Structural/Thermal Packaging for 30-cm Ion Thruster Power Processing Units

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Solar Electric Propulsion (SEP) currently is being studied for possible use in a number of near-Earth and planetary missions. The thruster subsystem for these missions would consist of 30-cm ion thrusters with Power Processor Units (PPU) clustered in assemblies of from 2 to 10 units. A preliminary design study of the electronic packaging of the PPU has been completed at NASA Lewis Research Center. This study evaluates designs meeting the competing requirements of low system weight and overall mission flexibility. These requirements are evaluated regarding structural and thermal design, electrical efficiency, and integration of the electrical circuits into a functional PPU layout.

Introduction

RESEARCH and development work has been carried on since the late 1950's on components for solar electric propulsion (SEP). One of the most critical of these components is the power processor unit (PPU). It is used to convert raw dc power to the various voltages and currents required by the ion thruster.

Power processors were developed successfully and flown on both the SERT I (1964)[1] and SERT II (1970)[2] spacecraft. The SERT I spacecraft successfully demonstrated that ion thrusters could operate and produce thrust in space.[1] The SERT II spacecraft was launched to 1) prove the reliability and endurance of an ion thruster, and 2) ascertain ion thruster operating characteristics in the space environment.[2]

The thruster power processor circuitry for the SERT I mission was packaged in two pressurized boxes. For SERT II, the power processor was packaged in a single electronics box incorporating command, telemetry, and power circuitry. The SERT II power processor transformers incorporated open construction.

Recently, work has been done on the development of both SCR[3] and transistorized[4] versions of power processing circuits for the SEP 30-cm ion thrusters. Both power processor versions use open construction similar to SERT II and are packaged in a flat plate design where the high heat dissipation components are alotted areas on a radiator plate according to their dissipation. Thus heat is conducted from the components into the radiator plate and then radiated directly to space.

Thermal control for a dual shear plate packaging design[5] of the PPU is by direct radiation through louvers. The electrical circuits for a dual shear plate design are mounted to channel or *I*-section cross-beams that span the width of the rectangular radiator plate. A second rectangular plate on the back of the PPU structurally stabilizes the cross-beams. Spacecraft shear loads are transferred to the surrounding spacecraft frame through both the radiator and the back shear plate.

This paper presents the results of a parametric analysis of various PPU conceptual designs that meet the mechanical, electrical, and thermal requirements imposed by the proposed SEP missions. The trades associated with thermal control achieved by 1) a combination of direct radiation through louvers and conduction to a remote radiator by variable-conductance heat pipes (VCHP), 2) direct radiation through louvers, or 3) an all-VCHP system were studied. The study reported in this paper utilizes the comprehensive work done by others[3-5] on the dual shear plate packaging design and a study (performed by the authors) using variable-conductance heat pipes for thermal control. Weights were calculated as a function of thermal control concept, thermal environment, electronic component junction temperature, electrical efficiency, and radiator efficiency. The detailed thermal analysis reported herein was based on CINDA[6] programs. Structural analyses were based in part on the NASTRAN[7] programs.

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PPU Packaging Requirements

The PPU packaging studies of this paper were constrained by a number of specific thermal, mechanical, and electrical requirements. These requirements were in addition to the obvious functional requirements. The SEP mission and PPU thermal environmental requirements are listed in Table 1. The PPU typically rejects heat from outboard-facing surfaces as shown in Fig. 1. Therefore, the PPU thermal design must be compatible with the thermal influence of the solar arrays such as those proposed in Ref. 13.

Typical electrical component temperature limits to assure high reliability are -50° to 100°C (nonoperating). For optimum interchangeability between different SEP spacecraft, the basic PPU package thermal design must be thermally independent from other spacecraft components.

For structural weight savings, the power processor package should be constructed so that the spacecraft and PPU launch acceleration loads can be transmitted through the PPU structure. A shear load requirement of 11.25 kg/cm (63 lb/in.) along each side of the PPU was assumed for this study based on Ref. 5.

The maximum thrust and lateral quasistatic (launch vehicle acceleration plus launch vehicle low-frequency sine vibration) is given in Ref. 8 for candidate SEP launch vehicles. The unamplified spacecraft qualification sine and random vibration environments for the various launch vehicles also are given in Ref. 8. Component vibration qualification levels for typical SEP spacecraft also are presented. The cross-beams should be designed for beam resonances and web resonances above 200 Hz to avoid vibration coupling with other major spacecraft systems.

