SUMMARY REPORT

TASK VI SPACE STORABLE PROPELLANT MODULE ENVIRONMENTAL CONTROL TECHNOLOGY

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SUMMARY REPORT

TASK VI STORABLE PROPELLANT MODULE ENVIRONMENTAL CONTROL TECHNOLOGY

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Contract NAS 7-750

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SUMMARY

The objective of Task VI was to identify and briefly investigate possible thermal control concepts for a F_2/ N_2H_4 (fluorine/hydrazine) propulsion module. Preliminary thermal, structural, and propulsion analyses have been conducted which indicate that all major requirements (long term in flight storage, no F_2 venting, and no frost or condensation build up during ground hold) can be accomplished with a baseline design system weight (including propellants) of approximately 3406 pounds. This is 67 pounds heavier than the similar OF_2/B_2H_6 system studied under tasks II and III. Propellant weight (which increased by 96 pounds) is responsible for the weight increment.

From a thermal requirements point of view, the major difference between the current F_2/N_2H_4 system and the previous OF_2/B_2H_6 system is that the two propellants for the current system must be stored at widely different temperatures (fluorine < 200°R, hydrazine 490 - 560°R), whereas with the previous system, both propellants could be stored at approximately 250°R. Because of the large temperature gradient, the low fluorine temperature, and the no vent requirement, the RTG has been repositioned out of view of the fluorine tank, boron filament support tubes have been replaced on the fluorine tank by lower conductance epoxy fiberglass tubes, flat plate radiation shields have been placed between tanks, and solar impingement on the fluorine tank, its support struts and plumbing lines has been restricted to short periods ($t < 10$ days). Preliminary calculations show that under these conditions, passive radiation from the insulated fluorine tank to space can maintain the fluorine at an equilibrium temperature of approximately 100°R (with a hydrazine temperature of 530°R). Heat capacity of the fluorine and its tank would then provide a maximum margin of safety in the event of inadvertent heat leaks or solar impingement.

Calculations also show that the addition of only 24 to 38 Btu/hr (depending on insulation thickness) raises the fluorine equilibrium temperature to the maximum acceptable limit for firing (200°R). Since the equilibrium temperature is this sensitive to heat leaks and since it is uncertain at this time whether or not direct and reflected solar impingements can be sufficiently limited, four auxiliary techniques have been considered briefly for providing contingency cooling. Of these four techniques (inflight removal of insulation, a deployable radiator, a heat pump, or an expendable cryogen), only two (the second and third) appear to be potentially effective enough to justify further consideration, and both of these require considerable development and impose certain weight penalties. It is, therefore, recommended that more detailed analytical model(s) of the basic passive system for controlling the fluorine temperature be created during Task VII so as to establish heat paths and solar impingement limits more accurately.

Preliminary analysis has identified at least seven different acceptable combinations of components for thermal control of the hydrazine tank. Of these seven, four are recommended for further study based on a systematic relative evaluation procedure. Three of the recommended systems are passive and utilize thermal radiation, a heat pipe, or a solid aluminum bar to couple the hydrazine tank to the RTG. The fourth system is semi-passive and utilizes a louvered panel to couple the tank to the RTG. All of the recommended systems use passive radiation from the insulated surface as the main coupling between the hydrazine tank and space.

1.0 INTRODUCTION

This is the Task VI summary report of the Space Storable Propulsion Module Environmental Control Technology Project accomplished under Contract NAS 7-750. Task VI had as its objective to identify and briefly investigate possible thermal control concepts for a F_2/N_2H_4 (fluorine/hydrazine) propulsion module. The concepts are to be analyzed more fully under Task VII.

Operational requirements for the F_2/N_2H_4 module are similar to those described in the Task I summary report(1) for the OF_2/B_2H_6 module, except storage temperatures are significantly different. Some of the groundhold cooling and frost prevention concepts described and analyzed in the summary reports(2),(3) for Tasks II and III are, however, applicable to the fluorine tank of the present module. An attempt has been made to utilize as much of the previous work as possible and limit the discussions in the present report to problems not common with the previous system.

Section 2 discusses the principal differences in thermal control requirements between the present (F_2/N_2H_4) and the previous (OF_2/B_2H_6) propulsion module designs and identifies several possible concepts for thermally coupling the RTG, hydrazine tank, fluorine tank, and helium pressurant tank to each other and to space. Sections 3 and 4 discuss the resulting differences in the propulsion and structural designs, respectively. Subjective evaluations of various concepts are discussed, and relative rating factors are assigned in Section 5. Conclusions and recommendations are presented in Section 6.

2.0 THERMAL DESIGN

An F_2/N_2H_4 propulsion module may present somewhat more difficult thermal control problems than the previous OF_2/B_2H_6 module. The main difference is that the fluorine must be stored at a colder temperature (<200°R*) and the hydrazine at a warmer temperature (490-560°R) than the previous propellants (250°R). The wide difference in temperature makes thermal isolation of the fluorine tank (from the hydrazine tank, from the RTG, and from the sun) extremely critical. The temperature of the hydrazine and helium tanks can be controlled quite easily by balancing heat input from the RTG with heat rejection to space. Rejection of absorbed heat from the fluorine tank to space, however, is much more difficult because of fluorine's low storage temperature.

Groundhold requirements and considerations are essentially the same as for the OF_2/B_2H_6 propulsion module systems studied under tasks II and III, except that only one of the tanks (fluorine) now needs to be cooled with auxiliary equipment to prevent boil-off and insulated with closed cell foam to prevent frost build up.

In light of the groundhold and flight requirements, the thermal baseline design that has been considered is to insulate the entire surface area of the fluorine tank with at least 3/4 inch of sprayed-on closed-cell foam. A single layer of 3 mil second surface silvered Teflon is bonded to the outer surface of the foam to provide a high emittance but low (and u.v. stable) solar absorptance. The hydrazine tank is placed between the RTG and the fluorine tank and its entire surface is insulated with multilayer aluminized Mylar. Heat is conducted from the deployed RTG to the hydrazine tank by a system of two heat pipes or two solid aluminum bars and a woven wire coupled flexible joint. In order to provide a low emittance surface capable of withstanding the high temperature that would occur during solar impingement, several outer layers of insulation on the hydrazine tank are aluminized Kapton (rather than Mylar) with the aluminized side facing outward. The helium pressurant tank is insulated in the same way (with multilayer aluminized Mylar and Kapton) and is thermally "clamped" to the hydrazine tank by means of a heat

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*Liquid, subcooled 20°F below saturation temperature at 300 psia.

pipe or solid aluminum bar. Flat plate radiation shields (.020-inch aluminum), placed between the fluorine and hydrazine tanks and between the fluorine and helium tanks, minimize radiant coupling. All support struts for the fluorine tank are epoxy-impregnated fiberglass tubes. These tubes and any plumbing or instrumentation leads from the fluorine tank are to be insulated in the same way as the tank itself so that the total net heat leakage into the fluorine is minimized.

Calculations indicate that in the absence of solar impingement, this system would result in a fluorine tank temperature of about 100°R*. Drawing SK406961 (2 sheets) shows the thermal baseline configuration layout that has been considered. Special features of and possible modifications for each tank are discussed in the following subsections.

2.1 FLUORINE TANK

The basic approach is to thermally isolate the fluorine tank as well as possible from all heat sources, and then rely on the heat capacity of the fluorine and the tank to absorb the bulk of any short term inadvertent heat input due to direct or reflected solar impingement.

This approach differs from that used with the OF_2/B_2H_6 module in that no louvers are used on the F_2 tank. The main reason for this change is that the fluorine must be stored at a lower temperature than either OF_2 or B_2H_6, and at this lower temperature, louvers would provide little control. Elimination of louvers on the fluorine tank is a major simplification, becuase it eliminates the problem of how to insulate the louvers against frost buildup on the ground but provide efficient radiation in space. An important factor in being able to maintain the fluorine temperature between limits without louvers is that the fluorine tank is thermally isolated and most of the heat leakage that does occur comes from the warm hydrazine tank which is maintained between rather narrow temperature limits.

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*The system should be designed so that the F_2 tank is in equilibrium at or near its lower temperature limit because residual or unintentional heat leaks will most likely be larger than anticipated rather than smaller. A bias of this type will provide maximum pad in case of inadvertent solar impingement.

2.1.1 Heat Capacity

The estimated inflight heat capacity is based on the following assumptions,

(1) Fluorine and its tank are initially at a temperature just above the freezing temperature of fluorine (100°R).

(2) 1800 pounds of fluorine are to be stored for 1793 days.

(3) No fluorine is vented and none is used for mid-course maneuvers.

(4) Temperature of the fluorine and its tank can be allowed to rise to 200°R.

Total heat that can be absorbed by the fluorine then is:

$$Q_{fluorine} = W_F C_{P_F} \quad (T_c - T_i) \quad = \quad (1800)(.363)(200-100)$$

$$Q_{fluorine} = 67{,}300. \text{ Btu}$$

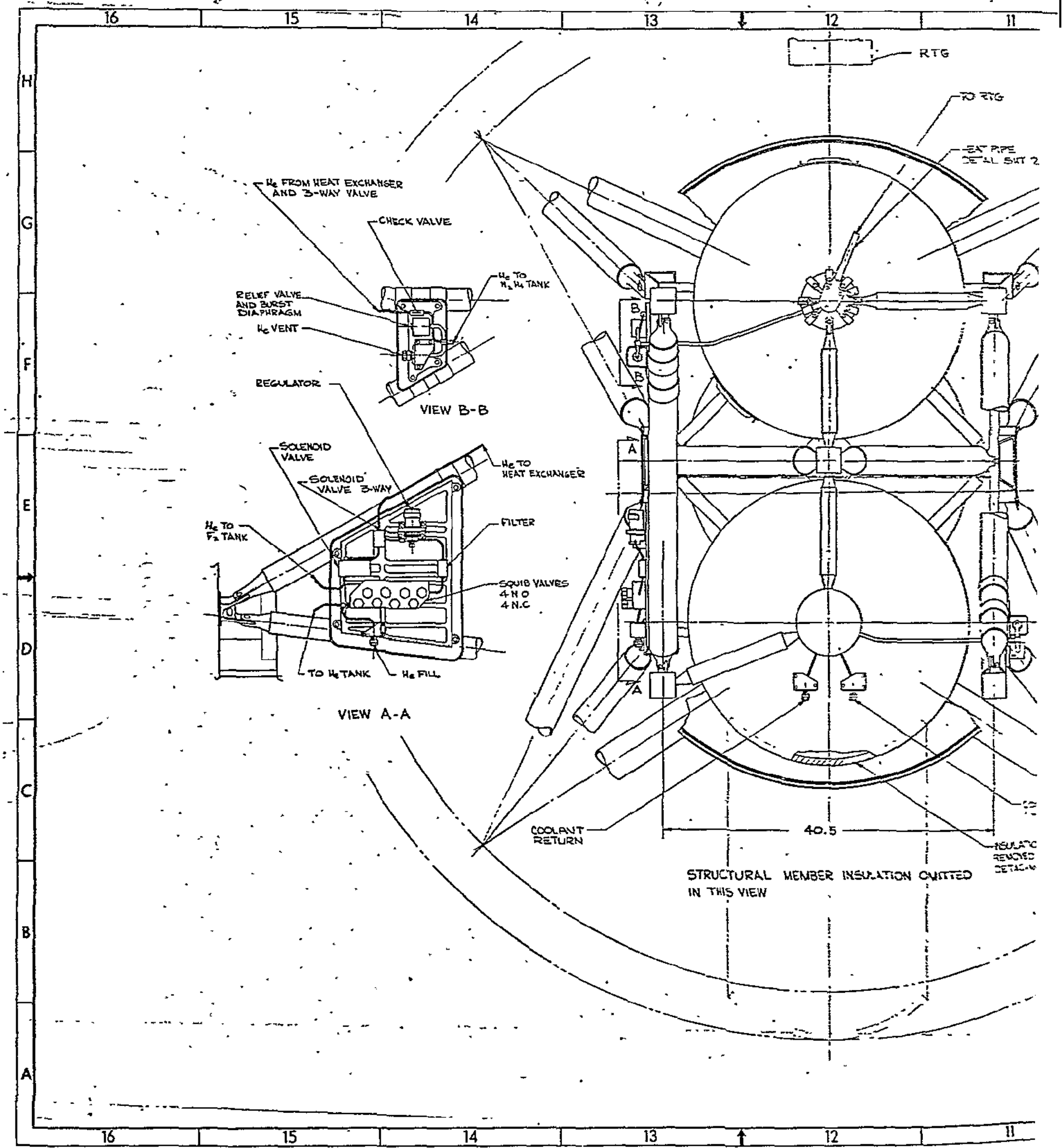
Total heat that can be absorbed by the fluorine tank is

$$Q_{tank} = W_T C_{P_T} \quad (T_f - T_i) \quad = \quad (59.6)(.25)(200-100)$$

$$Q_{tank} = 1530. \text{ Btu}$$

The total net heat leakage that can be absorbed by heat capacitance this is:

$$Q_{total} = 67{,}300 + 1530 \quad - \quad 68{,}830 \text{ Btu.}$$



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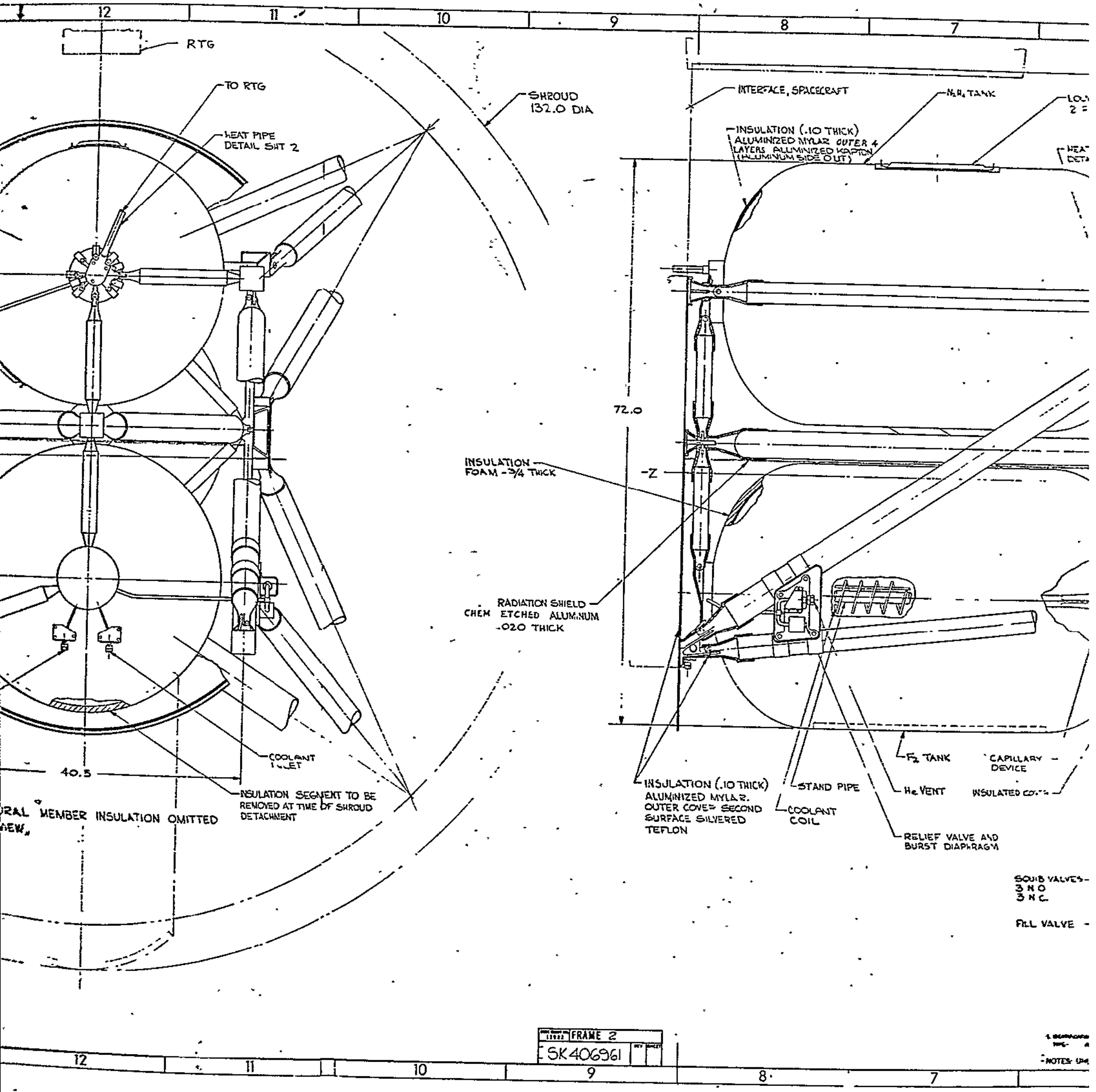

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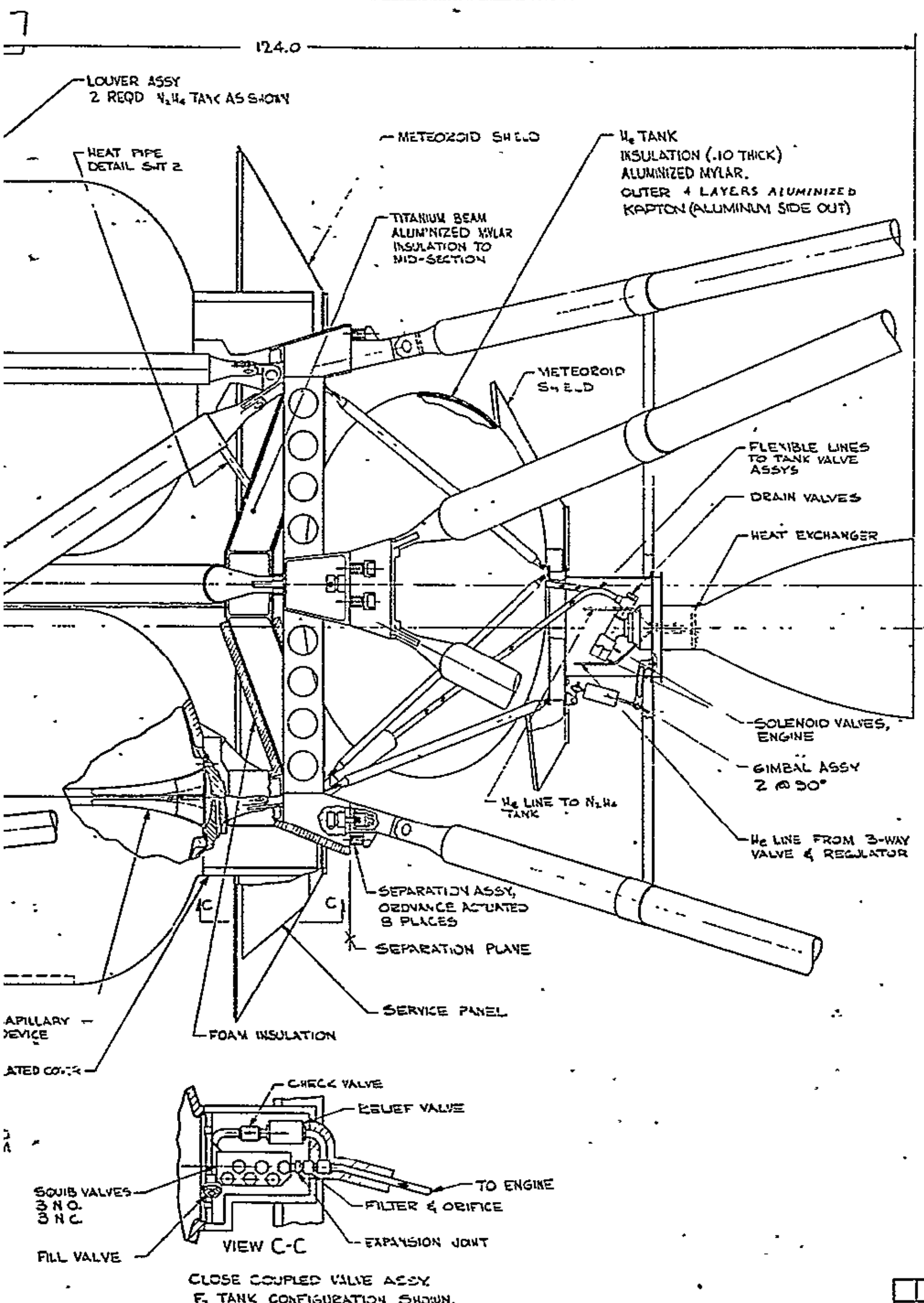

CLOSE COUPLED VALVE ASSY.
F_2 TANK CONFIGURATION SHOWN.
N_2H_4 TANK VALVE ASSY SIMILAR EXCEPT
SOLENOID VALVE REPLACES ORDNANCE

