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FLAT-PLATE THERMOELECTRIC GENERATORS FOR SOLAR-PROBE MISSIONS

by Valvo Raag, Robert E. Berlin, and William J. Bifano
Lewis Research Center
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TECHNICAL PAPER proposed for presentation
at Intersociety Energy Conversion
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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E-4497

FLAT-PLATE THERMOELECTRIC GENERATORS FOR SOLAR-PROBE MISSIONS*

by Valvo Raag and Robert E. Berlin
Radio Corporation of America
Harrison, New Jersey

and William J. Bifano
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

ABSTRACT

The suitability of thermoelectric generators for solar-probe missions is considered. Design of a flat-plate thermoelectric generator for operation at 0.25 AU or less from the Sun is then presented; design output is 150 watts at 28 volts. Generator electrical performance, temperature profiles, and component weights are included. Layout drawings illustrate the generator configuration. The operation of the generator under a variety of off-design conditions, in terms of variable absorptance and emittance characteristics of generator surfaces and its operating distance from the Sun, is discussed.

INTRODUCTION

The broad objective of NASA's Pioneer program is to explore the solar environment at distances from the Sun ranging from 10 AU or more to 0.1 AU or less (an astronomical unit, AU, is defined as the mean earth-sun distance). Present generation Pioneer spacecraft, designed primarily for orbiting the sun at distances ranging from 1.5 to 0.5 AU, are cylindrical vehicles with n-on-p silicon solar cells mounted on the lateral surface for the generation of on-board electrical power. The solar cell output power at earth's distance from the sun is about 80 watts. Since no thermal control is provided for the solar cells, the increased solar flux encountered as the spacecraft moves toward the sun results in an increase in both output power and cell temperature, the latter causing an attendant decrease in cell efficiency. For future solar missions to distances less than 0.5 AU from the sun, it is likely that thermal control will be required to prevent excessive cell temperatures which would degrade output power and could ultimately result in power system failure. Accordingly, a number of modifications to the Pioneer spacecraft are presently being considered (1), in an attempt to extend its range of usefulness to 0.4 and possibly 0.2 AU (where the solar flux is 6.25 and 25 times that at earth, respectively). These include the use of highly reflective coatings, selective interference filters (2) and thermal shielding (3). Another approach being pursued is to develop silicon solar cells capable of operating efficiently at high temperature and high solar flux conditions (4).

Another possibility for future solar approach missions is to use a 3-axis-oriented spacecraft (5) employing planar solar cell arrays. For such a spacecraft, tilting would appear to be the most practical method of controlling cell temperature under conditions of variable solar flux. For example, the solar cells could be oriented normal to the incident solar flux at earth and continuously tilted as the spacecraft moved toward the sun so as to provide a relatively constant power profile. At close solar approach distances, however, extremely large tilt angles would be required. For example, at a distance of 0.27 AU from the sun (solar flux 13.7 times that at 1 AU), the tilt angle required for maximum solar cell power is estimated to be 80° (6). For closer approaches, increasingly large tilt angles would be necessary and extremely accurate control of solar cell orientation would be required. Hence, for this type spacecraft, the distance of closest approach would ultimately be limited by the precision and accuracy achievable with future orientation control systems.

Active cooling of solar cell panels is another technique which has been considered (7), however it is generally concluded that the added weight associated with cooling system components would be excessive.

In view of the thermal control problems anticipated with silicon solar cells in the vicinity of 0.2 AU or less from the sun, it is likely that an alternate power system will be required for use in this range. One possible candidate is the solar thermoelectric (TE) flat-plate generator, which has a much higher temperature capability than solar cells. As shown in Ref. 6, such a generator could be designed to operate efficiently over a limited range of distance from the sun with tilting used to provide thermal flux control. For example, a TE panel designed to operate at 0.25 AU normal to the suns rays would provide constant output power to about 0.1 AU, continuous tilting to a maximum of 80° being assumed. Thus, it appears that a power system composed of both solar cells

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and solar TE flat-plate generators might be used for missions close to the sun. In such a hybrid system, solar cells would be used between Earth and the distance from the sun where solar cell temperature limits are reached, and solar TE flat-plate generators for closer distances. The TE generator, in addition to being useful under high solar flux conditions, also exhibits better radiation resistance than solar cells and hence would be less likely to suffer permanent damage as a result of solar flares produced during periods of high solar activity.