The primary electrical requirement of the PPU is to convert electric power efficiently into voltages and currents required by the ion thruster. Secondary requirements are 1) modularization of the circuitry to facilitate circuit repair and replacement, and 2) separation of high-voltage and high-amperage power output from the low-voltage circuitry in or-

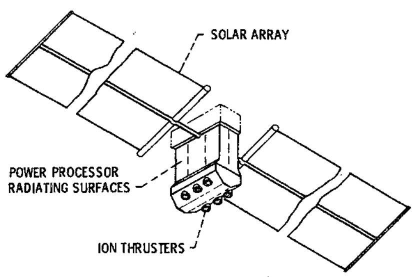

Fig. 1 Electric propulsion spacecraft.

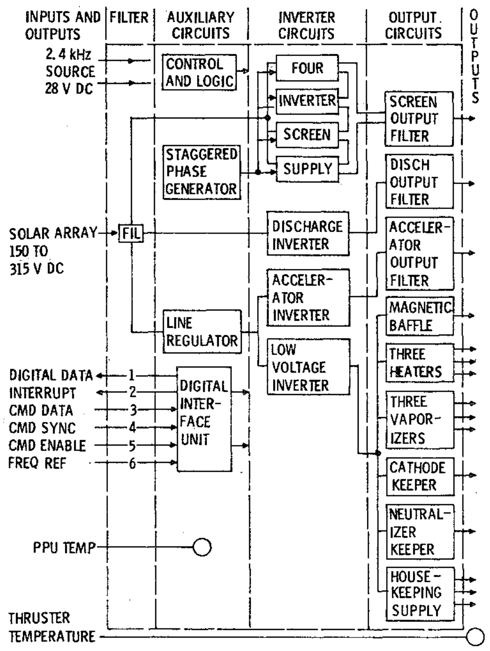

Fig. 2 30-cm bridge rectifier transistorized power processor block diagram.

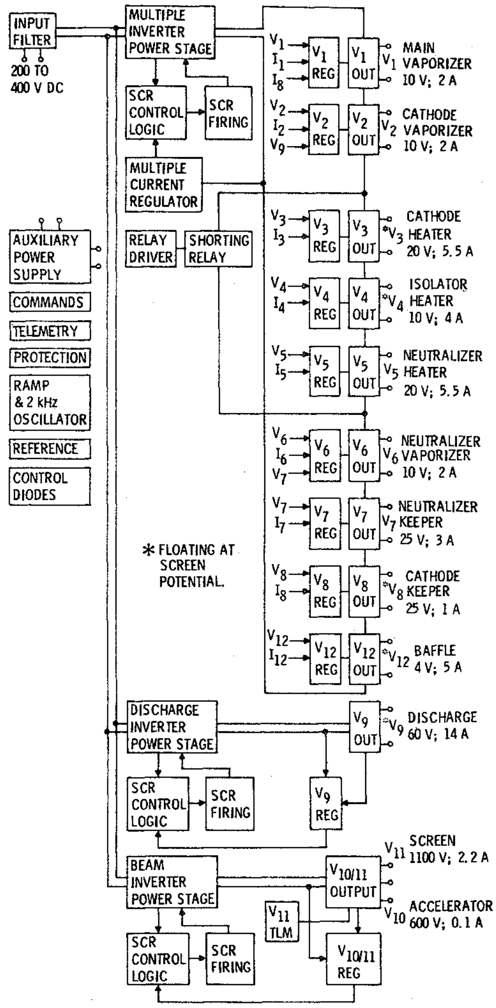

Fig. 3 Block diagram for series resonant SCR 3 inverter system.

der to limit electromagnetic interference (EMI) in the sensitive circuits.

A functional block diagram for bridge-rectifier transistorized PPU circuits is shown in Fig. 2. The block diagram for the series resonant SCR PPU circuitry is shown in Fig. 3. These block diagrams are used as starting points for the modularization of the circuitry. Modularization then is completed in conjunction with the actual packaging design layouts.

Options and Design Approach

Three different PPU packaging design concepts were studied. Total PPU package weight (including thermal control system weight) was estimated for each design. The three conceptual design systems were 1) an all-louver system as shown in Fig. 4, 2) a variable-conductance heat pipe and louver system (both working concurrently) as shown in Fig. 5, and 3) an all-variable-conductance heat pipe system (VCHPS) as shown in Fig. 6.

