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A THERMAL CONTROL APPROACH FOR A SOLAR ELECTRIC PROPULSION THRUST SUBSYSTEM

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INTRODUCTION

NASA has under consideration several energetic missions for exploring the solar system and for conducting geosynchronous operations. These mission include comet and asteroid rendezvous, planetary orbiter, solar probe, magnetic tail mapping, satellite observation, and space platform transportation and positioning. In order to perform these missions, there will be a need to augment the Shuttle-IUS Space Transportation System with a solar electric propulsion system (SEPS).

Since 1974, LeRC has been working on the SEPS thrust subsystem technology focused for these applications. Sponsored by the NASA Office of Aeronautics and Space Technology (OAST), the technology effort has been in the areas of the 30-cm mercury ion thrusters, power processors, propellant subsystem, thrust vector subsystem, and thermal control subsystem. Reference 1 selected a modular thrust subsystem approach for SEP vehicle design to examine thrust subsystem interactions and to identify engineering solutions for integration of the technology elements into a thrust subsystem. This design approach, termed a BIMOD engine system consists of two thruster/gimbal subsystems, two power processors, propellant distribution, heat pipe thermal control subsystem, and interconnecting structure. A mass simulation of this BIMOD engine system designed, fabricated, and assembled at LeRC is shown in figure 1. During fiscal year 1978, LeRC worked on the definition of a SEP thrust subsystem to perform the Halley Flyby/Tempel 2 mission (in support of the JPL/LeRC Comet/Ion Drive Program sponsored by the Office of Space Science). Figure 2 shows the layout drawing for the thrust subsystem to perform the Halley Flyby/Tempel 2 rendezvous mission.

Two design goals were to create simple interfaces between the thrust subsystem and avionics module and within the thrust subsystem, to create BIMOD engine systems that are autonomous. For the thermal control subsystem, these goals are achieved by placing a thermal insulation blanket between the avionics module and the thrust subsystem, thereby making them thermally independent. Also, it was desired to make the thermal control subsystem of the BIMOD engine systems thermally independent from adjacent engine systems. This report discusses the thermal design approach for the thrust subsystem and BIMOD engine system and presents the study approach used to confirm the thermal control subsystem design autonomy of the thrust subsystem and BIMOD engine system.

The primary design tool used in this study is a thermal model developed for the thrust subsystem. A 114 node analytic model of the total SEPS was coded on the System Improved Numerical Differencing Analyzer (SINDA, ref. 2) program. The SEPS thermal model developed utilizes the outputs of thrusters, power processors, and heat pipe radiator programs as input parameters.

THRUST SUBSYSTEM CONFIGURATION

As shown in figure 3, a typical vehicle using solar electric propulsion for planetary missions would consist of a planetary spacecraft, an avionics module, solar arrays, and a thrust subsystem. For earth orbital missions, the planetary spacecraft would be replaced by a payload. As shown on figure 2, the thrust subsystem consists of an interface module and BIMOD engine system. The interface module provides structural support for the BIMOD engine systems and hard points to the avionics module. The interface module houses the propellant tank, thruster controller, and power distribution unit. As shown in figure 4, a BIMOD engine system (refs. 1 and 3) consists of two 30-cm mercury-ion thrusters and gimbal subsystems, two power processors (PPU's), a thermal control subsystem, a supporting structure, and propellant feed lines.

THERMAL REQUIREMENTS

Simply stated, the functional requirement of the thermal subsystem is to maintain the thrust subsystem's components within operational limits. The thermal subsystem design must provide for a wide range of external and internal environments. Table 1 lists the thrust subsystem component temperature limits. The trajectory in figure 5 shows that for the Halley/Tempel 2 mission, the SEPS will be exposed to a thermal environment ranging from 1 to 3.1 AU. Figure 6 shows the sequence of operating thrusters to accomodate the change in thrust subsystem input power over the trajectory. Figure 7 shows the wide range of power processor input power as a function of mission time. The thermal subsystem will be required to perform its function over the correspondingly wide range of power processor heat dissipation.

In order to provide for simple thermal control subsystem interfaces, the thrust subsystem must be thermally independent from the avionics module and the BIMOD engine systems must be thermally independent of each other. The thermal design must also provide for meteoroid and cometary dust protection.

THERMAL SUBSYSTEM - BASELINE DESCRIPTION

The thrust subsystem thermal configuration is shown in figure 8. As shown in figure 8, the interface module will be wrapped in multilayer insulation blankets (MLI). This MLI serves two purposes. First, it provides a thermal enclosure for the interface module equipment. The heat generated by the interface module electronics along with supplementary heaters will be used to maintain the interface module components within their allowable temperature ranges. Rejection of excess heat dissipated within the interface module will be provided for by a passive radiator (5 cm by 7.6 cm) with a surface emittance of 0.9.

The second purpose of the MLI is to provide a heat flow barrier between the avionics module and the thrust subsystem. The MLI blankets between the avionics module and thrust subsystem will consist of 20 layers of 1/2 mil crinkled aluminized Kapton with an outer layer of 5 mil aluminized Kapton.

To insure meteorite and cometary dust protection, the MLI blankets for the space exposed surfaces of the interface module will consist of the materials listed in table 2.

The BIMOD engine system thermal control subsystem consists of multilayer insulation blankets, variable conductance heat pipes, heat pipe radiators, and supplementary heaters (figs. 8 and 9). Two power processors will be mounted to opposite sides of a common heat pipe evaporator saddle and will be wrapped with a MLI blanket. This MLI blanket is the same MLI that serves as the thermal barrier between the interface module and each BIMOD engine system.

The required temperature environment for the power processor will be maintained by methanol stainless steel variable conductance heat pipes (ref. 4) and supplementary heaters. Each power processor (PPU) will have an electrical efficiency of 87% and dissipate 410 watts at full power. The minimum capacity for each variable conductance heat pipe is 220 watts. Two sets of 3 heat pipes (fig. 9) are embedded in the heat pipe evaporator saddle with one pipe in each set being a redundant pipe. The mounting arrangement of the heat pipes within the heat pipe evaporator saddle allows for heat dissipated from either PPU or PPU's to be distributed to both heat pipes radiators of a BIMOD.

