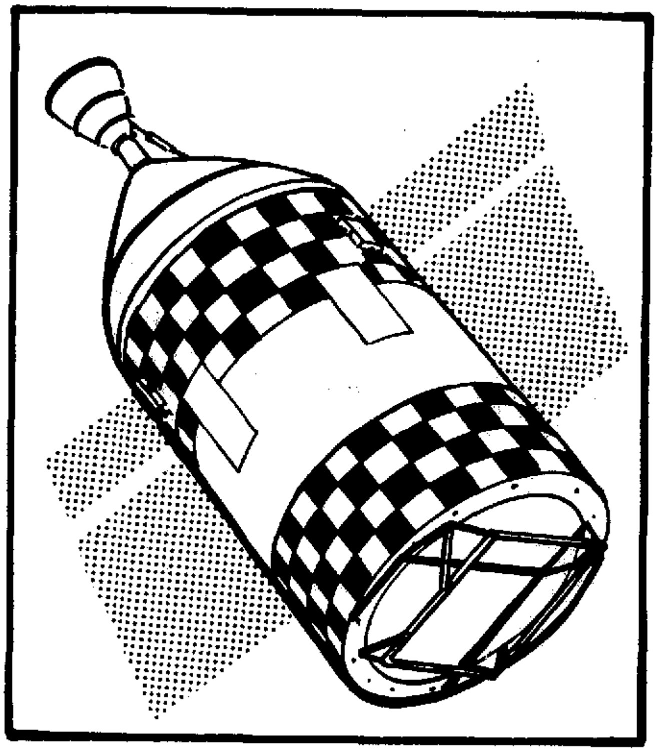
MCR-74-146
Contract NAS8-29670

Executive Summary

September 1974

Space Tug Thermal Control



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MARTIN MARIETTA

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SPACE TUG THERMAL CONTROL

Prepared for:
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center,
Alabama 35812

Approved

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FOREWORD

This document is the Executive Summary Report submitted by the Martin Marietta Corporation, Denver Division, under Contract NAS8-29670.

This study was performed for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center under the technical direction of the Astronautics Laboratory, Thermal Engineering Branch, with Mr. Jack D. Loose serving as Technical Monitor. The work described here was performed from 1 July 1973 to 30 April 1974.

The work of the following major contributors to the study is acknowledged: J. Michael Connolly and Solomon H. Eichenbaum.

CONTENTS

1. INTRODUCTION AND SUMMARY

The introduction of a full capability Tug into the Shuttle mission spectrum in the 1980s will significantly broaden the Shuttle's capability. To fully realize that capability it will be essential that the Tug be designed to perform its mission within a broad range of thermal environments with mission durations up to 7 days. The primary objective of this study was to develop a thermal design that satisfies the Tug mission requirements for low-inclination geoschynronous deploy and retrieve missions. Key to this design was to evolve to a system that was reusable and minimized ground refurbishment requirements.

Passive concepts were demonstrated analytically for both the forward and intertank compartments. Each compartment used an external paint pattern tailored to the desired environment. The forward compartment, which contains the majority of the avionics equipment, included circumferential heat pipes of the regular design to take out the wide variance of skin temperatures resulting from constant attitudes. The results also indicate that the equipment used for rendezvous and docking, such as the television, laser radar, and its associated electronics, represent one of the more severe thermal control problems. Many solutions are feasible; however, the most promising appears to be to mount the equipment on thermal conditioning panels. The panels can be used to reduce heater power requirements. Louvers mounted on the skin side of the panel would be used to further reduce panel heat losses in the cold environments. The fuel cell electrical power subsystem required an active concept in the form of a pumped fluid radiator. Continued development of heat pipe radiators could result in their future application to the fuel cell problem.

Worst-case thermal environments were determined for use in the study to provide the external heating environment. All mission phases were incorporated into the study with the most significant one being the heating of Tug in the orbiter after reentry and landing. At this particular time cargo bay purging was found to be required to enable maintaining both operating and nonoperating temperature limits of the equipment.

A series of three catalogues were created to provide representative equipment data for use in the study. The catalogues were particularly useful in the study and rather unusual at this point in the development of a spacecraft. Additional information could be added to the catalogues to further expand the usefulness of this approach.

Significant thermal control systems were carried an additional step to include a preliminary set of design and performance specifications. Three specifications were developed covering specific areas of concern relative to the forward compartment thermal design, battery louvers, and fuel cell heat rejection system.

A follow-on plan was developed highlighting the breadboard testing of the above key areas, which were advanced to the preliminary specification phase including a honeycomb conductivity test. In addition, several areas of analytical concern were identified that were beyond the original scope of the study.

2. DESIGN STUDIES

The thermal design of Tug represents a key element in the development of the full-capability Tug vehicle. The requirement to provide a reusable vehicle capable of extended mission durations and the broad range of specific mission applications leads to some basic thermal design requirements. Most of the Tug mission phases will require a steady-state mode of operation. The design must be durable and reliable, as well as reusable. In support of the reusability requirements, the design must be easily maintained.

Having sized the Tug in terms of mission performance for propulsion, avionics, etc, a thermal design was considered in this study that would satisfy the above considerations. The design of a vehicle to operate continuously in steady state offers many approaches centered around the application of the several active and passive thermal control techniques used on past spacecraft. In addition, each component could be isolated and the problem of each component could be worked separately, or a more integrated design could be developed. Figure 1 presents the Tug configuration baselined in the study. This basic configuration presents several areas of concern to the thermal designer, however the scope of the study was limited largely to the avionics systems. Within that scope, three compartments are available for locating equipment. The forward and intertank compartments are enclosures by design, while the engine compartment is not, and would present the widest range of external environment extremes. Location of the majority of the avionics equipment in the forward compartment was required to satisfy many of the operational requirements of this equipment, while providing ready access for installation and checkout purposes. The only exception to this was the location of the electrical power subsystem in the intertank compartment to provide close proximity to the cryogenic storage tanks. The engine compartment was devoted to the necessary equipment required by the engine.

Considering the avionics system, the major thermal concerns were primarily isolated to the forward and intertank compartments. Further, the preliminary equipment locations and major structural arrangement resulted in an inherent integral thermal design problem.

An external paint pattern that would result in desirable internal thermal environements was investigated. A parametric study of the external environments was made in terms of incident solar albedo and earth-emitted heating and radiation to space and compartmental heat to be dissipated. All of the heat dissipated within each compartment was uniformly distributed on the skin nodes. The tank insulation and/or forward beta cloth shield completed the compartment enclosures. The radiation average internal sink