All-Louver Configuration

The all-louver system resembles the dual shear plate design described in Ref. 5. In this design, electrical component thermal dissipations are conducted to the module outer flange and then to the outer shear plate. High heat dissipation components are located on the outboard (radiator facing) flanges of the submodule cross-beams to provide for a more direct thermal path to the radiator. Waste heat is radiated from one side of the radiator through thermostatically controlled louver

Table 1 Representative SEP missions and PPU thermal requirements

Mission	PPU thermal dissipation, W	Distance from sun, a.u.	Solar array temperature, °C[a]	Required component junction temperature °C
Encke[8]	387[b]	0.7	140	85
Comet rendezvous	0	3.5	-112[c]	-15
Earth[9-12] orbital	387[b]	1	50	85
14,824-m (8000-n.mi.) altitude or greater	0	1	-220	-15

[a]The solar array was assumed to be 175.3 cm from the PPU radiating surfaces. The assumed view factor from the PPU to the solar array is 0.17.
[b]Based on 87% efficient PPU.
[c]At 2.5 a.u. ≈ -100°C.

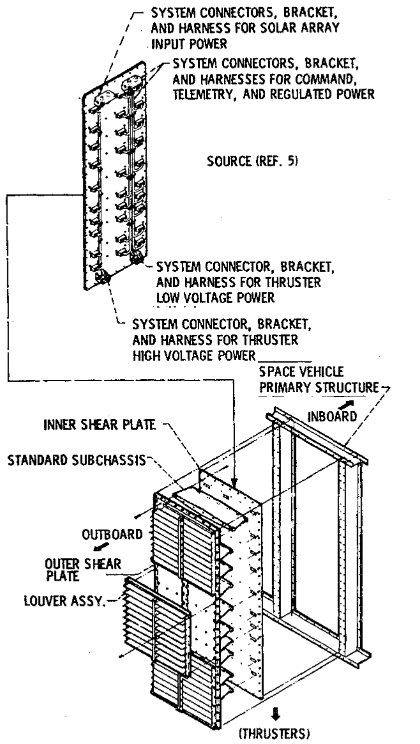

Fig. 4 All-louver system with dual shear plate power processor.

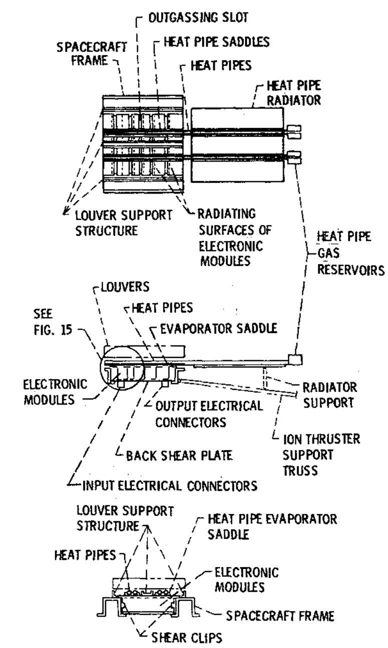

Fig. 5 Variable-conductance heat pipe and louver with power processor.

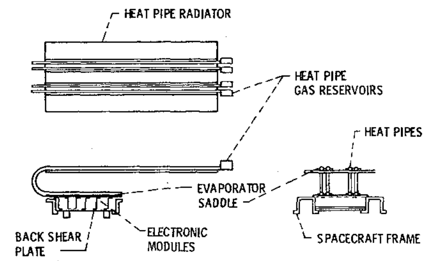

Fig. 6 All-VCHPS PPU configuration.

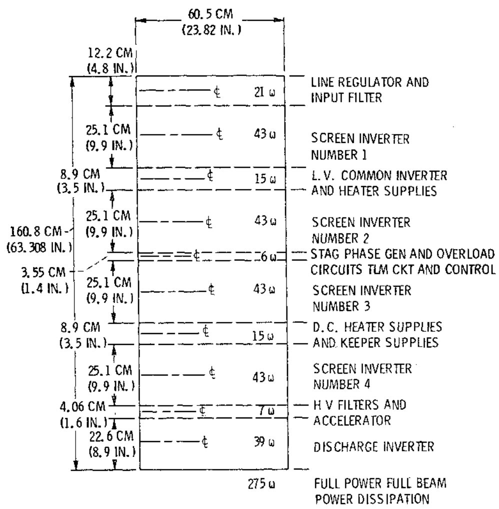

Fig. 7 PPU overall circuit layout for all-louver configurations.