Although a number of studies have been conducted regarding the use of flat-plate solar TE generators, most of these studies have concentrated on missions in the region between Earth and Mercury [8,9,10]. An exception to this is Ref. 6, which considered missions to as close as 0.1 AU from the sun. However, TE panel fabrication techniques were not treated in detail in Ref. 6. Hence, a program was initiated with the objectives of designing a solar flat-plate TE generator suitable for operation at 0.25 AU from the sun or closer, and fabricating representative modules. The generator, using silicon-germanium, Si-Ge, thermoelements, is to produce 150 W of electrical power at a load voltage of 28 V.

The approach used to develop a reference design generator is presented herein. The effect of variations in both design parameters and operating conditions is considered analytically. Generator performance and weight estimates are also included for the reference design case.

DESIGN CONSIDERATIONS

The generator design is based on the following groundrules: The unit thermoelectric couples are to consist of p- and n-type Si-Ge thermoelements metallurgically bonded to silicon-molybdenum disilicide alloy hot shoes. A schematic of such a couple is shown in Fig. 1. The hot shoes serve both as heat reception plates and electrical connectors at the hot junction. The cold ends of the thermoelements are connected to the heat rejection plate by means of electrically insulating cold stacks so as to allow rejection of waste heat to space by radiation. This configuration is known as an Air-Vac type thermocouple [11]. The solar absorptance and total hemispherical emittance of the hot shoe surface is taken as 0.85 and 0.1 respectively at 1089° K (1500° F). (These values are representative of the multi-layer interference coating, MgF_2-Mo-CeO_2-Mo developed by Honeywell Inc. This coating is presently being evaluated at the Lewis Research Center). Because of uncertainty regarding the performance of the proposed solar absorptance coating at elevated temperatures, the maximum hot shoe temperature was fixed at 1089° K (1500° F) for the design phase. The total hemispherical emittance of the radiator surface is taken as 0.85, characteristic of calcium titanate, $CaTiO_3$, which is to be used as the radiator coating.

METHOD OF ANALYSIS

Since solar probe spacecraft are typically weight limited, the generator design was optimized on the basis of specific power, i.e., watts per pound. In performing the optimization, a mathematical model of the thermoelectric device was developed which included several unique features not generally considered in previously thermoelectric analyses [10,12,13]. Some of the unique features of the model are the inclusion of effects due to Thomson heat generation (absorption) in the thermocouple legs, the consideration of temperature drops due to transverse heat flow in the heat-reception and heat-rejection plates and across thermoelectrically passive members of the device, and the option to consider either radiative or conductive shunt heat transfer. The sequence of calcaulations is performed by assuming a variety of values for all variables that have a first order bearing on device performance. Such variables typically are thermoelement length, the cross-sectional areas of the two legs, the area of the heat-reception and heat-rejection plates, and the ratio of load to internal electrical resistance. A complete spectrum of performance characteristics, temperatures, and weights is calculated for each combination of assumed values of the variables. Graphical display of the results allows the determination of the exact values of the variables for which any desired performance parameter (in the present instance, the specific power) is optimized. For a detailed treatment of the mathematical model see Ref. 15.