BOOSTER

~~NOTES: UNLESS OTHERWISE SPECIFIED~~

TRW

SINGLE TANK CONFIGURATION
SINGLE WRAPPED INSULATION
WITH HEAT PIPE

J 11982 SK406361

SK406361

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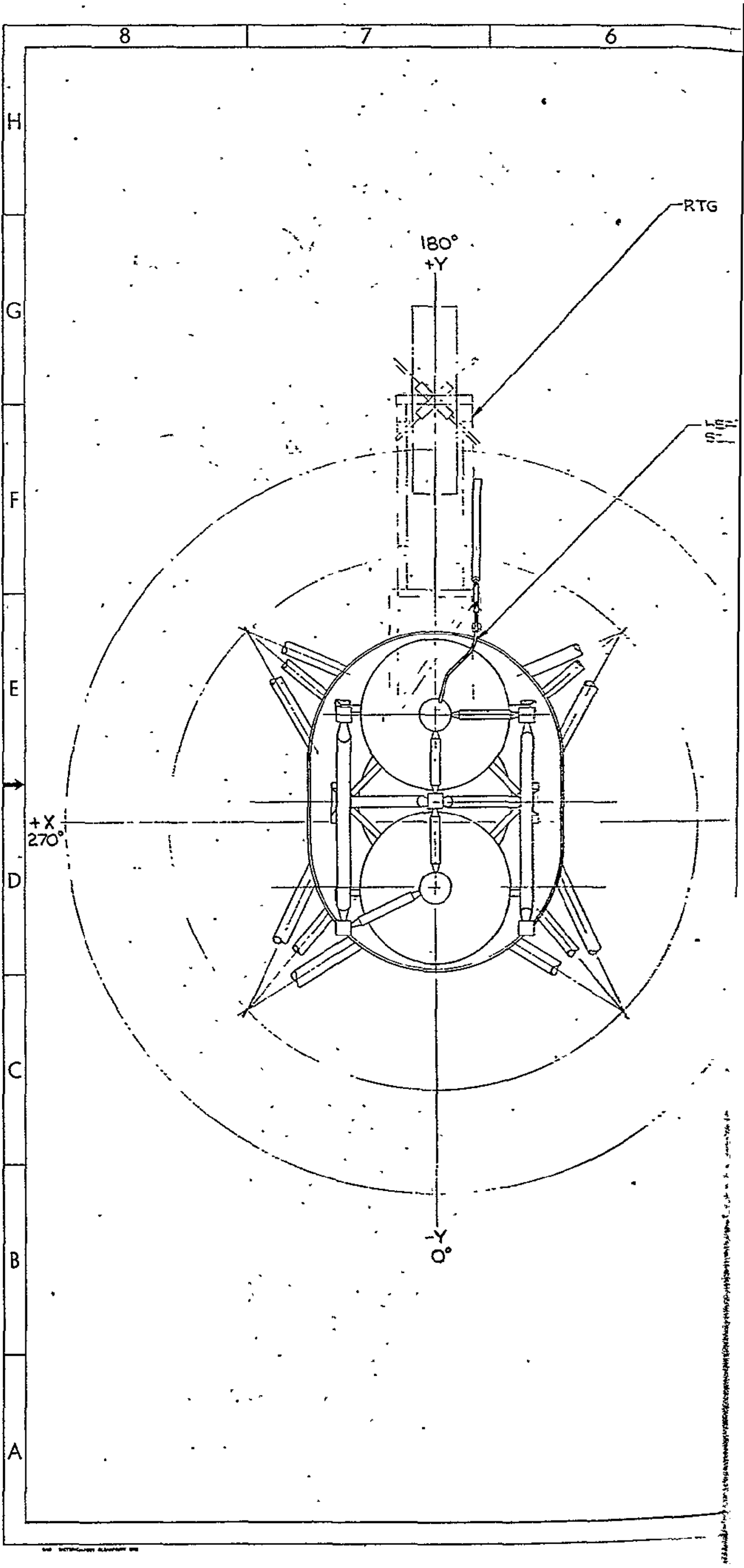

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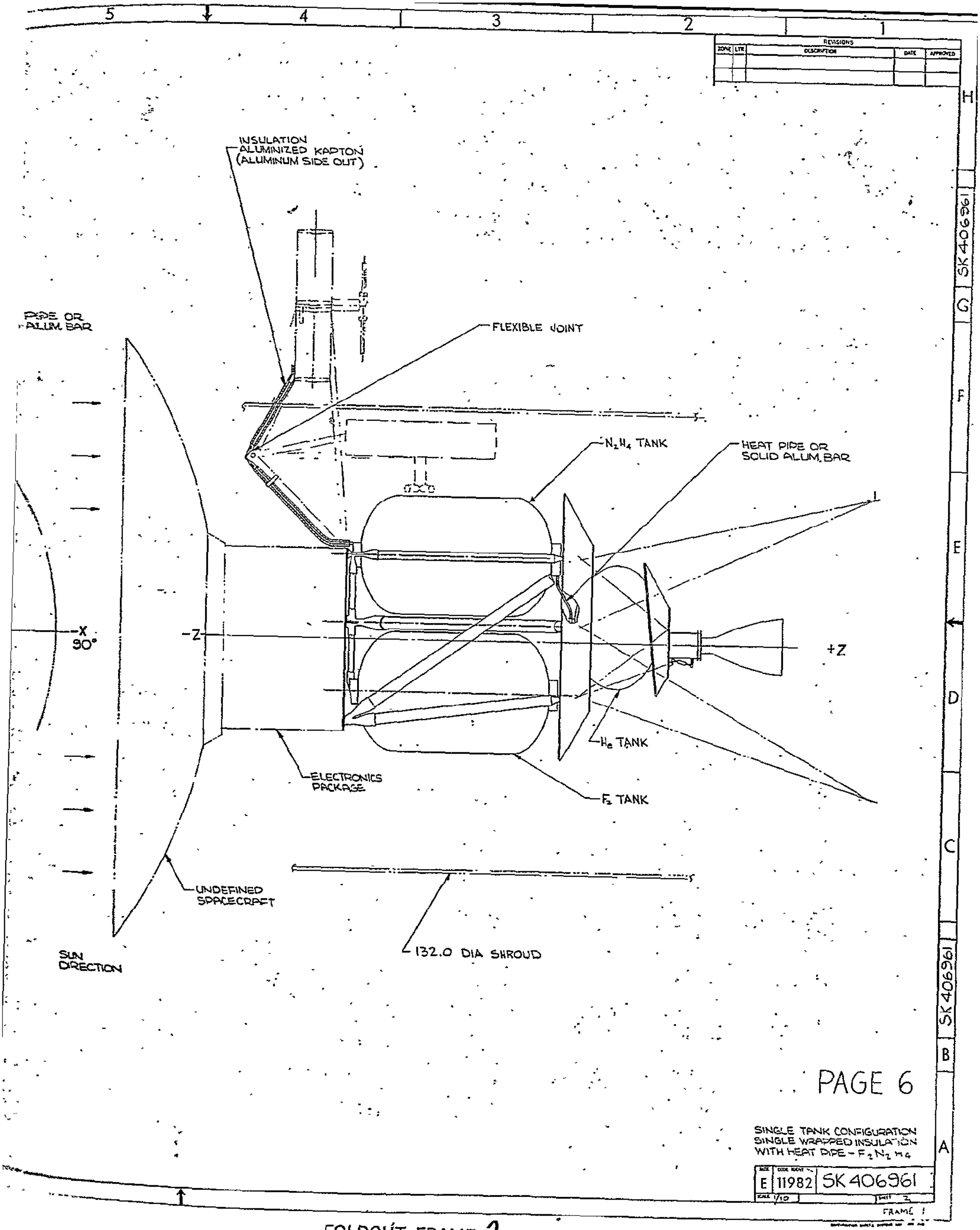

SINGLE TANK CONFIGURATION
SINGLE WRAPPED INSULATION
WITH HEAT PIPE – $F_2N_2H_4$

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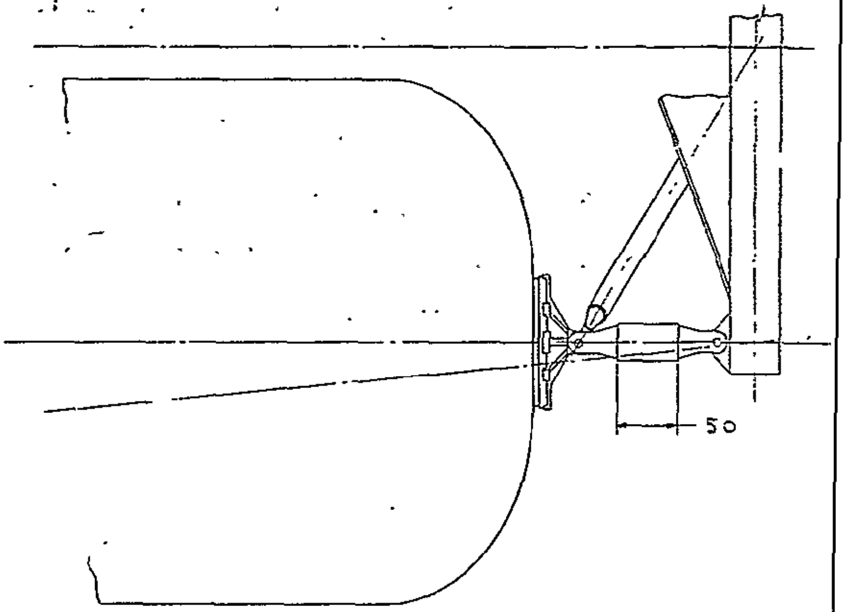
FOLDOUT FRAME 1



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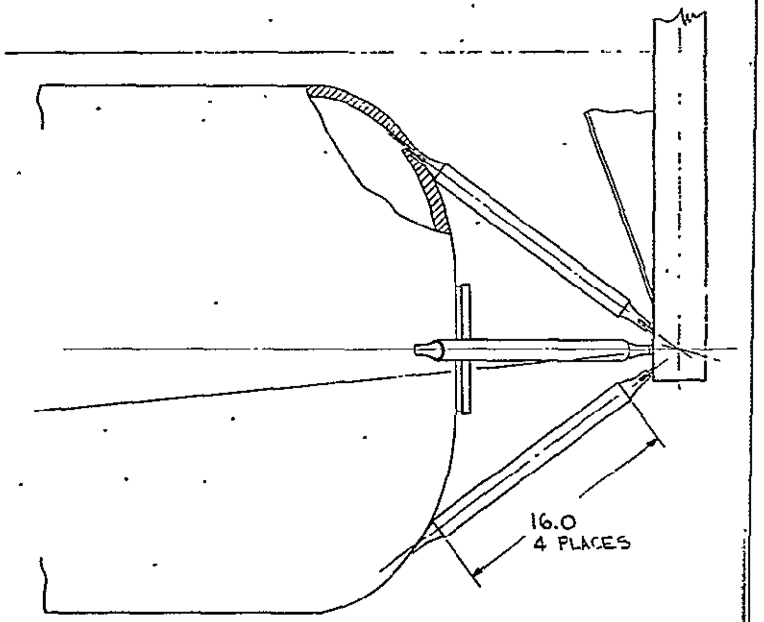

TYPE 3.

1. IDENTIFICATION MARKING PER PR 12 1
TYPE______CLASS______PART NUMBER______

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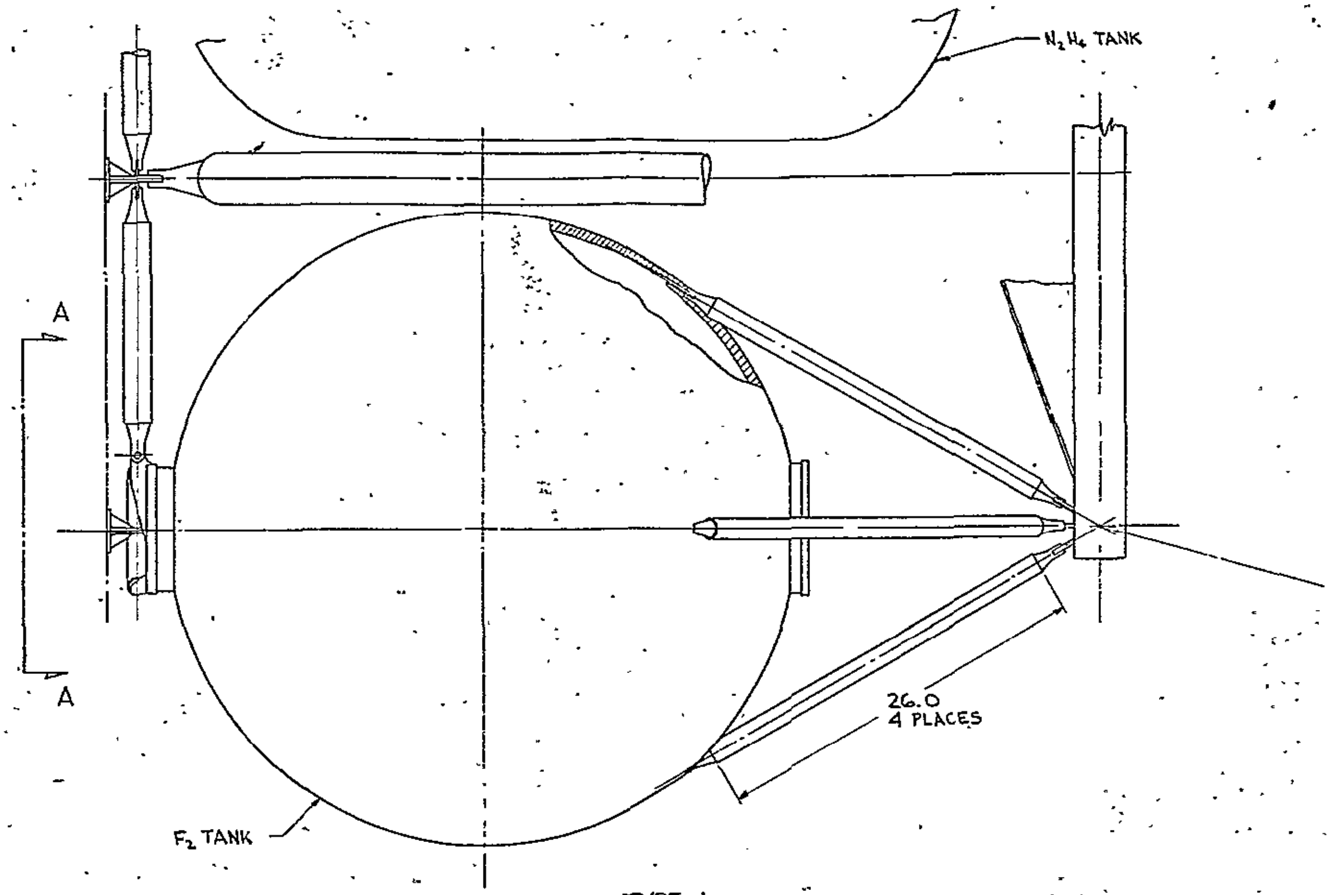

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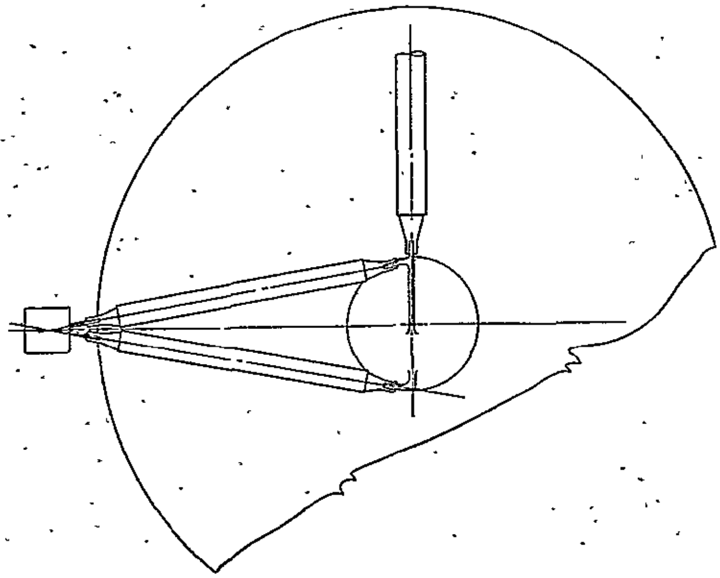

VIEW A-A
TORSION TUBE LAYOUT (TYP)

PAGE 7

CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC

PARTS LIST

QTY REQD PER ASSY • CONFIGURATION

PR 121

APPLICABLE SPECIFICATIONS

DO NOT SCALE DRAWING

DRAWN J. WEDGBURY 15 Ju 75

CHECKED

OTHER APPROVALS

THE FOLLOWING EO'S HAVE BEEN ATTACHED TO THIS PRINT

TRW

F_2 TANK INSULATION -
SUSPENSION SYSTEMS.
N_2H_4/F_2 S.S.P.V.

SIZE E
CODE IDENT NO. 11982
SK 407042
SCALE 1/4

SK 407042

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Table 2-1 shows that the Type 1 support system (see Drawing SK 407042) has the lowest thermal conductance. With that system, an end-to-end temperature difference of, say, 100°F on the struts will result in a heat leak of 0.613 Btu/hr. The type 2 support system which is shown in Section 4.0 to be more practical, has approximately twice this much thermal conductance.

Plumbing to the fluorine tank consists at present of three stainless steel lines. One of these is a 0.75 inch (nominal) inner diameter, 1.14 inch (nominal) outer diameter convoluted stainless steel flex-hose with a wall thickness of 0.013 inch for transporting propellant approximately 38 inches to the rocket engine. Another is a 1/4 inch (nominal) O.D., 0.016 inch wall thickness pressurant line running approximately 40 inches to the pressurant valve panel. The third is a 1/2 inch (nominal) O.D. 0.16 inch wall thickness line running approximately 28 inches to the pressure relief valve. Estimated end-to-end thermal conductances for these three potential heat flow paths are given below in Table 2-2. Cooling coil lines and instrumentation wires were also considered but deemed to be negligible compared to those represented in Table 2-2.

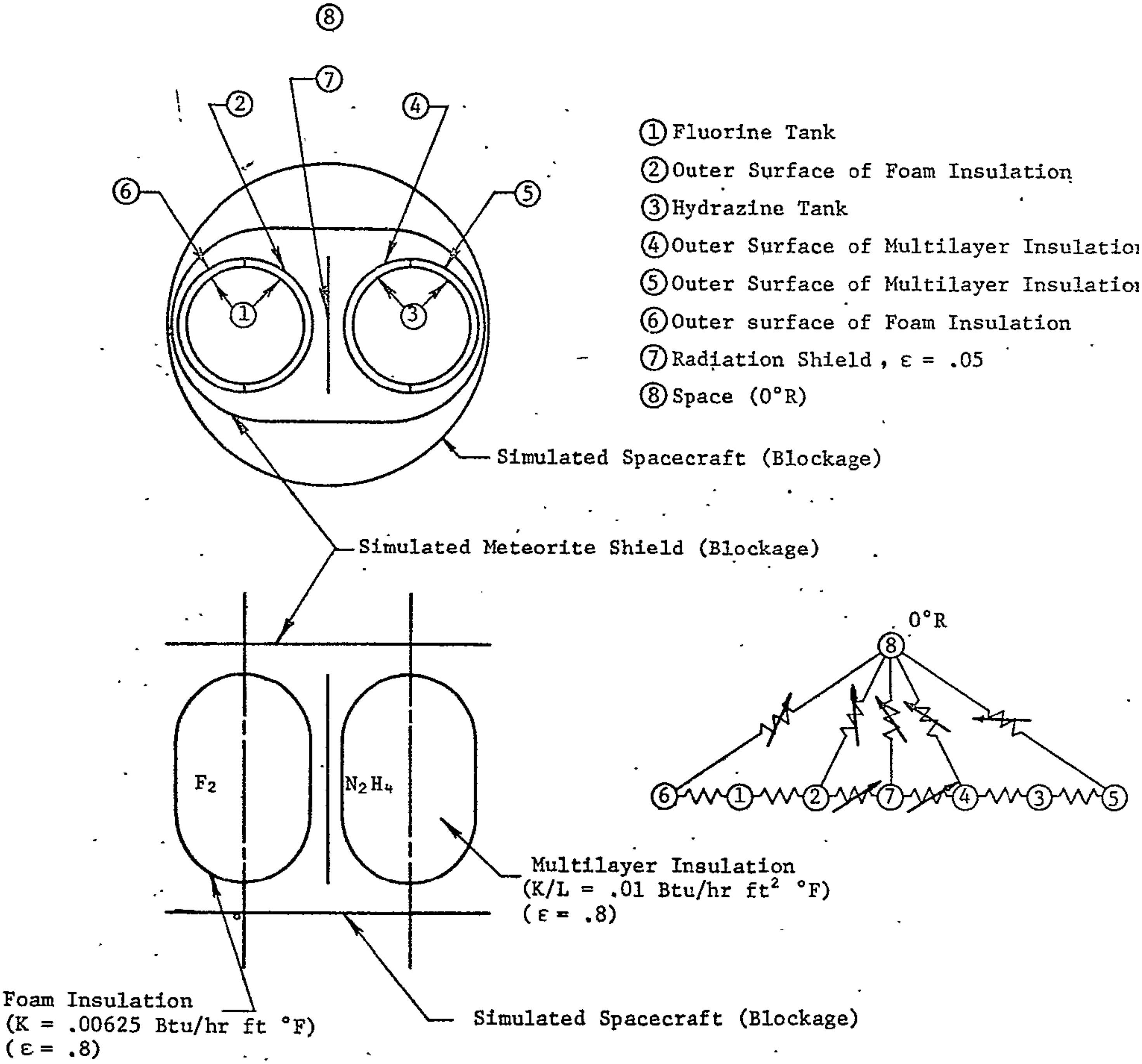
TABLE 2-2. THERMAL CONDUCTANCES OF THE PLUMBING LINES INTO THE FLUORINE TANK

LINE	NOMINAL DIAMETER (inches)	WALL THICKNESS (inches)	EFFECTIVE LENGTH (inches)	CONDUCTANCE* (Btu/hr°F)
Propellant	.95	.013	76	.000425
Pressurant	.25	.016	40	.000240
Relief	.50	.016	28	.000750

*Includes a slight amount of conductance due to gaseous helium conduction (K = .07 Btu/hr ft °F) within each tube.