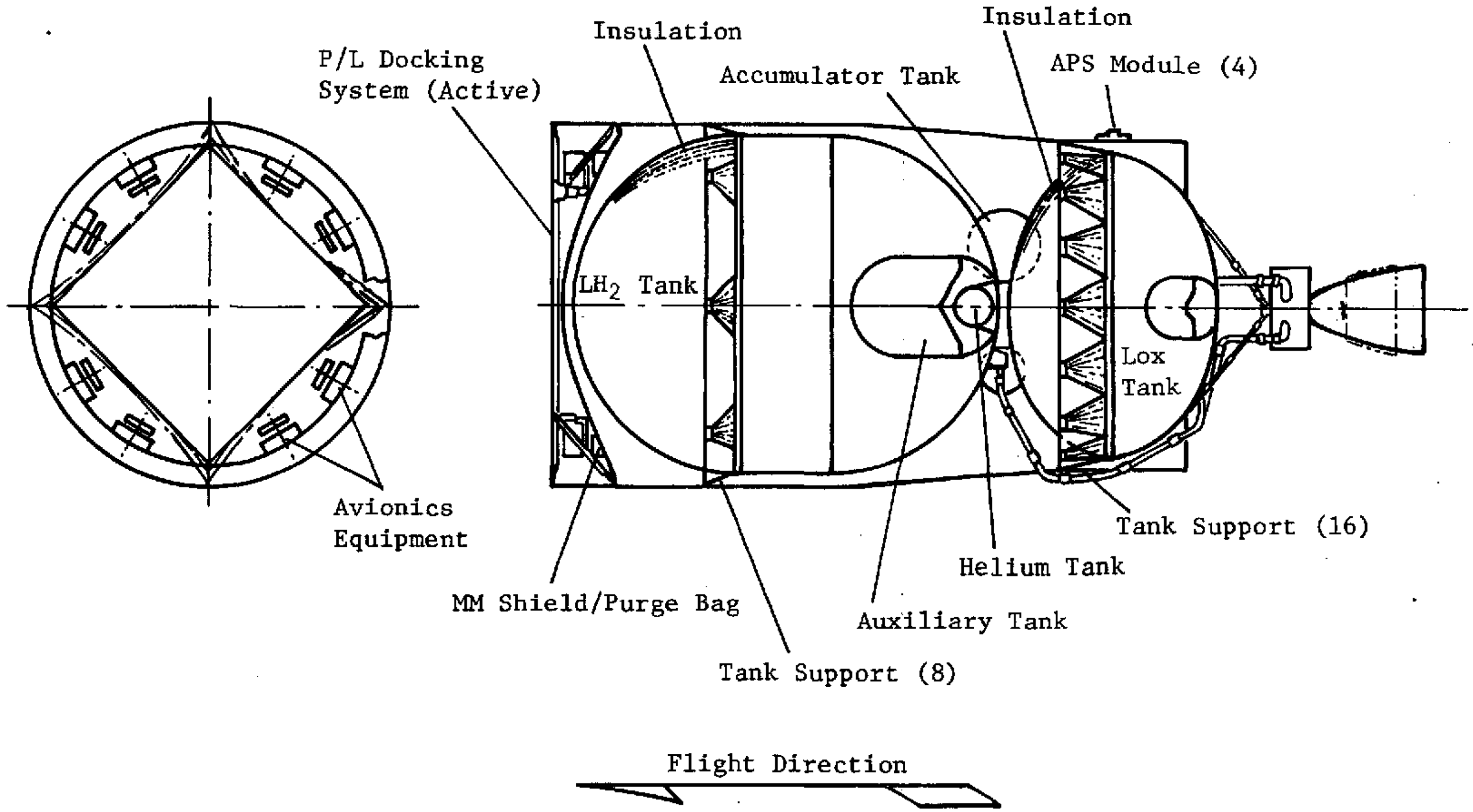

Figure 1 Baseline Tug Overall Configuration

temperature derived from this study was plotted as a function of external paint properties for various anticipated compartmental heat loads. Figures 2 and 3 present the forward hot and cold case extremes resulting from steady-state calculations at each external flux level for the mission. The hot-case temperatures were derived from the park orbit with the Tug oriented perpendicular to the sun, while the cold case temperatures were derived from the shadow conditions at synchronous altitude. The solid line curves resulted from the baseline configuration and indicated that the compartment was biased cold with a black or an aluminum painted exterior. The beta cloth shield was modified to include 24 layers of gold-coated single side kapton with separator to reduce the heat loss through the shield. The dotted line curves represent the resulting change to the internal environment. Approximately 30°K (40°F) rise in internal sink temperature was achieved. This permitted the selection of a paint pattern that would result in an internal sink temperature range of 297 to 200°K (75 to -100°F). The choice of this range was based upon review of component qualification specifications and Titan IIIC Transtage experience.

Significant temperature differentials around the vehicle resulting from fixed attitudes were observed at synchronous altitude. While this did not result in lower temperatures on the cold side than the results of Figure 3, it did represent potential heater power requirements for a hot-case attitude on the shadow side of the vehicle. Reviewing the park orbit and transfer orbit data, similar but less severe conditions were observed. Considering the desirability of demonstrating that no attitude constraints be applied to Tug, circular heat pipes were incorporated into the forward compartment to reduce the sun side-to-shadow side temperature difference to less than 6°K (10°F). This gives the same results as if the vehicle were in a continuous roll about the longitudinal axis and results in skin temperatures being averaged to the internal sink temperatures.

Figure 4 presents the exterior thermal design of Tug evolved from the study. The forward compartment was a complete enclosure with the forward shield consisting of beta cloth for micrometeorite protection with 24 layers of insulation on the inside and white exterior coating. The skin was considered to be painted in a checkerboard pattern of white and aluminum paint with average properties of solar absorptivity (α) = 0.2375 and emissivity (ε) = 0.475. This results in per unit area paint distribution of 63.5% aluminum paint and 36.5% white paint. The intertank compartment was analyzed in a similar manner with the paint pattern selection of α = 0.246 and ε = 0.41 or 75% aluminum paint and 25% white paint.

Figure 2

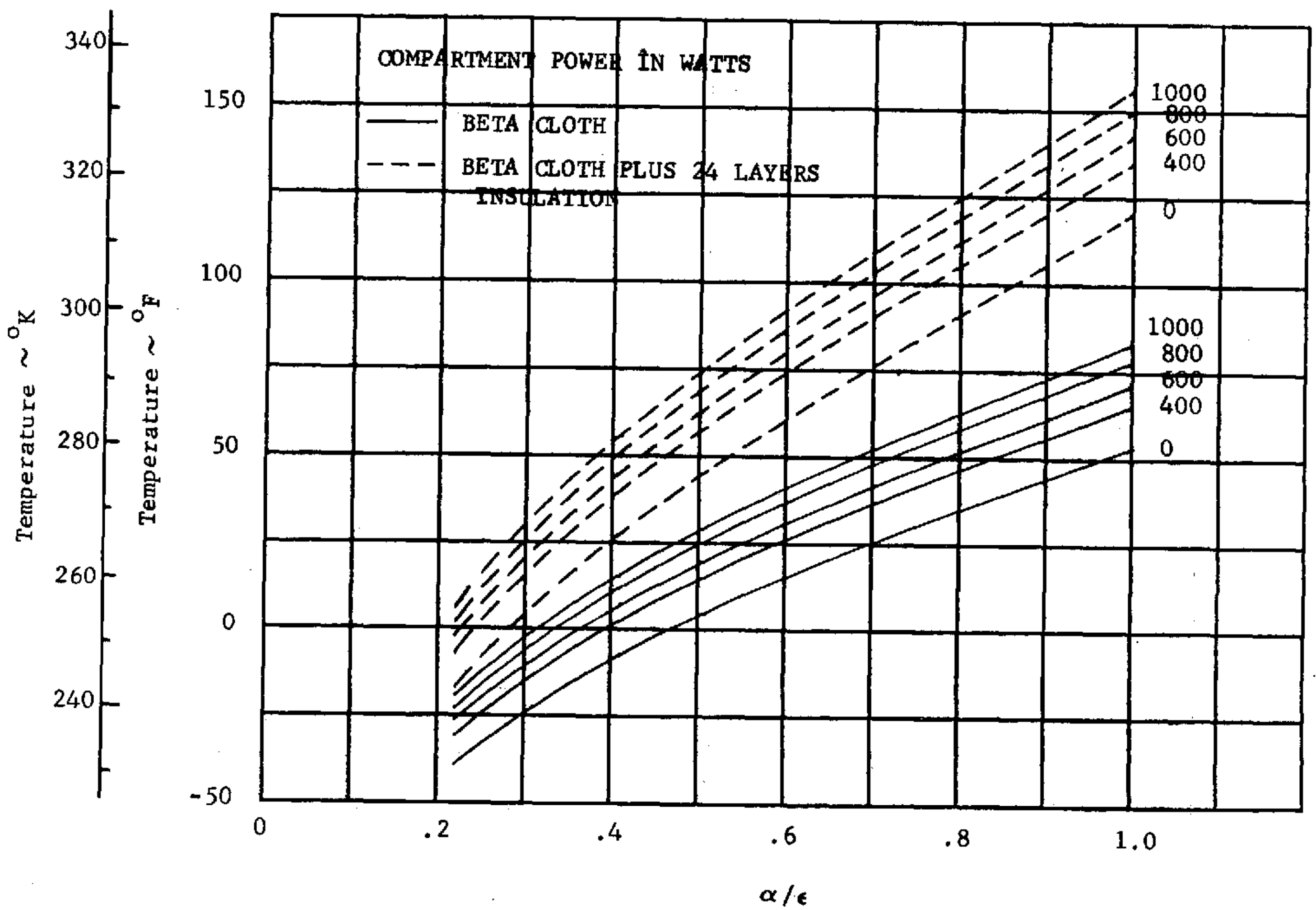

Figure 2
Parametric Runs, Forward Compartment Average Sink Temperature, Park Orbit Case 4

