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ANALYSIS OF SOLAR THERMOELECTRIC FLAT-PLATE GENERATORS OPERATING IN THE RANGE OF 1.0 TO 0.1 ASTRONOMICAL UNIT

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SUMMARY

An analysis of solar thermoelectric flat-plate generators is presented for the following mission design points: 1.0 AU (Earth), 0.722 AU (Venus), 0.388 AU (Mercury), 0.25 AU, and 0.1 AU. Both lead telluride and silicon-germanium thermoelectric materials are evaluated for the generators. With the exception of the solar absorber coatings, for which long-term performance stability has yet to be demonstrated, the panel materials chosen for the study are considered state of the art. Tilting of the thermoelectric panels from 0^{o} (panel normal to the incident solar radiation) to a maximum of 80^{o} is used for thermal control.

The results indicate that a thermoelectric flat plate can be designed to produce as much as 104 watts per square foot (1120 W/sq m) at 0.1 AU, although a panel designed for 1.0 AU produces only about 3 watts per square foot (32.2 W/sq m). The performance of thermoelectric flat plates is strongly dependent on input solar flux, and severe variations in output power are encountered as the system travels from Earth (1.0 AU) to design point. For a limited range of distance from the Sun beyond design point (about 60 percent of the design point distance), tilting of the panels to a maximum of 80^{o} is useful in maintaining constant output power. The specific weight of thermoelectric flat plates varies from 30 pounds per kilowatt electric (13.6 kg/kWe) for a 0.1 AU design to 120 pounds per kilowatt electric (54.5 kg/kWe) for a 1.0 AU design.

INTRODUCTION

Flat-plate thermoelectric panels fabricated to date have been designed primarily for Earth orbital applications. These panels consist of p- and n-type semiconductors (typically bismuth telluride alloys, ref. 1) sandwiched between thin aluminum absorber and radiator plates. They are designed to operate at absorber (hot junction) and radiator (cold junction) temperatures of approximately 472° F (518° K) and 158° F (343° K), respectively, at 1.0 AU. (One AU is defined as the mean Earth-Sun distance.)

For missions directed toward the Sun, the increasing incident solar flux allows higher operating temperatures. In general, these higher operating temperatures result in higher energy-conversion efficiencies (assuming a properly designed system that uses the appropriate materials) and, therefore, for such missions, thermoelectric flat plates may be useful. This study considers thermoelectric panels for use in the 1.0 to 0.1 AU range with either lead telluride or silicon-germanium semiconductors for operating temperatures up to 1000° F (811° K) and 1800° F (1255° K), respectively. The following mission design points are evaluated: 1.0 AU (Earth), 0.722 AU (Venus), 0.388 AU (Mercury), 0.25 AU, and 0.1 AU.

SYMBOLS

A	area, sq ft (sq m)
ℓ	thermoelectric element length, in. (cm or mm)
P	electrical power, W
Q	thermal power, W
S	solar constant, W/sq ft (W/sq m)
T	temperature, °F (°K)
α	solar absorptance
ϵ	infrared emittance
η	efficiency, percent
σ	Stefan-Boltzmann constant

Subscripts:

a	absorber plate
C	cold junction
c	thermoelectric cross sectional
d	thermoelectric device
H	hot junction
i	interplate losses
m	mica supports

r radiator plate

s surface of absorber

t thermal power input

METHOD OF ANALYSIS

System Description

A schematic diagram of a unit thermoelectric couple is shown in figure 1(a). In general, the couple consists of an n-type and a p-type semiconductor element directly joined at one end (hot junction). Waste heat is rejected at the cold junction, and useful power is obtained by placing a load between the p and n legs, as shown in figure 1(a).

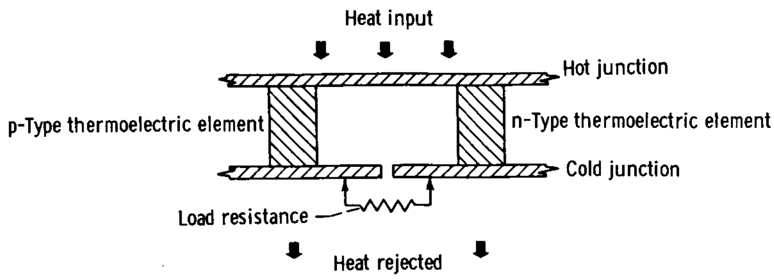
Figure 1(b) depicts one of several possible thermoelectric flat-plate designs in which thermoelectric elements are sandwiched between absorber and radiator plates. A selective coating is applied both to the absorber to obtain the proper solar absorptance and infrared emittance and to the radiator to obtain a high infrared emittance.

The function of a solar absorber coating is to absorb a large fraction of the incident solar radiation (predominantly in the 0.2- to 2.0-micron wavelength range) and to reradiate as little infrared energy as possible. In general, coatings with a high ratio of solar absorptance to infrared emittance α_a/ϵ_a are chosen for this study. Although coatings with the desired α_a/ϵ_a are available, they have not demonstrated as yet long-term stability at temperature.