It can be seen that if the lines are well insulated along their length, they will <u>not</u> present any major heat leak problem even if the valve blocks at the far end are several hundred degrees warmer than the fluorine tank.

Another potential heat leak is thermal radiation from the hydrazine tank. An eight-node analytical model as shown in Figure 2-1 was used to make a preliminary evaluation of this heat path.



① Fluorine Tank
② Outer Surface of Foam Insulation
③ Hydrazine Tank
④ Outer Surface of Multilayer Insulatio
⑤ Outer Surface of Multilayer Insulatio
⑥ Outer surface of Foam Insulation
⑦ Radiation Shield , ε = .05
⑧ Space (0°R)

FIGURE 2-1. EIGHT NODE ANALYTICAL MODEL

The Figure 2-1 network has been solved for various fixed values of fluorine tank temperature (T_1) and various thicknesses of foam insulation (K = .00625 Btu/ft hr °F). The resulting net heat rate ($q = q_{6-1} + q_{2-1}$) into the fluorine tank is presented in Table 2-3. Table 2-4 gives the corresponding results with the radiation shield removed. Negative values of q indicate a net heat loss (to space) by the fluorine tank.

A comparison of Tables 2-3 and 2-4 indicates that insertion of a flat plate radiation shield between the tanks is an effective means of reducing heat input to the fluorine tank, especially at lower fluorine tank temperatures. With the shield in place, the equilibrium temperature (net q = 0) is approximately 100°R regardless of insulation thickness.

TABLE 2-3. NET HEAT RATE INTO FLUORINE TANK DUE TO THERMAL RADIATION†
(Intertank Radiation Shield in Place)

INSULATION THICKNESS (Inches) →	0.75	1.5	3.0
Fluorine Tank Temp., (T_1) (°R)	q (Btu/hr)	q (Btu/hr)	q (Btu/hr)
200	-37.43	-31.35	-24.45
100	0	+ 0.03	+ 0.11
0	+ 2.74	+ 2.74	+ 2.74

†Hydrazine Tank Temperature = 70°F, incident solar flux = 0.

TABLE 2-4. NET HEAT RATE INTO FLUORINE TANK DUE TO THERMAL RADIATION† (Intertank Radiation Shield Removed)

INSULATION THICKNESS (Inches) →	0.75	1.5	3.0
Fluorine Tank Temp., (T_1) (°R)	q (Btu/hr)	q (Btu/hr)	q (Btu/ hr)
200	-19.25	-15.90	-12.33
100	+39.50	+18.45	+12.70
0	+43.10	+43.20	+42.40

†Hydrazine Tank Temperature = 70°F, incident solar flux = 0.

Thus, heat must be added in order to maintain any temperature above 100°R. A heat rate of only 24 to 38 Btu/hr (depending on insulation thickness) will cause the equilibrium temperature to rise to the upper limit for firing (200°R). A simplified transient analysis indicates that this temperature rise would require 4 to 6 months (90% response).

The final potential source of heat input to the fluorine tank that has been considered is direct or reflected solar impingement. This was done by simply applying various amounts of heating to Node 6 (outer surface of the foam insulation) on the existing 8-node analytical model and re-evaluating the net heat rate into Node 1 (the fluorine tank). The results are plotted in Figure 2-2. It is seen that increasing the thickness of the foam insulation will significantly reduce the effect of solar impingement. Even with three inches of foam, however, solar impingement must be avoided or restricted to short periods. For example, suppose one solar constant ($G = 430$ Btu/ft^2 hr) impinges at right angle ($\theta = 90°$). The projected area (A_p) of the fluorine tank for a side-looking sun is approximately 12 ft^2. If the outer surface of the insulation were covered with one layer of second surface silvered Teflon (for minimum and stable α_s/ϵ_H), the <u>surface</u> would absorb the following heat rate:

$$GA\alpha_s \cos\theta = (430)(12)(.1)(1) = 515. \text{ Btu/hr}$$

Figure 2-2 shows that with three inches of foam insulation, this surface heat rate would result in a net heat input rate of about 70 Btu/hr to the fluorine tank. An insulation thickness of 3/4 inch would increase the net heat input rate to about 220 Btu/hr. Based on the previously estimated heat capacity, the latter rate could be sustained for approximately ten days before the upper temperature limit for firing would be exceeded.

To summarize the fluorine tank calculations, it has been shown that conduction type heat leaks due to tank supports and plumbing lines are relatively small compared to heat inputs due to thermal radiation. Radiation input from the hydrazine and helium tanks can be suppressed by flat plate radiation shields to achieve an equilibrium temperature of approximately 100°R in the absence of solar impingement. Maximum solar impingement with a side-looking sun can be sustained for approximately ten days without exceeding the 200°R fluorine temperature limit for firing.

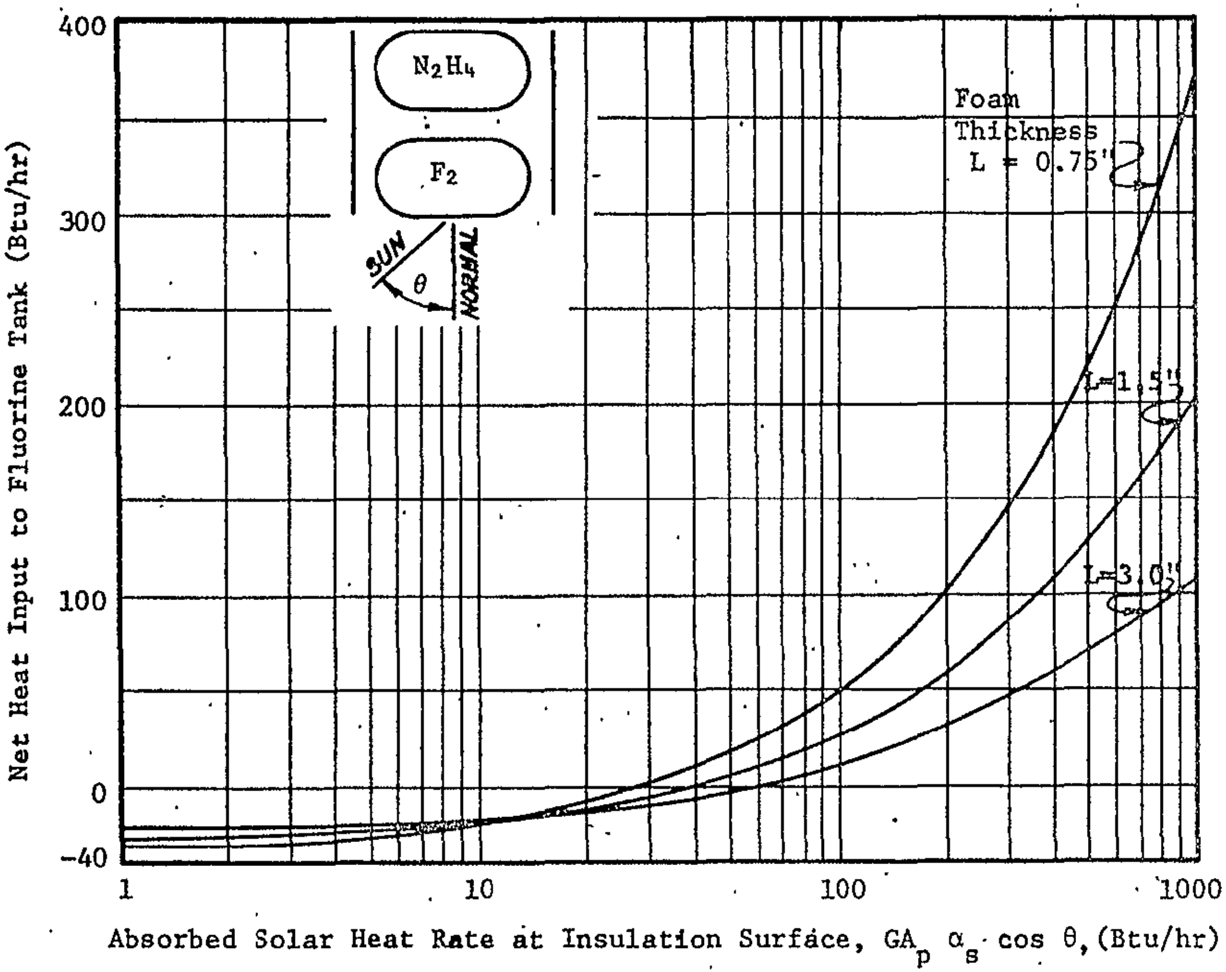


FIGURE 2-2. NET HEAT INPUT RATE TO FLUORINE TANK DUE TO DIRECT OR REFLECTED SOLAR IMPINGEMENT.
(THERMAL CONDUCTIVITY (K) OF THE FOAM = 0.00625 Btu/ft hr °F.)

2.2 CONTINGENCY COOLING OF FLUORINE TANK

Four methods have been considered for increasing the heat rejection rate from the fluorine tank in the event that inadvertent heat leaks from the sun, the RTG, the hydrazine tank, the helium tank, the rocket engine, or the electronics package should cause the fluorine temperature to rise above the maximum desired temperature (200°R). These methods are discussed separately in the following subsections to provide a basis of comparison.

2.2.1 Selective Insulation Removal

During groundhold and the first few hours of flight, the entire surface of the fluorine tank must remain thermally insulated to prevent frost and planetary heating, respectively. Once the S/C leaves the vicinity of Earth, however, heat removal from the fluorine tank could be increased by removing insulation from those areas of the tank surface that are shaded from the sun but have a substantial view of space. This could include perhaps as much as one half of the total surface area of the tank or about 22 square feet. The previously described 8-node analytical model was therefore used to estimate how much benefit could be derived by removing the outboard half (Node 6) of the foam insulation. Table 2-5 shows the resulting heat rejection rate increase due to total removal of three different initial thicknesses of insulation.

TABLE 2-5. INCREMENTAL HEAT REJECTION CAPABILITY GAINED BY TOTALLY REMOVING FOAM INSULATION FROM THE OUTBOARD HALF OF THE FLUORINE TANK SURFACE AREA†

INSULATION THICKNESS (Inches) →	0.75	1.5	3.0
Fluorine Tank Temp. (T_1) (°R)	Δq (Btu/hr)	Δq (Btu/hr)	Δq (Btu/hr)
200	9.83	15.03	20.63
100	0.09	0.17	0.30

†Bare tank surface is assumed to have the same emittance as the foam insulation ($\varepsilon_H = 0.8$).

It is quite clear from Table 2-5 that removing insulation from the fluorine tank does not "buy" a great amount of heat rejection capability at the low temperatures required. In addition, removing the insulation makes avoidance of solar impingement all the more critical.

Due to practical considerations, insulation removal would probably have to be an irreversible process. Thus, it would not be initiated unless the fluorine temperature was approaching its upper limit. Even then, removal might best be done progressively (perhaps 1/3 of the area at a time) so that the terminal temperature at time of burn would not be too cold.

Admittedly, there are some practical problems involved in designing removable foam insulation. There is little doubt, however, that it could be done with negator springs using pyrotechnic or electromechanical release. The entire spring and release assembly would be beneath the insulation to avoid local heat leakage.

2.2.2 Deployable Radiator

A deployable radiator could be used as either an alternative or supplement to the removable insulation approach. Drawing SK 407046 is a conceptual drawing of one type of deployable radiator that has been considered. This particular design consists of several overlapping radiator panels that are spring-loaded to unfold by side rotation (like a carpenter's folding rule) to form a long rectangular radiator. Each joint is designed to provide easy rotation during deployment but to lock solidly for low thermal resistance after deployment. Because of the need for low thermal resistance and weight, cryogenic heat pipes are imbedded within honeycomb panels to form the individual radiator sections.

The thermal heat paths for a deployable radiator of this type can be drawn schematically as follows.

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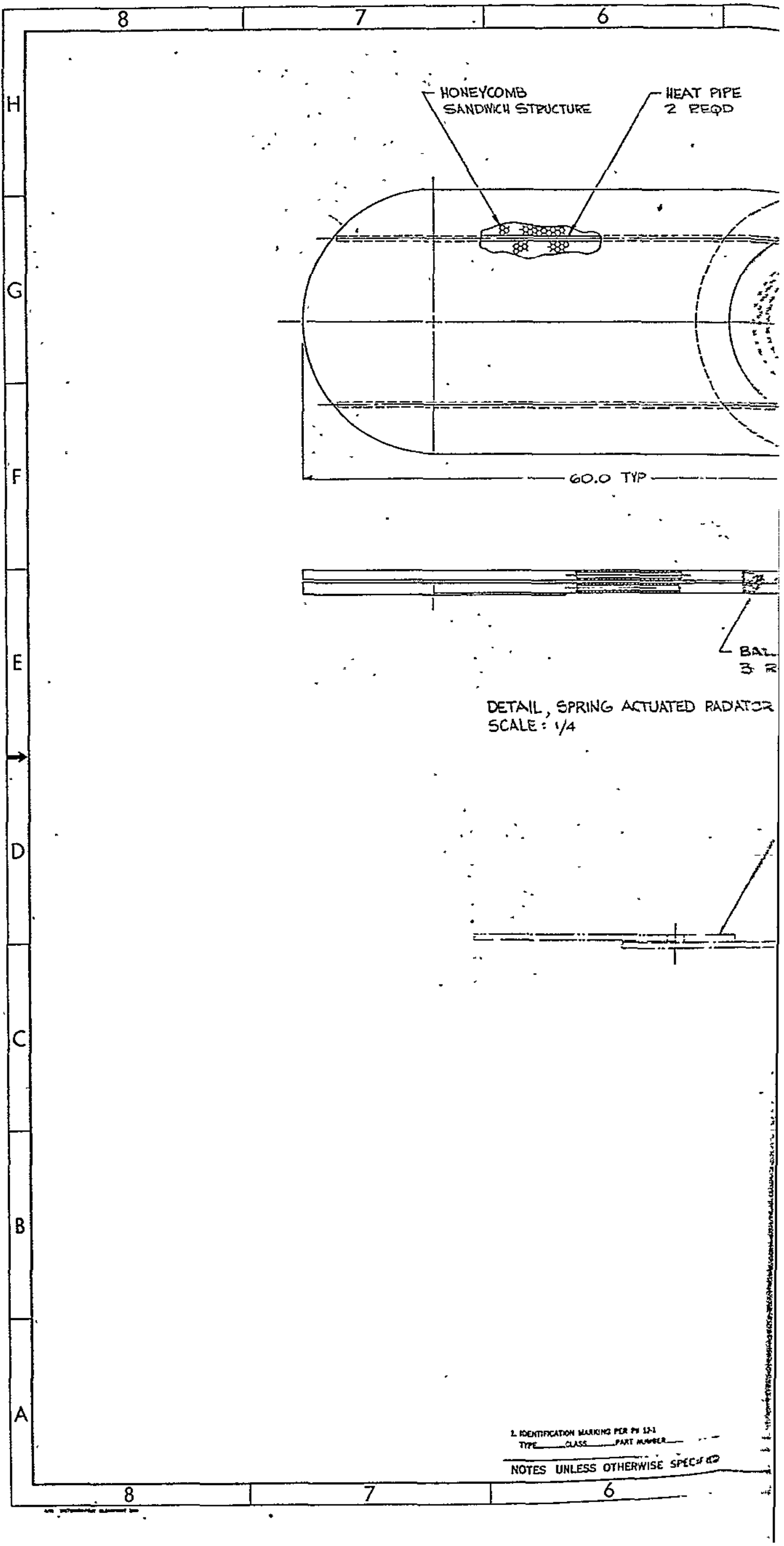

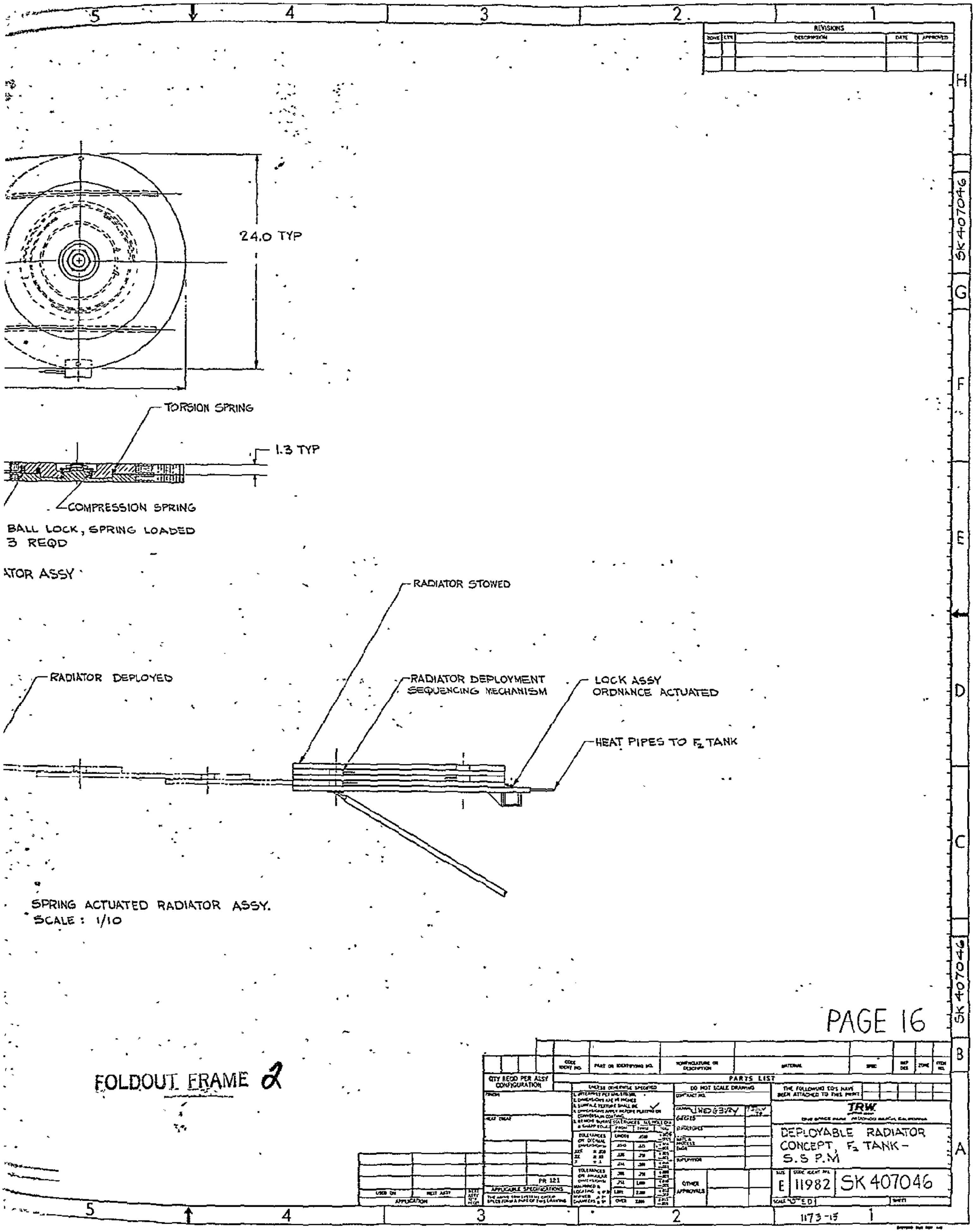

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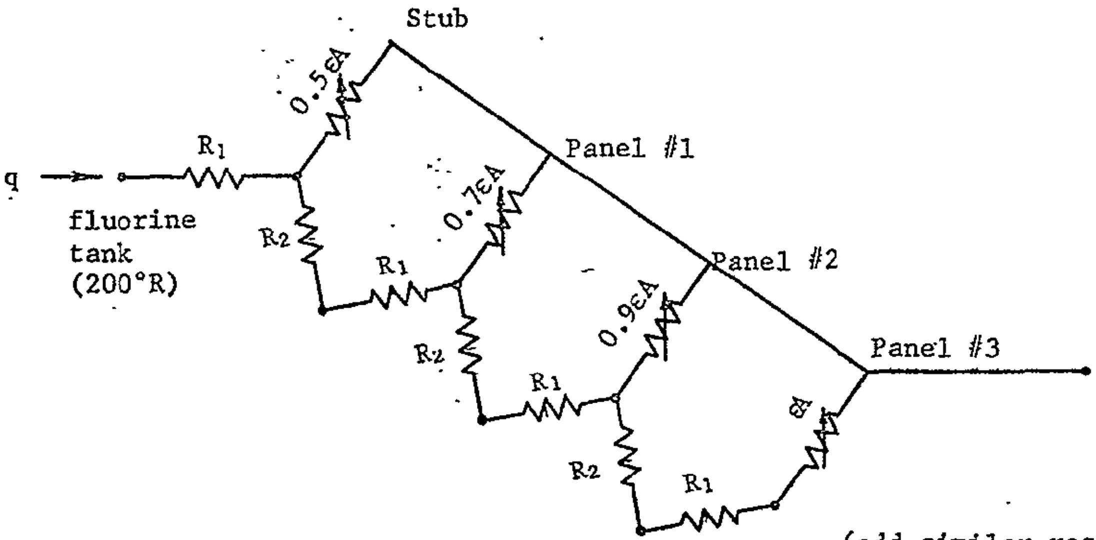
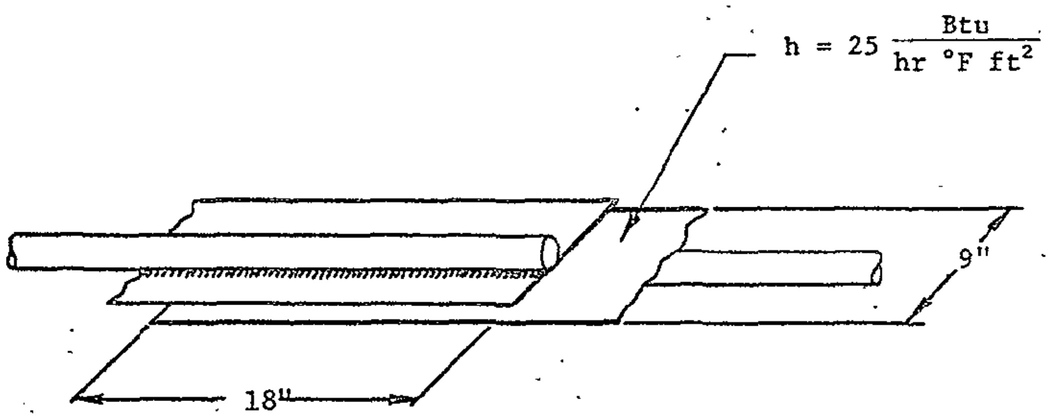


(add similar resistors
for additional panels)

where:

R_1 = heat pipe resistance per section
R_2 = joint resistance per section
q = rate of heat removal from fluorine tank
ε_H = hemispherical emittance of the radiator (0.9)
A = radiator area (single side) per section (6 ft^2)

Preliminary calculations indicate that a 1/2-inch diameter heat pipe with a .010-inch thkck saturated wick, an 18-inch long evaporation section, and an 18-inch long condensing section would impose a thermal resistance (R_1) of about 0.03°F hr/Btu. Two such pipes each attached to separate 25 mil face-sheets and overlapping each other co-linearly by 18 inches as shown below would produce a joint resistance (R_2) of approximately 0.25°F hr/Btu.