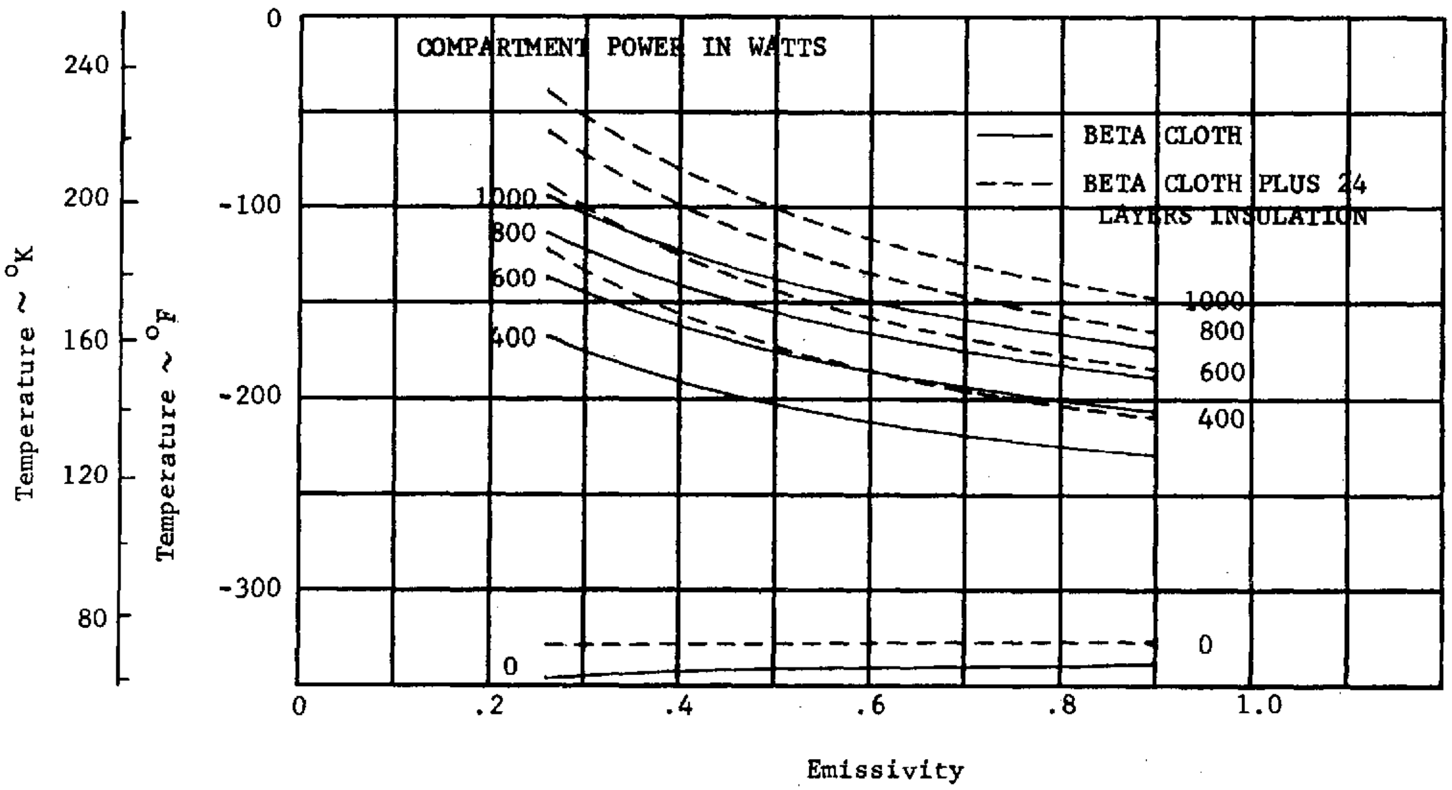

Figure 3
Parametric Runs, Forward Compartment Average Sink Temperature, Synchronous Orbit Case 7, Earth Shadow

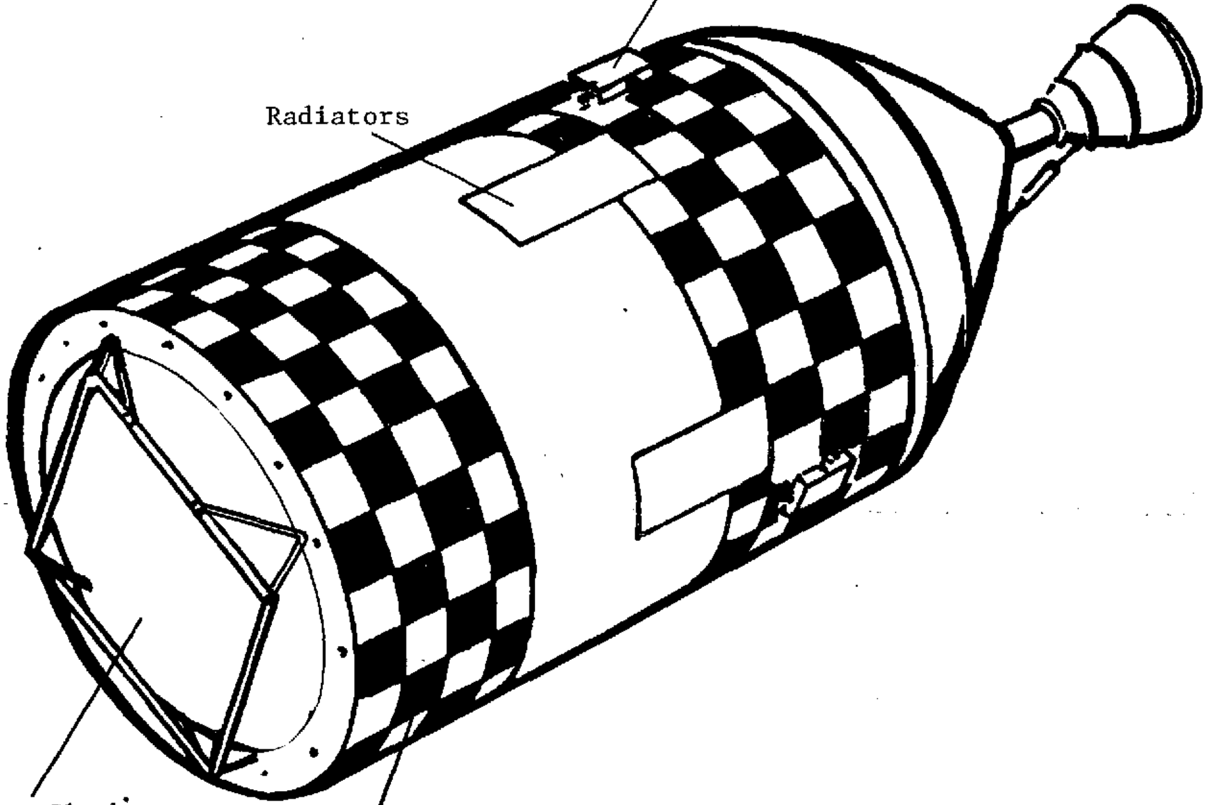

Figure 4 External Profile

The influence of the honeycomb structure on compartment temperatures was also reviewed. The results of the study are presented in Figures 5 and 6. The change in compartment sink temperature as function of conductivity through the honeycomb was evaluated, because conduction is the primary mode of heat transfer. As shown, significant ΔTs result when the honeycomb conductivity is less than $3.5 \frac{\text{watts}}{\text{meter}^2\ {}^\circ\text{K}} \left(2 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}{}^\circ\text{F}}\right)$. Not accounting for the bondline influence on the effective conductivity through the honeycomb results in an optimistic value of $3.4 \frac{\text{watts}}{\text{meter}^2\ {}^\circ\text{K}}$. This value results from an aluminum core honeycomb skirt 1.5 cm thick. The use of a nonmetallic core would significantly reduce the conductivity and would result in higher ΔTs. Hence, the choice of the honeycomb structure for Tug will have a significant influence on the thermal design and could impact the basic passive concept chosen.