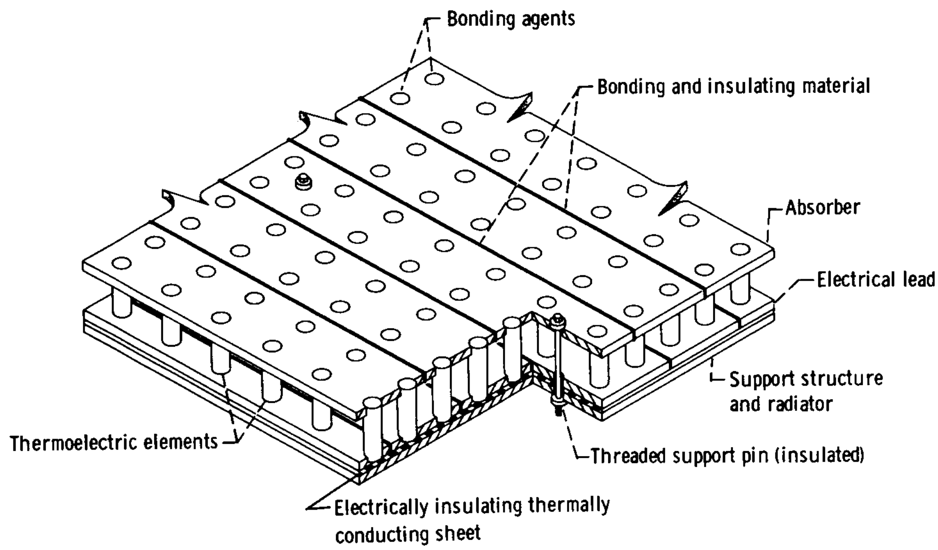
Each element is surrounded by four thin mica supports, as shown in figure 1(c). Ribbed supports are provided on the radiator plate to improve the structural rigidity of the panel, and an insulating sheet is employed to isolate electrically the elements from the radiator. Interplate heat loss is minimized either by applying low-emittance radiative-barrier coatings to the inner surfaces of the plates or by using solid thermal insulating material between the plates; the choice depends on operating temperatures.

Device Performance

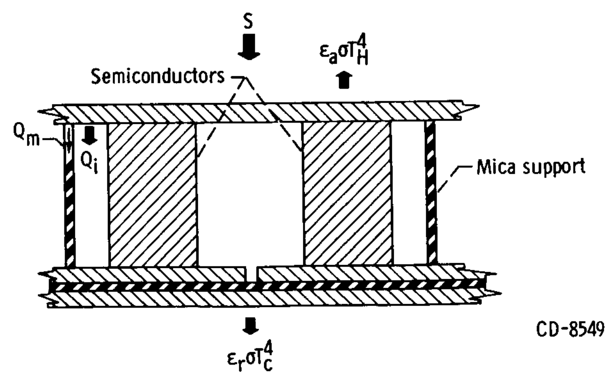
This report considers two different semiconductor materials that may be used in a thermoelectric flat-plate design, lead telluride and silicon-germanium. Cylindrical thermoelectric elements, 0.1 inch (2.54 mm) in diameter and 0.2 inch (5.08 mm) long, are assumed. Rigid plates, 5 mils (0.127 mm) thick, are assumed for both absorber and radiator. Four thin mica support sheets, 0.4 inch (10.16 mm) by 0.2 inch (5.08 mm)



(a) Schematic.



(b) Isometric view.



(c) Cross section.