Thus, with only one heat pipe per radiator section, the total resistance ($R_1 = R_2$) per section would be 0.28°F hr/Btu. With two parallel heat pipes per section, total resistance ($R_1 + R_2$) would drop to 0.14°F hr/Btu.

An important problem with the deployable radiator is that the radiating surface(s) must be protected (by shades or insulation) from solar irradiance. Ideally, the deployable radiator should be positioned in the spacecraft shadow and edgewise to the sun and should be allowed to radiate from both sides as shown schematically in Figure 2-3. In this position, however, regular off-pointing angle variations (plotted in Figure 2-3) and random ± 5 degree pointing angle uncertainty (parallel to the plane of the paper) would result in exposing the radiator surface to shallow angle solar irradiance at least part of the time. Even if the radiating surface(s) were covered with a low α_s/ε_H coating, such as second surface silvered Teflon, the resulting absorbed solar flux would be unacceptably large (46.2 Btu/hr per panel for only 5 degrees misalignment). To avoid this fate, overhanging edge shades could be added to each panel, but this introduces serious mechanical problems during deployment and reduces the panel view factor to space. A better alternative might therefore be to pitch the deployable radiator 5 or 10° so that the sun never impinges on one side and insulate the sunward side. Figure 2-4 shows the heat rejection rate that can be achieved with typical resistances for a one-sided deployable radiator of this type as a function of the number of radiator panels. Each panel would weigh approximately 6.5 pounds based on

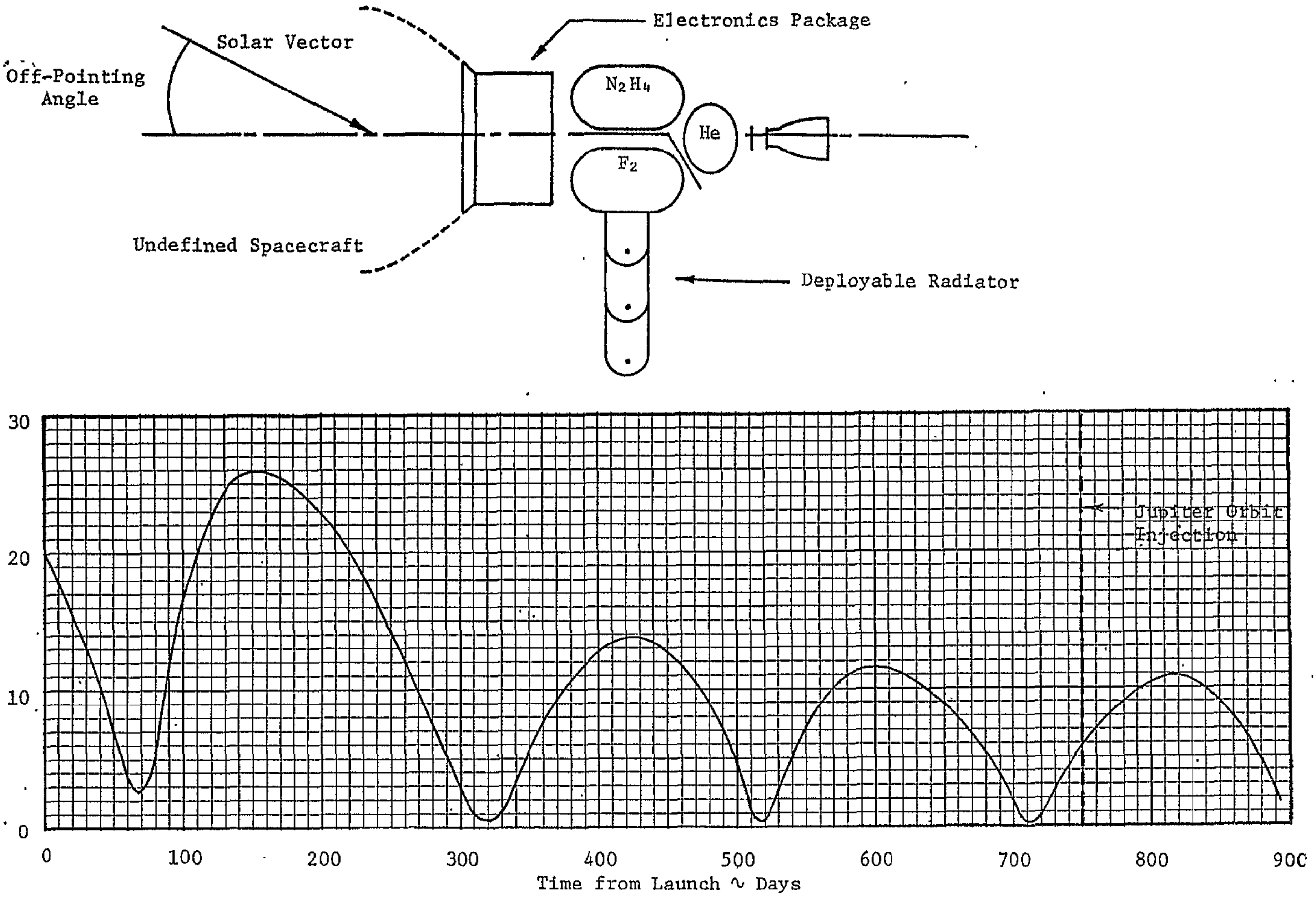


FIGURE 2-3. EXPECTED ANGLE OF SOLAR INCIDENCE

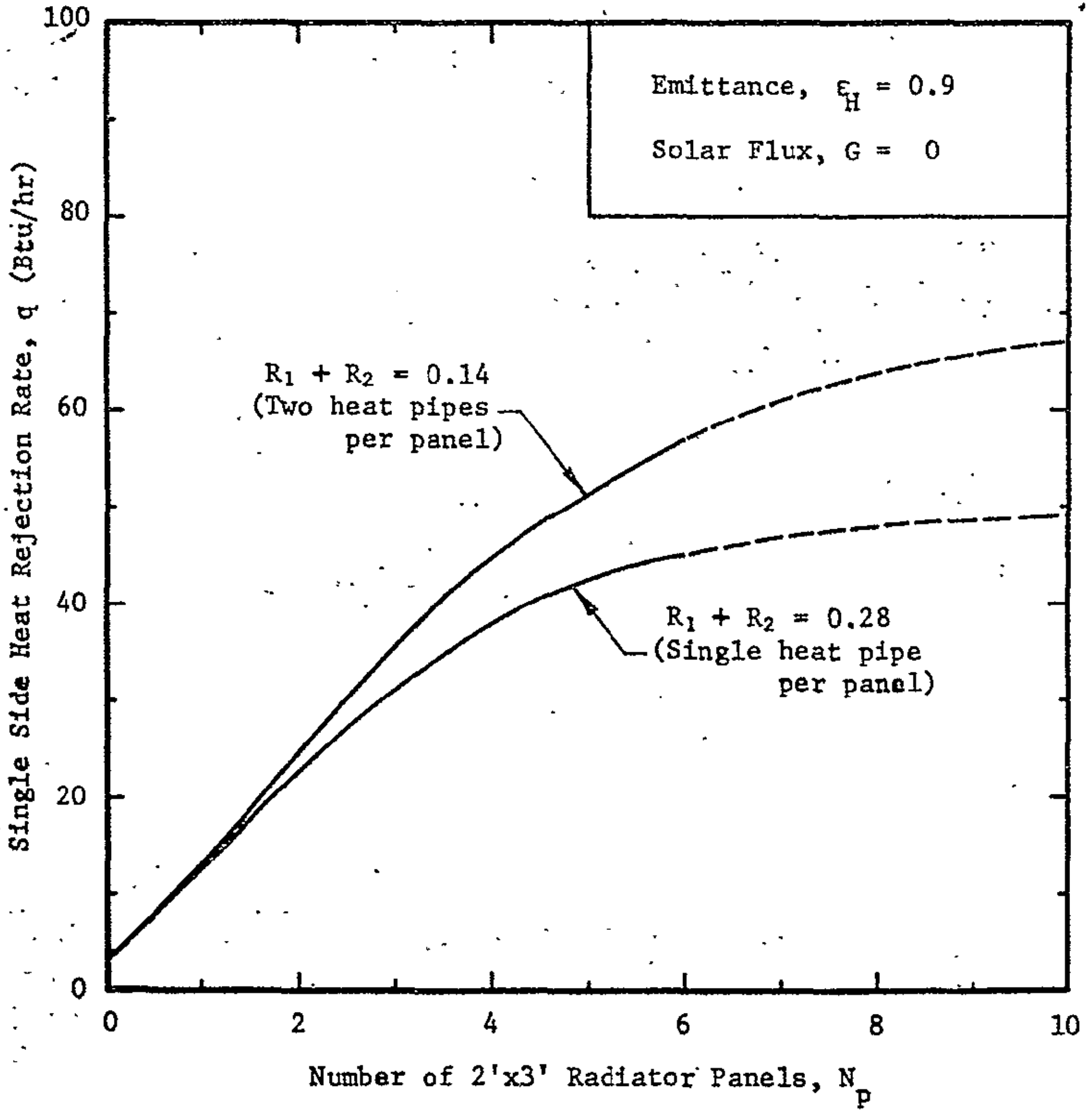


FIGURE 2-4. HEAT REJECTION RATE
FOR A DEPLOYABLE RADIATOR

25 mil aluminum facesheets on both sides. It can be seen that for the particular design considered, the point of "diminishing returns" is reached at approximately the fourth to sixth panel.

The main point to be made here is that at least one method of deploying a space radiator appears to be practical and to have some merit as a means of cooling the fluorine tank. Other deployment schemes such as a flexible roll-out or a laterally hinged fold-out or a telescopic slide-out radiator might prove to be superior to the model discussed here.

2.2.3 Heat Pumps

Four types of heat pumps have been considered for possible use in moving heat from the fluorine tank to a warmer radiator from which it could then be more easily rejected to space. With the possible exception of the Vuilleumier cycle, none appears suitable. A brief discussion of the four types and the reasons why they are unsuitable follows.

Vapor Compression Cycle

Vapor compression cycles require mechanical work to turn the compressor and such work is not available in the present application. In addition, it is doubtful whether the required low temperatures could be achieved by vapor compression even with a cascade system.

Absorption System

Absorption systems use heat as the driving force rather than mechanical work. A refrigerant is alternately absorbed and then liberated by the absorbant. The RTG as presently designed, operates at 960°R and radiates approximately 10,000 watts of heat to space. This heat in principle could be used to drive an absorption type refrigerator or heat pump. Unfortunately, all of the presently known absorption systems require gravity for operation, and most of them use either water-ammonia or lithium bromide-water as the absorbant-refrigerant combination. Thus for the present appoication, a wicking system would have to be developed so as to replace hydrostatic pressure due to gravity with capillary pressure. An absorbant-refrigerant combination would have to be found that would allow the cycle to work at the desired low temperature.

Solid State Cooling

Thermoelectric elements are at present limited by practical considerations to temperatures above 230°R(4). In addition, they require a prohibitive amount of electical power (200 watts to achieve less than 1 watt of refrigeration at 234°R(4)).

Vuilleumier Cycle

The Vuilleumier Cycle is the most promising of the heat pump methods investigated. It is a heat driven refrigeration cycle that is independent of gravity. An experimental model has delivered 5 watts of refrigeration at 135°R(5). That particular model weighed only 18 pounds and required approximately 480 watts of heat from a 1460°R source(5). The refrigerator described in Reference 5 consists of two different sized displacers (pistons) operating at 90 degrees to each other on a common crankshaft pin as shown in Figure 2-5. While pressure differentials are small and rotational speed is low, the fact that moving parts are involved would probably make this system unsuitable for full time use because of the long life requirement. It could perhaps be used intermittently (say, once every six months) to compensate for unexpected heat leakages into the fluorine tank.

AiResearch Manufacturing Company (Torrance, California) is presently developing a Vuilleumier engine which does not have any moving parts. However, the efficiency of that engine is considerably reduced, and the development work is approximately three years from completion.

2.2.4 Expendable Frigerant

This method involves storing another cryogenic fluid for venting through a heat exchanger within the fluorine tank. Required properties for the frigerant are:

(1) Non-corrosive to spacecraft materials so that venting can be tolerated

(2) High heat of vaporization

(3) High weight density

(4) Boiling temperature near the maximum fluorine storage temperature

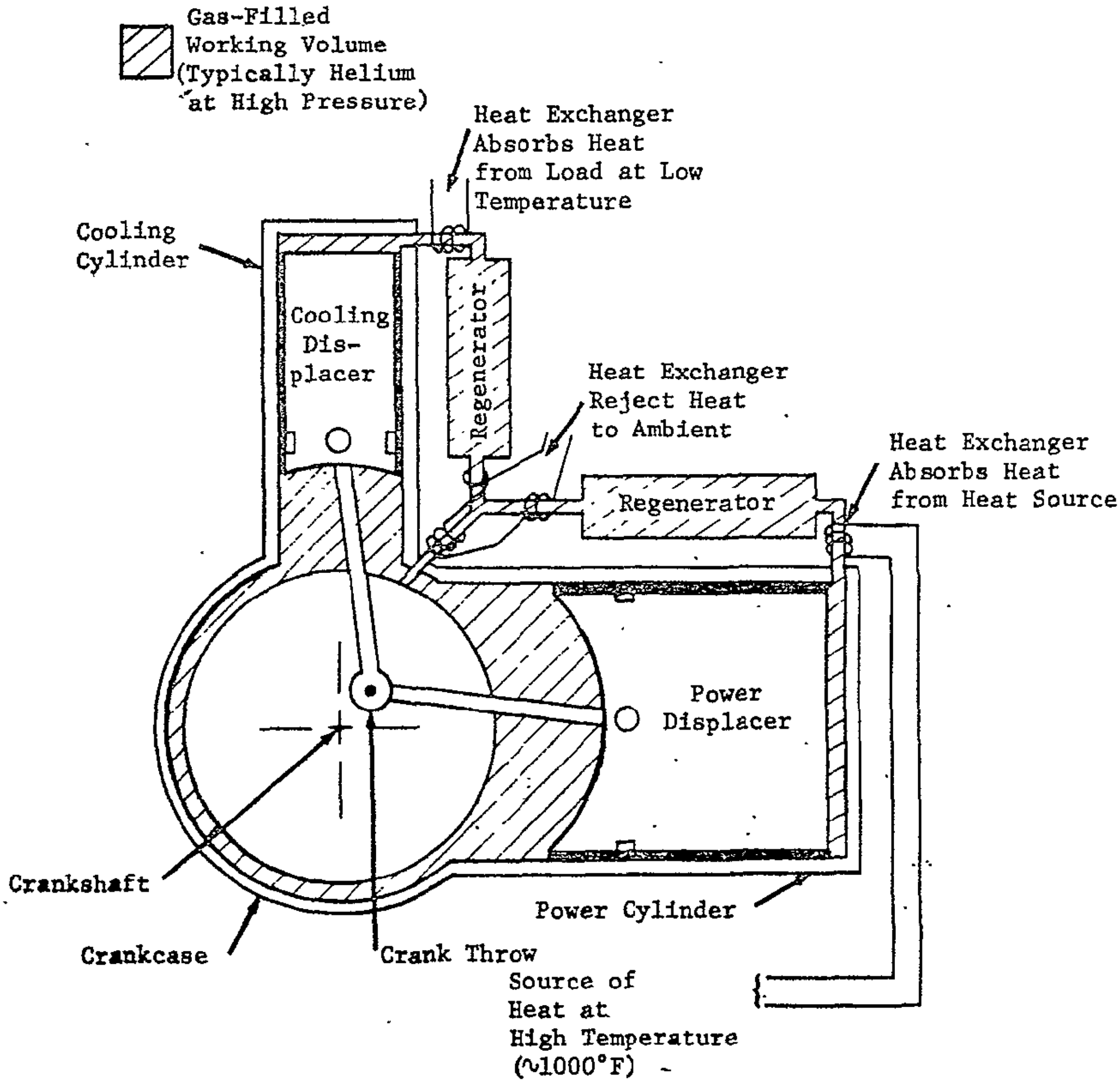


Figure 2-5. Schematic of Basic Vuilleumier Cryogenic Refrigerator

Methane (CH_4) appears to be a relatively attractive candidate. It boils (atmospheric pressure) at 201.4°R, absorbs 219.2 Btu/lb. as it boils, and weighs approximately 26.46 lb./ft^3 (as a liquid). It can easily be seen that a large weight penalty must be accepted in order to achieve any significant amount of cooling by this method. For example, to simply match the 68,830 Btu that can be absorbed by the fluorine and its tank would require:

$$W_{methane} = \frac{68{,}830}{219.2} = 314.\ \text{lbs.}$$

Some additional cooling could be achieved by subcooling the methane to the fluorine freezing point (97°R) before launch. This would place the methane approximately 66.5°F below its own freezing point so that the heat of fusion (25.2 Btu/lb.) could be utilized along with the normal heat capacity associated with temperature rise first as a solid and then as a liquid. The 314 pounds of methane could absorb approximately another 12,000 Btu in this way. Dividing the total heat that can be absorbed by 314 pounds of methane by the total storage time (42,600 hours) gives the average heat leakage rate that could be accomodated by the expendable frigerant.

$$\dot{Q} = \frac{68{,}830 + 12{,}000}{42{,}600} = 1.9\ \text{Btu/hr.}$$

2.3 HYDRAZINE TANK

Thermal control of the hydrazine tank is accomplished by shielding the tank as much as possible from the varying solar flux (430 Btu/ft^2 hr at Earth, 16 Btu/ft^2 hr at Jupiter) and then balancing heat input from the RTG with thermal radiation to space. This is the same basic approach that was used on the OF_2/B_2H_6 module studied under Tasks I, II, and III. However, due to the higher storage temperature of the hydrazine, several alternate methods of transporting heat have been reconsidered. Figure 2-6a shows the most promising passive and semi-passive concepts for transporting heat from the RTG to the hydrazine tank, while Figure 2-6b shows three passive and semi-passive methods of rejecting heat from the hydrazine tank to space. Detailed analyses have not been performed for any of these concepts; that will be done