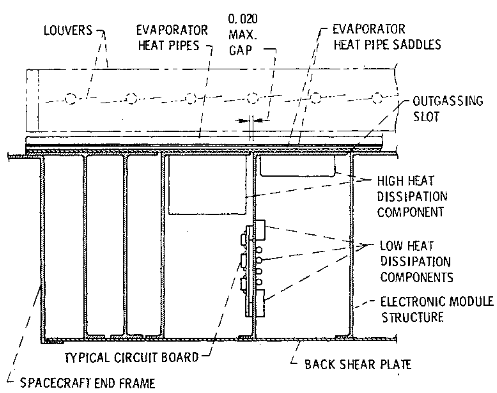

Fig. 8 Typical PPU cross section for modules running widthwise.

blades to space. When direct radiation through louvers is used for thermal control, a temperature gradient of 10°C or less must be maintained over the radiator surface in order to prevent the components of the individual modules from exceeding the component operating temperaure limits.

The functional block diagram for the bridge-rectifier transistorized PPU circuits has been converted into circuit modules. The modules and their arrangement for the all-louver system are shown in Fig. 7. This arrangement incorporates uniform heat load distribution and minimizes temperature gradients. However, the arrangement is not electrically ideal in that is was not possible to separate the high- and low-voltage circuits and still meet the thermal gradient requirements.

VCHPS-Louver Configuration

In the VCHPS-louver configuration shown in Fig. 5 the electrical components also are mounted on individual *Z*-section cross-beam modules. Physically large components and high thermal dissipation electrical components are mounted directly on the radiating (outboard or space-facing) flanges of the *Z*-section cross beams. The radiating flanges then are bolted directly to the evaporator saddles of the VCHPS. (An outer shear plate is not required.) Components with the largest thermal dissipations are mounted close to the evaporator saddles, as shown in Fig. 8. Components with lower thermal dissipations and printed circuit cards are mounted to the cross-beam webs. The single-sided louvered radiating area of the PPU proper was assumed to be 61 × 71.1 cm (24 × 28 in). Two heat pipes are attached to each VCHPS saddle, with the second pipe being redundant. Waste heat in excess of the capacity of the louvered radiating area is conducted by the heat pipes to a remote thermally isolated 40-mil aluminum single-sided radiator. Magnesium alloy ZK60AT5 was chosen for the Z section cross-beams because of its high thermal-conductivity-to-weight ratio. AZ31BH24 magnesium

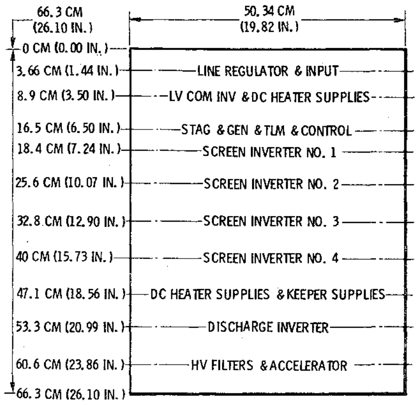

Fig. 9 PPU overall circuit layout for VCHP-louver configuration.

alloy was chosen for the back shear plate for its light weight, since a high thermal conductivity was not necessary.

The same bridge-rectifier transistorized circuit modules as were used for the all-louver system are used for the VCHPS-louver configuration. However, the module arrangement as shown in Fig. 9 is electrically ideal with maximum possible separation of the high-voltage and high-amperage circuits from the input power, control, and telemetry circuits. This module arrangement was made possible only by using heat pipes for thermal control, since the 10°C thermal gradient requirements of the all-louver system no longer applied. Although the bridge-rectifier transistorized circuitry was used to illustrate the packaging approach, the same procedure is valid for the series-resonant SCR PPU circuitry.

All-VCHPS Configuration

For the all-VCHPS configuration as shown in Fig. 6, the electronic components are mounted on individual *Z*-section cross-beam modules and arranged identical to the VCHPS-louver configuration. However, the total heat load is dissipated by the single-sided heat pipe radiator. Therefore, a larger total radiator area is needed than for the VCHPS-louver configuration.