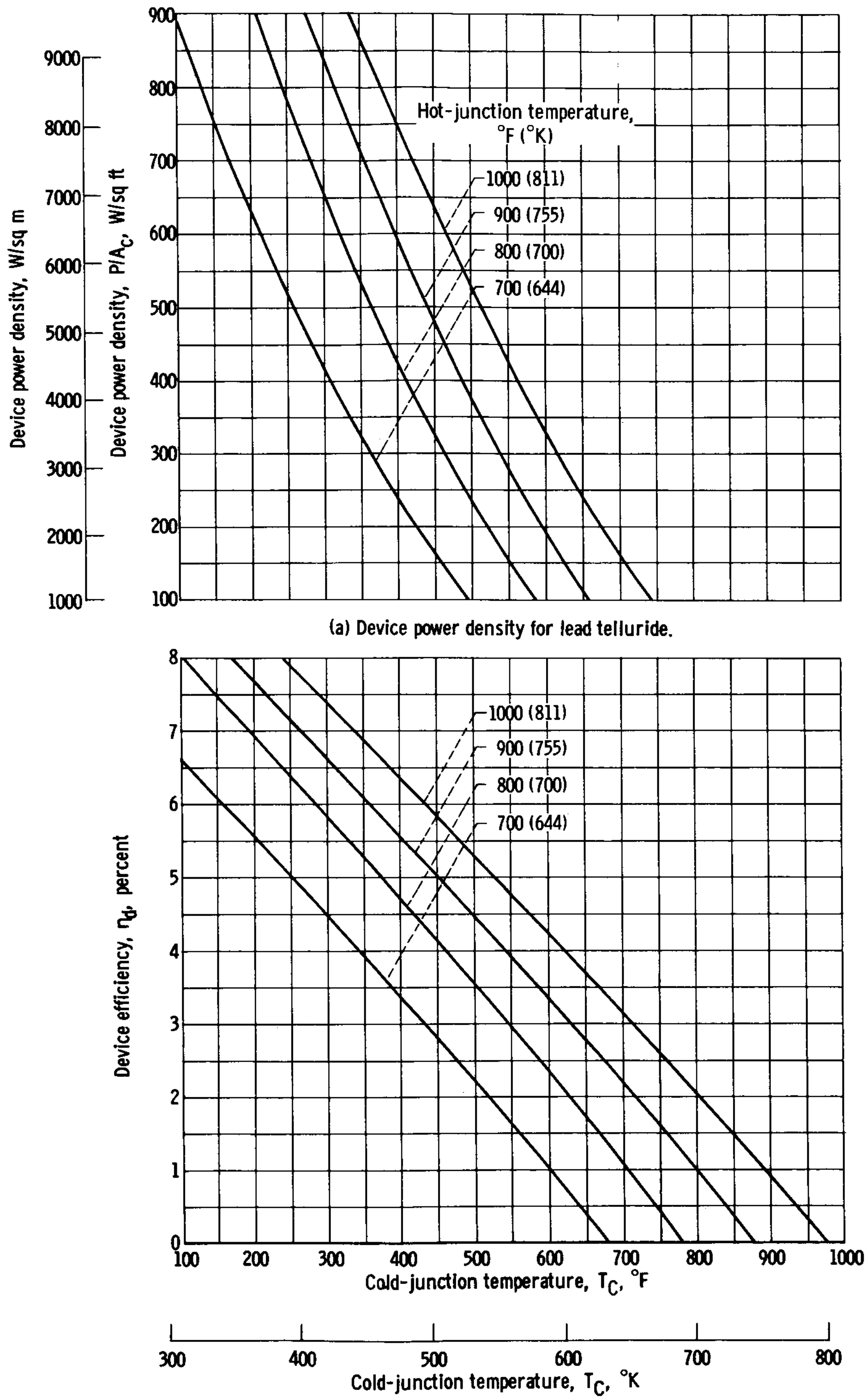
Figure 1. - Thermoelectric couple and assembled flat plate.

by 0.001 inch (0.0254 mm), are included per couple.

Device power density P/A_c and device efficiency η_d were calculated by using the equations presented in reference 2 for a range of hot- and cold-junction temperatures. The device power density is defined as the electrical power produced per unit thermoelectric cross-sectional area. Device efficiency is defined as the ratio of the electrical output power to the thermal input power delivered to the thermoelectric device. Both device power density and efficiency, which are presented for lead telluride and silicon-germanium in figure 2, are based on an electrical lead resistance equal to 10 percent of the thermoelement resistance and an electrical contact resistance per junction of approximately 2 percent of the thermoelement resistance. (The electrical contact resistance is the resistance of the junction interface between the thermoelement and either the absorber or the radiator plate.) For a given hot-junction temperature T_H, both thermoelectric device power density and efficiency increase with decreasing cold-junction temperature. For example, as shown in figures 2(a) and (b), at a hot-junction temperature of 1000° F (811° K) and a cold-junction temperature of 700° F (644° K), the lead telluride device power density and efficiency are 162 watts per square foot (1745 W/sq m) and 3.15 percent, respectively. When the cold-junction temperature is reduced to 500° F (533° K), device power density and device efficiency are increased to 530 watts per square foot (5710 W/sq m) and 5.3 percent, respectively. Figures 2(c) and (d) show a similar behavior for silicon-germanium where, for example, at a hot-junction temperature of 1800° F (1255° K), the device power density and efficiency increase from 1480 watts per square foot (15 940 W/sq m) and 4.3 percent at a cold-junction temperature of 1100° F (866° K) to 3170 watts per square foot (34 200 W/sq m) and 6.2 percent at a cold-junction temperature of 800° F (700° K).