The performance equations were derived [14,15] and programmed for solution on the RCA 601 computer at the David Sarnoff Research Center. An existing subroutine was used for each combination of variables representing a number of different thermocouple configurations for finding the roots of the integral equation (Eq. (18) in Ref. 15) that describes the heat balance on the heat-rejection plate. In this subroutine, an adaptive search is conducted by a quadratic extrapolation and root-finding scheme that uses Muller's method. Special care is exercised to avoid bypassing near multiple zeros. The subroutine permits recursive use for solving nonlinear systems of equations. For each combination of variables, the following thermocouple characteristics were printed out: the cross-sectional area of shunt heat transfer, the n- and p-type thermoelement cross-sectional areas, the heat-reception plate area, the thermoelement length, the ratio of load to internal electrical resistance, the heat incident on the thermocouple, the heat transmitted through the thermocouple, the shunt heat, the electrical power output, the load current, the load voltage, the efficiency, the total weight, the weight per unit area, the power per unit weight, the hot and cold junction temperatures, and the maximum and minimum temperatures on the heat-reception and heat-rejection plates.

The thermoelectric property data used [14,15] is representative of the silicon-germanium alloy (nominally 63.5 atomic percent Si) after some initial change has taken place. This change occurs in the n-type alloy because of a change in dopant concentration in solid solution [16,17,18,19]. The process is exponential in time and, therefore, most of it occurs relatively early in life (approximately one half of the total change in five years of operation will have taken place in the first 1500 hours). The effect of this change on the properties of the alloy is a slight increase in its electrical resistivity ρ and Seebeck coefficient S such that the quantity S^2/ρ, which is proportional to the electrical output, is slightly decreased. In five years of operation, the net result on an n- and p-type silicon germanium thermocouple is a reduction in performance of from five to ten percent, depending on operating temperature.

In the design calculations, the thermocouple configuration illustrated in Fig. 1 was assumed. Since thermal insulation is more effective for minimizing shunt heat transfer than existing low emissivity coatings at the high temperatures anticipated for generator operation, high temperature fibrous insulation (Johns-Manville Min-K 2002) was selected for this purpose. Heat-reception and heat-rejection plates were assumed to have identical areas. The incident heat flux corresponding to a distance of 0.25 AU from the sun, was fixed at 2.24 W/cm^2.

The parameters that have a first-order effect on thermocouple performance were varied over extensive ranges in order to determine the thermocouple configuration that optimizes specific power. The parameters included in this variation were the area of thermal insulation, the thermoelement areas, the thermoelement length, and the ratio of load to internal electrical resistance. Other component thicknesses (electrical connectors, cold stacks, and the heat-reception and heat-rejection plates) were chosen which were considered consistent with previous experience with Air-Vac type thermocouples. (Slight additional gains in specific power may be possible by optimizing these dimensions, however, such an optimization was not performed in this analysis.) The weight of generator support structures, such as panel mounting frames, was not included in weight optimization since the design of such structures depends on the particular spacecraft configuration and generator deployment method used.

RESULTS AND DISCUSSION

For a maximum heat-reception plate temperature of 1089° K (1500° F) (from solar absorptance coating considerations) and a 2.83 cm (1.112 inch) by 2.83 cm (1.112 inch) square heat reception plate (maximum size based on fabrication considerations), it was found that specific power optimizes for a thermocouple configuration of 0.600 cm (0.24 inch) leg length and n- and p-type leg areas of 0.164 cm^2 (0.025 inch^2) and 0.100 cm^2 (0.015 inch^2) respectively. The optimum ratio of load to internal electrical resistance is about 1.2. The detailed performance characteristics of this optimum design thermocouple are tabulated in Table I.

For a generator to produce 150 W at 28 V, 548 couples must be combined in series-parallel. This arrangement, in addition to giving the desired voltage, enhances the reliability of the system. The performance characteristics of a generator with 548 couples are:

Power output, W	150.1
Load voltage, V	28.8
Load current, A	5.22
Total area, ft^2	4.70
Total weight, lb	12.02

The indicated area and weight of the generator do not include contributions from the mounting frame and ribs on the heat-rejection plates. It is apparent that the heat reception plate does not possess a uniform 1089° K (1500° F) temperature because of transverse heat flow. Except for the peripheral areas of the plate, the temperature is generally less than 1089° K (1500° F). The slightly higher temperatures indicated at the periphery of the plate are not expected to adversely affect the characteristics of the absorption coating.

