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SUMMARY

An analysis of solar thermionic conversion systems is presented for mission design points ranging from 1 AU (Earth) to 0.1 AU. Performance is based on a four-converter generator-solar concentrator system sized to produce 200 watts of electrical power at design point. Solar flux regulating systems are not included in this evaluation; however, direct control of the diode cesium reservoir temperature and electrical load resistance is considered as a means of controlling power output.

Results indicate thermionic system specific weights of between 20 and 100 pounds per kilowatt electric (9.1 and 45.4 kilograms per kilowatt electric) for the 0.1 to 1.0 AU range. Without thermal flux control, however, a large variation in output power occurs as the system moves from the Earth toward the Sun.

INTRODUCTION

A solar thermionic conversion system is considered for missions ranging from 1.0 AU, where the solar intensity S is 130 watts per square foot (1400 W/sq m), to 0.1 AU, where S is 13 000 watts per square foot (140 000 W/sq m). The system consists basically of a solar concentrator, an absorber, and thermionic energy converters. The design of such a system for a given mission would depend on the output power requirements. For example, the system might be required either to ensure a given minimum level of electrical output power throughout the entire mission or to provide the maximum conversion efficiency and minimum weight at design point regardless of the performance elsewhere. The former would require the use of a solar flux controller in order to maintain a relatively constant thermal input to the thermionic generator as the system changed position relative to the Sun. Because the effectiveness of such controls for the missions studied herein is uncertain, the latter concept, which is based on maximum system performance at design point assuming no thermal control, is considered in this evaluation.

Systems are evaluated at the following mission design points: 1.0 AU (Earth), 0.722 AU (Venus), 0.388 AU (Mercury), 0.25 AU, and 0.1 AU. System performance is based on both power profile and specific weight at design point.

SYMBOLS

A area, sq cm

p power density, W/sq cm

R resistance, ohm

r reflectivity

S solar intensity, W/sq ft or W/sq m

T temperature, ^{o}K

σ Stefan-Boltzmann constant

η efficiency, percent

φ rim angle, deg

Subscripts:

Cs cesium reservoir

C-A collector-absorber system

d diode

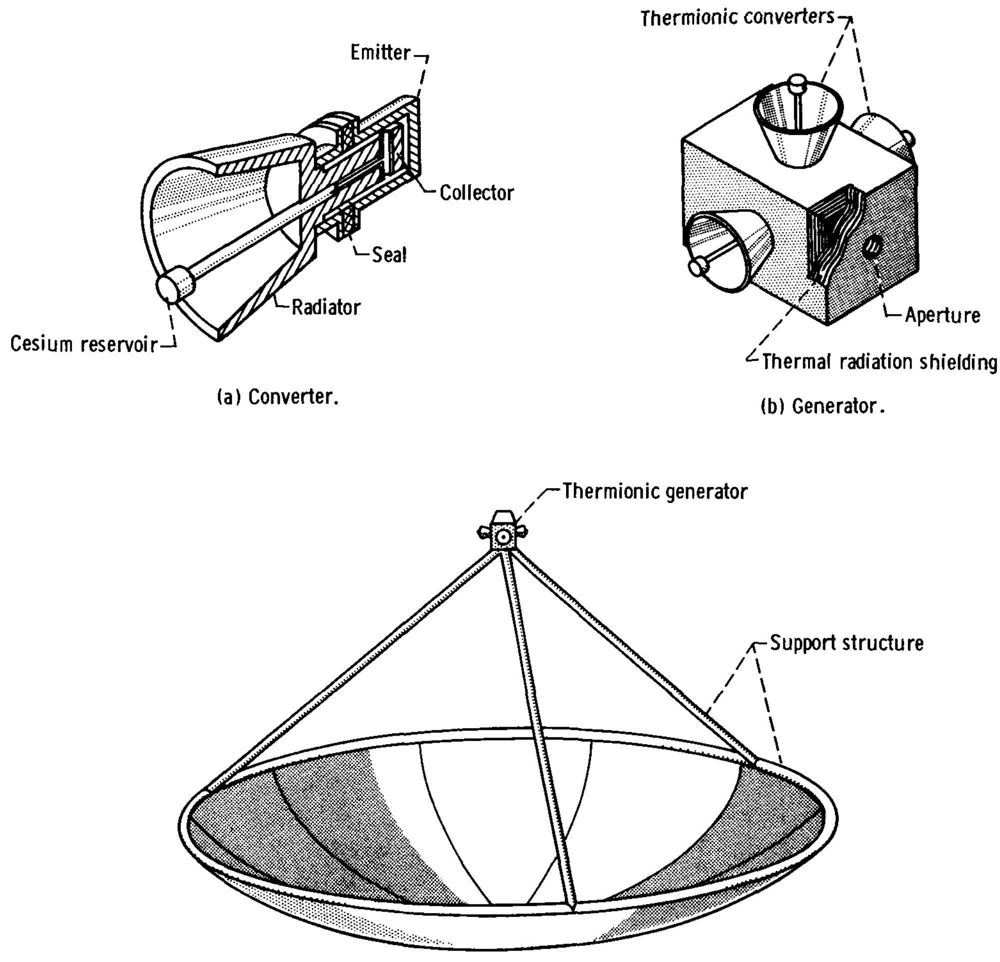
E emitter

L load

METHOD OF ANALYSIS

System Description

A cross-sectional view of a typical planar cesium vapor diode is shown in figure 1(a). Four such conversion devices mounted on the outer walls of a solar absorber, as shown in figure 1(b), constitute the solar thermionic generator assumed for this study. In application, solar energy is directed through the aperture into the absorber by a one-



(a) Converter.

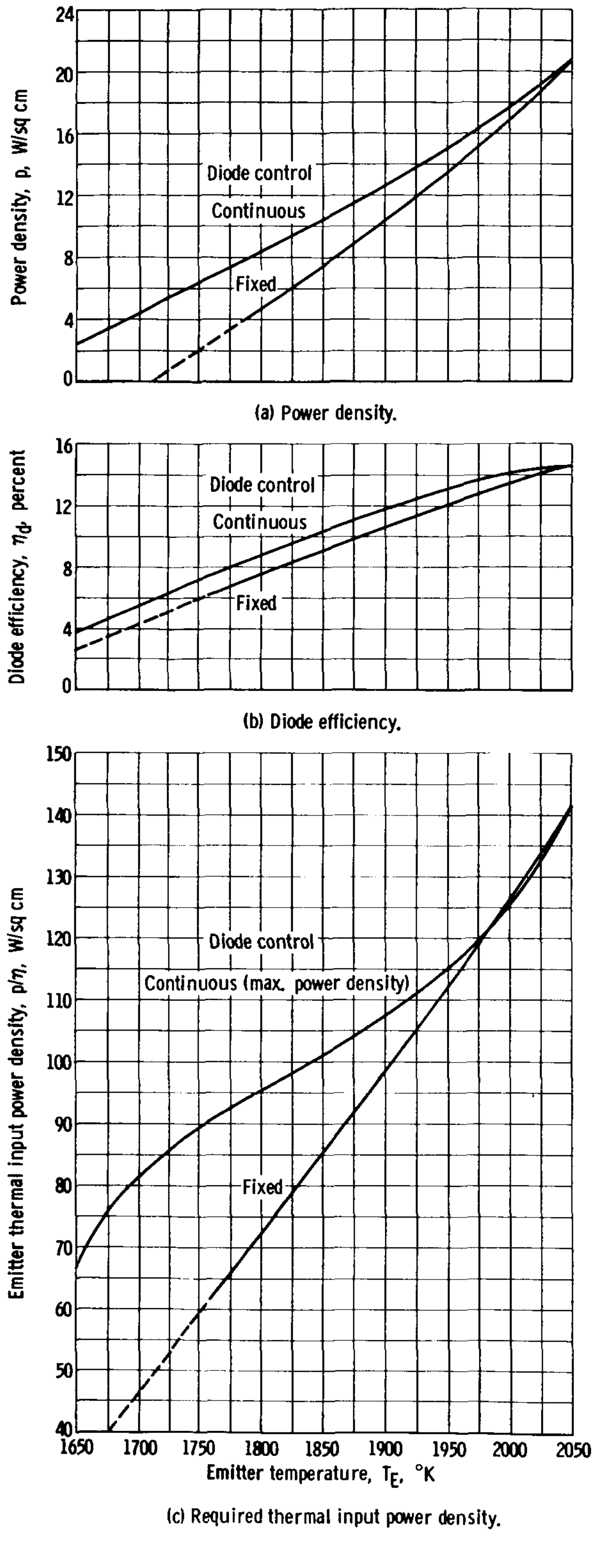
(b) Generator.