Thermal Considerations

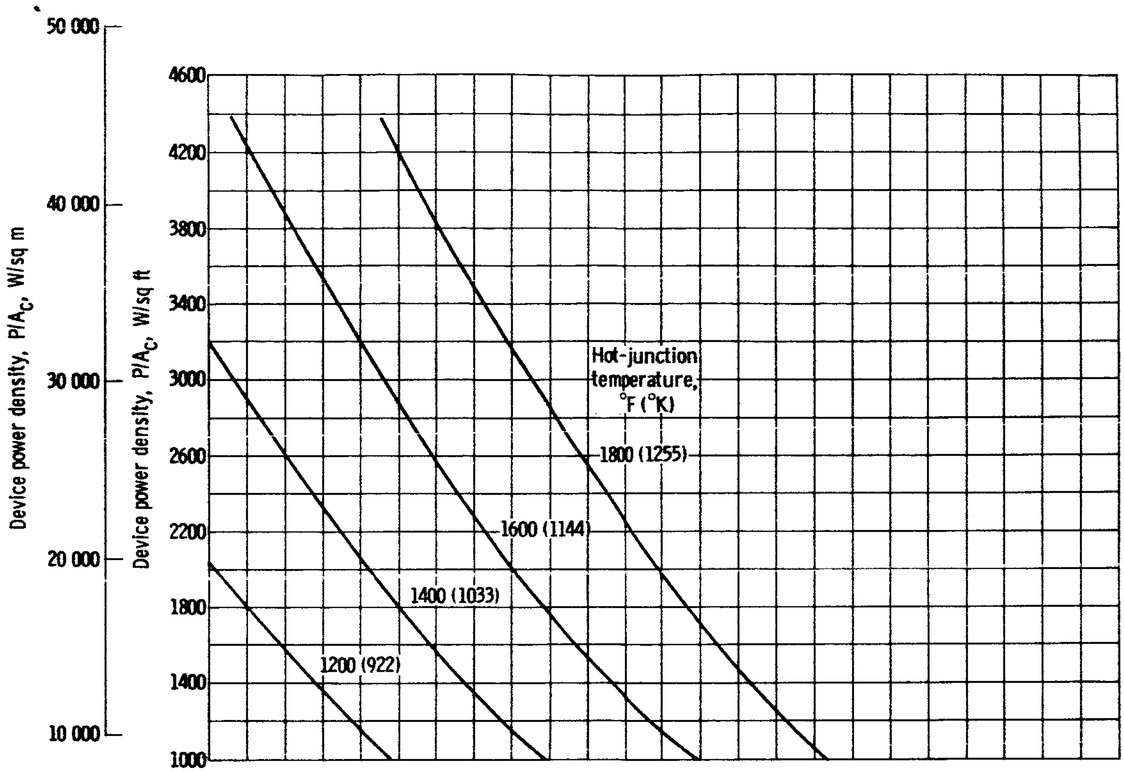
A thermoelectric flat plate system approaching the Sun experiences a continuously increasing thermal flux (inverse square law), which presents a difficult thermal design problem. The design of a thermoelectric flat plate would depend on the output power requirements of the particular mission. There are two possible approaches to this design problem. (1) If constant output power is desired between Earth (1.0 AU) and Mercury (0.388 AU), for example, the thermoelectric panel design would be based on the solar flux of 130 watts per square foot (1400 W/sq m) at Earth, and tilting of the panel would be required to maintain this input solar flux as the system approached Mercury, where the solar flux is 865 watts per square foot (9330 W/sq m). (2) If the utilization of the maximum thermal flux at Mercury with the thermoelectric panel operating normal to the Sun's rays is desired, only a small fraction of the design point



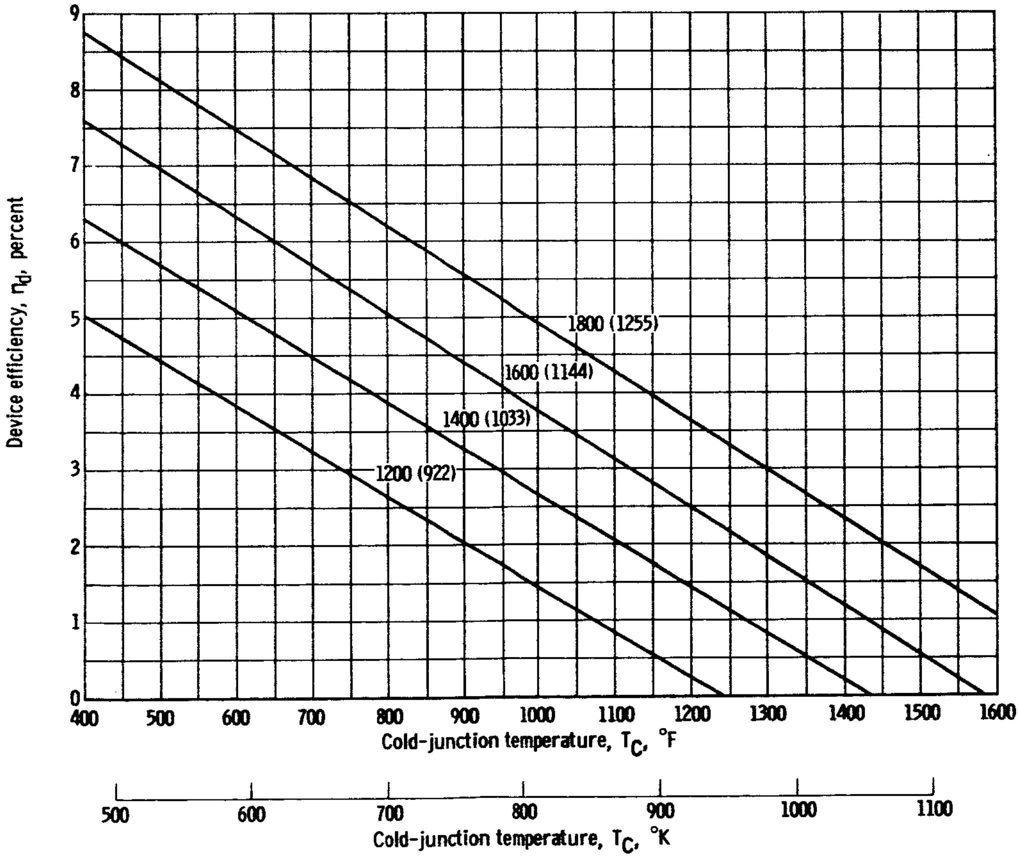
(a) Device power density for lead telluride.