The design studies were continued to include the components into the modeling activity to enable predicting a time history of each component from liftoff to landing. Key to this activity was the timelines associated with the operation of the various subsystems. The data management subsystem was ground ruled as operating from liftoff to after landing. The remaining avionics equipment was on from 3.7 to 98.6 hr except for the inertial updating and rendezvous equipment, which was turned on and off at the appropriate times during the mission. Landing occurred at 100.8 hr. Reference 1 further describes the mission timelines.

Figure 7 presents the internal component arrangements used for the study. The results indicated that without exception peak temperatures were achieved after landing occurred, based on internal cargo bay liner temperatures. These temperatures are discussed further in Reference 1. It was also noted that the desirability of a cargo bay purge initiated approximately ½ hour after landing was essential to avoid exceeding most of the nonoperating temperature limits.

The cold-case design condition was assumed; no external heating was applied to the vehicle. In reality this is not quite possible for an earth orbiting vehicle; however, it can be approached by assuming that the vehicle is aligned with the solar vector with the engine looking at the sun. In this condition the two compartments demonstrated similar trends of approaching steady-state conditions after 10 hr. Most of the equipment was observed to cool below the minimum design case temperatures. Most of the equipment that operated continuously could be warmed up sufficiently by reducing the exterior coating emissivity. This was possible since the hot-case results were inadvertently biased cold due to the anticipated affected heat dissipation being some 200 watts higher than the selected components demonstrated. A coating change however would not handle those components which are used only a few times during the mission. For example, the laser radar, its electronics, and the TV were some of the critical items and required heater power in excess of 400 watts to maintain allowable temperature ranges.

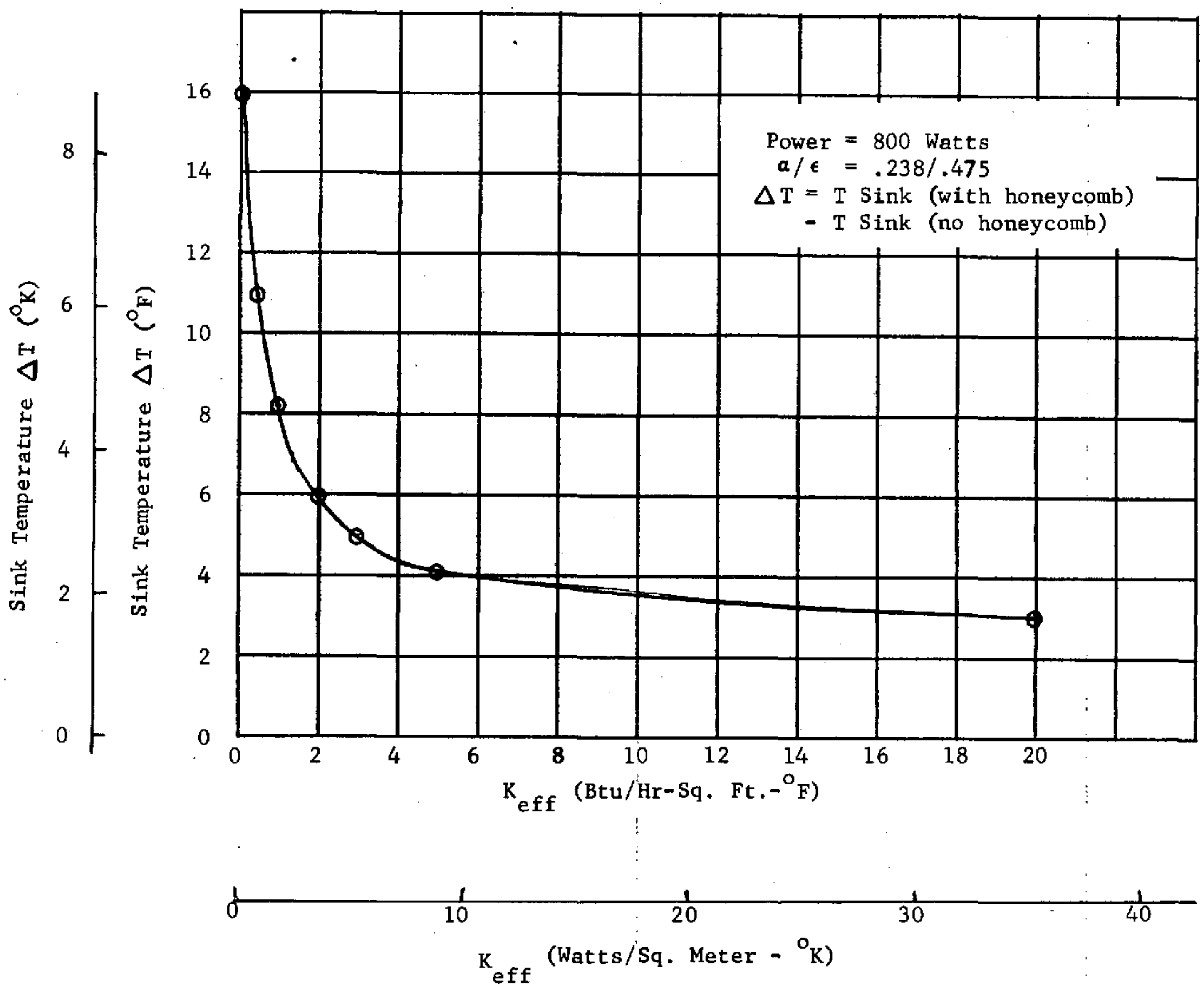

Figure 5 Effect of Honeycomb Conductance on Compartment Sink Temperature, Hot Case