After a review of the thermocouple configuration of the optimum design, it was concluded that the required thermoelement dimensions were somewhat extreme in relation to present silicon-germanium thermocouple technology. To formulate a practical design, a thermocouple configuration was chosen with slightly larger thermoelement cross-sectional areas. It was also necessary to increase thermoelement length in order to comply with the specified 1089° K (1500° F) heat-reception plate temperature.

The thermoelement length was fixed at 1.0 cm (0.394 inch) and detailed design calculations, similar to those discussed previously, were repeated to precisely define a new configuration. For a heat-reception plate of the same area as before, it was found that thermoelements having cross-sectional areas of 0.2684 cm^2 (0.04 inch^2) (n-type) and 0.1632 cm^2 (0.0254 inch^2) p-type yielded heat-reception plate temperatures that on the average satisfy the 1089° K (1500° F) constraint. Thermoelements having these indicated dimensions are also consistent with existing fabrication techniques. Detailed performance characteristics as listed in Table II were accordingly determined for this design, henceforth designated as the reference design.

To obtain a generator with the desired power and voltage characteristics (approximately 150 W and 28 V) 480 reference design couples are used in a series-parallel arrangement. Two identical panels of 240 couples each are employed; each panel consists of 20 sections, and each section has 12 couples.

The over-all performance of the reference design generator is as follows:

Power output, W	149.8
Load voltage, V	26.6
Load current, A	5.63
Total area, ft^2	4.12
Total weight, lb	13.29

The total generator area and weight does not include contributions from the mounting frame and ribs of the heat-rejection plates. (Note that the use of a larger thermocouple in the reference design has resulted in an increase in generator weight of about 10 percent relative to the optimum design).

The performance characteristics of the reference design generator are graphically illustrated in Fig. 2 as a function of load current. From Fig. 2, it may be seen that the load voltage can be increased from 26.6 (m=1.2) to the design value of 28 V by slightly increasing the load resistance. The resultant effect on power output is negligible.

Figure 3 schematically illustrates the configuration of the reference design thermocouples. The heat-reception plates have tapered cross-sections based on minimum weight and transverse heat flow considerations. Figure 4 illustrates the assembly of 20 sections into a panel, each section consisting of 12 thermocouples. The 150 W generator would consist of two of these panels.

The total weight of the reference design thermocouples as well as the weights of individual components is shown in Table III.

Additional weights which have not been included in Table III (for a generator with 480 couples) are: mounting studs 0.016 lb, nuts 0.026 lb, panel section ribs 1.315 lb., and mounting frames 2.918 lb. Because the ribbing on the panel sections and the mounting frames for the sections have not been subjected to design optimization, the listed weights of these components are preliminary and, at best, only represent upper limit values. It is expected that upon optimization, the weights of these components will be considerably reduced. Just as in the case of generator weight, the total generator area has contributions from factors other than the thermocouples. These factors are the edges of the mounting frames and the spacings between the heat-reception plates of adjacent thermocouples. Thus, whereas the combined area of all the thermocouples is 4.12 square feet, the total area of the generator, including the factors just mentioned, is 4.49 ft^2.

Off-Design Performance of Reference Design Generator

It is obvious that the performance of a solar thermoelectric generator is strongly dependent on the emittance and absorptance characteristics of the coatings on the heat-reception and heat-rejection plate surfaces as well as on the incident solar heat flux. Because the properties of the coatings may change with time, it is valuable to know how such changes would affect the performance of the reference design generator. Moreover, inasmuch as the incident solar flux depends on the distance and/or the orientation of the generator with respect to the sun, it is also of interest to know how the performance of the reference design generator depends on incident flux. Detailed calculations of the performance of the reference design generator, were accordingly performed for variable values of the emittance and absorption characteristics of the heat-reception and heat-rejection plate surfaces and the incident solar flux.