(b) Device efficiency for lead telluride.

Figure 2. - Device power density and efficiency as functions of cold-junction temperature for lead telluride and silicon-germanium. Length, 0.2 inch.



(c) Device power density for silicon-germanium.



(d) Device efficiency for silicon-germanium.

Figure 2. - Concluded.

power would be available at Earth. A continuous increase in system output power would then result as the system moved away from the Earth, and a maximum would be reached at the design point. The second approach is assumed for this study. Calculations are made for a number of design points ranging from 1.0 to 0.1 AU, and panel tilting is assumed to maintain constant power beyond the design point. (A tilt angle of 0° corresponds to panel orientation normal to the Sun's rays). The missions or design points evaluated were 1.0 AU (Earth), 0.722 AU (Venus), 0.388 AU (Mercury), 0.25 AU, and 0.1 AU.

System Performance and Optimization

For a given design point, system performance is determined over a range of hot-junction temperatures by using a heat balance approach, and the design with the maximum output is selected as the optimized system. Maximum operating temperatures are 1000° F (811° K) for lead telluride and 1800° F (1255° K) for silicon-germanium. The selective absorber coating which is compatible with the assumed substrate material and which has proper solar absorptance and infrared emittance characteristics is employed.

For a given mission and an assumed hot-junction temperature T_H, the net thermal power input to the absorber is found by

$$\frac{Q_t}{A_s} = \alpha_a S - \epsilon_a \sigma T_H^4 \tag{1}$$

The cold-junction temperature is found by assuming that all the input heat is rejected (i.e., $\eta_d = 0$), which is expressed as

$$T_C = \left(\frac{\frac{Q_t}{A_s}}{\epsilon_r \sigma}\right)^{1/4} \tag{2}$$

Since equations (1) and (2) assume uniform absorber and radiator plate temperatures, fin effectiveness was calculated by using the approach employed in reference 3. Fin effectiveness represents the fraction of heat radiated from a plate with a maximum temperature T_o relative to a plate at a uniform temperature T_o. For all design points considered herein, calculated fin effectiveness was 0.92 or greater if 5-mil-thick

(0.127 mm) absorber and radiator plates were assumed. Since values of fin effectiveness greater than 0.9 result in only slight changes in system performance, the simplifying assumption of a fin effectiveness of 1.0 was employed throughout the study.

For given hot- and cold-junction temperatures then, the actual device efficiency and power density were determined from the device performance curves. It was found that the cold-junction temperature determined with a device efficiency of zero (eq. (2)) was adequate for the analysis, and iteration was unnecessary.

The thermoelectric cross-sectional area coverage required A_c/A_s is found by an iterative process that includes thermal loss considerations. The thermoelectric cross-sectional area coverage is given by

$$\frac{A_c}{A_s} = \frac{\dfrac{Q_t}{A_s} - \dfrac{Q_m + Q_i}{A_s}}{\dfrac{\dfrac{P}{A_c}}{\eta_d}} \tag{3}$$

The product of the thermoelectric device power density and the area coverage ratio is then taken as the generator output power density. This is expressed as

$$\frac{P}{A_s} = \frac{P}{A_c}\frac{A_c}{A_s} \tag{4}$$

This procedure is repeated with new, assumed, hot-junction temperatures until a maximum value of output power is found. The variation in output power density (power profile) between Earth and design point is then calculated for each configuration by using equations (1) to (4). To maintain constant thermal power input as the system moves from design point toward the Sun, tilting of the panel through angles up to 80° is assumed. The variation of solar absorptance with tilt angle is neglected in this analysis.