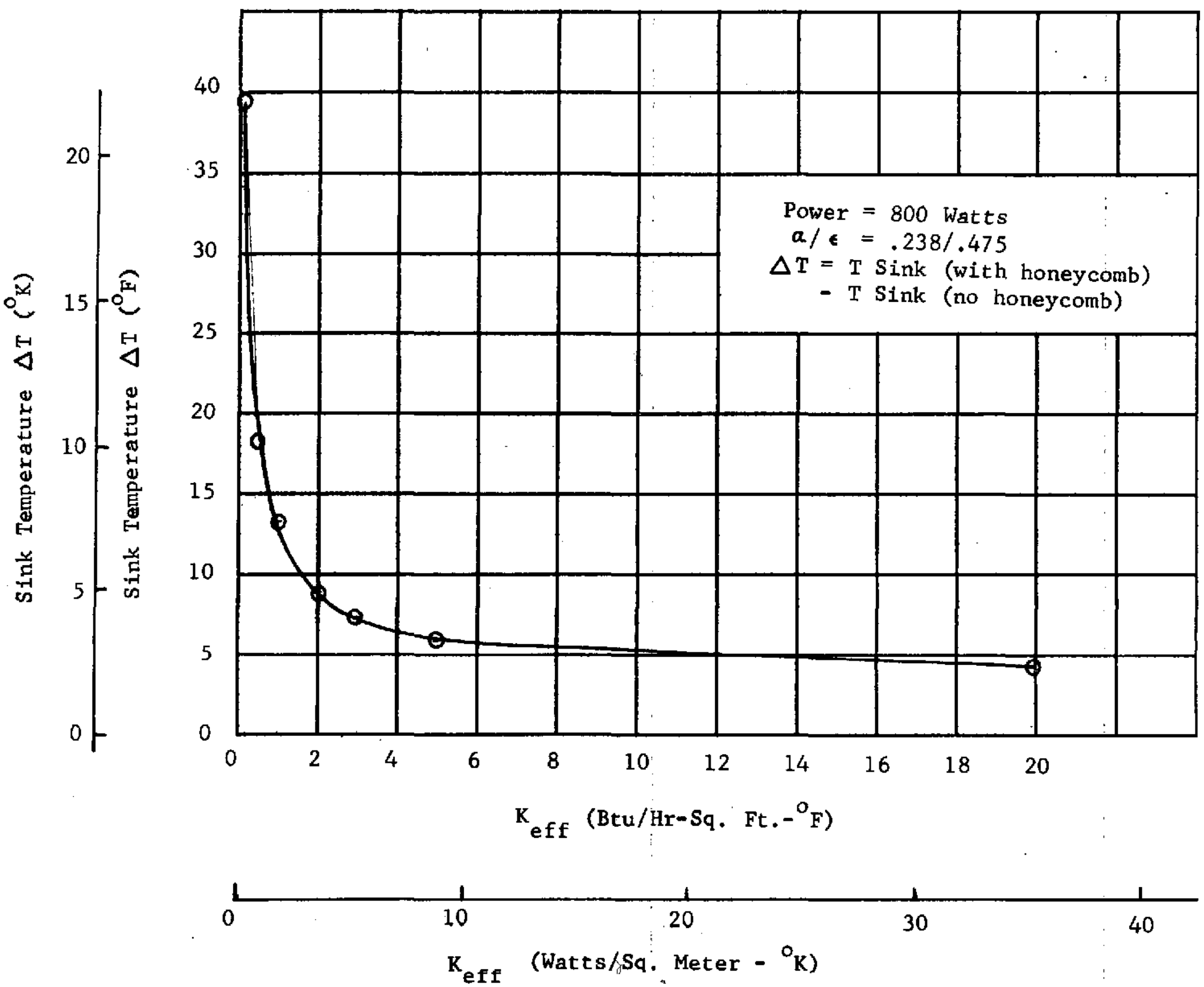

Figure 6 Effect of Honeycomb Conductance on Compartment Sink Temperature, Hot Case

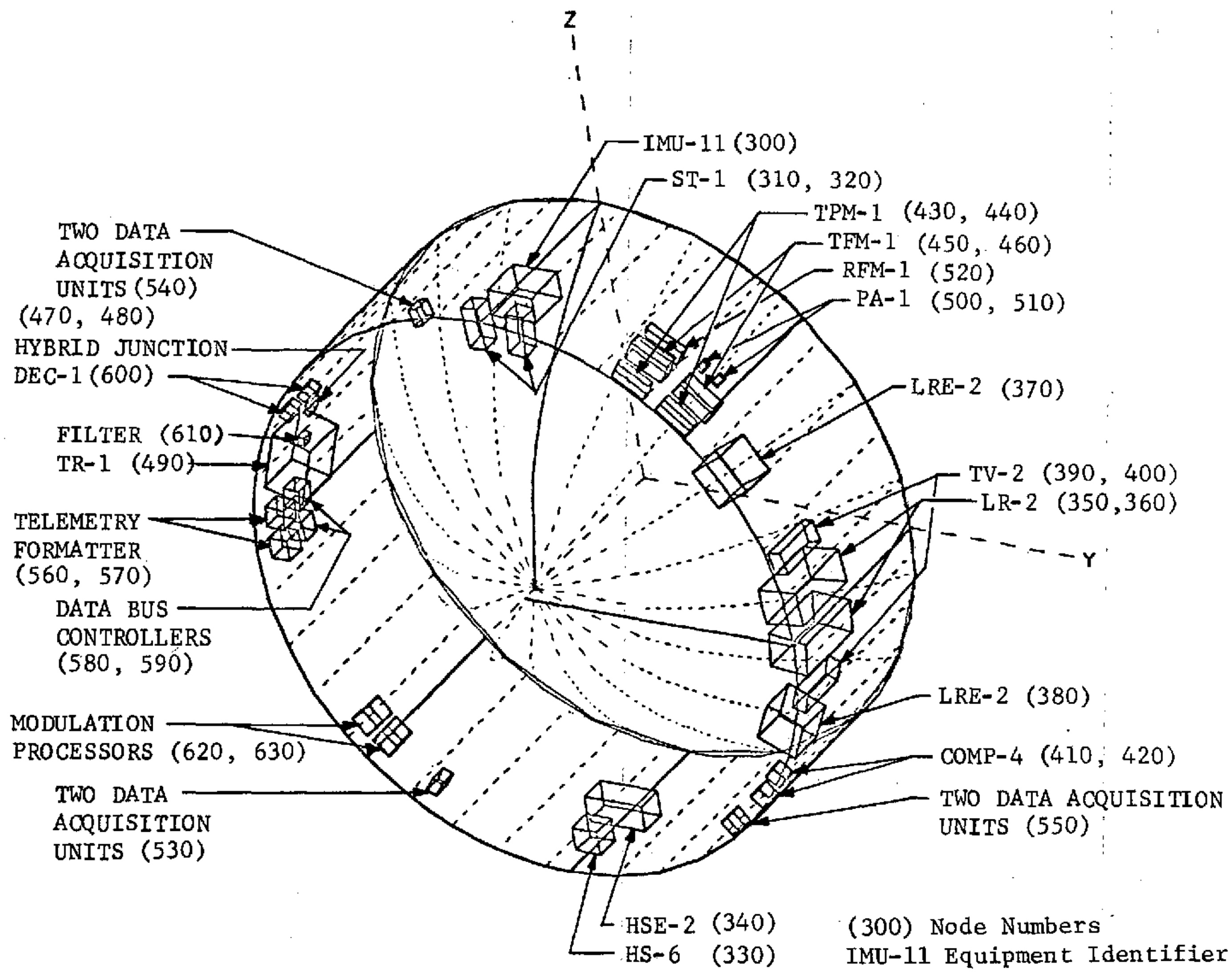

Figure 7 Tug Forward Compartment Equipment

Figure 7

At this point a different component mounting and layout was conidered desirable. Individual mounting of components to a honeycomb structure was not considered an optimum configuration by structural designers. Hence, another change to the baseline was necessary. The application of the thermal conditioning panel developed by MSFC was considered ideal here. The panel is a flat plate that can be designed to satisfy the structural and dynamic requirements, while providing an isothermal mounting plate for the equipment. References 1 and 2 further describe the panel. Heat pipes are an integral part of the panel design and provide the means of reducing panel temperature gradients. This provides an ideal means of sharing heat between components. In the cold-case environments, the application of louvers on the skin side of the panel enables the panel to operate at a temperature level that satisfies all of the mounted equipment temperature limits. This concept is shown in Figure 8.

Thermal control of the fuel cell electrical power subsystem required an active system to maintain the desired operating temperatures. A pumped fluid system using Freon E-1 was selected with a redundant fluid loop through the radiators. Figure 9 presents a flow schematic for one of the flow loops. The pumps and control system were assumed to be packaged within a single box designated as the Thermal Control Unit. Everything in the system is redundant except for the regenerator, which was assumed to have a redundant secondary fluid loop, thus providing a simplified fluid interface with the fuel cell. The pump was sized for a 1.8 kg/min (4 lb/min) mass flowrate. Four individual radiators in series with each other with series flow through each radiator are shown. In addition, the radiators are bypassed by the thermal control valve varying flow through the radiators to achieve the desired fluid heat rejection.

The radiators were sized to reject the maximum heat load during maximum external heating. The four radiators were sized at $8.05 m^2$ ($22 ft^2$) or $2.01 m^2$ ($5.5 ft^2$) per panel. The maximum heat load of 825 watts accounted for the fuel cell and radiator pumps of which 744 watts were derived from the fuel cell under a maximum electrical load of 1500 watts. Silver-coated Teflon tape was selected as the radiator coating because of its desirable optical properties, stability of properties, and ease of maintenance and application. The cold case was also explored to insure against fluid freezing at minimum heat load conditions. No external heating was applied for the cold case with 362 watts of heat to be rejected. This relates to a minimum fuel cell load of 600 watts electrical resulting in 281 watts of heat to be rejected less pump power. The cold case resulted in minimum fluid temperatures of 228°K (-50°F), which is well above the freezing temperature of Freon E-1.