Each heat pipe radiator was sized using the following assumptions; (1) the radiator has a view factor to the solar array of 0.05, (2) the radiator has a view factor of 0.95 to space with no solar flux incident on the radiator, (3) the emittance of both the radiator and solar array is 0.8, (4) the radiator dissipates heat at 50° C, (5) and the radiator is 20 mil thick aluminum. Figure 4 shows the heat pipe radiator configuration along with its dimensions 69 cm wide by 209 cm (183 cm + 26 cm) long. In order to keep the heat pipe working fluid (methanol), above its' freezing point of -93° C, strip heaters will be mounted in line with the heat pipes on the back side of the radiator. There is no need for (see section on results) insulation behind the heat pipe radiator or between adjacent BIMODs (fig. 8).

The propellant feed lines will be located in the BIMOD structure cavity. Thermal control of the feed lines is provided by a combination of isolation, insulation, and heaters. Thruster spacing from the aft MLI will be consistent with requirements for; vaporizer thermal control, gimbal system thermal control, and propellant feed line thermal control. Both the aft MLI on each BIMOD (fig. 8) and the END MLI on the exterior sides of the end BIMOD engine systems will provide for meterorite and cometary dust protection.

THERMAL MODELS

In order to predict the thermal characteristics of the thrust subsystem, a series of analytical models were developed using the Systems Improved Numerical Differencing Analyzer program (SINDA) described in reference 2.

Initially, a single BIMOD thermal model consisting of 34 nodes was developed as shown in figure 10. This model was then expanded to encompass 3 BIMOD engine systems and an interface module consisting of 114 nodes as shown in figure 11. The model initially contained insulation blankets between the BIMOD engine systems (nodes 25, 74, 75, and 114) as well as other areas as shown in figure 11.

Modifications such as changing conductor values, adding or deleting conductor values, changing boundary temperature values and/or heat dissipations can be made with relative ease in either model.

It was not the purpose of this study to have very sophisticated and complex models. Therefore, the main components of the thrust subsystem were simulated using very few nodes. Single node models were used to represent the power processing units (PPU's), the heat pipe saddles and ion thrusters. Each radiator consisted of 4 nodes. There was no attempt made to model the structure.

The justifications for using single node models for the thrust subsystem components mentioned in the preceeding paragraph are:

1. A 62 node thruster thermal model has been developed separately. The accuracy of this model has been verified by tests and therefore, justifies using single node boundary temperatures for the thrusters when operating (ref. 5).

2. A 1300 node PPU model (ref. 6) has been developed separately. The accuracy of this model has also been verified by tests and justifies using single node boundary temperatures for the PPU's when operating.

3. The absence of a heat pipe thermal model does not significantly impact the thermal characteristics of the thrust subsystem since a separate radiator model that has been developed was used to reasonably predict the radiator temperatures when the PPU's are operating.

4. The absence of a structural thermal model does not significantly impact the thermal characteristics of the thrust subsystem.

Figure 12 is an analysis flow model showing how information from the above mentioned models was used in the BIMOD engine system and thrust subsystem models.

Therefore, for the situations where the PPU's thrusters, and radiators were operating, the corresponding nodes were set as boundary temperatures in the analysis. For the situations where they were not operating, they were allowed to come to their equilibrium temperatures based on the interactions with the other portions of the model.

In addition to using the model to validate the design, the single BIMOD thermal model has been modified to be used in defining the thermal environmental system for the BIMOD engine system tests to be conducted in the near future at LeRC.

The results of these tests will be used to partially verify both the BIMOD engine system thermal design and the BIMOD analytical model. Additional modifications to the model will be made, if necessary, to assure reasonably accurate predictions on the system level.

METHOD OF THERMAL INVESTIGATION

The thermal interactions that were accounted for during the analysis are indicated by figure 13. The model was used to verify the baseline thermal design described in an earlier section and to investigate alternative configurations and placement of multilayer insulation within the BIMOD engine system and SEPS thrust subsystem. The model was also used to determine; (1) whether louvers or a passive radiator should be used on the interface module, (2) the amount of supplementary heating required and location of heaters, and (3) whether there is a need for MLI behind the heat pipe radiators.

The following variable parameters were included in the analysis of the possible design configuration.

1. Thruster sequence (number of thrusters on at a time) as shown in figure 6
2. The solar input (which is determined by the angle of solar incidence and helocentric distance) into the thrust subsystem
3. The minimum temperature of the heat pipe radiator
4. The avionics module interface temperature.

Two type of steady state solutions (hot cases and cold cases) were determined. For the steady state hot case, it was assumed that; (1) the avionics module was maintained at 40° C, (2) the PPU heat pipe saddle was maintained at 50° C, (3) the operating thrusters were at 125° C, (4) each PPU dissipated 410 watts, and (5) there was solar flux at 1 AU normal to the insulation on the end of the thrust subsystem (see fig. 8). For the steady state cold case, it was assumed that; (1) the avionics module was at 5^{o} C, (2) the PPU's were dissipating nothing, (3) no thrusters were operating, and (4) there was no solar flux on the insulation. Table 3 lists the dissipations of the interface module components assumed for the hot and cold cases. These assumptions were based on the conditions expected during the Halley/Tempel 2 mission. Table 4 lists the material properties used in the analyses.

SUMMARY OF RESULTS

Typical output format from the analytic program is shown in figure 14 for the interface module and BIMOD engine system using the nodal definition given in figure 11. For example, node 42 on figure 11 is defined as PDU (power distribution unit), while figure 14 shows that node 42 is -28^{o} C.

Table 5 presents the steady state temperature predictions for the main components of the thrust subsystem. Also given in table 5 is the calculated supplementary heating required for maintaining components within their prescribed temperature limits.

The baseline configuration, used as the base for comparison, consisted of having; MLI between the mission module and the thrust subsystem, MLI around the PPU's, MLI behind the heat pipe radiator, variable conductance heat pipe and radiator systems, and a passive radiator located on the interface module. Cases 1-A and 1-B are the hot and cold steady state predictions for the baseline configuration. A review of the predictions for cases 1-A and 1-B shows all the main components can be maintained within the required temperature limits for both the hot and cold cases. The only exception is the warm temperature prediction for the controller. Since the computer program treats the controller as a single node, the predicted 57^{o} C is considered to be an average temperature and fully acceptable considering the simplicity of the model. For the cold case, 43 watts of supplementary heater power is required. If the requirement to maintain the heat pipe radiator above the freezing point of the heat pipe working fluid (-93^{o} C for methanol) is imposed on the thrust subsystem thermal design, comparison of cases 1-B and 1-C shows that an additional supplementary heating power of 322 watts would be required.