Specific Weight

The components considered in the calculation of panel specific weight (i.e., the ratio of generator weight to output power in lb/kWe) were semiconductor elements, electrical interconnections, 5-mil-thick absorber and radiator plates, interplate thermal insulation (when necessary), mica insulating supports, and ribbed support structure.

TABLE I. - THERMOELECTRIC PANEL MATERIAL PROPERTIES AND CALCULATED VALUES OF SYSTEM PERFORMANCE

[Radiator coating, calcium titanate; thermal insulating supports, mica; density of thermal insulating supports, 0.1154 lb/cu in., 3.19 g/cu cm.]

Properties	Semiconductor					
	Lead telluride			Silicon germanium		
	Design point					
	Earth	Venus	Mercury	Mercury	----	----
	Distance from Sun, AU					
	1.0	0.722	0.388	0.388	0.25	0.10
Solar constant, W/sq ft (W/sq m)	130 (1400)	248 (2670)	865 (9310)	865 (9310)	2075 (22 350)	13 000 (140 000)
Solar absorptance, α_a	[a].90	[a].90	.86	.85	[b].85	.36
Emittance						
Absorber plate, ϵ_a	[a].05	[a].05	.22	.072	[b].072	.15
Radiator plate, ϵ_r	.90	.90	.90	.90	.90	.90
Temperature, ^{o}F (^{o}K)						
Hot junction, T_H	700 (644)	800 (700)	1000 (811)	1200 (922)	1600 (1144)	1800 (1255)
Cold junction, T_C	168 (349)	306 (425)	400 (477)	540 (555)	785 (691)	1098 (865)
Difference, ΔT	532 (295)	494 (275)	600 (334)	660 (367)	815 (453)	702 (390)
Net thermal input to absorber, Q/As, W/sq ft (W/sq m)	71 (765)	158 (1700)	249 (2680)	457 (4920)	1103 (11 900)	2690 (29 000)
Ratio of thermoelectric element, cross-sectional area to plate area, Ac/As	.0046	.0124	.0179	.012	.0237	.0698
Device power density, P/Ac, W/sq ft (W/sq m)	710 (7650)	638 (6880)	750 (8070)	1415 (15 240)	2090 (22 500)	1480 (15 900)
Generator output power density, W/sq ft (W/sq m)	3.3 (35.5)	7.9 (85)	13.4 (144)	17.0 (183)	49.5 (533)	103.8 (1120)
Efficiency, percent						
Device, η_d	5.87	5.76	6.35	4.20	5.13	4.30
Overall, η_o	2.53	3.18	1.55	1.97	2.38	.80
Interplate surface emittance, ϵ_p	.03	.03	.03	.03	.03	None
Panel specific weight, lb/kWe (kg/kWe)	117.0 (53.2)	97.5 (44.3)	73.6 (33.4)	82.4 (37.4)	30.8 (14.0)	31.6 (14.35)
	Absorber plate					
	Copper			Molybdenum		
Density, lb/cu in. (g/cu cm)	0.322 (8.89)	0.322 (8.89)	0.322 (8.89)	0.370 (10.2)	0.370 (10.2)	0.370 (10.2)
Thickness, in. (mm)	.002 (0.0508)	.004 (0.102)	.005 (0.127)	.005 (0.127)	.005 (0.127)	.005 (0.127)
	Radiator plate					
	Aluminum			Molybdenum		
Density, lb/cu in. (g/cu cm)	0.098 (2.71)	0.098 (2.71)	0.098 (2.71)	0.370 (10.2)	0.370 (10.2)	0.370 (10.2)
Thickness, in. (mm)	.003 (0.0762)	.005 (0.127)	.005 (0.127)	.005 (0.127)	.005 (0.127)	.005 (0.127)
	Absorber coating					
	Hass dark mirror		Tabor chemical treatment 110-30	Optical interference coating (MgF_2-Mo-CeO_2)		Polished molybdenum
	Interplate radiation barrier coating					
	Gold			Gold		None
	Interplate thermal insulation					
	None			None		Min-K 200
Density, lb/cu in. (g/cu cm)	None			None		0.011 (0.304)

[a]Represent projected values; however, coating has demonstrated $\alpha_a > 0.8$ and $\epsilon_a < 0.07$.

[b]Represent measured values at 1250° F (projected to 1600° F).

The materials used for the various systems and their physical properties are listed in table I.

For the lead telluride system, it is assumed that the absorber and radiator plates serve as the electrical leads while, for the silicon-germanium system, stack-type interconnections are used as follows: At the end of each element, a 0.020-inch-thick (0.508 mm) tungsten shoe is bonded to the silicon-germanium semiconductor. A 0.020-inch-thick (0.508 mm) niobium electrical conducting strap is used to connect adjacent elements, and 0.010-inch-thick (0.254 mm) beryllia spacers electrically insulate the elements from the absorber and radiator plates.