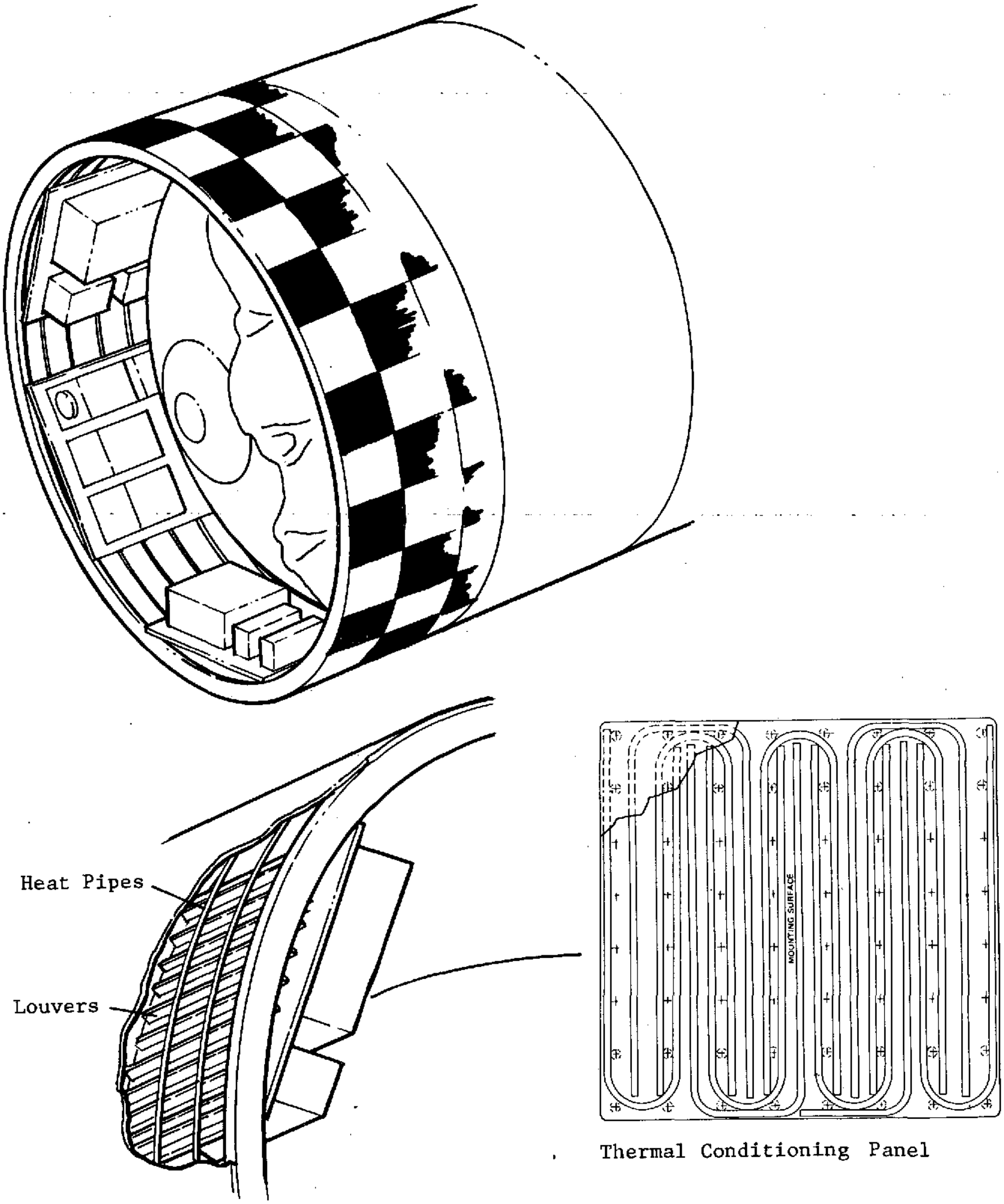

Figure 8 Forward Compartment Thermal Control Concept

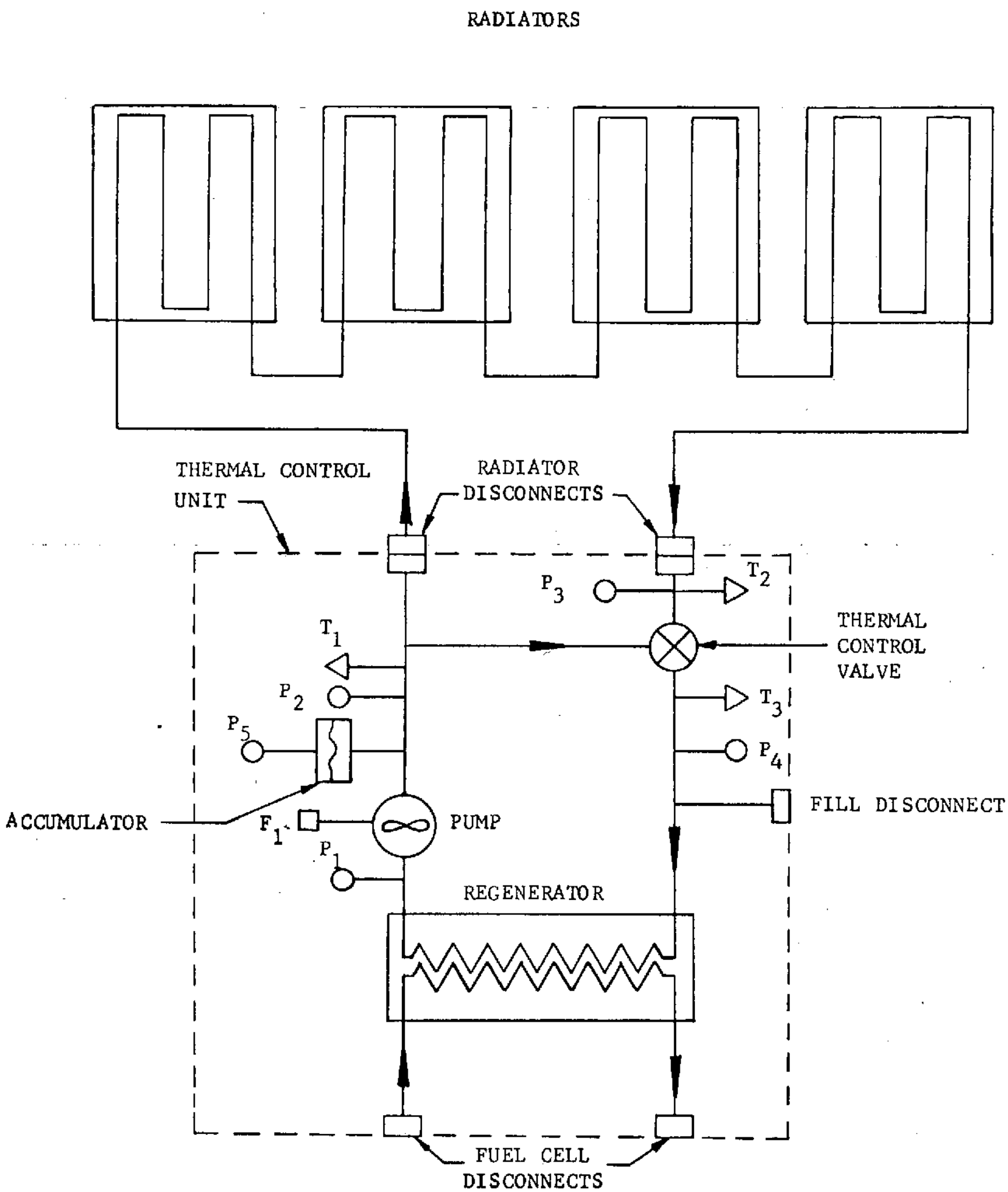

Figure 9 Fuel Cell Heat Rejection System

Inherent in the design of this system is the requirement to operate the fluid system in the radiators through the transition region. Hence, breadboard testing of a radiator panel is warranted before proceeding further with the design. While this design might represent a precedent, the Skylab Airlock Module was designed as a laminar flow system and was tested and operated at Reynolds numbers up to 2500. The Transtage radiators operated at Reynolds numbers down to 7000. This does however represent the only known design intended to operate from turbulent laminar through the transition region to laminar.