Figures 5 and 6 pertain to the incident solar flux of 2.24 W/cm^2 at the design distance of 0.25 astronomical unit from the sun, and show the effects of varying values of absorptance and emittance of plate surfaces on reference design generator performance. Of these properties, it is the emittance of the heat-rejection plate that has the least effect on generator performance. Similarly, it is the emittance of the heat-reception plate that has the greatest effect on performance.

The high solar absorptance, multi-layer interference coating, MgF_2-Mo-CeO_2-Mo, proposed for this generator, requires an extremely smooth substrate surface in order to yield emittance values of the order of 0.1. Preliminary results of work performed at Honeywell, Inc. with this coating indicate that polishing of the silicon-molybdenum alloy heat-reception plates prior to the application of the interference coating is necessary in order to obtain suitable surface conditions. The "off-design" calculations of generator performance indicate that this may be a crucial problem requiring further consideration.

The performance of the reference design generator as a function of distance from the sun is shown in Fig. 7 in terms of generator hot and cold junction temperatures, total heat transmitted per couple, and generator efficiency. Electrical power output per couple may be easily obtained from the data in Fig. 7 by multiplying the efficiency by the heat transmitted per couple. Total power is 480 times that product.

The large dependence of generator performance on its operating distance from the sun is quite apparent in Fig. 7. It is seen that generator output is low at distances from the sun greater than about 0.4 AU. At closer distances, however, performance rapidly increases with decreasing distance. This effect is quantitatively illustrated in Table IV in terms of generator performance for operating distances from the sun near the design point distance. It is noted that performance increases several fold for relatively small decreases in operating distance. Attendant with the performance increases, of course, is also an increase in the operating temperatures of the generator. In fact, in view of its high temperature operating limit of about 1089° K (1500° F), it is questionable whether the absorption coating on the heat-reception plates of the thermocouples can withstand some of the indicated temperatures. In order to decrease these temperatures and thus make still closer approaches to the sun practical, it would be necessary to use an absorption coating of lower absorptance and/or higher emittance. Depending on the type of coating used on the heat-reception plate surfaces, it is therefore possible to design silicon-germanium solar thermoelectric power conversion systems that have extremely attractive performance characteristics in applications to near-sun missions.

CONCLUSIONS

A newly developed mathematical model has been used to design a weight-optimized, silicon-germanium flat-plate thermoelectric generator for operation at a distance of 0.25 AU or less from the sun. The utility of the model has been demonstrated by the detailed analysis of the performance of the generator under a variety of operating conditions. The results of the analysis indicate that high-temperature silicon-germanium solar thermoelectric generators offer very attractive performance characteristics as auxiliary power sources for spacecraft in near-sun missions. For the design distance of 0.25 AU, the reference design generator is estimated to weight 3.23 lb/ft^2 and produce over 36 W/ft^2.

CONCLUDING REMARKS

Flat-plate segments of the reference design generator are to be evaluated at the Lewis Research Center. Initially, the panels will be tested without the high solar absorptance coating. The absorptance coating is also to be evaluated at Lewis using both silicon-molybdenum alloy and pure molybdenum substrates.

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TABLE I. - PERFORMANCE OF THERMOCOUPLE

FOR OPTIMUM SPECIFIC POWER

Heat-reception plate outer edge temperature, °K; °F	1099.0; 1518.4
Heat-reception plate center temperature, °K; °F	1055.9; 1440.9
Hot junction temperature, °K; °F	1055.2; 1439.6
Cold junction temperature, °K; °F	713.9; 825.3
Heat-rejection plate center temperature, °K; °F	690.0; 782.2
Heat-rejection plate outer edge temperature, °K; °F	685.0; 773.2
Thermocouple efficiency, percent	3.13
Specific power, W/lb	12.49
Power output/couple, W	0.274
Weight/area, lb/ft^2	2.56
Power output/area, W/ft^2	31.97
Load voltage/couple, V	0.1051
Load current/couple, A	2.612