Parametric Study Results

In performing the parametric analysis, certain assumptions were made based on the wide range of expected PPU environmental conditions. A list of the general thermal assumptions is shown in Table 2. The solar array temperature variation corresponds to 1) SEP mission sun-to-spacecraft distances ranging from 0.7 to 3.5 a.u., as discussed in Ref. 9, and 2) tilting of the array to limit its maximum temperature to

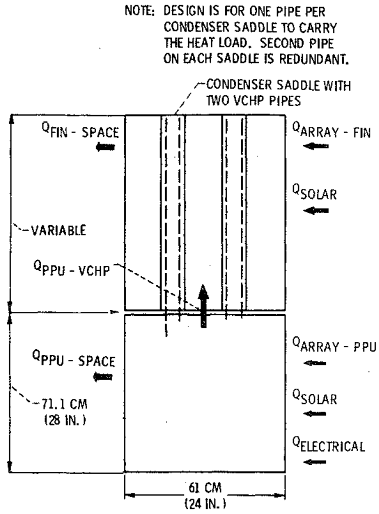

Fig. 10 Major heat paths for typical configuration.

140°C. Radiator thickness and weight were allowed to increase in order to meet the all-louver requirement for a 10°C temperature gradient across the radiator surface. The weight assumptions for the VCHPS are based on the Communications Technology Satellite VCHPS technology described in Ref.14. A schematic representation of the major heat paths accounted for in the analysis is shown in Fig. 10. In the analyses VCHP radiator fin efficiency was defined as

$$\text{fin efficiency} = \frac{\text{calculated area at constant temperature}}{\text{actual required area}}$$

where fin efficiency accounts for both temperature drop from the condenser saddle to the radiating fin, and temperature gradients along the fin. A typical electronic component junction temperature rise above the VCHP saddle or front radiator plate (all-louver configuration) was 24°C. This was based on a calculated thermal resistance of 2°C/W between a typical 12-W dissipation bridge rectifier case junction and the VCHP saddle.

Some of the results of the parametric studies are included in Tables 3a-3c and Figs. 11-17, where curves compare the PPU system weight as a function of 1) thermal control concept, 2) component junction temperature (12-W dissipation assumed), 3) solar array temperature, 4) radiator emittance, 5) total heat load, and 6) VCHPS radiator fin efficiency. These weights are for preliminary designs of the PPU package, not for final or flight designs.

Figures 11 and 12 compare the PPU system weights as a function of solar array temperature, component junction tem-

Table 2 General thermal assumptions

	Configuration		
	All-louver	VCHP-louver	VCHPS
Solar array temperature	...		50°C at 1 a.u. (range -100° to 140°C)
Solar array emmittance	...		0.8
Radiator view factor to space	...		0.83 (range: 0.775 to 0.94)
Radiator view to solar array	...		0.17 (range: 0.225 to 0.06)
Louver radiator emittance	0.65 (0.70)	0.65 (0.70)	...
Louver absorptance	0.2 to 0.32	0.2 to 0.32	...
VCHP fin emittance	...	0.88	0.88
VCHP fin absorptance	...	0.2 to 0.32	0.2 to 0.32
Thermally isolated from other PPU's	yes	yes	yes
Temperature gradient	10° maximum vertically along the front radiator 3°C transverse across radiator		1°C from VCHP evaporator to condenser

perature, and electrical heat load. The curves show that 1) for any one set of conditions, an all-louver PPU system is always heavier than the VCHPS-louver system, 2) for any one set of conditions, the VCHPS-louver PPU concept system weight is less sensitive to both component junction temperature change and solar array temperature change than the all-louver PPU concept system weight, and 3) the system weights for an all-VCHPS concept and a VCHPS-louver concept (where the louver-covered area is 61 × 71.1 cm) are nearly the same when single-sided radiators are used for both designs. Weight saved

Table 3a All-louver system weights (kg/lb)