Table 5 can be used to determine the effect of a variation from the baseline configuration. For example, by comparing the results of the analysis of case 4 with that of 1-A (baseline), one can determine the effect of using a louver system vs a passive radiator on the interface module. Analysis of case 4 shows no advantage of a louver system over a passive radiator on the interface module. Hence, since the louver system would add weight and cost to the thermal control system, a passive radiator was selected. To minimize the temperature swing between the hot and cold cases, the size of the passive radiator was optimized.

The temperature predictions for the configuration where the thrust subsystem is thermally coupled to the avionics module (no insulation between the avionics module and the thrust subsystem and no insulation around the power processors--see figs. 8 and 9) are given as cases 2-A and 2-B. For case 2-A, both the power distribution unit (PDU) and controller exceed their upper temperature limit. This is partially due to the interface structure looking at a 40° C avionics module (avionics module maximum temperature limitation). For the 2-B case (all thrusters off and minimal avionics module power), both the PDU and controller are within their limits, but the power processors (PPU's) are far below their minimum temperature limits (-30° C). In order to maintain the PPU's at or above -30° C, an additional heating power of 34 watts (see results for case 2-C) is required. It must be pointed out that for cases 2-B and 2-C the avionics module is at 5° C (the minimal allowable temperature for the avionics module for the Halley/Tempel 2 mission). A heat balance between the avionics module and the thrust subsystem shows that in order to achieve the component temperatures as predicted for cases 2-B and 2-C (while the avionics module is at 5° C), there has to be a heat flux of 75 watts from the module to the interface module. For the Halley/Tempel 2 mission, there will be periods when there will be less than 75 watts of power on within the module. Under this condition, the components in both the module and the thrust subsystem would run colder than stated. Cases 3-A, B, and C show the effect of removing the insulation between the avionics module and the interface (thermal coupling of module and interface module) but keeping the insulation wrapped around the PPU's. The temperature predictions for case 3-A show that the interface module area would be too warm while those for case 3-B show that the PPU's will run at -100° C (70° C below minimum allowable temperature). For this configuration, case 3-C shows that 15 watts of supplementary heating power would be required to maintain the PPU's at or above -30° C. This is less than half the power required for the configuration where the module is thermally coupled with the total thrust subsystem. As in cases 2B and 2-C, the avionics module was assumed to be 5° C for cases 3-B and 3-C. Comparing the temperature predictions between cases 1-D (insulation removed from the backside of heat pipe radiators) and 1-B, there is essentially no effect of removing the insulation blankets behind the heat pipe radiators.

CONCLUSIONS

A 114 node analytic model of the total Solar Electric Propulsion System (SEPS) was developed and coded on the System Improved Numerical Analyzer (SINDA) program at the Lewis Research Center. Analytic temperature profiles of various SEPS thermal configurations were generated. An analysis of these predicted temperature profiles resulted in the definition of a SEPS thermal control subsystem.

From the results of the analytic study, it was concluded that:

1. A BIMOD engine system thermal design can be autonomous.

2. An independent thrust subsystem thermal design is feasible.

3. The interface module electronics temperatures can be controlled by a passive radiator and supplementary heaters.

4. Maintaining heat pipes above the freezing point would required an additional 322 watts of supplementary heating power for the situation where no thrusters are operating.

5. Insulation is required around the power processors, and between the interface module and the avionics module, as well as in those areas which may be subjected to solar heating.

6. Insulation behind the heat pipe radiators is not necessary.

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5. OGLEBAY, Jon C.: Comparison of Thermal Analytic Model with Experimental Test Results for 30-cm Diameter Engineering Model Mercury Ion Thruster. NASA TM X-3541, 1977.

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TABLE 1. - COMPONENT OPERATIONAL TEMPERATURE LIMITS

Operational temperature limits	Max (^{o}C)	Min (^{o}C)
Power processor		
Component case	85, on; 100, off	-15, on; -30, off
Baseplate	50	-15, on; -30, off
Propellant tank and lines	100	-30
Radiators	50	-170 (-93)[a]
Gimbals (stepper motor winding)	125	-40
Solar array drive	66	-46
Thruster vaporizer	300	-30
Power distribution unit	50	-15
Controller	50	-15

[a]If there is a requirement to maintain the heat pipe working fluid (methanol) above freezing.

TABLE 2. - MATERIALS FOR SPACE EXPOSED MULTILAYER INSULATION BLANKETS

1/2 mil scrimmed Kapton with 1 mil black coating on one side, which is conductive (outer layer)
1 mil double aluminized dimpled Mylar
1 mil double aluminized flat Mylar
1 mil double aluminized dimpled Mylar
3 layers of 2 mil Tedlar
15 layers of 1/2 mil double aluminized Mylar separated by Dacron net
1 mil double aluminized Teflon

TABLE 3. - INTERFACE MODULE COMPONENT

DISSIPATION SUMMARY

	Hot case, W	Cold case, W
Power distribution	55.6	7.5
Thruster controller	6.0	6.0

TABLE 4. - MATERIAL PROPERTIES

Insulation effective emittance	0.02
Insulation lateral conductivity, Btu/hr-ft-^{o}R	0.06
Insulation emissivity	0.05/0.8
Solar array emissivity	0.80
Interface module component emissivity	0.9
Silvered Teflon emissivity (radiator)	0.8
Insulation absorptivity, Kapton	0.6

TABLE 5. - THERMAL CONFIGURATION STUDY RESULTS

Case (limits)		Insulation between BIMODs	Insulation between avionics module and thrust subsystem	Insulation around PPU's	Louvers on interface module	Radiator on interface module	Supplementary heaters	Tank (100° C/ -30° C)	PDU (50° C/ -30° C)	Controller (50° C/ -15° C)	PPU (50° C/ -30° C)	Radiator (50° C/-170° C (-93° C))	Heater power, W		
													Component	Propellant lines	Total
1 (Baseline case)	A Hot		✓	✓		✓		26	47	57	50	50		0.5	0.5
	B Cold		✓	✓		✓	✓	-17	-29	23	-30	-90	362	2.7	364.7
	C Cold		✓	✓		✓	✓	-18	-30	23	-30	-170	40	3.4	43.4
	D Cold		✓	✓		✓	✓	-17	-28	-23	-25	-90	365		365
2	A Hot					✓		48	56	71	50	50			
	B[b] Cold					✓		-4	0	32	-48	-162			
	C[b] Cold					✓	✓	6	2	35	-30	-162	34	3.4	37.4
3	A Hot			✓				37	48	63	50	50			
	B[b] Cold			✓				-2	2	30	-100	-170			
	C[b] Cold			✓			✓	-2	2	30	-30	-170	15	3.4	18.4
4	Hot		✓	✓	✓			23	45	55	50	50			

[a]Minimum radiator temperature to maintain methanol fluid in heat pipes above freezing.
[b]Heat flow from avionics module to thrust subsystem of 75 watts.