TABLE II. - REFERENCE DESIGN

THERMOCOUPLE PERFORMANCE

Heat-reception plate outer edge temperature, °K; °F	1100.9; 1521.9
Heat-reception plate center temperature, °K; °F	1064.4; 1456.2
Hot junction temperature, °K; °F	1063.8; 1454.1
Cold junction temperature, °K; °F	702.8; 805.3
Heat-rejection plate center temperature, °K; °F	687.5; 777.7
Heat-rejection plate outer edge temperature, °K; °F	683.3; 770.2
Thermocouple efficiency, percent	3.57
Specific power, W/lb	11.27
Power output/couple, W	0.312
Weight/area, lb/ft^2	3.23
Power output/area, W/ft^2	36.36
Load voltage/couple, V	0.1108
Load current/couple, A	2.817

TABLE III. - REFERENCE DESIGN

THERMOCOUPLE WEIGHT

Member	Weight per thermocouple, lb	Generator weight, lb (480 couples)
Heat-reception plate	0.007170	3.441
Insulation	.007250	3.479
Thermoelements	.003369	1.617
Cold stack	.003786	1.817
Electrical connector	.000752	.361
Heat-rejection plate	.005363	2.575
Total	0.027690	13.290

TABLE IV. - REFERENCE DESIGN GENERATOR

PERFORMANCE AS A FUNCTION OF

DISTANCE FROM SUN

Distance from sun, AU	0.354	0.250*	0.204	0.177
Incident heat flux, W/cm^2	1.12	2.24	3.36	4.48
Power output, W	51.0	150.0	252.0	350.0
Load voltage, V	16.0	26.6	34.0	39.7
Load current, A	3.25	5.63	7.40	8.80
Hot junction temperature, °C	463.0	791.0	947.0	1064.0
Cold junction temperature, °C	342.0	430.0	485.0	524.0
Specific power, W/lb	3.9	11.3	19.2	26.5
Power per unit area, W/ft^2	12.5	36.4	61.2	84.8
Conversion efficiency, percent	2.06	3.57	4.60	5.27
Total heat transmitted, W	2490.0	4190.0	5490.0	6620.0

*Reference design.

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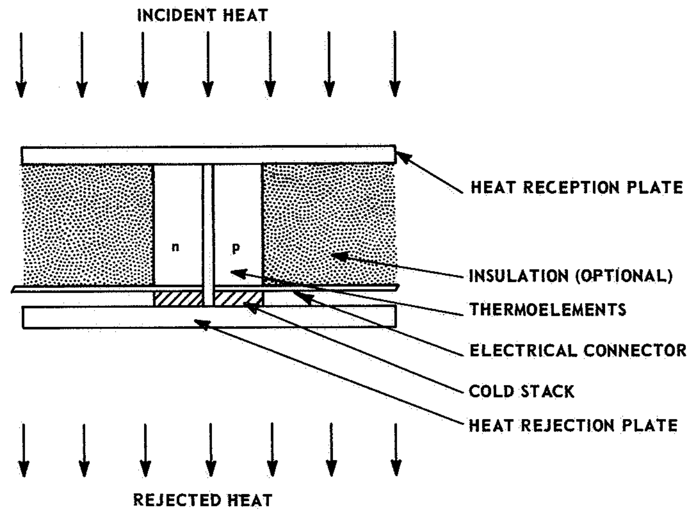