Elements	Radiator area, m^2/ft^2			
	0.650/7	1.208/13	1.765/19	2.044/22
1) Electrical components	13.89/30.61	13.89/30.61	13.89/30.61	13.89/30.61
2) Harness	1.16/2.55	1.56/3.45	1.97/4.35	2.18/4.80
3) Connectors	1.13/2.50	1.13/2.50	1.13/2.50	1.13/2.50
Total electrical component weight	16.18/35.66	16.58/36.56	16.99/37.46	17.20/37.91
4) Hardware	1.76/3.88	1.76/3.88	1.76/3.88	1.76/3.88
5) Cross-beams	2.20/4.85	2.20/4.85	2.20/4.85	2.20/4.85
Total module weight	20.14/44.39	20.54/45.29	20.95/46.19	21.16/46.64
6) Back shear plate	1.17/2.58	2.17/4.78	3.17/6.98	3.67/8.10
Total	21.31/46.97	22.71/50.07	24.12/53.17	24.83/54.74
7) Radiator plate	2.31/5.10	7.89/17.40	16.87/37.20	22.63/49.90
Total	23.62/52.07	30.60/67.47	40.99/90.37	47.86/104.64
8) Louver and Louver support weight	3.43/7.56	6.37/14.04	9.31/20.52	10.78/23.76
Total	27.05/59.63	36.97/81.51	50.30/110.89	58.24/128.40

Table 3b VCHP-louver system weights (kg/lb)

Elements	Heat pipe radiator area, m^2/ft^2			
1) Electrical components	13.89(30.61	13.89/30.61	13.89/30.61	13.89/30.61
2) Harness	0.68/1.50	0.68/1.50	0.68/1.50	0.68/1.50
3) Connectors	1.13/2.50	1.13/2.50	1.13/2.50	1.13/2.50
Total electrical component weight	15.69/34.61	15.69/34.61	15.69/34.61	15.69/34.61
4) Hardware	1.34/2.96	1.34/2.96	1.34/2.96	1.34/2.96
5) Cross-beams	2.37/5.23	2.37/5.23	2.37/5.23	2.37/5.23
6) Back shear plate	0.43/0.94	0.43/0.94	0.43/0.94	0.43/0.94
Total PPU	19.83/43.74	19.83/43.74	19.83/43.74	19.83/43.74
7) Louver and louver support structure 1.08 psf +0.45 = 5.05; +0.45 = 5.50	1.24/5.50	2.49/5.50	2.49/5.50	2.49/5.50
Total	22.32/49.24	22.32/49.24	22.32/49.24	22.32/49.24
8) Evap. heat pipes and saddles (3 + 3)(0.52)(26)(0.1) + 1.04 = 1.85	0.84/1.85	0.84/1.85	0.84/1.85	0.84/1.85
9) Heat pipe gas reservoirs	0.80/1.76	0.80/1.76	0.80/1.76	0.80/1.76
10) Condenser heat pipes and saddles	0.78/1.73	2.35/5.18	3.92/8.64	5.49/12.1
11) Heat pipe radiator	0.77/1.69	2.30/5.08	3.84/8.47	5.38/11.85
Total	25.51/56.27	28.61/63.11	31.72/69.96	34.83/76.80

Table 3c All-VHCP system weights (kg/lb)

Elements	VCHP fin area, m^2/ft^2				
	0.279/3	0.836/9	1.394/15	1.951/21	2.508/27
1) Electrical components	13.89/30.61	13.89/30.61	13.89/30.61	13.89/30.61	13.89/30.61
2) Harness	0.68/1.50	0.68/1.50	0.68/1.50	0.68/1.50	0.68/1.50
3) Connectors	1.13/2.50	1.13/2.50	1.13/2.50	1.13/2.50	1.13/2.50
Total	15.70/34.61	15.70/34.61	15.70/34.61	15.70/34.61	15.70/34.61
4) Hardware	1.34/2.96	1.34/2.96	1.34/2.96	1.34/2.96	1.34/2.96
5) Cross-beams	2.37/5.23	2.37/5.23	2.37/5.23	2.37/5.23	2.37/5.23
6) Back shear plate	0.43/0.94	0.43/0.94	0.43/0.94	0.43/0.94	0.43/0.94
Total PPU	19.84/43.74	19.84/43.74	19.84/43.74	19.84/43.74	19.84/43.74
7(Fin support structures[4]	0.18/0.40	0.18/0.40	0.18/0.40	0.18/0.40	0.18/0.40
Total	20.02/44.14	20.02/44.14	20.02/44.14	20.02/44.14	20.02/44.14
8) Evaporation VCHP and saddles	0.84/1.85	0.84/1.85	0.84/1.85	0.84/1.85	0.84/1.85
9) VCHP gas reservoir	0.80/1.76	0.80/1.76	0.80/1.76	0.80/1.76	0.80/1.76
10) Condenser VCHP and saddles	0.78/1.73	2.35/5.18	3.92/8.64	5.49/12.10	/15.56
11) VCHP radiator	0.77/1.69	2.30/5.08	3.84/8.47	5.38/11.85	...
Total	23.21/51.17	26.31/58.01	29.42/64.86	32.52/71.7	...