(c) Overall view.

Figure 1. - Solar thermionic conversion system.

piece parabolic mirror or concentrator, as shown in figure 1(c). A portion of this input is lost either by thermal reradiation and reflection from the aperture or by conduction and radiation to the outer walls of the generator. The remainder is the thermal input to the emitting electrodes of the thermionic converters. Based on the diode performance that is assumed for this study, a maximum of approximately 15 percent of this thermal input is converted to electricity, while the remaining 85 percent or more is rejected to space by the diode radiator.

The concentrator and generator are connected by support arms (fig 1(c)) such that the aperture, located on the front side of the generator, is in the focal plane of the concentrator. The outer walls of the generator are covered with thin-foil thermal radiation shielding (fig. 1(b)), which limits the thermal loss from the generator to 10 percent of the net thermal input power.



(c) Required thermal input power density.

Figure 2. - Device efficiency, power density, and required thermal input power density as functions of emitter temperature for rhenium-molybdenum diode with interelectrode spacing of 3 mils (0.0762 mm).

In order to determine overall system performance, the following procedure is used: (1) For each design point, the generator is designed to produce a maximum of 200 watts of electrical output power (i.e., each of four planar diodes is sized to produce 50 watts of electrical power at design point when operating at an emitter temperature of 2050° K). (2) The solar concentrator is designed to deliver the net thermal input required by the generator and also to withstand the maximum operating temperatures reached during the mission.

Diode Performance

Thermionic diode performance for this study is based on a rhenium emitter - molybdenum collector diode with a 3-mil (0.0762 mm) interelectrode spacing (ref. 1). Diode power density and efficiency are plotted against emitter temperature for such a converter in figure 2. The power density is obtained directly from reference 1. Since the corresponding diode efficiency is not presented in reference 1, however, the efficiencies were calculated by using an energy balance approach. Two curves are presented for both power density and efficiency in figure 2; one represents diode performance obtained by continuous adjustment of the cesium reservoir temperature T_{Cs} and the load resistance R_L, and the second represents the performance obtained by fixing T_{Cs} and R_L at the required optimum values for an emitter temperature of 2050° K. The first case is referred to as continuous diode control and the second as fixed diode control.

As shown in figure 2, the diode power density and calculated efficiency for the continuous diode control case vary from 20.8 watts per square centimeter and 14.8 percent at an emitter temperature T_E of 2050° K to 10.4 watts per square centimeter and 10.3 percent at a T_E of 1850° K. For the fixed diode control case, the cesium reservoir temperature and load resistance are fixed at 643° K and $0.0181/A_E$ ohm, respectively, where A_E is the diode emitter area in square centimeters. The diode power density and calculated efficiency for the fixed diode control vary from 20.8 watts per square centimeter and 14.8 percent at a T_E of 2050° K to 7.5 watts per square centimeter and 9 percent, respectively, at a T_E of 1850° K.

Collector-Absorber Performance

Solar collector-absorber performance used herein is calculated for a parabolic collector with a rim angle φ of 60°, a reflectivity r of 0.9, and a normal distribution of collector surface errors with a standard deviation σ of 6 minutes. A digital computer program is used to predict the collector-absorber efficiency η_{C-A} as a function of distance from the Sun, as seen in figure 3, for a perfectly oriented 5-foot-diameter (1.525-m)

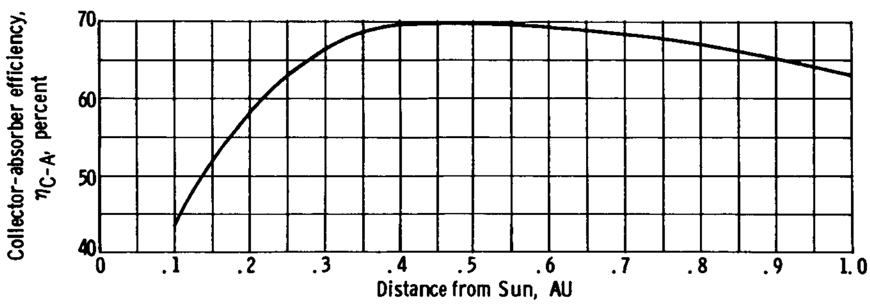


Figure 3. - Maximum collector absorber efficiency as function of distance from Sun for cavity temperature of 2050° K.