The sum of the element, lead, plate, and support weights is taken as the structure weight. The structure would include ribs or other stiffeners that are applied to the panel.

RESULTS AND DISCUSSION

Design parameters and system performance values are summarized in table I. Panel output power density is plotted against distance from the Sun in figure 3 for 0.1, 0.25, and 0.388 AU missions. As shown in figure 3, for a given mission design point, panel output power density P/A_S exhibits a slow increase initially with decreasing astronomical unit (moving from the Earth toward the Sun) followed by a sharp increase

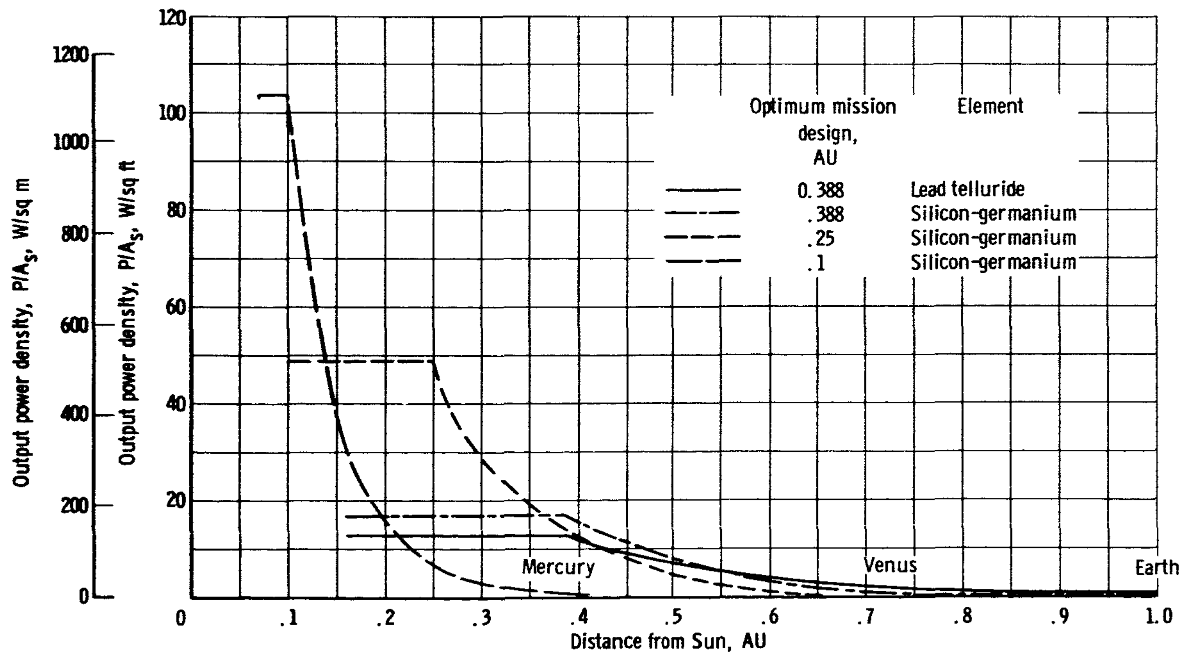


Figure 3. - Power density profiles for solar thermoelectric flat-plate systems optimized for 0.1, 0.25, and 0.388 AU missions.

as the system nears design point. For example, a lead telluride system designed for 0.388 AU exhibits an increase in output power density from about 1 watt per square foot (10.77 W/sq m) at 1.0 AU to 13 watts per square foot (140 W/sq m) at 0.388 AU, although it remains constant with the assumption of continuous tilting to about 0.16 AU, where the limiting tilt angle of 80° is attained. Although lead telluride was also considered for 0.722 and 1.0 AU missions, the power densities were relatively low and are not presented in the figures.

A silicon-germanium flat plate designed for 0.388 AU exhibits a variation in output power relative to position in space similar to the lead telluride system but with a slightly higher power density of 17 watts per square foot (183 W/sq m) at design point. The silicon-germanium systems designed for 0.25 and 0.1 AU are of special interest because of their possible use in solar probe missions. As shown in figure 3 the 0.25 AU system exhibits a power density increase from 14 watts per square foot (151 W/sq m) at 0.388 AU to 49 watts per square foot (528 W/sq m) at 0.25 AU, and it remains constant to about 0.1 AU where the required tilt angle is 80°. The 0.1 AU system power density variation is similar, increasing from 1 watt per square foot (10.77 W/sq m) at 0.388 AU to 104 watts per square foot (1120 W/sq m) at 0.1 AU. Again, tilting of the panels is assumed to maintain constant output power density to 0.04 AU, where the limiting tilt angle of 80° is reached.