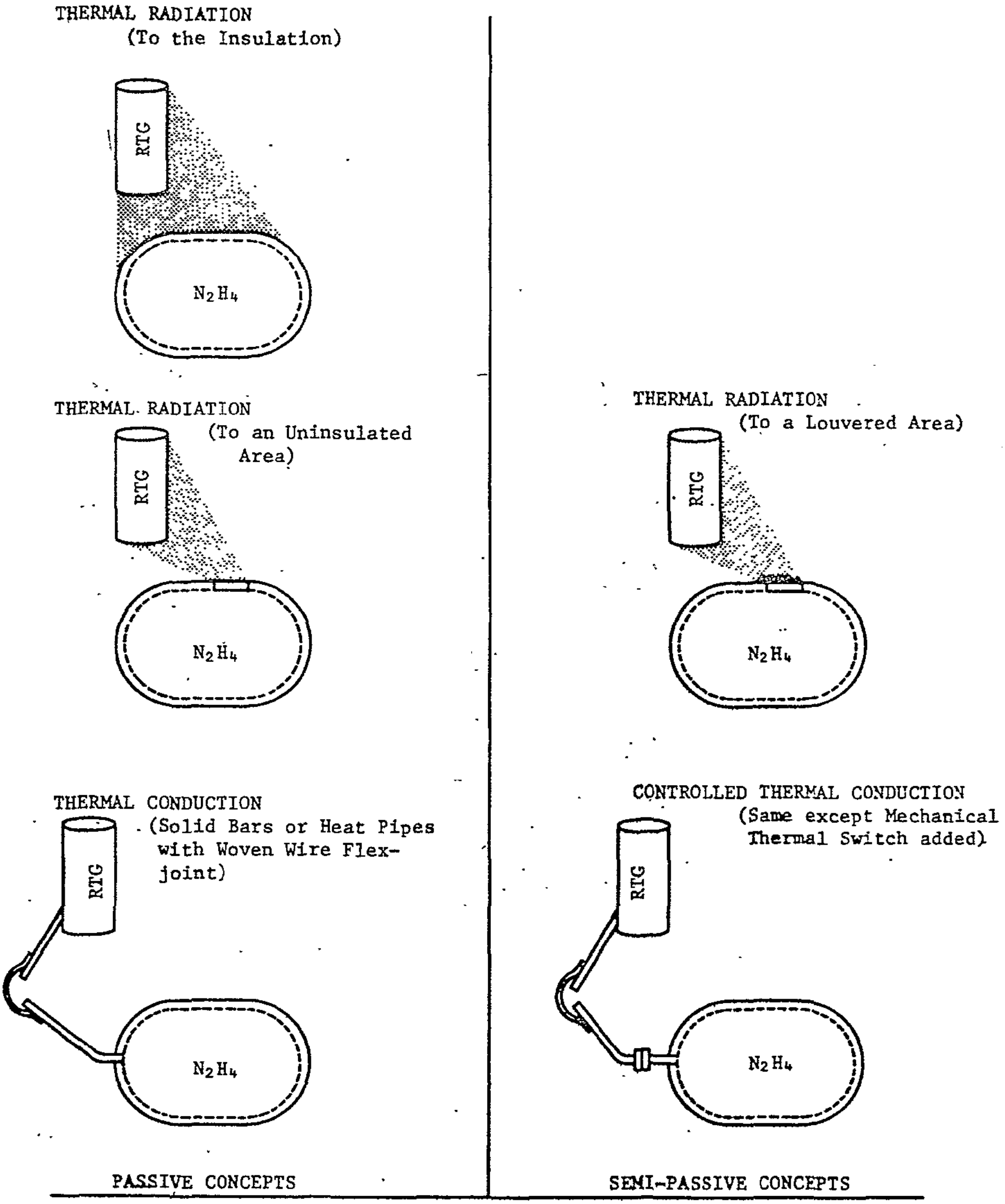
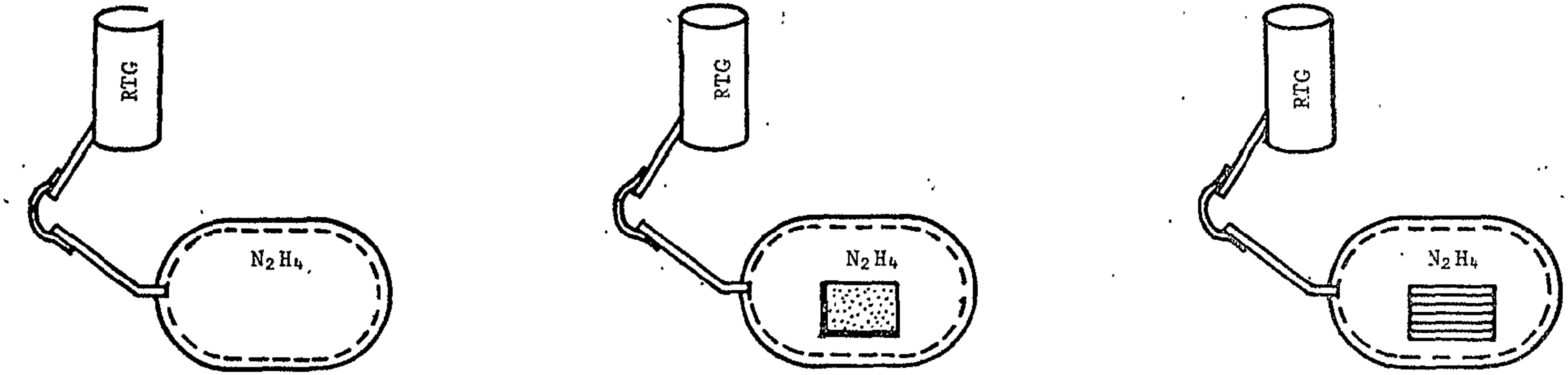


FIGURE 2-6a. CONCEPTS FOR TRANSPORTING HEAT FROM THE RTG TO THE HYDRAZINE TANK

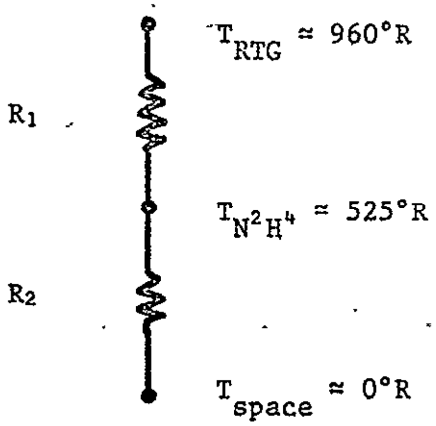


Thermal Radiation from
Fully Insulated Tank
(passive)

Thermal Radiation from
an Uninsulated Area
(passive)

Thermal Radiation from
a Louvered Area
(Semi-Passive)

FIGURE 2-6b. HYDRAZINE TANK TO SPACE THERMAL COUPLING CONCEPTS under Task VII. Based on a simple "voltage divider" network, however, it would appear that a purely passive means of thermal control would require that the RTG temperature not vary more then about twice the allowable variance in hydrazine temperature. To see why this is true, consider the following diagram upon which the nominal temperatures are indicated.



where:

R_1 = overall equivalent thermal resistance between the RTG and the hydrazine tank

R_2 = overall equivalent thermal resistance between the hydrazine tank and space

The resistances R_1 and R_2 can be considered linear over small ranges of temperature change so that by proportion:

$$T_{N_2H_4} = \frac{R_2}{R_1+R_2} \quad T_{RTG} \qquad [2\text{-}1]$$

Differentiating both sides gives:

$$dT_{N_2H_4} = \frac{R}{R_1+R_2} \quad dT_{RTG} \qquad [2\text{-}2]$$

By solving equation [2-1] for $R_2/(R_1+R_2)$ and substituting the result into equation [2-2], one obtains

$$dT_{N_2H_4} = \frac{T_{N_2H_4}}{T_{RTG}} \quad dT_{RTG} \qquad [2\text{-}3]$$

or numerically:

$$\Delta T_{N_2H_4} \simeq \frac{1}{2} \quad \Delta T_{RTG} \qquad [2\text{-}4]$$

Thus if the hydrazine tank must be held to 525°R ± 25°R, a purely passive system cannot be used unless the RTG temperature is approximately 960°R ± 50°R under all conditions.

2.3.1 Passive Systems

Present thinking is that if a purely passive system can be used, the conduction coupling concept between the RTG and the hydrazine tank may be best because of its high degree of predictability and testability. Another major advantage with conduction coupling for this particular application is that the heat input to the hydrazine tank can then be made quite independent of whether or not the RTG is in the stowed or the deployed position. Let us assume for the moment that the helium tank is thermally "clamped" to the hydrazine tank and the entire surface area of both tanks (≈ 62.4 ft^2) is insulated with multilayer aluminized film ($K/L \approx .01$ Btu/ft^2 hr °F). Assume also that the outer several layers are Kapton with the aluminized side out ($\varepsilon \approx .05$) so that neither tank receives significant heat input by thermal radiation from the RTG. Then, if the insulated tanks have an overall view factor to space of, say, 0.75 and the inside temperature is nominal (525°R), the emitted flux to space would be approximately 88 Btu/hr. This is the heat rate that must be transported from the RTG to the hydrazine tank by the conduction bar in order to maintain thermal equilibrium under the assumed conditions. The combined thermal resistance required for the conduction bar, the flex-joint, and the end interfaces is thus:

$$R_1 = \frac{960 - 525}{88} = 5.94 \quad \frac{°F\ hr}{Btu}$$

An allowance of approximately 1 °F hr/Btu should be adequate for the end interfaces and a short woven wire flex strap. This would leave 4.94°F hr/Btu for the conduction bars. Sheet two of drawing SK 406961 shows the total length of the two conduction bars to be approximately 5 feet. Solution of the steady state one-dimensional heat flow equation shows that if the bars were made of 1100 aluminum (K = 128 Btu/ft hr °F), the required cross sectional area would then be:

$$A = \frac{L}{KR} = \frac{5}{(128)(4.94)} = .0115 \text{ ft}^2$$

or:

$$A = 1.66 \text{ in}^2$$

For a circular cross section, this translates into a bar diameter of about 1.45 inches. Total weight for 5 feet of 1.45-inch diameter aluminum bar is approximately 10 pounds A thermally equivalent heat pipe system using 5 feet of 1/2-inch diameter stainless steel tubing with 35 mil wall thickness would weigh approximately 1 pound.

A purely passive system utilizing thermal radiation rather than conudction as the coupling agent between the RTG and the hydrazine tank has been briefly examined using the eight node analytical model shown in Figure 2-7. The model was run repeatedly each time varying either the uninsulated tank area (A_4) or the view factor (F_{41}, from the uninsulated area to the RTG) to obtain the results plotted in Figure 2-8. For convenience, it was arbitrarily assumed that the view Factor F_{21} from the insulated area (Node 2) to the RTG was equal to F_{41}. This is not a necessary condition, but it could be easily achieved if desired. It can be seen in Figure 2-8 that for a given view factor, varying the amount of uninsulated area has little effect on the equilibrium temperature of the hydrazine unless the exposed area falls below approximately four square feet. The reason for this is that the total heat rate radiated to space by the tank is dominated by the uninsulated area if that area is on the order of four square feet or greater. Thus, doubling the exposed area under this condition doubles not only the heat input rate from the RTG but also the heat rejection rate to space. With less than about four square feet of exposed area, radiation

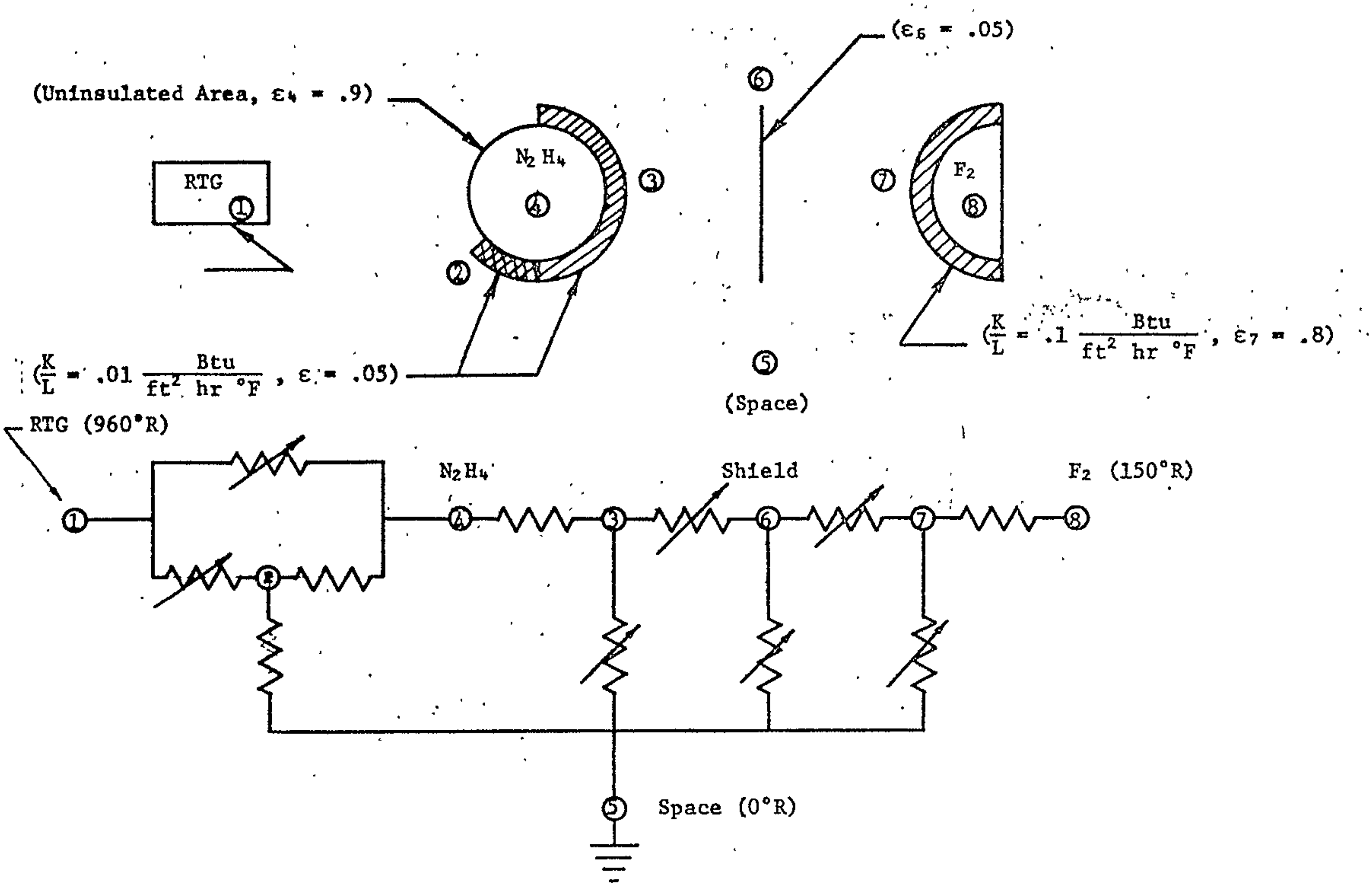


FIGURE 2-7. EIGHT NODE THERMAL RESISTANCE NETWORK
FOR ANALYZING THE RTG TO HYDRAZINE TANK THERMAL RADIATION COUPLING

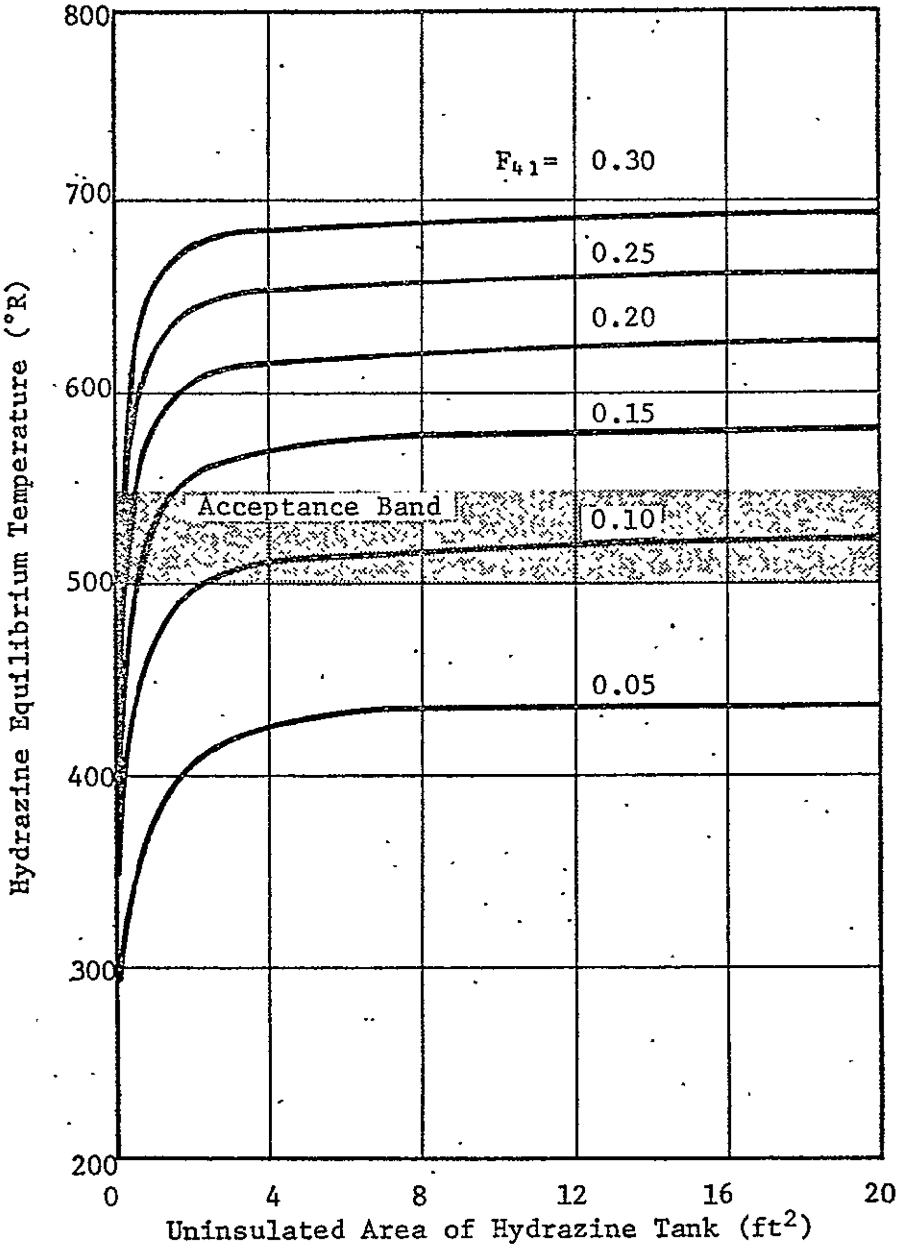


FIGURE 2-8. EQUILIBRIUM TEMPERATURE OF THE HYDRAZINE TANK WITH THERMAL RADIATION COUPLING TO THE RTG. PARAMETER F_{41} IS THE VIEW FACTOR FROM THE UNINSULATED TANK AREA TO THE RTG.

from the large insulated area accounts for a large part of the total heat rejection rate to space so that a change in exposed area still has a significant effect on the heat input rate but not on the heat rejection rate. The important conclusion that can be drawn from Figure 2-8 then is that in the absence of solar impingement on the uninsulated area and with a stable 960°R RTG temperature, the hydrazine equilibrium temperature can be passively maintained within the required limits (500 - 550°R) by providing approximately four square feet of uninsulated area with this area having a view factor to the RTG of approximately 0.1.

Since a fully insulated tank offers maximum protection against inadvertent solar impingement, some of the data (for $A = 0$) from Figure 2-8 has been cross-plotted in Figure 2-9 to show more clearly how the hydrazine equilibrium temperature is related to the view factor (F_{21}) for a fully insulated tank. It can be seen from Figure 2-9 that a view factor of approximately 0.6 would be required in order to maintain the nominal hydrazine equilibrium temperature with only thermal radiation coupling and a fully insulated tank. If the RTG and the hydrazine tank are characterized as parallel cylinders of infinite length and zero separation (external tangential contact) with respective diameters of 10 and 34 inches, the maximum possible view factor F_{21} from half the tank (Node 2) to the RTG is approximately 0.15. Radiation coupling between the RTG and the hydrazine tank is therefore an unworkable concept if the hydrazine tank is fully insulated.

2.3.2 Semi-Passive Systems

If variable resistance is required in order to maintain the hydrazine tank within temperature limits, the advantages of the conduction coupling concept are not as clear cut. For one thing, thermal switches are not as well developed as louvers, so if conduction coupling were used it would probably be used in the same manner as described previously for a purely passive system but with a louver system added as shown in Figure 2-6b to provide variable emittance to space. The thought occurs, therefore, that if a louver system is to be used, it may as well face toward the RTG as shown in the upper right hand corner of Figure 2-6a to provide variable thermal radiation coupling and thus eliminate the need for conduction coupling.

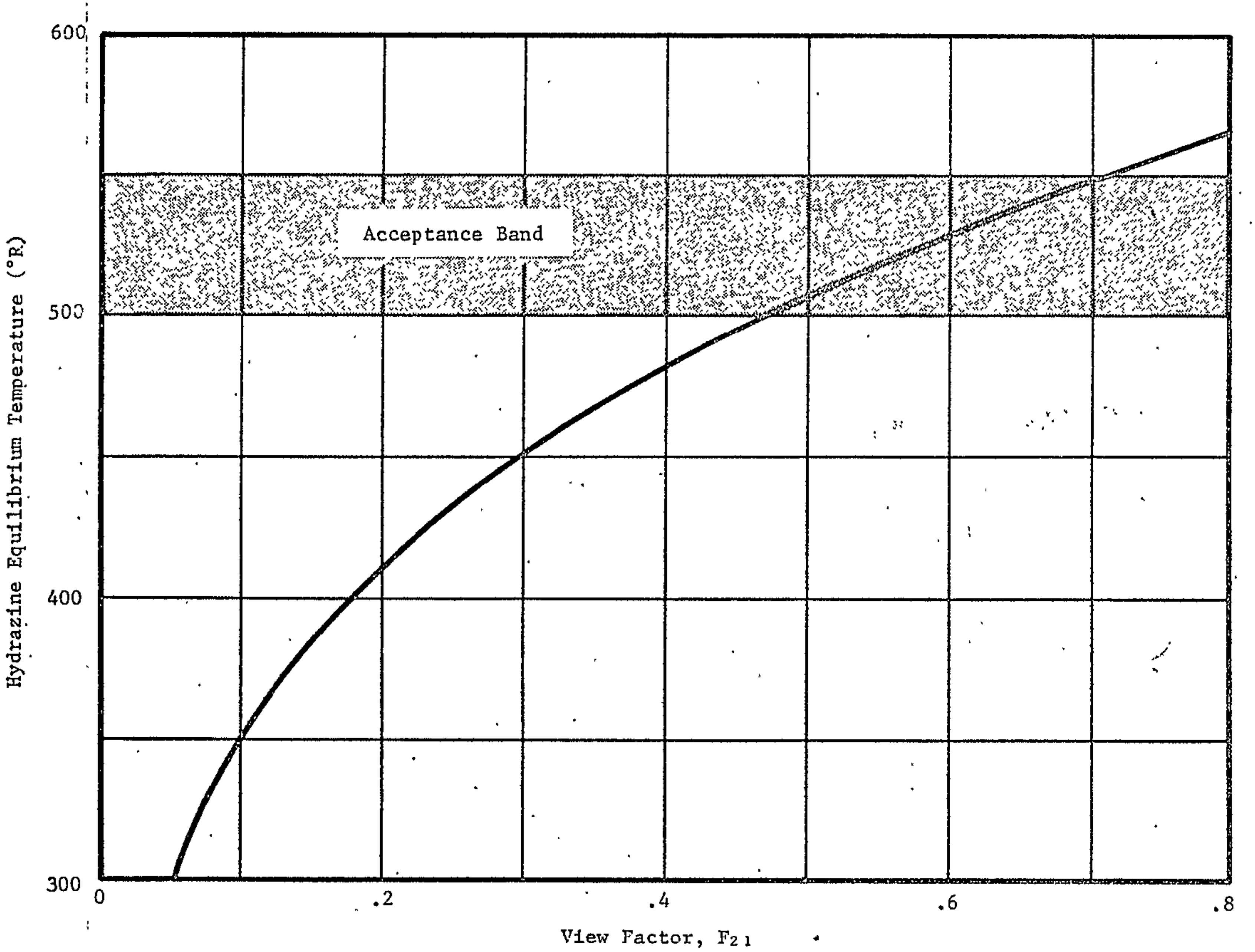


FIGURE 2-9. HYDRAZINE TEMPERATURE WITH A FULLY INSULATED TANK AND THERMAL RADIATION COUPLING TO THE RTG.