concentrator and for a cavity temperature of 2050° K. Corrections are included for energy losses from the absorber due to reflection, by using the approach outlined in reference 2, assuming a cavity length-to-width ratio of 2 and an inner wall emittance of 0.5. Reradiation losses from the aperture are calculated by assuming a cavity with blackbody characteristics. In addition, an obscuration efficiency of 95 percent is included. The sharp decrease in collector-absorber efficiency for distances less than 0.3 AU should be noted (fig. 3). Because of the increased size of the Sun's image in this region, the solar energy directed into the aperture of the generator is focused less sharply, requiring relatively large aperture areas. The increased thermal loss from the aperture thus results in a reduction in collector-absorber efficiency. It is important to realize that figure 3 represents the performance of a collector-absorber system with a variable aperture; that is, each point on the abscissa of figure 3 represents a different optimum aperture size.

The effect of misorientation of the solar concentrator was determined for the 1.0 AU design point only. It was found that a misorientation angle of approximately 10 minutes results in a 10 percent reduction in output power at design point. For distances less than 1.0 AU, the effect of misorientation is expected to decrease since the solar energy focused into the generator aperture is less sharply defined.

Thermal Analysis

The total emitter area in square centimeters required to produce 200 watts of electrical power at an emitter temperature of 2050° K is determined from the following relation:

$$A_E = \frac{200}{p_{2050^\circ \mathrm{K}}}$$

For each design point, the solar collector size necessary to deliver the required thermal flux is determined. The variation in output power with distance or power profile is then found by allowing the input thermal flux to the diodes to vary at the same rate as the incident solar flux with distance from the Sun (i.e., inverse square relation). The thermal power density required by the thermionic diodes is the ratio of electrical power density to efficiency. Thus, for a given decrease in thermal flux, the corresponding change in electrical power density can be found by using figure 2.

SPECIFIC WEIGHT

The system specific weight is calculated for each design point assuming the following components: solar concentrator, generator (including thermionic converters and thermal shielding), and generator supports.

Lightweight aluminum solar concentrators proposed for Earth orbital missions are not suitable for the higher temperatures encountered by solar probes. Therefore, the following concentrator weight estimates are assumed for this study: 0.6 pound per square foot (2.94 kg/sq m) for 1.0 and 0.722 AU, and 1.0 pound per square foot (4.89 kg/sq m) for 0.388, 0.25, and 0.1 AU.

The thermionic converter specific weight (including radiator) is scaled from the solar energy thermionic system diode weight (i.e., 0.22 lb/sq cm (0.1 kg/sq cm) of emitter area) presented in reference 3. The generator support structure is taken as 25 percent of the collector weight.

The thermal shields are considered to be thin parallel plates arranged such that the heat transfer between shields is due solely to radiation. Weight calculations are based on the use of 0.3-mil-thick (0.0076 mm) tantalum shields with an emissivity of 0.3.

RESULTS AND DISCUSSION

Electrical output power is plotted against distance from the Sun for a 200-watt system in figure 4 for 0.1, 0.25, 0.388, and 0.722 AU missions. For a given mission, output power increases sharply with decreasing distance from the Sun for both continuous and fixed diode control conditions. The useful range of operation could be extended beyond design point by using, for example, a shutter-type thermal control system. However, since the effectiveness of such controls has not been established for the missions evaluated in this analysis, performance predictions are made assuming no thermal control.

For a 0.1 astronomical unit mission, a solar thermionic system that employs continuous diode control does not begin to produce electrical power until the system reaches about 0.25 AU (fig. 4). From 0.25 to 0.1 AU, the power rises sharply reaching 200 watts at 0.1 AU. At distances less than 0.1 AU, the increased solar input would result in excessive generator operating temperatures and a corresponding degradation of system output power. Although such a system appears unattractive from a power profile viewpoint, it is potentially useful for future solar probe missions such as a continuous orbit-