The pumped system and the heat pipe design were considered and the pumped system was selected based on the current state of art of these systems. A variable conductance (VC) heat pipe design would be faced with state of the art control problems and persistent contamination and noncondensible gas generation within the pipes. Successful performance and life demonstrations of VC heat pipe designs would warrant reexamination of this choice in the future. The pumped fluid system does represent a weight penalty to the vehicle versus the use of a heat pipe design. Continued development and solution of the VC pipe problems is needed.

3. SUPPORTING TASKS

3.1 CATALOGUING

Preceding the parametric studies that led to the proposed Tug thermal design, candidate components that could be used to satisfy the avionics system requirements were catalogued. The catalogues were organized in a manner that presented the thermal and physical characteristics and constraints. The compilation of data at this time in the preliminary design of the Tug has proven extremely useful in the early identification of component thermal problems. A computerized method of compiling and organizing the data was used to provide the thermal designer with the essential data required to proceed with the thermal design task.

Examples of the catalogues are presented in Tables 1 and 2. Table 1 is a typical page of the Thermal Requirements Catalogue, which emphasizes the allowable component case temperatures as they relate to the various mission phases, and the on or off requirements during each phase. Table 2 presents the typical page from the Characteristics and Constraints Catalogue, which provides the designer with more specific thermal design information.

A more detailed description of the catalogues and the third catalogue, which served as the data source, is discussed in References 1, 3, and 4. A catalogue of this nature is useful to many engineers involved in the design of spacecraft. Generalization and expansion of the data included in the catalogues would be helpful to the designers in each engineering discipline if the data were organized to present the functional characteristics and the test requirements.

3.2 THERMAL SPECIFICATIONS

At the completion of the parametric studies, three thermal control concepts used in the proposed design were carried into a preliminary specification phase highlighting the thermal design requirements for each concept. Specifications were generated for the:

1) Louver battery;

2) Fuel cell heat rejection system;

3) Forward compartment thermal design.

The final report, Reference 1, presents the above specifications.

Table 1

EQUIPMENT THERMAL REQUIREMENTS CATALOGUE

GUIDANCE NAVIGATION AND CONTROL SUBSYSTEM

EQUIPMENT ITEM STAR TRACKERS

REF. NO.	DESCRIPTION AND MANUFACTURE	THERMAL DESIGN GROUND/ ORBITAL	POWER WATTS MIN/ MAX	MISSION PHASE THERMAL REQUIREMENTS AND TEMPERATURE LIMITS DEGREES KELVIN / (FAHRENHEIT) - MIN / MAX PRELAUNCH	SHUTTLE CARRY	MANEUVERS SHUTTLE TUG	TUG ORBITAL	PAYLOAD TUG	REENTRY AND LANDING	REMARKS
ST 1	CT-401 SENSOR 33RD	PASSIVE PASSIVE	5/ 5	OFF 243/333 (-22/140)	OFF 243/333 (-22/140)	OFF 243/333 (-22/140)	ON 243/333 (-22/ 0)	ON 243/333 (-22/140)	OFF 243/333 (-22/140)	ON DURING PRELAUNCH FOR CHECKOUT
ST 2	STAR TRACKER HONEYWELL	PASSIVE PASSIVE	3/ 3	OFF 255/302 (0/ 85)	OFF 255/302 (0/ 85)	OFF 255/302 (0/ 85)	INT 255/ 50 (-22/ 50)	INT 255/283 (0/ 50)	OFF 255/302 (0/ 85)	ON DURING PRELAUNCH FOR CHECKOUT
ST 3	MMOS ITT GILFILLAN	PASSIVE PASSIVE	20/ 20	YES 293/323 (68/122)	OFF 288/323 (60/122)	OFF 288/323 (60/122)	ON 293/323 (68/122)	ON 293/323 (68/122)	OFF 288/323 (60/122)	ON DURING PRELAUNCH FOR CHECKOUT
ST 4	5698 STAR TRACKER EMR PHOTOELECTRIC	PASSIVE PASSIVE	3/ 3	OFF 218/348 (-67/167)	OFF 218/348 (-67/167)	OFF 218/348 (-67/167)	INT 218/113 (68/113)	INT 218/318 (-67/113)	OFF 218/348 (-67/167)	ON DURING PRELAUNCH FOR CHECKOUT
ST 5	574 STAR CAMERA EMR PHOTOELECTRIC	PASSIVE PASSIVE	4/ 4	OFF 218/343 (-67/158)	OFF 218/343 (-67/158)	OFF 218/343 (-67/158)	INT 218/104 (68/104)	INT 218/313 (-67/104)	OFF 218/343 (-67/158)	ON DURING PRELAUNCH FOR CHECKOUT
ST 6	OAO STAR TRACKER BENDIX CORPORATION	PASSIVE PASSIVE	6/ 6	OFF 238/327 (-30/130)	OFF 238/327 (-30/130)	INT 238/310 (-30/100)	INT 238/100 (68/100)	INT 238/310 (-30/100)	OFF 238/327 (-30/130)	ON DURING PRELAUNCH FOR CHECKOUT
ST 7	OMA ATM STAR TRKR. BENDIX CORPORATION	PASSIVE PASSIVE	18/ 28	OFF 233/327 (-40/130)	OFF 233/327 (-40/130)	OFF 233/327 (-40/130)	INT 233/ 90 (68/ 90)	INT 233/305 (-40/ 90)	OFF 233/327 (-40/130)	ON DURING PRELAUNCH FOR CHECKOUT
ST 8	KS-199 STAR TRKR KOLLSMAN INSTR.	PASSIVE PASSIVE	8/ 18	OFF 272/310 (30/100)	OFF 272/310 (30/100)	OFF 272/310 (30/100)	INT 272/ 70 (68/ 70)	IN 272/310 (30/100)	OFF 272/310 (30/100)	ON DURING PRELAUNCH FOR CHECKOUT