Since varying the louver opening is in effect the same as varying the uninsulated area, some insight into how well this system might work can be obtained by reconsidering Figure 2-8, which is based on a constant emittance of 0.9. Note that with a view factor (F_{41}) of 0.15, the hydrazine equilibrium temperature can be changed from the upper acceptance limit to the lower acceptance limit by reducing the uninsulated area from approximately two square feet to approximately one square foot. In other words, an area (or effective emittance) ratio of only 1:1 can produce 50°F or more change in temperature under the realistic conditions assumed. Louvers (with inward facing blades for solar rejection) can currently achieve effective emittance variation between 0.13 and 0.72 for an open-to-closed ratio of abour 5:1. It would appear, therefore, that a 2- to 3-square foot panel of louvers with a view factor to the RTG of 0.15 could provide significant compensation for any uncertainty or variance in the RTG temperature, solar impingement, or insulation effectiveness.

2.4 HELIUM TANK

Current thinking is that from a thermal point of view the helium pressurant gas should be stored at a temperature somewhere near that of the hotter propellant (hydrazine). The reasoning is that if the helium were stored at or near the cold propellant temperature (100°R - 200°R), the expansion that would occur after the cold helium is injected into the warm tank might cause over-pressurization. Therefore, it is felt that the helium tank should be thermally close-coupled to the warm hydrazine tank. Since both tanks are to be insulated against radiation to space, the inter-tank coupling will probably have to be done by conduction. In the case of the previous OF_2/B_2H_6 module, conduction coupling was provided by a light weight aluminum beam. However, the higher fuel tank temperature required for the present F_2/N_2H_4 module will increase the heat loss rate to space and thus will require lower resistance coupling for a given temperature difference between tanks. Figure 2-10 shows a plot of the estimated helium tank equilibrium temperature as a function of conductor weight based on an assumed path length of 2 feet, a hydrazine tank temperature of 530°R, and an insulated helium tank (K/L = .01 Btu/hr °F ft , $\varepsilon_{outer} = .05$, $F_{He\text{-}space} = 0.5$).

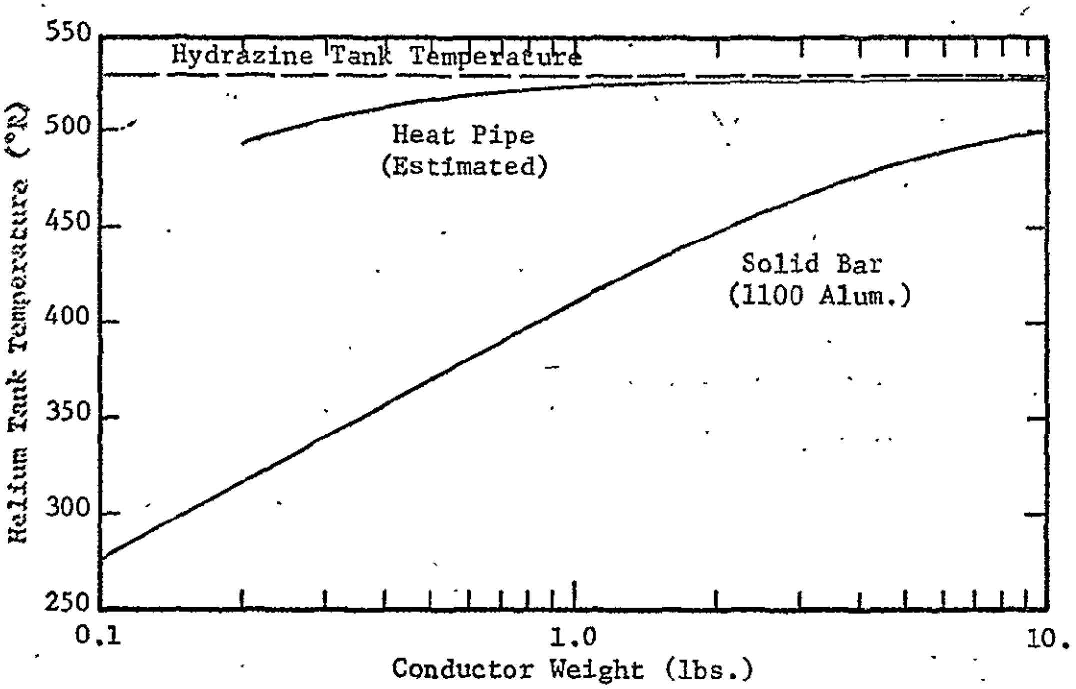


FIGURE 2-10. WEIGHT TRADE-OFF FOR CONDUCTION COUPLING BETWEEN THE HYDRAZINE AND HELIUM TANKS

It is doubtful at present whether there is any significant penalty in allowing the helium tank to remain at a temperature of, say, 400°R. If that is true, then it can be seen from Figure 2-10 that a heat pipe coupling system offers less than 1 pound weight advantage over solid conduction for this particular coupling application. Because of tank weight and size considerations, it would be advantageous to store the helium at a lower temperature, such as 180°R. This can be accommodated with a high resistance thermal coupling, but the increased RC time constant would make thermal control much more difficult, particularly if solar impingement occurs on the helium tank.

2.5 GROUNDHOLD THERMAL CONTROL

All of the comments made prior to this point have dealt with flight thermal control. There is, of course, the problem of keeping the fluorine cold during the groundhold phase. In addition, as intimated in the comments concerning the ability to accommodate sun heating, it may be highly desirable to launch with the fluorine in a highly subcooled state (approximately 100°R).

Because of the lower temperatures of fluorine, it is impractical or impossible to use LN_2 as the coolant, as can be done in the case of OF_2/B_2H_2, unless the liquid nitrogen is substantially subcooled or is reduced in temperature by lowering its pressure. From a practical point of view, both of these methods of lowering the temperature of LN_2 are impractical. This leads to the conclusion that either cooled helium or hydrogen must be used as the coolant. From a safety point of view, it is not wise to attempt circulating hydrogen directly inside the fluorine tank. Therefore, helium should be the coolant and the helium could be cooled either by an external helium cryostat or a helium/LH_2 heat exchanger.

Based upon calculations performed during Task III(3), the normal heat transfer to the fluorine tank during groundhold can be expected to be approximately 4,000 Btu/hr. To compensate for this heating, approximately 80 lbs/hr of helium at 40°R would be required as the coolant. Assuming the helium is cooled by LH_2, 4 ft^3/hr of liquid hydrogen would be vaporized.

An internal cooling coil similar to that used in the OF_2/B_2H_6 module would be required, but in this case, the length of the coil would have to be substantially larger because of the lower film coefficient between the coolant and the tube wall and because of the lower temperature differential between the coolant and the propellant. Based upon the analysis reported in Task III, this coil would have to be approximately 100 ft. in length in order to reduce the fluorine temperature to 100°R. This is mechanically feasible and does not add a prohibitive amount of weight.

The main problem encountered in cooling the fluorine during groundhold may be that of preventing the coolant from picking up substantial quantities of heat in the line run from the coolant heat exchanger to the propellant tank. There is no doubt that this line would have to be vacuum jacketed.

One additional point should be noted. The thermal baseline design does not include any louvers. For groundhold thermal control, this is an advantage, since removable louver insulation is not required.

3.0 · PROPULSION SYSTEM DESIGN

The propulsion system is comprised of three types of equipment: engine, tanks, and plumbing. In compliance with customer direction, little attention has been given the engine configuration. The engine shown in the layout is the same as for the OF_2/B_2H_6 module except for the addition of a helium heat exchanger. Table 3-1 summarizes the propulsion system design guidelines.

Boron filament-wound tankage with 10-mil thick aluminum liners are shown in the layout. These are sized for an internal volume of 1.1 times the volume of 1808 pounds of fluorine at 180°R. Keeping both tanks equal in volume (per the Work Statement) provides over 28% ullage in the fuel tank, which would allow the mid-course firings to be made in a blowdown mode if so desired. The baseline helium tank is sized to contain 36 pounds of helium gas at 4,000 psia and 180°R. An eccentricity of approximately 0.784 was maintained in all the spheroidal elements of the tankage.

Figure 3-1 is the schematic diagram of the baseline overall propulsion system fluid circuit. Since the previous version, there have been two changes made. A check valve has been inserted in the hydrazine tank pressurization line to prevent hydrazine from entering the heat exchanger. This is necessary to eliminate the potential hazard of explosive decomposition of hydrazine in the heat exchanger when it gets hot after engine shutdown. Two bleed valves have been added just upstream of the propellant valves on the engine so that the feedlines may be cleaned and passivated. Mass estimates in this report reflect these changes.

Component parts are represented in the layout by blocks for each case where a JPL-approved design is lacking. Component locations are similar or the same as those shown for the OF_2/B_2H_6 SSPM. A panel mounted beside the tank contains the helium squib valves, the filter, regulator and solenoid-operated helium valves. Propellant tank vent and relief valves are located on small panels adjacent to the tops of the respective propellant tanks. Below each tank near the outlets are clusters of components consisting of the fill, isolation, return relief and check valves, plus the filters.

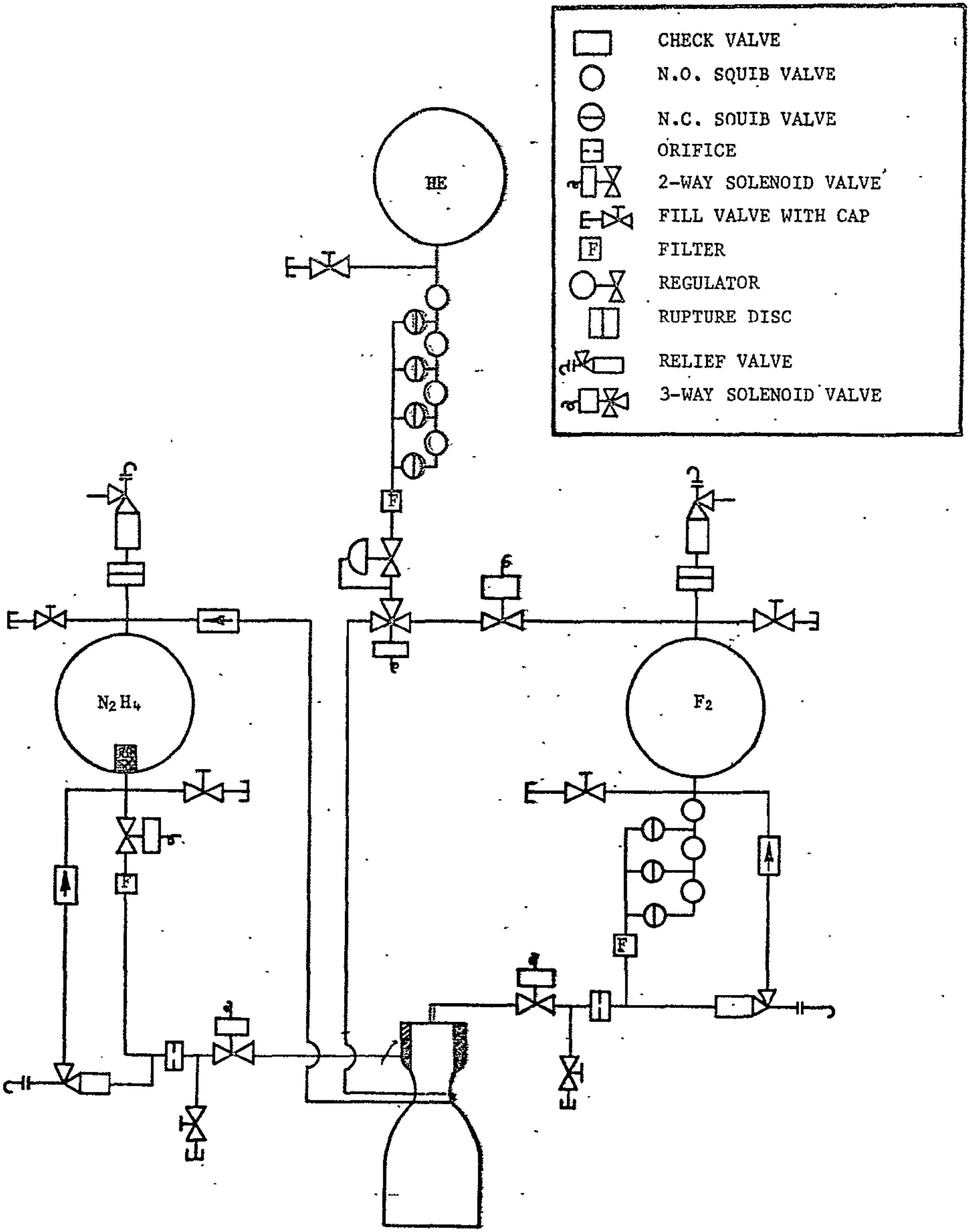


FIGURE 3-1. SCHEMATIC DIAGRAM OF F_2/N_2H_4 SPACECRAFT PROPULSION SYSTEM

Mixture ratio trimming orifices are located at the propellant valve inlet port flanges where the flexible (convoluted metal hose) feedlines attach to the valves.

Tubing runs are all assumed to be type 321 stainless steel with butt-welded joints. With this construction, very high quality joints can be made with wall thickness down to 0.016 inch or less. Helium flow rates are low enough to permit the use of 1/4-inch nominal tubing based on keeping the steady state Mach number below 0.1. For the high pressure section upstream of the regulator, a wall of 0.028 inch is adequate, and downstream all of the tubing could be 0.016 inch. Fill and vent line sizes have been arbitrarily set at 1/2-inch nominal size. Engine feedlines of 3/4-inch nominal size result in fluorine flow velocities below 8 ft/sec and hydrazine velocities below 6 ft/sec (assuming reasonable wall thicknesses and tolerences). If 1/2-inch feedlines were used, the velocities would be below 20 ft/sec and 15 ft/sec, respectively.

TABLE 3-1. PROPULSION SYSTEM DESIGN GUIDELINES

Mixture Ratio	2.0
Chamber Pressure	100 psia
I_{SP}	385
Thrust	1,000 lb_f
Propellant Temperature Limits	
Fuel	530^{+20}_{-30} °R
Oxidizer	$155 \pm {}^{25}_{55}$ °R
Pressurant	Helium
Pressurant Initial Pressure	4,000 psia @ 180°R
Propellant and Helium Tanks	Boron filament-wound with 0.010 aluminum liner
Propellant tank volumes (equal volumes)	1.1 x propellant volume
Propellant Tank pressure	300 psia
Oxidizer mass	1,735 + 73 (residuals) lb_m
Fuel mass	984 + 37 (residuals) lb_m
Pressurant mass	36 lb_m @ 155°R

4.0 STRUCTURAL DESIGN

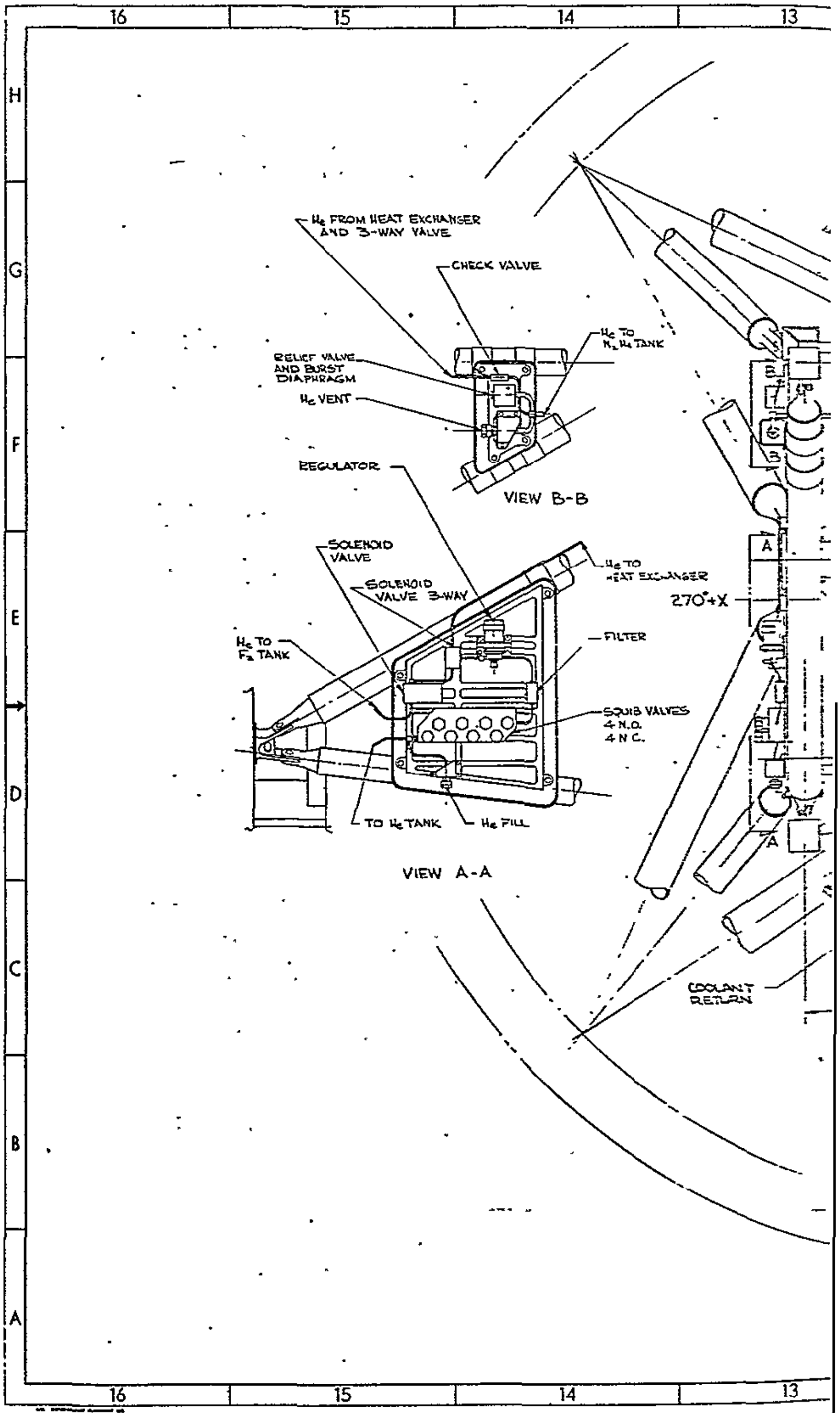
4.1 STRUCTURAL BASE LINE CONFIGURATION

The initial design utilizes an arrangement of components and structure is similar to the one utilized for the OF_2/B_2H_6 system described in the Tank II report. This is referred to as the structural baseline configuration and is shown by drawing SK 406922. Structural members have been moved to the extent necessary to accomodate the different propellant and pressurant tank sizes and to account for the center of gravity change dictated by the change in relative propellant weights. As for the previous design, the C.G. of the propellants is located along the centerline of the spacecraft so that under nominal conditions, no lateral C.G. shift will occur as propellants are consumed. Structural materials are the same as in the Task II design with the exception of the transverse beam that supports the three tanks. Whereas the entire beam was aluminum to provide thermal coupling between the tanks, it is now made in two parts. The section that connects the N_2H_4 tank and the pressurant tank is aluminum to provide good thermal conduction between those tanks, while titanium is used between the F_2 tank and pressurant tank to minimize heat transfer between them.

The loads in each structural member were calculated and the required size determined in order to obtain a reliable weight estimate. Table 4-1 presents a weight breakdown for the baseline design. Weight differences for possible modifications (discussed below) are given in Table 4-2. An overall weight comparison for several configurations is then made in Table 4-3.