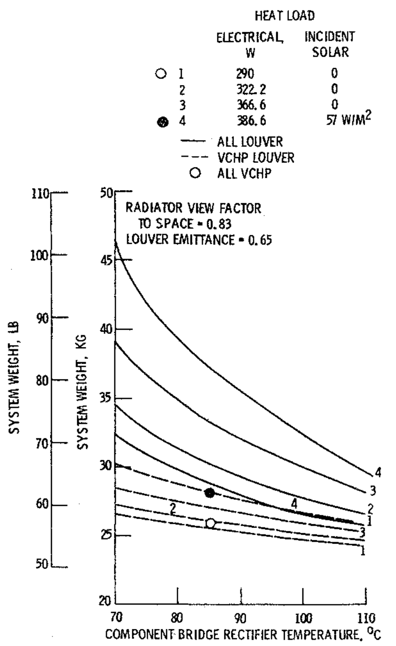

Fig. 11 Comparison of system weights for a solar array temperature of 50°C.

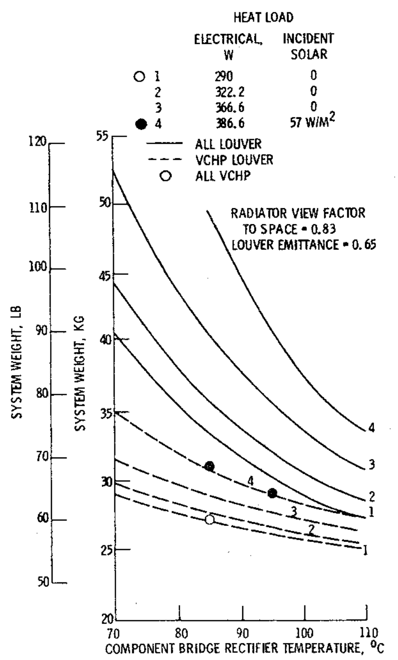

Fig. 12 Comparison of system weights for a solar array temperature of 140°C.

by removal of the louvers is nullified by weight of a larger VCHPS radiator and its supporting structure. However, for a louver radiator area larger than 61×71.1 cm, an all-VCHPS system would be lighter than a VCHPS-louver system. This is primarily due to the front radiating flange thickness increasing to maintain a radiator surface temperature gradient of 10°C.

Effect of Radiator View Factor to Space

From Figs. 13, 11, and 14, showing the effect n the system weight of radiator view factors to space of 0.775, 0.83, and 0.94, respectively, it should be noted that the VCHPS-louver system weight is less sensitive to change in radiator view factor to space than the all-louver PPU system weight.

Effect of Louver Emittance

A comparison of Figs. 11 and 15 shows that increasing the louver emittance from 0.65 to 0.70 reduces both system weight and weight sensitivity.

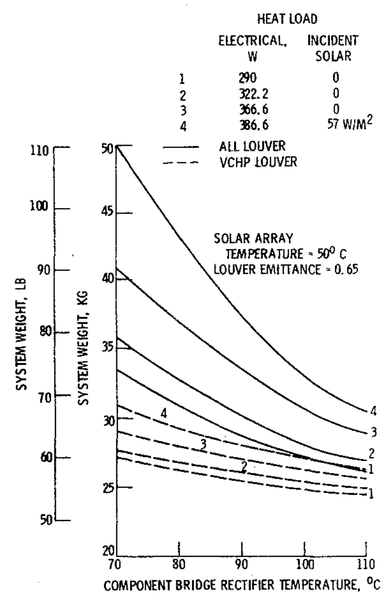

Fig. 13 Comparison of system weights for a radiator view factor to space of 0.775.