Panel specific weight at design point is plotted against distance from the Sun in figure 4. For a given distance from the Sun, the specific weight shown in figure 4 represents that of a system designed to produce maximum output power density at that distance with the panels oriented normal to the Sun's rays (i.e., tilt angle of 0°). For lead telluride, the design point specific weight decreases steadily from 1 to 0.388 AU, where the hot-junction temperature reaches 1000° F (811° K) (the limiting temperature for lead

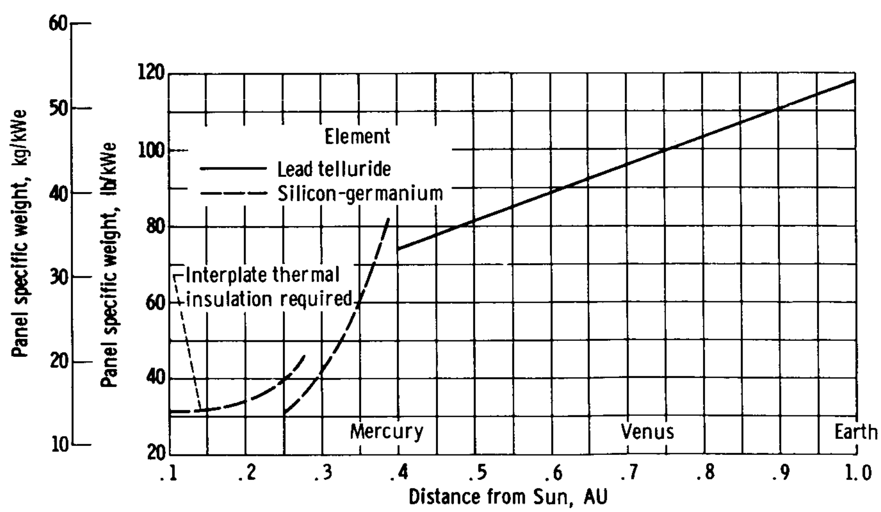


Figure 4. - Panel specific weight as function of design point distance from Sun for flat-plate thermoelectric generator.

telluride). For silicon-germanium, the design point specific weight decreases sharply between 0.388 and 0.25 AU for the panels without interplate thermal insulation, while a more gradual decrease is exhibited between 0.25 and 0.1 AU when interplate thermal insulation is employed. Low-emittance radiative barrier coatings for minimizing the thermal loss between the absorber and radiator plates are assumed to be usable only up to 1600° F (1144° K). Therefore, for design points less than 0.25 AU, which corresponds to absorber temperatures in excess of 1600° F (1144° K), solid thermal insulation is required between the plates.

As shown in figure 4, the specific weight of the lead telluride panels varies from 118 pounds per kilowatt electric (53.5 kg/kWe) at 1.0 AU to about 74 pounds per kilowatt electric (33.6 kg/kWe) at 0.388 AU, while that of the silicon-germanium panels varies from 82 pounds per kilowatt electric (37.3 kg/kWe) at 0.388 AU to 31 pounds per kilowatt electric (14.1 kg/kWe) at 0.25 AU without interplate thermal insulation and from 40 pounds per kilowatt electric (18.2 kg/kWe) at 0.25 AU to 31 pounds per kilowatt electric (14.1 kg/kWe) at 0.1 AU when interplate insulation is included.

SUMMARY OF RESULTS

The performance of solar thermoelectric flat plates was evaluated for missions ranging from 1.0 to 0.1 AU. With the exception of solar absorber coatings, for which long-term performance stability has yet to be demonstrated, the panel materials chosen for the study were considered state of the art. The results of the study are as follows:

1. Thermoelectric flat plates can be designed to produce as much as 104 watts per square foot (1120 W/sq m) at 0.1 AU, although a panel designed for 1.0 AU produces only about 3 watts per square foot (32.3 W/sq m).

2. Tilting of the thermoelectric panels is an effective method of maintaining constant output power over a limited range of distance beyond design point. (If the absorptance of the solar absorber coating is independent of angle of incidence and the maximum tilt angle is limited to 80°, this range of distance is of the order of 60 percent of the design point distance.)

3. The specific weight of thermoelectric flat plates varies from 30 to 120 pounds per kilowatt electric (13.6 to 54.5 kg/kWe) for designs of 0.1 and 1.0 AU, respectively.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 17, 1966,
120-27-06-02-22.

REFERENCES

1. Anon: Analysis, Design and Development of a Flat Plate Solar Thermoelectric Energy Conversion Panel. Final Rep. (Contract No. NAS5-3782), Melpar Inc., 1964.

2. Cadoff, Irving B.; and Miller, Edward, eds.: Thermoelectric Materials and Devices. Reinhold Publishing Corp., 1960.

3. Lieblein, Seymour: Analysis of Temperature Distribution and Radiant Heat Transfer Along a Rectangular Fin of Constant Thickness. NASA TN D-196, 1959.

NASA-Langley, 1966 E-3478