Table 1

Table 2

EQUIPMENT PHYSICAL CHARACTERISTICS AND CONSTRAINTS CATALOGUE

GUIDANCE NAVIGATION AND CONTROL SUBSYSTEM

EQUIPMENT ITEM STAR TRACKERS

REF. NO.	DESCRIPTION MANUFACTURER AND REMARKS	WEIGHT KG (LBS)	PACKAGE SHAPE	SURFACE AREA SQUARE CM (FT)	VOLUME CUBIC CM (FT)	RAD. ALPHA/ EMISS	POWER WATTS MIN/ MAX	POWER DENSITY Q/A W/ M2 (W/FT2)	TIME CONST. HOURS MIN MAX	ADIABATIC RISE RATE DEG K/HR DEG F/HR MIN	ADIABATIC RISE RATE MAX	THERMAL MASS W-HR/K BTU/F	ALLOWABLE SINK TEMP. DEG K/(F) DESIGN MIN	DESIGN MAX	QUAL MIN	QUAL MAX	OPERATION MODE
ST 6	OAO STAR TRACKEP BENDIX CORPORATION THE OAO-IV STRAPDOWN STAR TRACKER HAS A PASSIVE THERMAL CONTROL HEAT IS REJECTED BY CONDUCTION TO A RADIATION SHIELD HAVING A PER-MISSIBLE TEMPERATURE EXCURSION OF -29 TO 38 DEG.C(-20 TO 100 DEG F). NO HEATERS ARE REQUIRED WITHIN THIS RANGE. UNIT IS HARD MOUNTED TO VEHICLE MOUNTING FLANGE. UNIT REQUIRE CLEAR UNOBSTRACT-ED VIEW TO OPERATE PROPERLY	7.3 (15.0)	RECT	2877 (3.1)	9832 (.35)	.70/ .85	6/ 6	20/ 20 (1/ 1)	1.00 1.00	1 ?	1 2	5.3 2.6	236 -33	307 93	236 -33	307 93	INT
ST 7	OMA ATM STAR TRKR. BENDIX CORPORATION THE OMA ATM STAR TRACKER IS A GIMBALLED UNIT. THE ABOVE DIMENSIONS ARE EXTERIOR LIMITS SEE REF FOR MORE DETAIL DESCRIPTION. UNIT IS MARRIED TO ATM STAR TRACKER ELECTRONICS UNIT. UNIT HAS 3 INTERNAL HEATERS OF 10 WATTS EACH TWO OF THE HEATERS HAVE SET POINTS OF -23 .3 TO -15.0 (-9.9 TO 5.0 DEG.F) AND THE THIRD HEATER HAS SET POIN OF -15.3 TO -6.7 DEG C (5.5 TO 22.5 DEG.F). UNIT IS THERMALLY ISO LATED, PAINTED WHITE, AND HAS A SUPERINSULATION BLANKET COVERING.	19.1 (4?.0)	RECT	11211 (12.1)	77677 (2.74)	.25/ .90	18/ 28	16/ 25 (1/ 2)	.62 .61	1 2	2 4	12.9 6.6	236 -30	302 84	247 -14	30? 84	INT
ST 8	KS-199 STAR TRKR KOLLSMAN INSTR. THE KS-199 STAR TRACKER WAS BUILT FOR THE MOL PROGRAM. ONE ENGINE-ERING MODEL WAS BUILT AND FUNCTIONAL TESTED. THE GIMBAL SENSOR IS COUPLED TO AN ELECTRONIC UNIT. THE TRACKER HAS INTERNAL HEATERS TOTALING 10 WATTS AND ARE SUED FOR FAST WARM UP WHEN UNIT IS BELOW -11.8 DEG C(10 DEG. F). THE UNIT THERMAL DESIGN IS PASSIVE WITH UNIT THERMALLY ISOLATED FROM MOUNTING, AND COVERED BY SUPER-INSULA TION BLANKET TO MAINTAIN PROPER OPERATING TEMPERATURE.	9.1 (20.0)	RECT	4842 (5.2)	22184 (.78)	.20/ .75	8/ 18	17/ 38 (1/ 3)	.43 .42	3 5	6 11	3.0 1.6	247 -14	290 62	226 -51	307 93	INT

Table 2

3.3 FOLLOW-ON PLAN

Several areas were identified for future study and test that will lead to an orderly thermal development of the Tug vehicle. In a study of this nature as many questions are identified as are answered during the course of the study.

As the avionics system evolves in the future, the power dissipation level is expected to change. This will require altering the paint pattern and possibly increasing heater power for some components. Component placement and arrangement studies on the thermal conditioning louver panels is warranted to further develop this technique. Parametric studies investigating panel Q/A, equipment Q/A, component arrangement, matching of qualification requirements, proper mix of high and low duty cycle, and environment temperature ranges should be pursued to identify the capabilities and limitations of this concept. The APS thermal control will require some future investigations as that system evolves. The use of heater power to maintain the catalyst temperature may be required; however, the limit cycle pulsing of that system will contribute significantly to maintaining the desired temperatures. Early identification of the mission timelines will be essential in developing the engine module thermal design.

Breadboard testing in several areas of the Tug thermal design is warranted at this time. Two areas will be explored in the follow-on to this contract. The application of louvers to the thermal control of the battery is currently being investigated along with the performance of a thermal conditioning panel that will be coupled with a heat pipe radiator. Further demonstrations of the isothermalized panel capabilities will be achieved. The design of a variable conductance heat pipe radiator will be verified. The successful demonstration of the radiator design will provide added confidence in the VC capability to satisfy the fuel cell radiator requirements.

In the event that the variable conductance pipes continue to experience control problems, the pump fluid system would require further attention. The proposed design would require some breadboard level testing to verify the radiator's operation through the transition region and point to the predictability of the analytical models in design and mission analysis.

Additional testing would be required to determine the effective thermal conductance through some of the proposed honeycomb skin panels. The major unknown at this time is the influence of the two bondlines on the conductance. The data generated in the study indicate that the forward compartment thermal design is sensitive to this conductance value and could have a severe impact on the compartment design concept.

The forward compartment heat pipes were envisioned as six closed circular pipes. Current technology in heat pipes has generally been limited to relatively short pipes. One pipe, 4.5 m in diameter, has been built and tested. Continued development in this area is warranted.

Another test program that would be a logical extension of the current follow-on contract is the testing of the thermal conditioning panel louver configuration with component simulators. This test would demonstrate the proposed forward compartment equipment mounting configuration and its ability to achieve the desired temperature control.

4. THERMAL CONCERNS AND CONSIDERATIONS

The evaluation of the Tug design in the past few years has been challenging to structural designers. Inherent in the Tug mission is the goal of maximizing the payload delivery and retrieval capability. This has resulted in significant minimum weight requirements on all systems. The application of extensive use of composite structural designs has been explored to obtain a minimum weight structure.

A honeycomb design has been proposed for the forward skirt of Tug by most investigators. While this might result in a minimum weight design on the surface, further tradeoffs are necessary before arriving at the preferred baseline. The past use of the aluminum skin stringer, longeron design, while being potentially heavier than the honeycomb design, has given the thermal designer a significant amount of flexibility. Use of the skin as a radiation sink for heat to leave a compartment was a simple and reliable means of thermal control. However, the application of honeycomb designs in this area represents an added unknown to the problem, and in some cases would result in significant thermal design problems.

Heat transfer through thin aluminum skin panels results in small temperature drops ($\ll 1°K$) and is usually considered to be zero. The honeycomb material represents two surfaces separated by a core material that heat must be transferred through. Depending on the core material and the bondline characteristics, large temperature drops can result when transfering the required heat. The use of high conductivity materials such as aluminum is required because the major mode of heat transfer through the honeycomb is via conduction. The use of fiberglass or other low conductivity materials would severely impact the internal compartmental temperature in the hot case, and would require large holes in the skirt to allow heat to be dissipated in local areas depending on the equipment locations. Such a design would probably eliminate the weight advantages gained to achieve the required strength characteristics. Continued development of lightweight skirt structural concepts should include an evaluation of the thermal design impact that each concept might yield. One of the key requirements in a supporting thermal evaluation would be to determine the thermal characteristics of each candidate concept experimentally.

The thermal design of the APS was not specifically examined in this study. However, experience in the design and flight of the Transtage hydrazine attitude control system provides several guidelines for consideration. The selection of a hydrazine system for Tug will simplify the thermal design problem and will make it an integral part of the duty cycle requirements of the system. The thruster module thermal design is the primary concern. Depending on the individual thruster design, heat is required to maintain the catalyst temperature at some minimum level to ensure that the desired minimum impulse can be delivered on demand. The Transtage system used engine heat to maintain the catalyst bed temperatures above 644°K (700°F). Normal limit cycling of the engines required by the guidance system to maintain the required vehicle attitudes was sufficient to supply the major portion of required heat. Computer software was added to account for the fuel consumption over 10-minute periods, which was compared to cold-case requirements. Shortage of the required cold-case consumption in any 10-minute flight interval resulted in a burn of the required thruster to make up the difference. Hence, the design used the propellant consumption to satisfy module thermal design requirements versus the use of heaters. Further, definition of the module and engine design will be required before this question can be resolved. Local application of high temperature fiberous insulation will be required.

The propellant storage and feed system will require insulation and thermostatically controlled heaters to eliminate propellant freezing. This however should not represent a significant problem. In addition, the application of low conductance tank and feedline supports will be required.

5. REFERENCES

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