Fig. 1

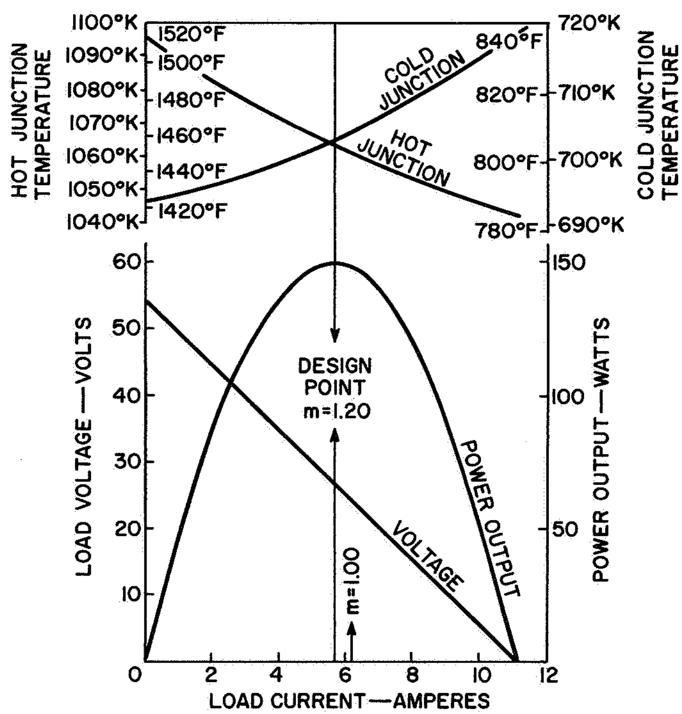

Fig. 2

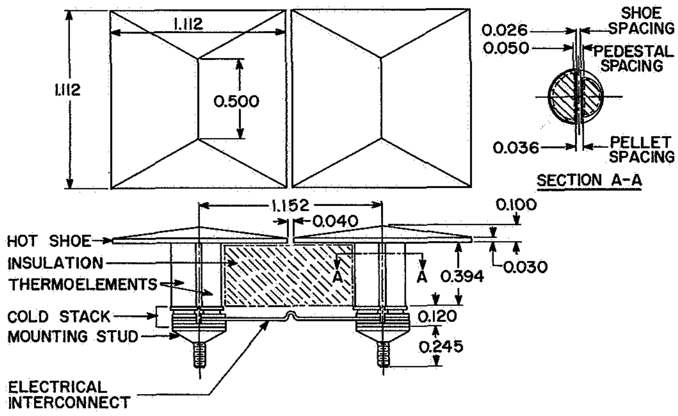
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Fig. 3

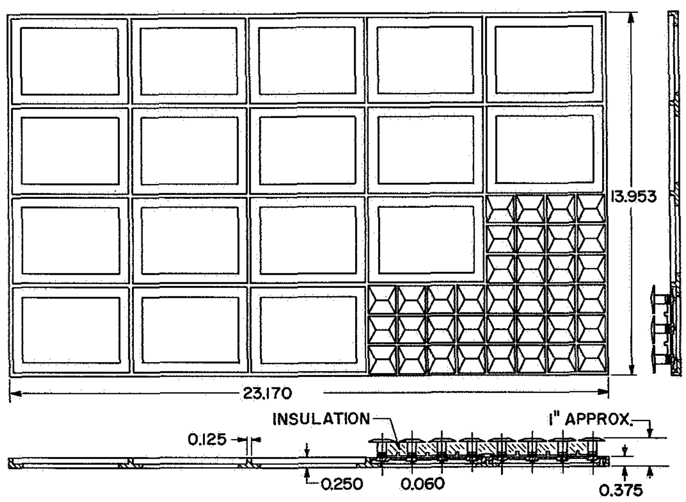
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Fig. 4