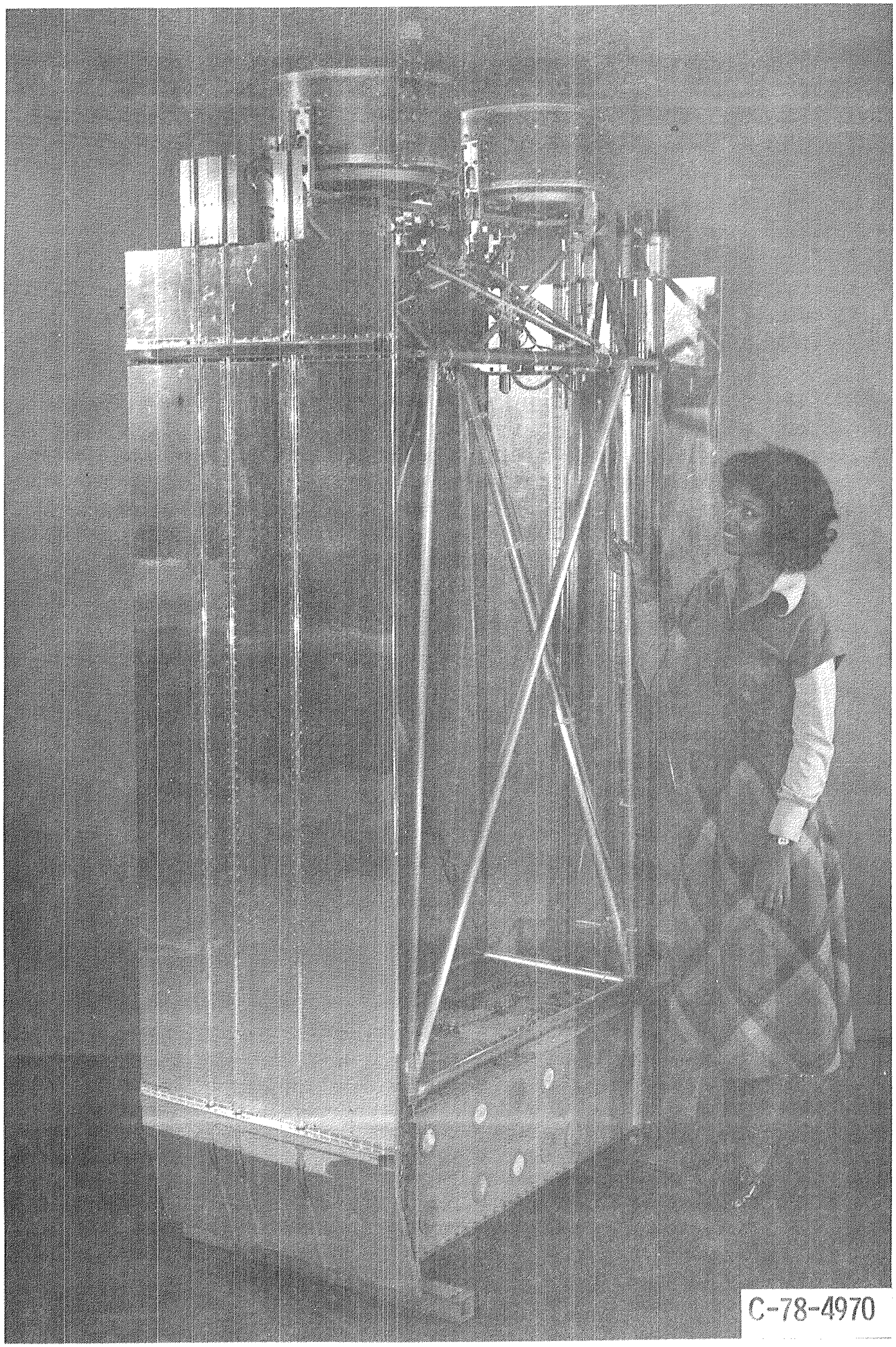


Figure 1. - Bimód engine system.

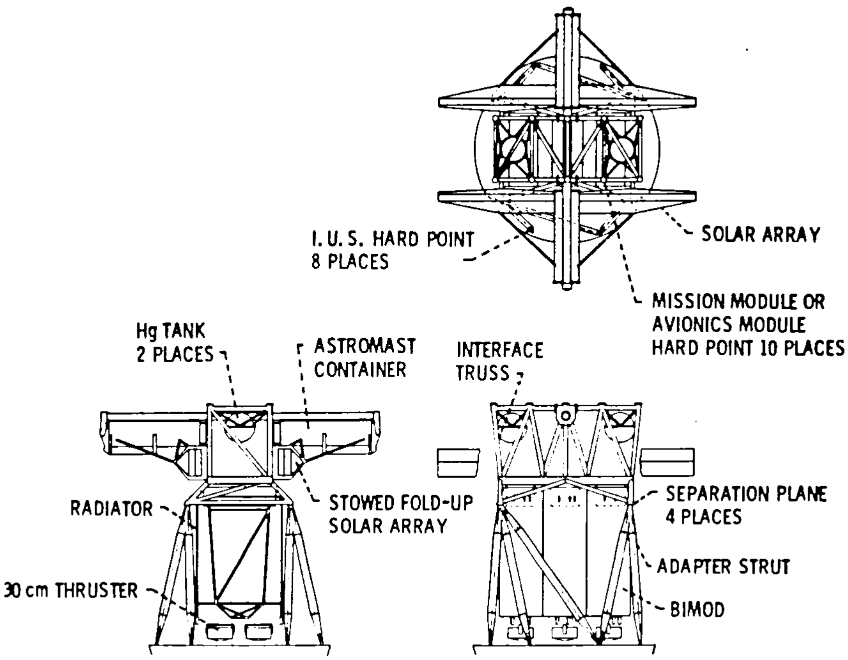


Figure 2. - Thrust subsystem layout.

