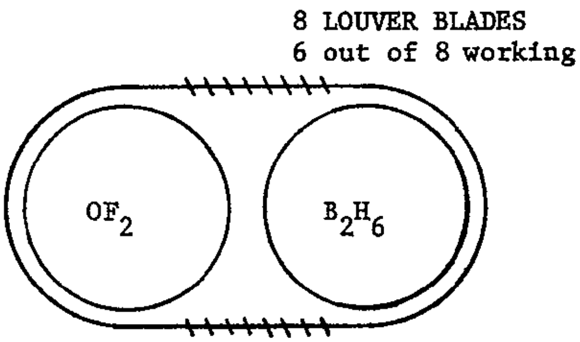
Configuration (2) - 3 of 4 louvers in each of four positions

$$R_2 = [R_A{}^4 + 4\ R_A{}^3\ Q_A]^4$$

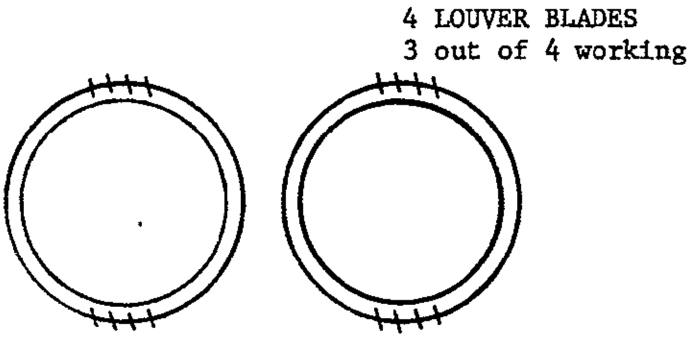
$$R_2 = [.99743]^4 = .9898$$

If the louver cover is considered as part of the louver assemblies, these reliabilities are further reduced by the reliability factor of the covers. The assembly reliabilities will then be:

DUAL WRAPPED LOUVER	0.99754
SINGLE WRAPPED LOUVER	0.9870



Configuration 1   Dual Wrapped Insulation



Configuration 2   Single Wrapped Insulation

FIGURE C-1   DIAGRAM OF CONFIGURATIONS