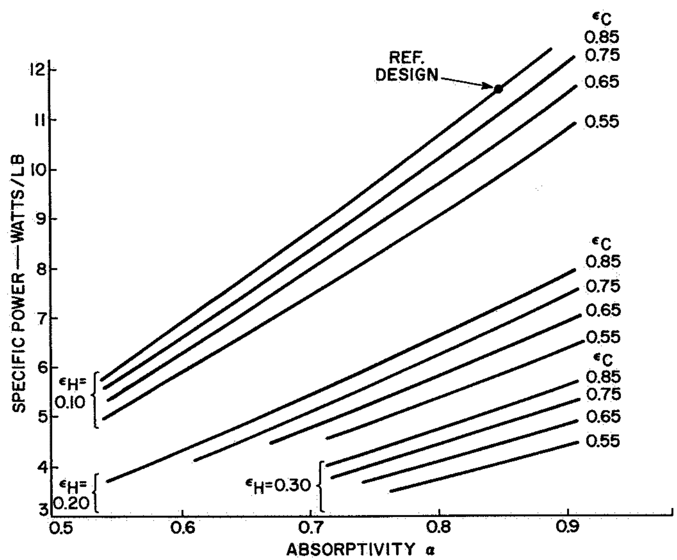
SPECIFIC POWER — WATTS/LB
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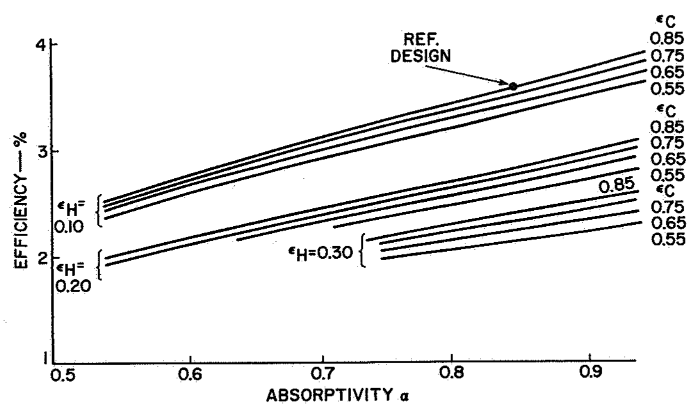
Fig. 5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1
2
3
4

Fig. 6

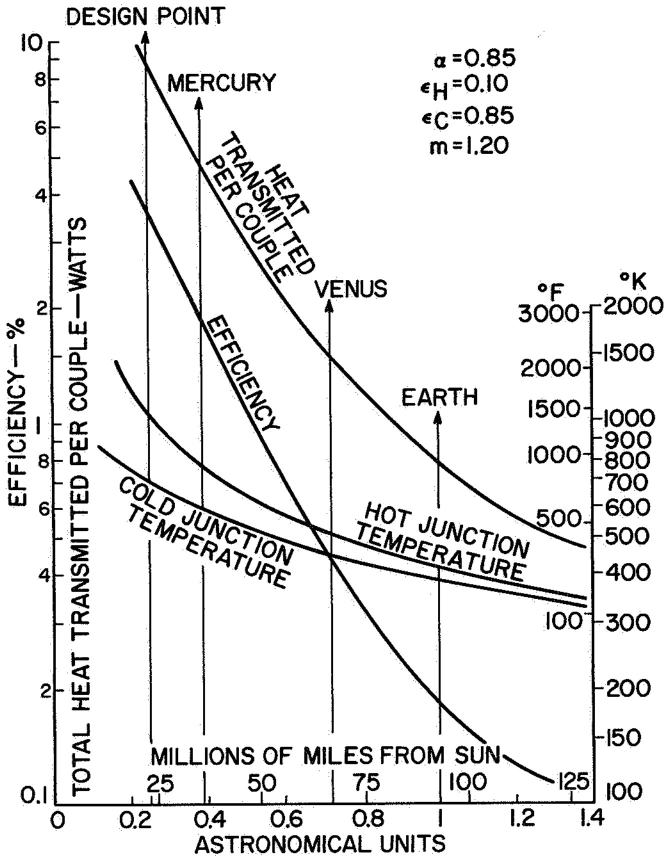
DESIGN POINT
MERCURY
VENUS
EARTH
α = 0.85
ϵH = 0.10
ϵC = 0.85
m = 1.20
HEAT TRANSMITTED PER COUPLE
EFFICIENCY
COLD JUNCTION TEMPERATURE
HOT JUNCTION TEMPERATURE
EFFICIENCY—%
TOTAL HEAT TRANSMITTED PER COUPLE—WATTS
°F
°K
MILLIONS OF MILES FROM SUN
ASTRONOMICAL UNITS

Fig. 7