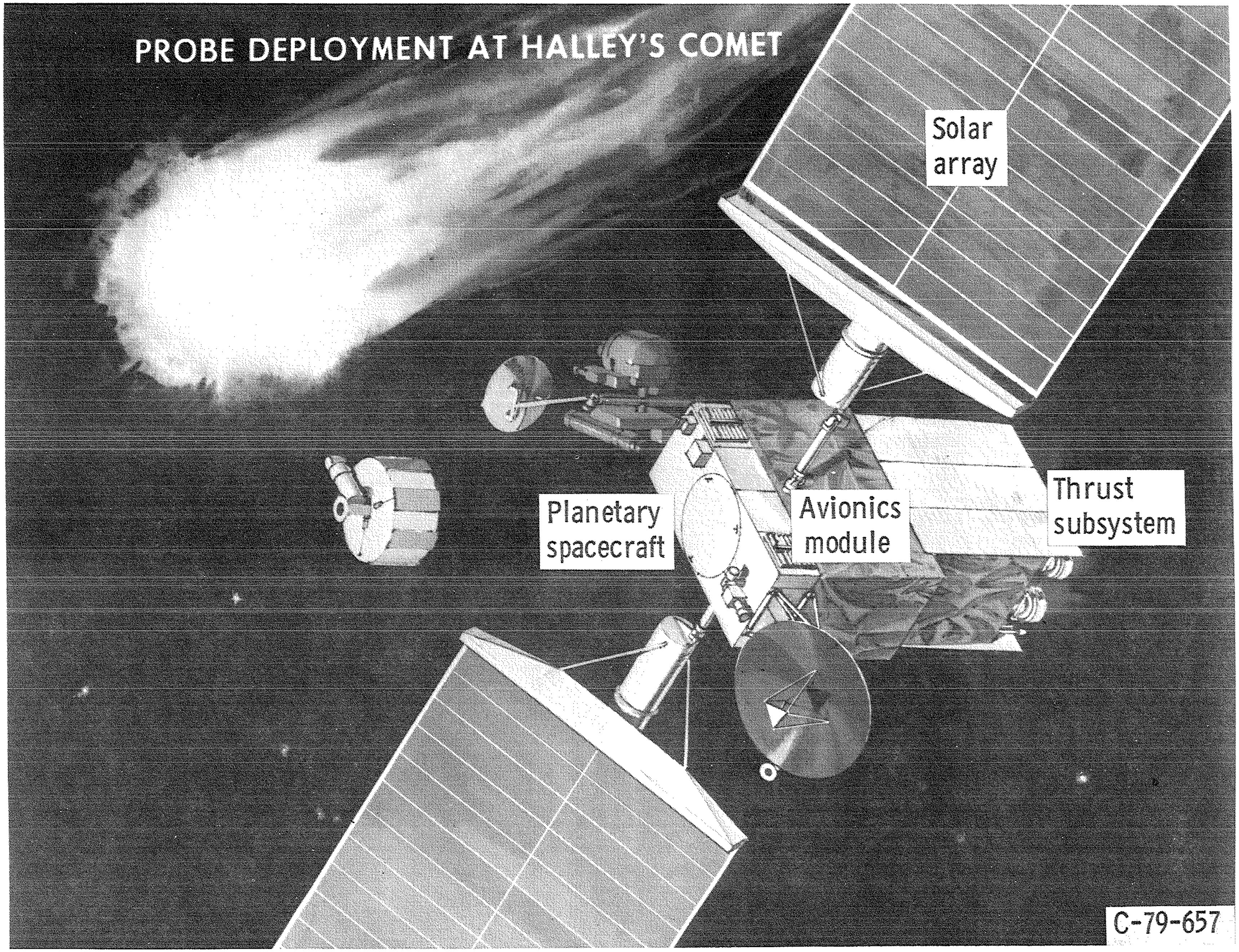


Figure 3. - Spacecraft with solar electric propulsion.

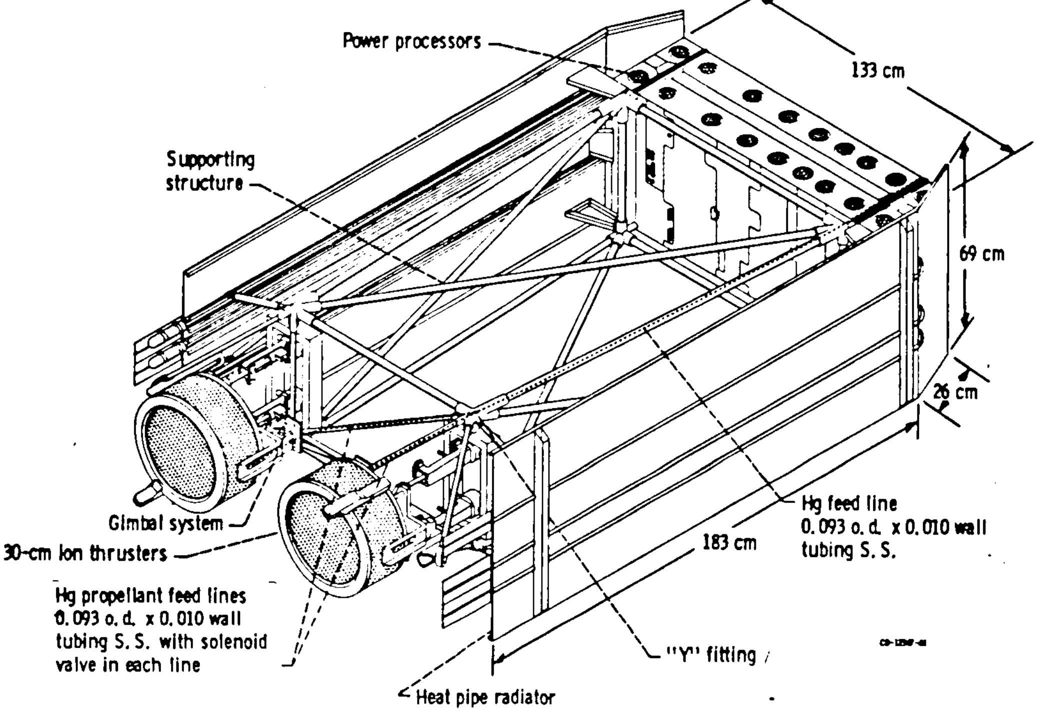


Figure 4. - BIMOD engine system.