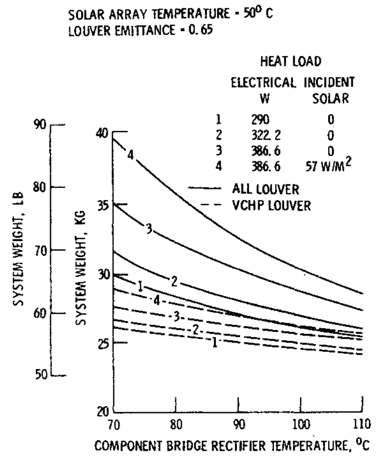

Fig. 14 Comparison of system weights for a radiator view factor to space of 0.94

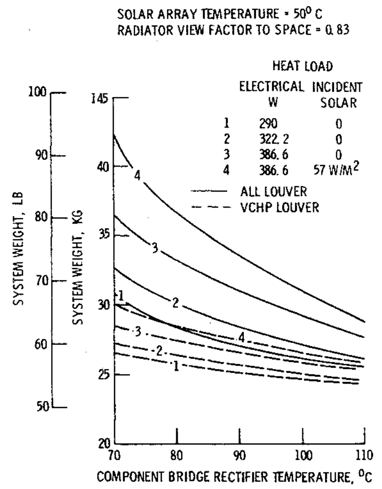

Fig. 15 Comparison of system weights for louver emittance of 0.7.

Effect of Solar Array Temperature

Figure 16 shows the system weight as a function of component junction temperature for various solar array temperatures. The VCHPS-louver PPU system weight is far less sensitive to solar array temperature than the all-louver PPU weight.

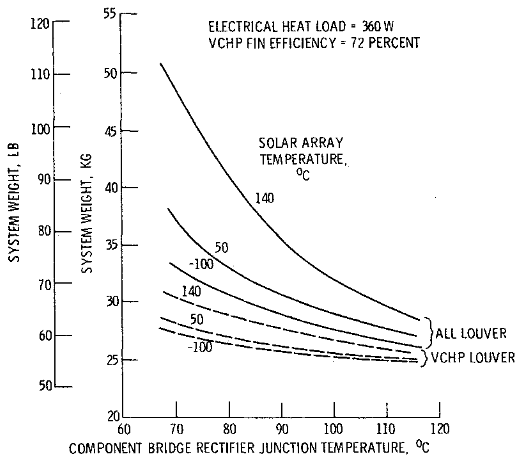

Fig. 16 Comparison of system weight for various solar array temperatures.

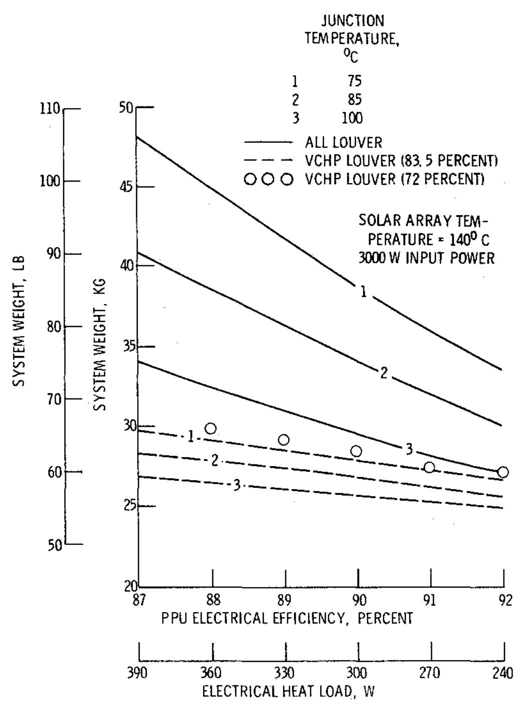

Fig. 17 Comparison of system weights as a function of PPU electrical efficiency.

Effect of PPU Electrical Efficiency

Figure 17 is a comparison of system weights as a function of PPU electrical efficiency at several component temperatures for an input power of 3000 W and for a solar array temperature of 140°C. The VCHPS-louver PPU system weight is far less sensitive to the electrical efficiency changes than the all-louver system weight.

Concluding Remarks

The results of this preliminary parametric study show that a PPU using a VCHPS-louver thermal control system would be less sensitive than a PPU using an all-louver thermal control system to 1) environmental conditions, 2) component junction temperature requirements, and 3) electrical efficiency. The present study also shows that a light-weight, compact PPU could be achieved by using a VCHPS-louver thermal control system. This VCHPS-louver construction permits 1) electrical circuits to be arranged to meet electrical requirements, and 2) a standard PPU configuration with test and qualification benefits, as well as a reduction in program costs for flight spares.

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