4.2 BASELINE CONFIGURATION PLUS HEAT PIPE

This concept utilizes a heat pipe to transfer heat from the RTG to the N_2H_4 tank as shown by drawing SK 406961. The RTG is shown in a relocated position on the N_2H_4 tank side of the spacecraft to prevent heat radiation to the F_2 tank. Although the heat pipe installation shown assumes an RTG deployment arrangement that is actually undefined at present, it would appear that the system has sufficient design flexibility to be adaptable to any other arrangement without imposing severe constraints.



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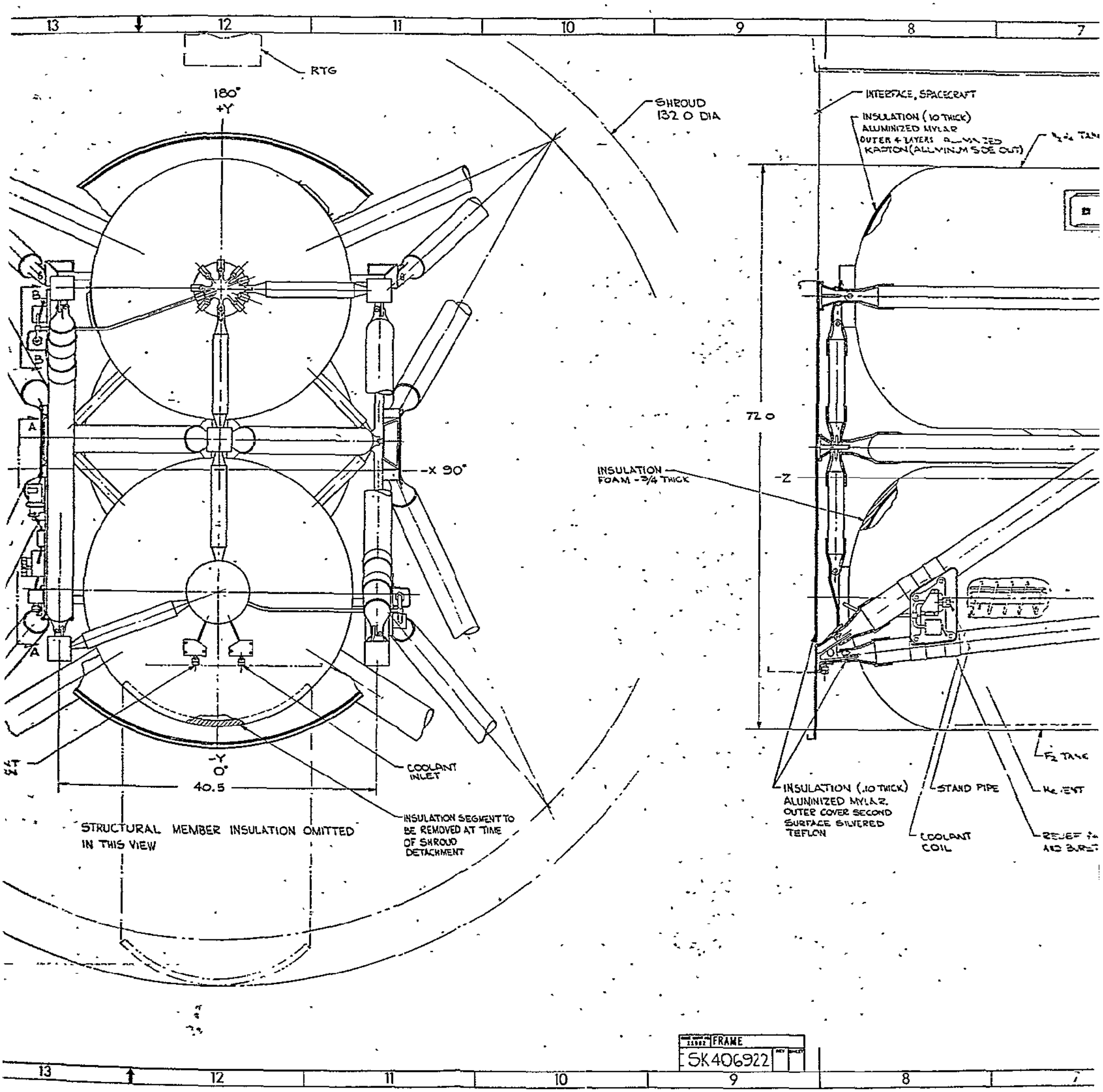

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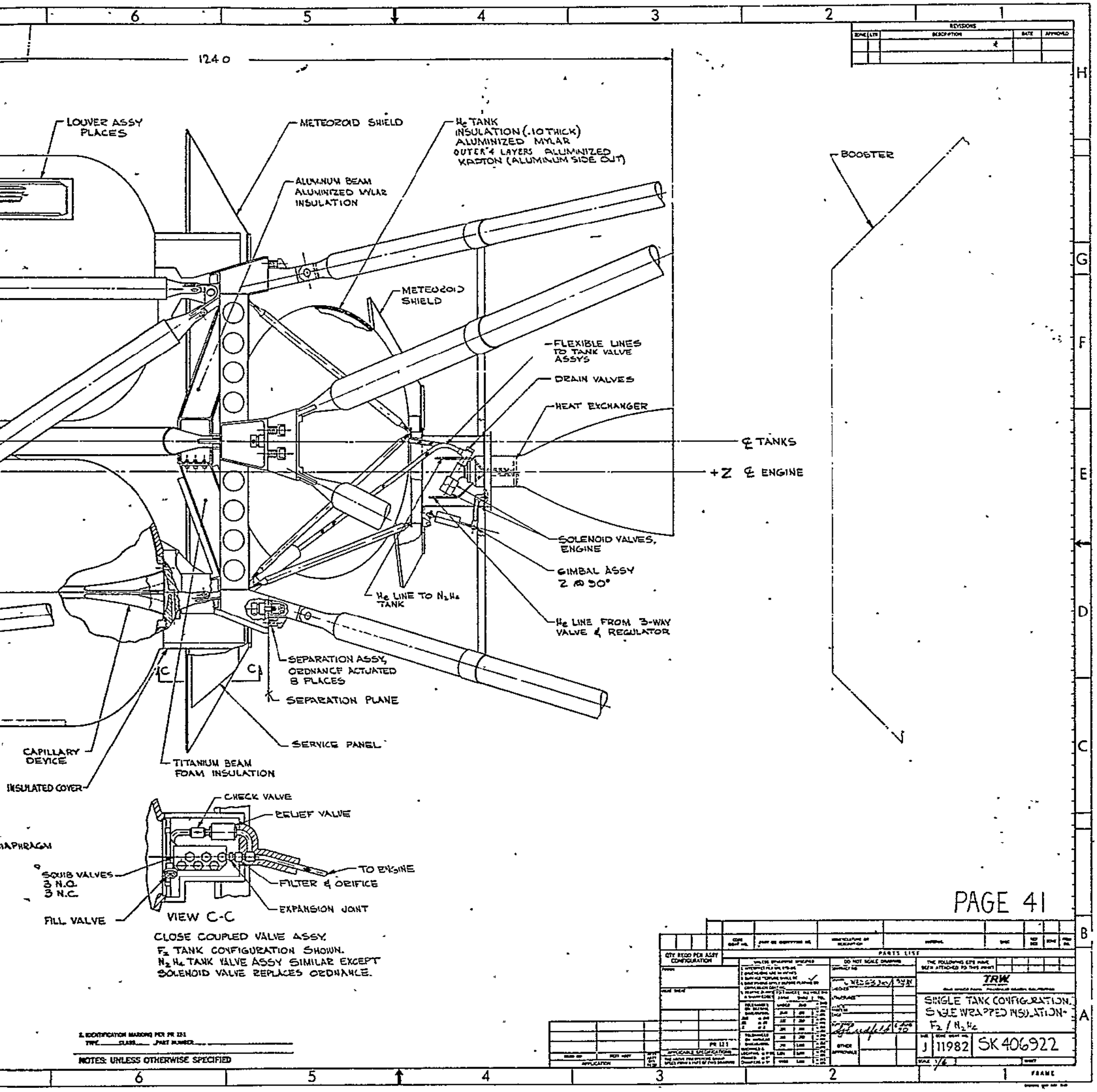

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TABLE 4-1. SUMMARY OF ESTIMATED SUBSYSTEM WEIGHTS
(BASELINE CONFIGURATION)

Tankage	1-Helium Tank @ 74.3 lb. ea.	74.30 lb
	2-Propellant Tanks @ 54.13 lb ea.	108.26 lb
	1-Propellant Surface Tension Screens @ 2.0 lb ea.	2.0 lb
		184.56 lb
Liquid Circuits	2-Fill Valves @ 1 lb ea.	2.0 lb
	1-Solenoid Valves @ 2 lb ea.	2.0 lb
	2-Filters @ 1 lb ea.	2.0 lb
	2-Relief Modules @ 1.2 lb ea.	2.4 lb
	2-Check Valves @ 1.0 lb ea.	2.0 lb
	3-PR Explosive Valves @ 3 lb ea.	9.0 lb
		19.4 lb
Gas Circuit	1-Fill Valve @ 1 lb ea.	1.0 lb
	4-PR. Explosive Valves @ 3 lb ea.	12.0 lb
	1-Filter @ 1 lb ea.	1.0 lb
	1-Regulator @ 2 lb ea.	2.0 lb
	1-Check Valve @ 0.5 lb ea.	0.5 lb
	2-Relief Modules (Disc Plus Valve) @ 1 lb ea.	2.0 lb
	2-Pressurization & Vent Valves @ 2 lb ea.	4.0 lb
	2-Solenoid Valves @ 2 lb. ea.	4.0 lb
		26.5 lb
Thrust Chamber Assembly	2-Propellant Valves @ 5.0 ea.	10.0 lb
	2-Orifice Assys, W/Flanges @ .5 ea.	1.0 lb
	2-Bleed Valves @ 1 lb ea.	2.0 lb
	1-Thrust Chamber W/Gimbal Mounts	43.0 lb
	2-Gimbal Actuators @ 2.25 ea.	4.5 lb
		60.5 lb
Fluids	Oxidizer (F_2)	1800.0 lb
	Fuel (N_2H_4)	1100.0 lb
	Helium (He)	36.0 lb
		2936.0 lb

TABLE 4-1 (Continued)

Structure-Above Separation Plane

Upper Truss Members	19.61 lb
Tank Upper Support Members	1.44 lb
Spacecraft Attachment Fittings	4.25 lb
Platform Members (Frame)	8.90 lb
Platform Fittings	5.25 lb
Engine Support Truss Members	1.28 lb
Engine Support Platform	2.75 lb
Tank End Fittings	2.70 lb
Valve Assy Brackets	6.76 lb
Meteoroid Shields	14.32 lb
	67.26 lb

Structure-Below Separation Plane

Truss Members	45.42 lb
Fittings (Separation)	2.50 lb
Stabilizing Frame	1.00 lb
	48.92 lb

Miscellaneous

Lines and Fittings	20.0 lb
Instrumentation	4.0 lb
Command and Squib Harness	8.0 lb
Contingency	16.0 lb
	48.0 lb

Insulation

Aluminized Mylar	(N_2H_4 Tank)	.91 lb
Foam	(F_2 Tank)	4.64 lb
Aluminized Mylar	(He Tank)	.40 lb
Aluminized Mylar	(Alum. Beam)	.05 lb
Foam	(Ti Beam)	.29 lb
Cooling Coil Assy	(F_2 Tank)	1.25 lb
Louvers	(N_2H_4 Tank)	2.25 lb
Radiation Shield	(F_2 Tank)	4.80 lb
		14.59 lb

TABLE 4-2

SUMMARY OF ESTIMATED SUBSYSTEM WEIGHT DIFFERENCES FOR VARIOUS MODIFICATIONS FROM BASELINE

Baseline & Heat Pipes		
Heat Pipe Weight		ΔW = + 3.5 lbs
Type 1 Support System*		
Tank		ΔW = + 8.6 lbs
Insulation		= - 0.4 lbs
Supporting Structure		= + 6.7 lbs
	Total	ΔW = +14.9 lbs
Type 2 Support System		
Tank		ΔW = - 6.3 lbs
Insulation		= - .6 lbs
Supporting Structure		= + 3.9 lbs
	Total	ΔW = - 3.0 lbs
Type 3 Support System		
Tank		ΔW = +11.7 lbs
Insulation		= - .6 lbs
Supporting Structure		= + 4.6 lbs
	Total	ΔW = +15.7 lbs

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*See Drawing SK 407042 and Section 4-3 for definition of the three types of support system.

TABLE 4-3

COMPARISON OF ESTIMATED WEIGHTS
FOR VARIOUS PROPULSION MODULE CONFIGURATIONS

System	Stage Weight	Mass * Fraction	Total ** Weight
Baseline (SK 406922)	3356.9	.831	3405.8
Baseline and Heat Pipe (SK 406961)	3360.4	.830	3409.3
Type 1 Support (SK 407042)	3371.8	.828	3420.7
Type 2 Support (SK 407042)	3353.9	.832	3402.8
Type 3 Support (SK 407042)	3372.6	.828	3421.5

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* Based on 2791 lbs. of burned propellant

** Includes weight below separation plane

4.3 F_2 TANK SUSPENSION SYSTEMS

Three different support systems were investigated for the F_2 tank in order to provide better thermal isolation from the supporting structure. These are shown in Drawing SK 407042 (Section 2.1.2) as Type 1, Type 2 and Type 3. Each of these systems provide support for the lower end of the tank by utilizing truss members extending to the frame in lieu of the direct attachment to the support beam incorporated in the baseline design. The truss members are glass filament-epoxy tubes used to reduce the heat transfer but at the expense of increased weight.

In each case, the tank configuration is altered by shortening its length and as a consequence increasing the diameter to maintain the same volume. This of course requires a change in the spacing and size of other structural members to accomodate the larger diameter and increased spacing between tank centerlines. Layouts of this modified structure have not been made, but it appears that no problems will be encoutered in accomplishing the change. One other minor change is shown on the drawing associated with the upper tank support. This consists of using a pair of tubes in place of one of the truss members used to support the tank. By attaching each of these tubes at the periphery of the tank boss, a truss is created to resist any torsional loads that result from the dynamic environment to which the tank is subjected.

Type 1 and Type 3 systems support the F_2 tank by means of a 4-member truss with the apex directly beneath the tank and attached to the frame. In order to accomodate the greater member lengths, the tanks are shortened and modified to incorporate four attachment points at tangential locations around the periphery. This type of attachment almost certainly precludes the use of boron-epoxy as a tank material due to the difficulty of incorporating structurally sound joints for the fittings into the wrap. As a consequence, the tanks will be somewhat heavier and an estimate of the increase in weight, considering the use of titanium is included in the summary of weights. The difference between Type 1 and Type 3 is basically the shape of the tank that is used to obtain different support member lengths. Of course, this difference also dictates a complete change in structural member locations throughout the module. As previously stated, a layout of these new locations has not been made. However, the effect on weight has been estimated and is shown in the weight summary.

Type 2 arrangement maintains a polar tank support but requires a shortening of the tank to provide space for installing a tubular truss between the tank boss and the frame. In this configuration, the apex of the three truss members is located at the tank attachment. One member is vertical and carries loads in the thrust direction directly to the frame. The two other members attach to the frame at side panel points and serve to carry lateral loads. With this system, the tank can be of boron-epoxy construction and, although the larger diameter causes some change in location of other structural members, the degree of change is small. The estimated change in weight from the baseline configuration is shown in the weight summary.

4.4 DEPLOYABLE RADIATOR

Drawing SK 407046 shows a concept for a deployable radiator that is thermally coupled to the F_2 tank by means of a heat pipe. Each panel of the radiator is of honeycomb construction, and the stowed panels are sequentially deployed by torsion springs. Although no detailed analysis has been performed, the concept is structurally feasible. During the boost phase of flight, the stowed panels can be well supported while being subjected to the high load environment. After deployment, the only significant loading is that resulting from engine firing. These loads would be in the order of 1/2 g, and the panels can easily be made to withstand loads of this magnitude.

5. EVALUATION

The foregoing preliminary investigation has been directed toward discrete potential problem areas which combine to form the overall thermal control design problem for an F_2/N_2H_4 propulsion module. The discrete areas of concern are:

- RTG/hydrazine coupling
- Hydrazine/space coupling
- Helium/hydrazine coupling
- Fluorine/hydrazine decoupling
- Fluorine/space coupling
- Fluorine/frame decoupling

In order to properly evaluate the various thermal control concepts that have been identified and considered for possible application to these key areas of concern, it is necessary to consider the concepts as part of an integrated thermal control subsystem which will be exposed to a variety of environmental conditions. The concepts can be grouped according to the major thermally important sections of the propulsion module as follows:

- Hydrazine Tank Control
    1. Fully Insulated, (passive)
    2. Uninsulated Area toward RTG,
        - Alone, (passive)
        - with Louvers to Space, (semi-passive)
    3. Louvered Panel Toward RTG, (semi-passive)
    4. Heat Pipe to RTG
    5. Conduction Bar to RTG
        - Alone, (passive)
        - with Thermal Switch, (semi-passive)
        - with Louvers to Space, (semi-passive)
- Fluorine Tank Control
    1. Fully Insulated, (passive)
    2. Insulation Removal in Flight, (passive)
    3. Deployable Radiator, (passive)
    4. Heat Pump, (active)
    5. Expendable Rrigerant, (active)
- Fluorine Tank Support
    1. Spherical Tank Truss Support
    2. Polar Tank Support
    3. Cylindrical Truss Tank Support
    4. Standard Frame Support

- Helium Tank Control
  1. Heat Pipe, (passive)
  2. Solid Conductor, (passive)

As was discussed in Reference 1, the individual sections of the thermal control subsystem are to a large extent independent of each other. For example, whether a heat pipe, solid conductor, or thermal radiation is used to couple the hydrazine tank to the RTG has very little if any bearing on the type of thermal control system chosen for the fluorine tank.

Three particular features have been established in the foregoing analysis which are considered to be essential requirements for the F_2/N_2H_4 propulsion module regardless of which of the many optional concepts are ultimately incorporated. A brief review of these essential features seems in order before attempting to evaluate the relative merits of the optional concepts.

1. Isolation from Solar Heating

In order to passively maintain the fluorine tank at its required low equilibrium temperature, it is necessary that the outside surface of the tank insulation have a low solar absorptance and a high emittance. Therefore, second surface silvered Teflon of about 3 mil thickness should be bonded to the outside of the fluorine tank foam insulation. Bonding is necessary in order to avoid possible frost or condensation build up on the foam underneath the Teflon during groundhold.

The hydrazine and helium tanks must also be isolated from solar heat input. However, due to the higher operating temperatures of these tanks, the surface emittance should be as low as possible in order to minimize the heat loss rate to space. This can be accomplished by utilizing aluminized film with the aluminum side facing outward, Kapton should be used rather than Teflon or Mylar because it can withstand the high surface temperature that can occur during solar impingement with the aluminized side facing outward.

To eliminate continuous solar heating the spacecraft should be designed to completely shade the tanks or if it does not, special shades must be provided. If it is desirable to orient the vehicle with the engine facing the sun, the aft meteoroid shield must be sufficiently large to accomplish the shading. In any event, the meteoroid shield must be sufficiently separated from the fluorine tank to reduce the blockage of the fluorine tank's view of space.

2. Inter-Tank Radiation Shielding

Free standing radiation shields are required between the fluorine tank and the two hotter tanks in order to minimize radiant heating of the fluorine and thus obtain the required low equilibrium temperature. A free standing shield blocks the radiation interchange between tanks but does not seriously impede radiation from the fluorine tank to space.

3. Groundhold Insulation and Cooling

Since the normal launch site temperature is within the acceptable temperature range for the hydrazine and helium tanks, no special groundhold cooling or heating provisions will be necessary on these tanks. In addition, no frost or condensation build up problems are anticipated on these tanks, so light weight multilayer radiation type insulation can be used.

Due to the low storage temperature of the fluorine, however, closed cell foam type insulation will be required on that tank in order to prevent frost or condensation buildup during groundhold. Radiant and convective heat input from the surrounds during groundhold will of course make auxiliary groundhold cooling necessary on the fluorine tank. The most realistic way of providing such cooling is to circulate a coolant through internal coils (as was done in the OF_2/B_2H_6 module). Gaseous helium would be an appropriate coolant because of the low temperatures involved and because helium is chemically inert. The helium could be cooled by a helium cryostat or by circulating it through liquid hydrogen.

5.1 COMPONENT EVALUATIONS

Following the evaluation procedure outlined in Task I (Reference 1), the various means of thermal control listed above will now be evaluated. Under this procedure, relative rating factors are assigned to each acceptable thermal control method by considering six specific characteristics. Weight receives a rating of 0 to 15; reliability, effectiveness, and adaptability are each rated 0 to 10; testability and cost are each rated 0 to 5. In all cases, 0 represents the best possible system. The resulting itemized tradeoff ratings for various concepts applicable to the hydrazine tank thermal control, fluorine tank thermal control, fluorine tank support, and helium tank thermal control are presented after discussions as Tables 5-1, 5-2, 5-3, and 5-4, respectively. A summary of the totals from Tables 5-1 to 5-4 is presented in Table 5-5 at the end of this section.

5.1.1 Hydrazine Tank Thermal Control

Absolute Requirements

Analysis has shown that with a fully insulated hydrazine tank, thermal radiation coupling to the RTG cannot by itself maintain the required tank temperature. This system is therefore obviously unacceptable. Analysis has also shown that a purely passive system of thermal control cannot maintain the hydrazine tank within its acceptable temperature range (525 ± 25°R), unless the RTG surface temperature uncertainty or variance can be reduced to ± 50°R or less. Passive systems are therefore considered to be acceptable subject to that qualification.