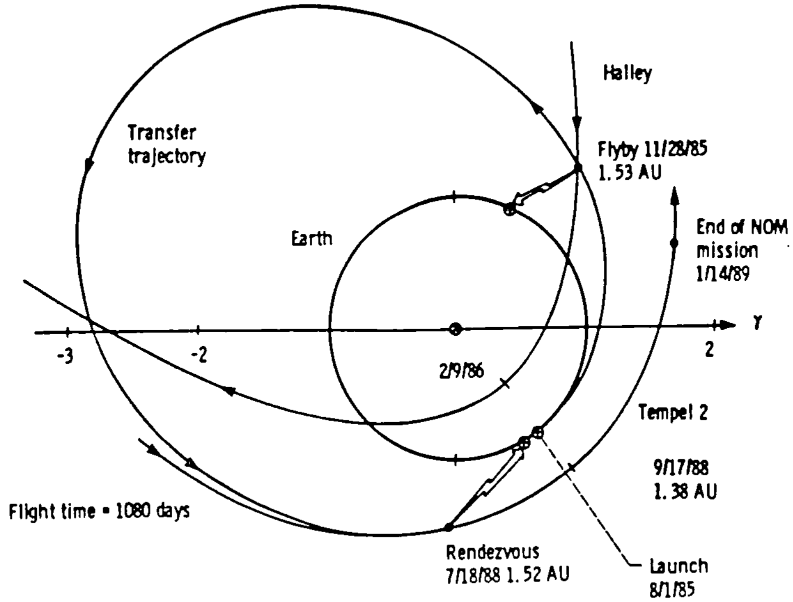


Figure 5. - Halley Flyby/Tempel 2 Rendezvous Trajectory (ecliptic plane projection)

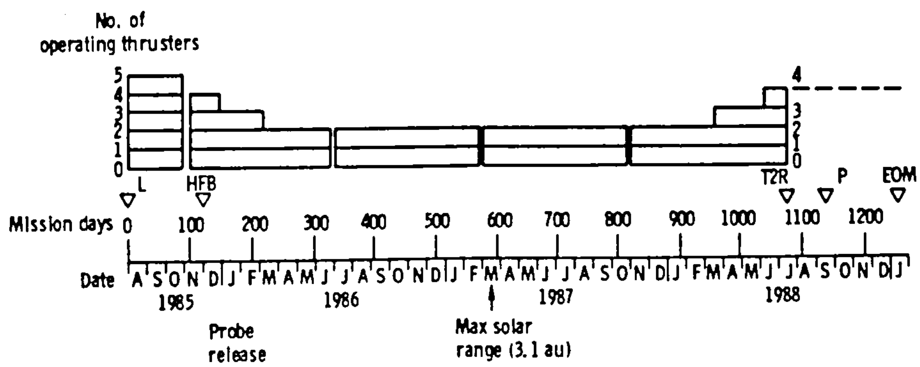
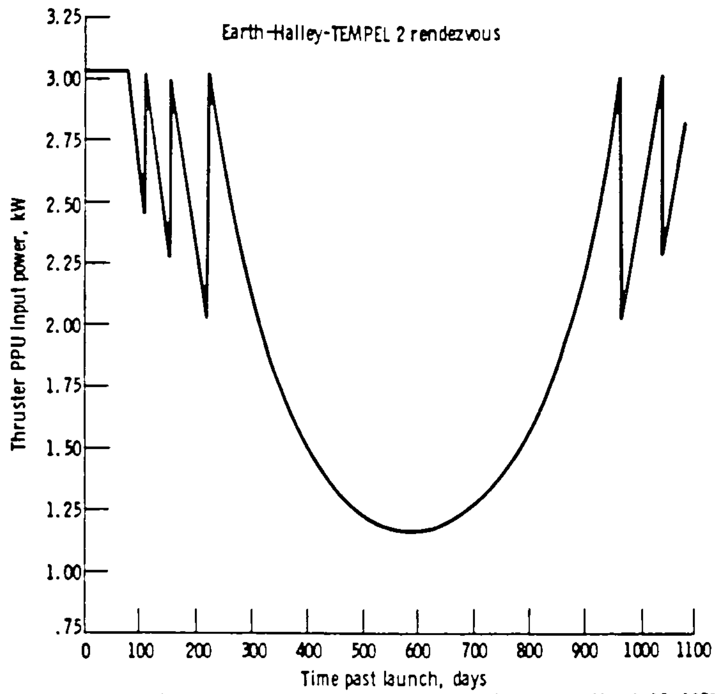


Figure 6. - Halley FLYBY/TEMPEL 2 rendezvous. Mission profile of operating thrusters.



Launch planet earth
Target planet TEMPEL 2
Trajectory date March 15, 1978
Post processor date March 19, 1978

Figure 7. - PPU input power per thruster.

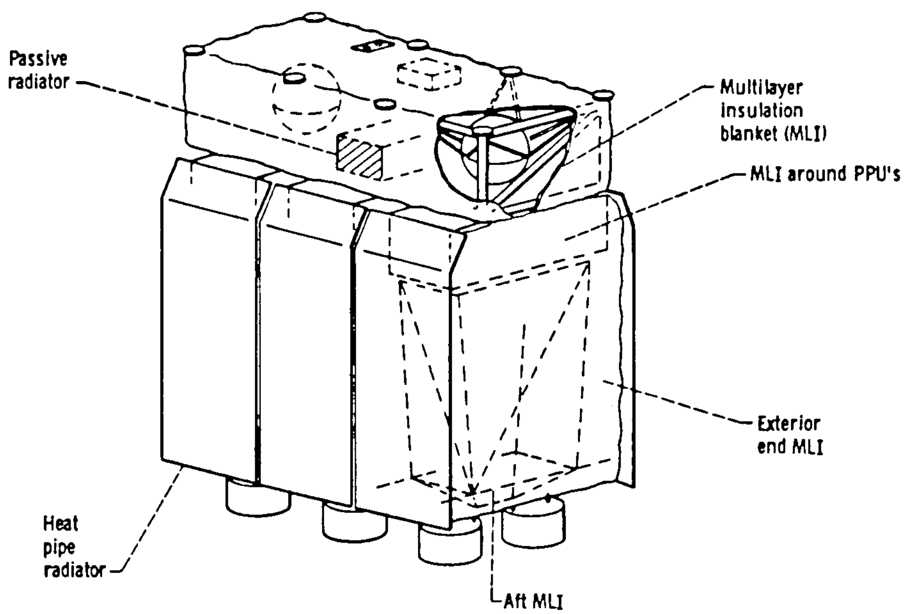


Figure 8. - Thrust subsystem thermal configuration.