The concept of leaving some fraction of the tank surface area uninsulated in order to increase the thermal radiation heat input from the RTG is theoretically feasible, but such a system would require a high degree of accuracy in thermal analysis, design, and fabrication in order to passively maintain the required hydrazine temperature. In addition, this system requires that the RTG be placed rather close to the uninsulated area so that a sufficiently large radiation view factor (0.1) is attained from the exposed area to the RTG. Unfortunately, closer placement of the RTG increases not only the incident thermal radiation but also the incident nuclear radiation. This could conceivable lead to material degradation problems.

The concepts of using a louvered panel, a heat pipe, or a solid aluminum conduction bar to thermally couple the hydrazine tank to the RTG all meet the absolute requirements of weight savings and temperature. Of these methods, only the louvered panel concept offers compensation for off-design operation.

Thermal switches or variable conductance heat pipes could provide such compensation but they are deemed unacceptable for the present application because of their relative lack of development.

Except for its variability, a louvered panel coupling to the RTG is similar to the uninuslated area concept. As such, it too would require that the RTG be places rather close. The analysis has shown in fact that the louvered panel coupling technique would need an even closer RTG placement than the uninsulated area concept in order to achieve the greater view factor required for adequate variability. Therefore, if variability is deemed necessary, the best combination may be to use a louvered panel facing toward space (away from the RTG) in conjunction with a heat pipe or solid conduction bar to the RTG. Seven acceptable thermal control combinations for the hydrazine tank are listed in Columns 1 and 2 of Table 5-1.

Subjective Factors

Weight. Weight estimates for a louvered panel, heat pipe, or conduction bar coupling to the RTG are 2.5 pounds, 1.0 pound, and 10.0 pounds, respectively. Heat pipe coupling to the RTG combined with louver coupling to space would thus weigh approximately 3.5 pounds. Likewise, solid conduction coupling to the RTG combined with louvers to space would weigh approximately 12.5 pounds. Relative weight rating factors for the seven acceptable hydrazine tank thermal control combinations have therefore been assigned as shown in Column 3 of Table 5-1.

Reliability. Though louvers are semi-passive, they have been demonstrated on several programs to be highly reliable. Calculations during Task III substantiated this finding even for a long duration mission. Actual reliability data for heat pipes is meager. However, from an engineering point of view, there should be no reason to presume that a highly reliable heat pipe could not be manufactured. There are no moving parts and few modes of possible failure. It is obvious, however, that the solid conduction bar would have the highest reliability. The uninsulated area concept should be almost equally reliable except for the possibility of surface property degradation. Based on these thoughts, relative reliability factors have been assigned to the seven acceptable hydrazine tank thermal control combinations and are listed in column 4 of Table 5-1.

Effectiveness. All of the concepts being considered for thermal control of the hydrazine tank are really nothing more than different methods for transporting heat from the RTG to the tank and from the tank to space. Given proper design, each of the acceptable methods could provide the required conductance (or resistance). Thus, all of the methods would be equally effective. Ability to accommodate design uncertainties and off-design operation is accounted for under adaptability. Consequently, all of the acceptable concepts have been assigned an effectiveness rating factor of 0 in column 5 of Table 5-1.

Adaptability. The ability of any given system to maintain the hydrazine tank within its temperature limits under off-design conditions depends of course on what condition is being considered. For example, if the RTG changes temperature for whatever reason, conduction coupled systems would be slightly less affected than radiation coupled systems because of the fourth power relationship. On the other hand, uncertainty in the heat leakage rate from the hydrazine tank to space would have slightly less effect on a radiation coupled system than on a conduction coupled system, again because of the fourth power relationship. A more important characteristic is perhaps how immune a particular system is to inadvertent solar impingement. Conduction coupled systems would appear to have a clear advantage here since the entire surface area of the tank can be heavily insulated. Obviously, a passive system will not be as adaptable to design uncertainties or off-design operation as a similar semi-passive system. All of these points have been taken into account in assigning the relative adaptability factors shown in column 6 of Table 5-1.

Testability. As indicated in previous Task reports, louvers can be tested on the ground to ascertain their operation in space. However, the fact that they do act as a variable in the system being tested means that the task of analyzing test data is substantially increased, and the accuracy which can be ascribed to the data is decreased. Heat pipes present certain potential problems in regard to ground testing because of the influence of the Earth's gravity on capillary pumping in the wick. The usual way of avoiding or minimizing the consequences of this effect is to test the pipe horizontally. This undoubtedly would be satisfactory for bench testing individual heat pipes, but it may impose serious complications on integrated ground tests of the propulsion module. Solid conduction bars and passive radiation from the insulated tank should present no major testing problems at the hydrazine storage temperature. Relative testability rating factors have been assigned in column 7 of Table 5-1 in accordance with the foregoing remarks.

Cost. The heat pipes being considered here are of the relatively simple tubular type with conventional wick structure, no sharp bends or area changes, and no conduction modulation. Total cost of designing, fabricating, and bench testing such pipes is estimated to be less than the total cost of a suitable louvered panel. Cost of the solid conduction bar or the uninsulated area concept would be essentially nil. Relative cost factors based on these thoughts are presented in column 8 of Table 5-1.

TABLE 5-1

RELATIVE EVALUATION FACTORS FOR ACCEPTABLE HYDRAZINE TANK THERMAL CONTROL COMBINATIONS

THERMAL CONTROL SYSTEM COMBINATION									
RTG/Hydrazine Coupling Concept	Hydrazine/Space Coupling Concept	Weight	Reliability	Effectiveness	Adaptability	Testability	Cost	Total	Recommended for further study
Uninsulated Area	passive radiation	0	2	0	10	0	0	12	√*
Solid Conduction Bar	passive radiation	12	0	0	3	0	0	15	√*
Heat Pipe	passive radiation	1	6	0	3	3	3	16	√*
Louvered Panel	passive radiation	3	4	0	5	2	2	16	√
Uninsulated Area	louvered panel	3	6	0	8	2	2	21	
Solid Conduction Bar	louvered panel	15	4	0	2	2	2	25	
Heat Pipe	louvered panel	13	10	0	2	5	5	25	

*Acceptability subject to RTG temperature uncertainty or variance being ± 50°R or less.

5.1.2 Fluorine Tank Thermal Control

Absolute Requirements

Preliminary analysis has shown that insulating the entire surface area of the fluorine tank with closed cell foam insulation will prevent frost or condensation build-up during groundhold but will still allow sufficient heat loss to space during flight to passively maintain the fluorine at an equilibrium temperature of approximately 100°R. This system is passive and simple and is believed to offer a weight advantage relative to comparable Earth storage propellant modules even though special care is required in shielding the fluorine tank from external heat sources.

None of the back-up systems look very attractive. Analysis has shown that selective in-flight removal of foam insulation provides little improvement in the heat rejection rate because at the low temperatures required, the insulation is not the main impedance to heat rejection. Such removal would simply make the fluorine tank all the more vulnerable to inadvertent solar impingement. Analysis has also shown that a prohibitively large amount of expendable frigerant would be required in order to achieve any significant cooling benefit. Both of these back-up systems have therefore been deemed unacceptable.

A Vuilleumier cycle heat pump appears to offer considerable promise for similar applications sometime in the future, but the required development time and effort are believed to be out of scope for the present application. Since no other form of heat pump is known which can operate at cryogenic temperatures without mechanical power or electricity, heat pumps have also been deemed unacceptable.

This leaves only two fluorine tank thermal control systems to be considered. One system consists simply of a conductively isolated, radiation shielded and foam insulated tank. The other is exactly the same but with a deployable radiator added for contingency cooling.

Subjective Factors

Weight. Foam insulation (3/4 inch thick) over the entire surface of the fluorine tank would weigh approximately 5 pounds. Incorporation of a deployable radiator would impose a weight penalty of approximately 26 pounds. Relative weight rating factors for these two concepts have been assigned (0 and 12 respectively) and are included in Table 5-2.

Reliability. Reliability of the foam insulation would be excellent. However, the deployable radiator will undoubtedly have a very low reliability. Aside from the mechanism necessary to cause its deployment, it would also be necessary to consider the possibility of heat pipe failure due to meteorite puncture or gas evolution. Cryogenic heat pipes have been built and successfully operated. However, experience in this temperature regime is limited. Reliability ratings of 0 and 10 have therefore been assigned to the insulation and deployable radiator concepts respectively. These values are included in Table 5-2.

Effectiveness. The primary purpose of the foam insulation is to prevent frost or condensation build up during groundhold. Its effectiveness at doing this can easily be demonstrated experimentally.

A secondary purpose of the foam insulation is to provide an increased RC time constant during inadvertent solar impingement. It cannot by itself provide long term protection against external heat sources which are at a higher temperature than the fluorine. Consequently, in flight effectiveness of the insulated tank concept is mainly a matter of conductive isolation and thermal radiation shielding both of which can be analyzed and predicted with reasonable accuracy. Because of virtually unavoidable heat leaks from external sources, there is little danger of the fluorine tank temperature dropping below 100°R. In other words, heat leakage into the fluorine tank will probably be larger than expected rather than smaller. At the upper temperature limit, the combined heat rejection from the insulated tank and a deployed radiator would be about twice that of the insulated tank alone. Effectiveness rating factors of 8 for the insulated tank plus radiator and 4 for the insulated tank alone have therefore been assigned and included in Table 5-2.

Adaptability. The insulated tank concept would be relatively unadaptable in regard to accommodating large variations in the spacecraft operation or mission. A deployable radiator would supply an additional option which could aid in accommodating certain mission variations provided solar radiation did not impinge upon the deployed radiating surface. Adaptability rating factors of 10 and 6 have therefore been assigned to the insulated tank and deployable radiator concepts respectively and these values have been included in Table 5-2.

Testability. As pointed out earlier, heat pipes present a potential testing problem because of the influence of the Earth's gravity on capillary pumping in the wick. Another potential problem with heat pipes designed to operate at cryogenic temperatures is that the internal pressure becomes extremely high if such a pipe is allowed to come up to room temperature. As far as testing the insulated tank concept is concerned, the only major problem is that of providing a cold enough sink. Since the fluorine is stored at approximately the temperature of LN_2, the conventional LN_2-cooled shroud will not be adequate. Gaseous hydrogen or helium would be the most probable substitutes. Testability rating factors of 3 and 5 have therefore been assigned to the insulated tank and deployable radiator concepts respectively, and these values are included in Table 5-2.

Cost. The cost of the basic insulated tank concept would be minimal since this system is passive and relatively simple. Designing, fabricating, and testing a depolyable radiator could however add a significant cost increment, perhaps of the order of $50,000 to $100,000. Therefore, relative cost rating factors of 0 and 5 respectively have been assigned and included in Table 5-2.

TABLE 5-2

RELATIVE EVALUATION FACTORS FOR ACCEPTABLE FLUORINE TANK THERMAL CONTROL COMBINATIONS

THERMAL CONTROL SYSTEM	Weight	Reliability	Effectiveness	Adaptability	Testability	Cost	Total	Recommended for further study
Basic Isolated Tank Concept	0	0	8	10	3	0	21	✓
Basic Isolated Tank and Deployable Radiator	12	10	4	6	5	5	45	

5.1.3 Fluorine Tank Support

Absolute Requirements

As indicated in the previous sections, all of the conceptual methods for supporting the fluorine tank are acceptable from a structural standpoint, and all of the concepts appear acceptable from a thermal point of view except for the standard frame support. The standard frame support system, which is similar to the support used with the OF_2/B_2H_6 module, would permit excessive heat leaks into the fluorine tank during operation both from the engine during heat soakback and from the hydrazine tank. The standard frame support is therefore unacceptable.

Subjective Factors

The only subjective factor which is applicable in determining the relative merits of the three acceptable tank support concepts is weight. Weight differences due to changing the method of supporting the oxydizer tank are shown in Table 4-2 to be approximately 15 pounds minus 3 pounds, and 16 pounds for the spherical tank truss support (type 1), the polar tank support (type 2), and the cylindrical tank truss support (type 3), respectively. Relative weight rating factors of 8, 0, and 8 respectively have been assigned to these three support configurations and for the sake of consistency, are presented in Table 5-3.

TABLE 5-3

RELATIVE EVALUATION FACTORS FOR ACCEPTABLE FLUORINE TANK SUPPORT CONFIGURATIONS

SUPPORT CONFIGURATION	Weight	Reliability	Effectiveness	Adaptability	Testability	Cost	Total	Recommended for further study
Spherical Tank Support (type 1)	8	0	0	0	0	0	8	
Polar Tank Support (type 2)	0	0	0	0	0	0	0	√
Cylindrical Tank Support (type 3)	8	0	0	0	0	0	8	

5.1.4 Helium Tank Control

Absolute Requirements

It is difficult at this time to evaluate the relative merits of the heat pipe and the solid conductor as means of controlling the helium tank temperature because the preferred temperature for storing the helium has not yet been clearly defined. Until requirements as dictated by the propulsion system are more fully ascertained, a definitive evaluation of the two coupling systems cannot be made. There are, however, certain intrinsic characteristics which can be discussed and tentatively evaluated.

Subjective Factors

Weight. For any given value of thermal coupling conductance, the heat pipe system will weigh less than an equivalent solid bar conductor. Thus, the higher the required conductance, the greater the heat pipe advantage. Analysis has shown that if the helium is to be stored at or near the hydrazine temperature and the helium tank is insulated with multilayer aluminized film, a suitable solid aluminum conduction bar would weigh approximately 10 pounds minimum. An equivalent heat pipe would weigh less than one pound (see Figure 2-7). On the other hand, if the helium temperature can be allowed to float say 100°F below the hydrazine temperature, the heat pipe weight advantage essentially disappears, since a one pound solid aluminum bar would then suffice. Based on these considerations, weight rating factors have been assigned two ways. First, assuming the helium is to be stored at or near the hydrazine temperature, the assigned rating factors are 15 for the conduction bar and 0 for the heat pipe. Second, assuming the helium can be stored 100°F or more below the hydrazine temperature, the assigned rating factors are both 0. Both sets of weight rating factors have been included in Table 5-4.

Reliability. Any heat pipe is less reliable than a solid conduction bar because of its vulnerability to meteorite puncture, non-condensable gas evolution, and wick deterioration. Consequently, reliability rating factors of 0 and 6 have been assigned to the conduction bar and heat pipe coupling systems respectively. These values which would not be a function of helium storage temperature have been included in Table 5-4.

Effectiveness. Either solid conduction bars or heat pipes can be designed to give the required thermal conductance. Both have therefore been assigned effectiveness rating factors of 0 as indicated in Table 5-4.

Adaptability. Solid conduction bars and heat pipes are considered to be equally adaptable (or unadaptable) to changes in orientation or mission plan. Both have been given adaptability rating factors of 3 in Table 5-4.

Testability. Heat pipes present a potential testing problem because of the influence of the Earth's gravity on capillary pumping action in the wick. This influence becomes insignificant if the heat pipe can be horizontal during ground tests. Otherwise, correction factor must be applied. Testability rating factors of 0 and 3 have been assigned to the solid conduction bar and heat pipe control systems respectively and are included in Table 5-4.

Cost. Cost of the solid conduction bar would be neglibible compared to the cost of designing fabricating and testing an equivalent heat pipe system. Cost rating factors of 0 and 5 respectively have therefore been assigned and included in Table 5-4.

TABLE 5-4

RELATIVE EVALUATION FACTORS FOR ACCEPTABLE
HELIUM TANK THERMAL CONTROL CONCEPTS

THERMAL CONTROL SYSTEM		Weight	Reliability	Effectiveness	Adaptability	Testability	Cost	Total	Recommended for further study
Hydrazine Tank to Helium Tank Coupling	Helium Tank Temperature								
Solid Conduction	$\bar{>}$ 500°F	15	0	0	3	0	0	18	✓
Solid Conduction	$\bar{<}$ 400°F	0	0	0	3	0	0	3	✓
Heat Pipe	$\bar{>}$ 500°F	0	6	0	3	3	5	17	✓
Heat Pipe	$\bar{<}$ 400°F	0	6	0	3	3	5	17	✓

TABLE 5-5

SUMMARY OF THERMAL CONTROL CONCEPT EVALUATIONS
)R THE MAJOR COMPONENTS OF THE F_2/N_2H_4 PROPULSION MODULE

Propulsion Module Component	Thermal Control Concept	Evaluation Rating	Recommended for further Study
Hydrazine Thermal Control	Uninsulated area/passive rad.	12	✓*
	Solid conduction bar/ passive rad.	15	✓*
	Heat pipe/passive rad.	16	✓*
	Louvered panel/passive rad.	16	✓
	Uninsulated area/ louvers to space	21	
	Solid conduction bar/ louvers to space	25	
	Heat pipe/louvers to space	25	
Fluorine Thermal Control	Basic Isolated Tank	21	✓
	Isolated Tank + Deployable Rad.	42	
Fluorine Tank Support	Spherical tank truss support (type 1)	8	
	Polar Tank Support (type 2)	0	✓
	Cylindrical Tank Support (type 3)	8	
Helium Thermal Control	Solid Conduction Bar/ Passive Rad.	3-18	✓
	Heat Pipe/passive rad.	17	✓

*Acceptability subject to RTG temperature uncertainty or variance being ± 50°R or less.

6. CONCLUSIONS AND RECOMMENDATIONS

The objective of Task VI was to identify and briefly investigate possible thermal control concepts for a F_2/N_2H_4 propulsion module. This objective has been met and the preliminary analyses indicate that all of the major requirements (long term in-flight storage, no venting, and no frost or condensation build-up during groundhold) can be accomplished with a baseline design system weight (including propellants) of approximately 3406 pounds.

Based on the present and previous (Tasks I, II, and III) analyses and design efforts, there are certain characteristics which are considered to be essential thermal control features for the F_2/N_2H_4 propulsion module.

- The propulsion system should utilize independently insulated tanks for each of the two propellants and for the pressurant.
- A free standing thermal radiation shield should be place between the fluorine tank and each of the other two tanks.
- The entire surface of the fluorine tank, its supports, and its plumbing lines should be spray coated with at least a 3/4-inch thickness of closed cell foam insulation.
- Silvered Teflon should be bonded to the entire outer surface of the foam insulation on the fluorine tank with Teflon side facing outward.
- The hydrazine and helium tanks should be individually wrapped with multilayer aluminized Mylar. The outer four layers should be aluminized Kapton with the aluminum side facing outward.
- The spacecraft should be designed and oriented to shade the propulsion module (particularly the fluorine tank) from direct solar impingement. If this is an unacceptable constraint, then special sun shades must be provided. These shades must stand off far enough to provide the fluorine tank an adequate view factor to space.

- The aft meteoroid shield must stand off sufficiently from the bottom of the propulsion module to afford the fluorine tank an adequate view factor to space.

These features are required in order to isolate the respective tanks from external heat sources and from each other. Desired temperatures are maintained by transporting heat from the RTG to the hydrazine tank which in turn radiates heat to space. The helium tank is thermally coupled to the hydrazine tank and also radiates heat to space. Heat leaks from the hydrazine and helium tanks to the fluorine tank are minimized and then balanced by radiation to space.

Seven acceptable combinations of RTG/hydrazine and hydrazine/space coupling concepts have been identified. Based on a subjective evaluation, four are recommended for further study in Task VII. Of these four combinations, three are passive and one is semi-passive. Table 2-1 of Reference 1 indicates that the RTG surface tmeperature variation or uncertainty is currently ± 100°R. Section 2.3 of the present analysis has shown that this uncertainty alone could cause ± 50°R variance in the hydrazine tank temperature with a purely passive thermal control system. Thus, unless the RTG temperature uncertainty can be reduced or the acceptable hydrazine temperature range (currently 500°R - 550°R) can be increased, the passive thermal control systems will be inadequate for thermal control of the hydrazine tank. In that event, the semi-passive system consisting of a louvered panel facing toward the RTG is recommended.

Two acceptable concepts for coupling the helium tank to the hydrazine tank have been identified. Both concepts have been evaluated two different ways and both are recommended for further study. Two concepts for rejecting heat from the fluorine tank to space were found to be acceptable, and one is recommended for further study. Three acceptable fluorine tank support configurations were evaluated, and one is recommended for further study. A summary of the acceptable and recommended concepts is presented in Table 5-5.

7.0 REFERENCES

(1) TRW Report 14051-6002-T0-00, "Summary Report, Task I Space Storage Propellant Module Environmental Control Technology", R. E. DeLand, O. O. Haroldsen, R. N. Porter and P. E. Schumacher, dated 14 January 1970.

(2) TRW Report 14051-6003-T0-00, "Summary Report, Task II Space Storage Propellant Module Environmental Control Technology", R. E. DeLand, O. O. Haroldsen, R. N. Porter, and P. E. Schumacher, dated 1 April 1970.

(3) TRW Report 14051-6004-T0-00, "Summary Report, Task III Space Storage Propellant Module Environmental Control Technology", R. E. DeLand, O. O. Haroldsen, and R. N. Porter, dated 1 June 1970.

(4) B. Shelpuk, M. S. Crouthanel, A. Amith, and M. Yim, "Low Temperature Solid State Cooling Technology", Technical Report AFFDL-TR-68-128, Wright Patterson Air Force Base, Ohio, 1968.

(5) F. N. Magee and R. D. Doering, "Vuilleumier Cycle Cryogenic Refrigerator Development", Technical Report AFFDL-TR-68-67, Wright Patterson Air Force Base, Ohio, 1968.