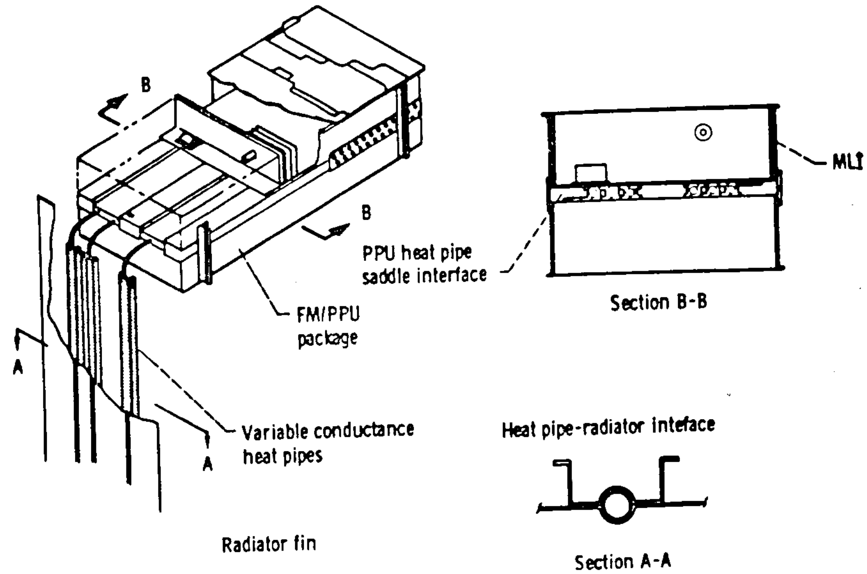


Figure 9. - BIMOD thermal control schematic.

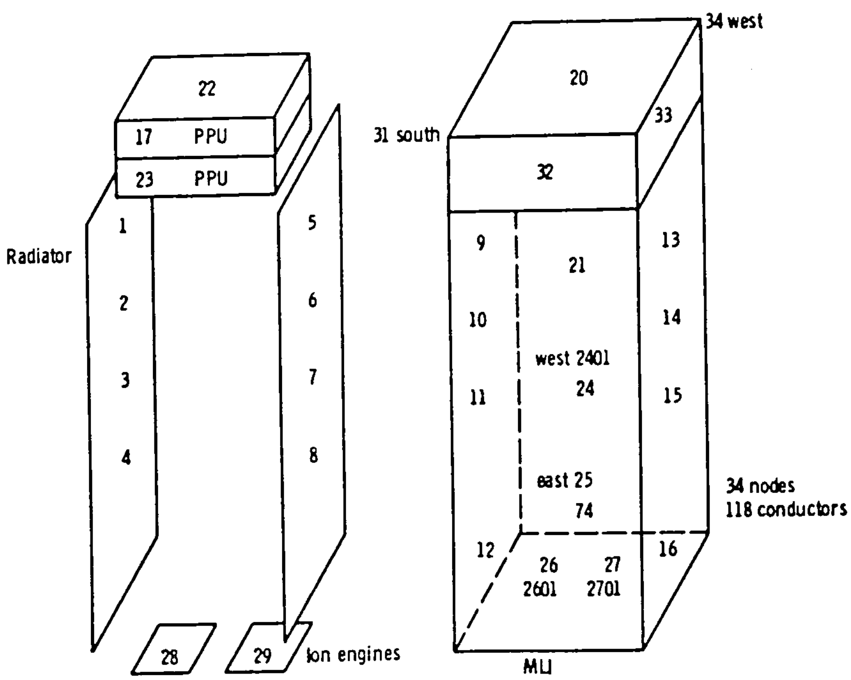


Figure 10. - Bimod nodal network.

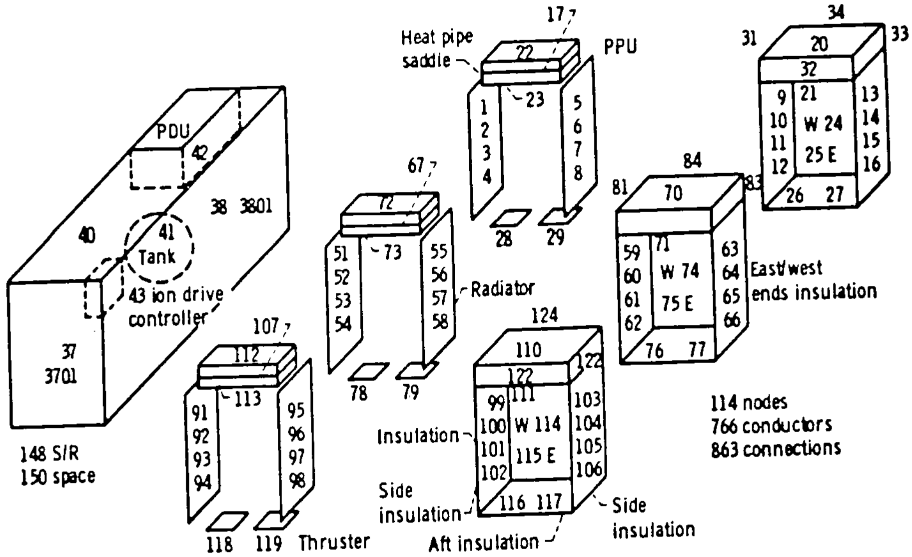


Figure 11. - Thrust subsystem nodal network. 3 bimod case.

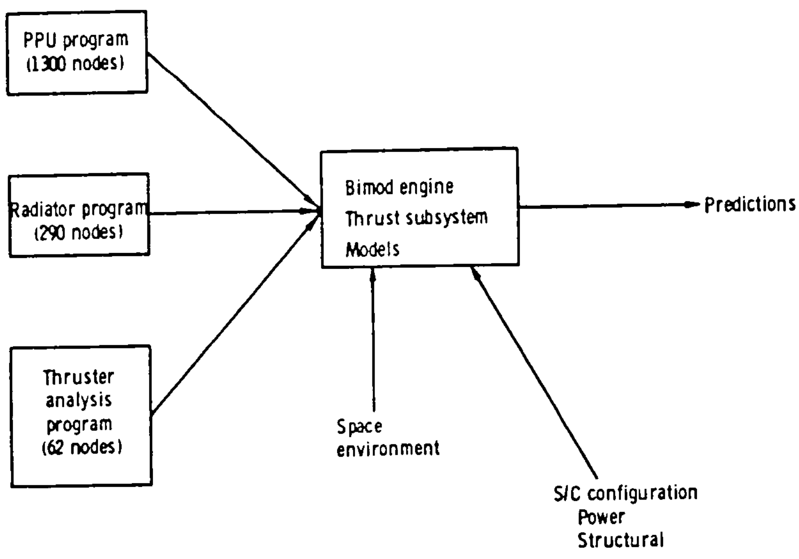


Figure 12. - Analysis flow model.

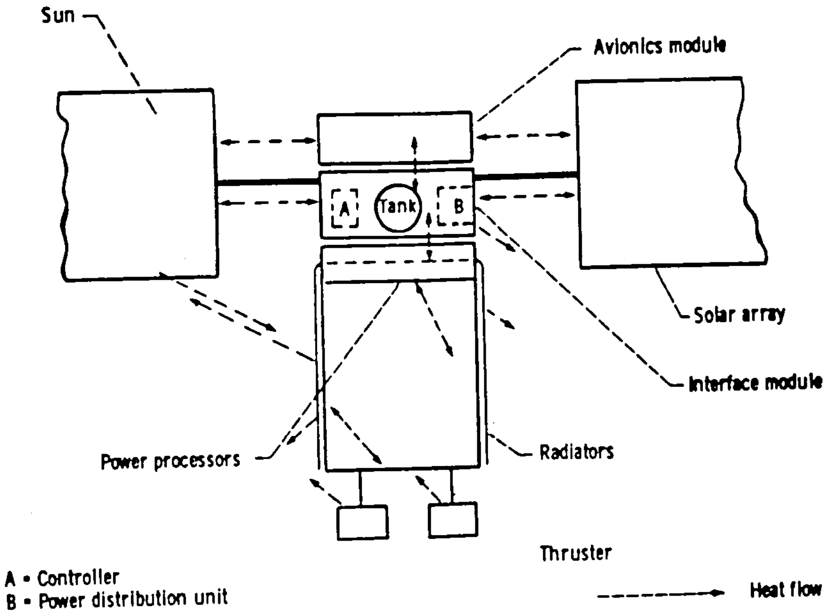


Figure 13. - Thermal interactions.

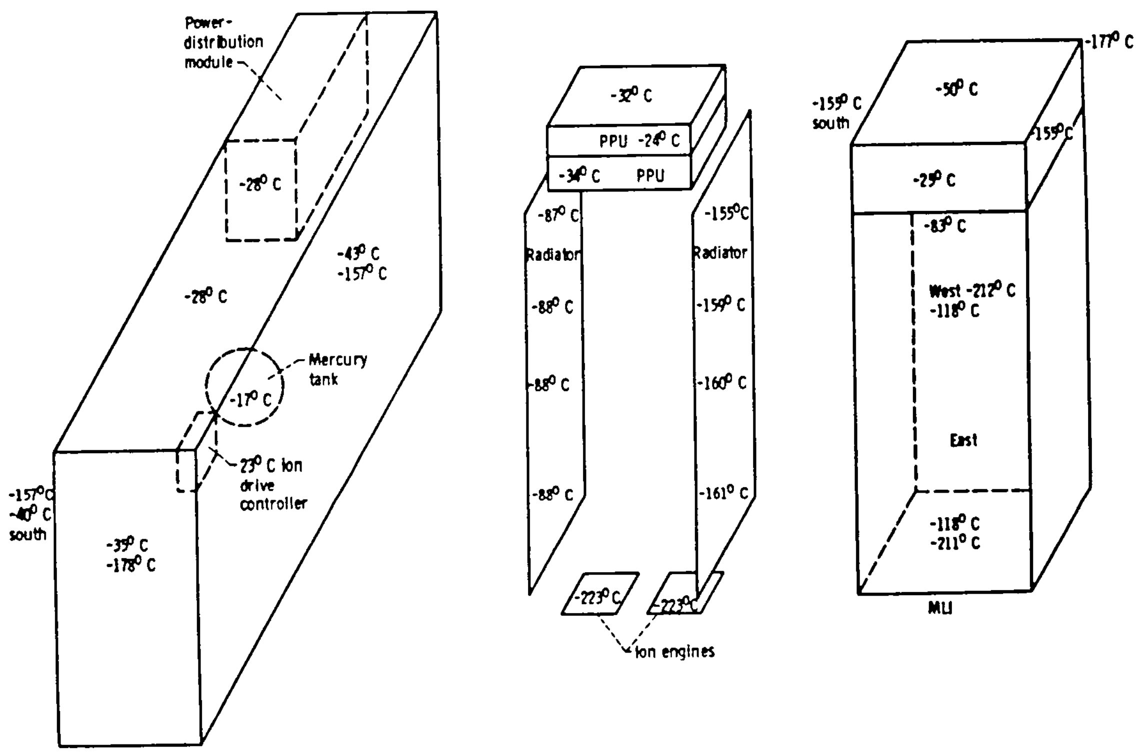


Figure 14. - Format of analytic program output. Thrust subsystem.

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16. Abstract
A thrust subsystem thermal control design is defined for a Solar Electric Propulsion System (SEPS) proposed for the comet Halley Flyby/comet Tempel 2 rendezvous mission. A 114 node analytic model, developed and coded on the Systems Improved Numerical Differencing Analyzer (SINDA) program, was employed. This report presents a description of the resulting thrust subsystem thermal design. Also presented is a description of the analytic model and comparisions of the predicted temperature profiles for various SEPS thermal configurations that were generated using this model. From the results of the analytic study, it was concluded that: (1) A BIMOD engine system thermal design can be autonomous; (2) An independent thrust subsystem thermal design is feasible; (3) The interface module electronics temperatures can be controlled by a passive radiator and supplementary heaters; (4) Maintaining heat pipes above the freezing point would require an additional 322 watts of supplementary heating power for the situation where no thrusters are operating; (5) Insulation is required around the power processors, and between the interface module and the avionics module, as well as in those areas which may be subjected to solar heating; and (6) Insulation behind the heat pipe radiators is not necessary.

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