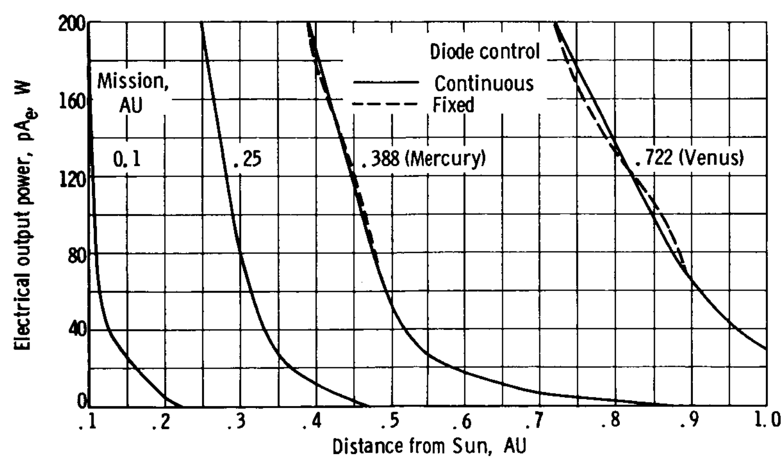


Figure 4. - Output power as function of distance from Sun for 200-watt solar thermionic conversion systems.

ing of the Sun at 0.1 AU or less.

For 0.722 and 0.388 AU missions, performance is presented in figure 4 for both continuous and fixed diode control conditions. It should be noted that, for the 0.722 AU mission, for example, fixed diode control power output is 54 watts, while continuous diode control power is only 50 watts at 0.85 AU. This occurs because the system is designed to produce maximum output power with the thermionic converters operating at maximum diode power density rather than maximum diode efficiency. (Typically, maximum diode efficiency occurs at higher values of electrode voltage than maximum power density for a given emitter temperature.) Thus, as shown in figure 2(c), for emitter temperatures less than 1980° K, more thermal power is required by the converters to operate at a given emitter temperature with continuous diode control than with fixed diode control. For example, at an emitter thermal input power density of 105 watts per square centimeter, the continuous diode control results in an emitter temperature of 1880° K and a power density (fig. 2(a)) of 11.8 watts per square centimeter, while fixed diode control results in an emitter temperature of 1925° K and a power density of 12.0 watts per square centimeter. Thus, for the 0.722 AU system, a more efficient utilization of thermal energy is effected at 0.85 AU with the fixed diode control condition and, hence, operation at a higher emitter temperature. In this case then, little or no advantage is gained from continuous diode control.

Design values of thermionic system specific weight are plotted against distance from the Sun in figure 5. This specific weight decreases continuously from 100 pounds per kilowatt electric (45.4 kg/kWe) at 1.0 AU to about 22 pounds per kilowatt electric (10 kg/kWe) at 0.1 AU. It should be noted that the specific weights presented in figure 5 represent the minimum weights determined for each design point rather than the specific weight of one particular system as a function of distance from the Sun. Thus, a solar thermionic system designed to produce 200 watts and have a specific weight of 22 pounds

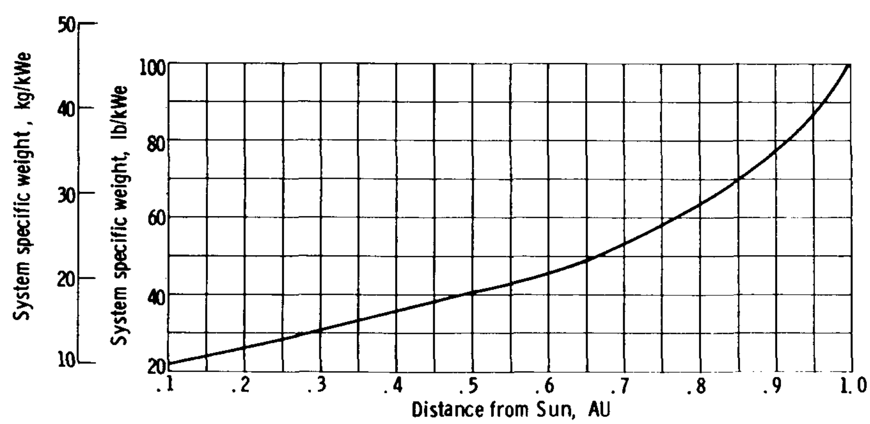


Figure 5. - Design point system specific weight as function of design distance from Sun for 200-watt solar thermionic conversion system.

per kilowatt electric (10 kg/kWe) at 0.1 AU would perform as in figure 4, where it is shown that very little power is produced until the system nears the design point.

SUMMARY OF RESULTS

Solar thermionic power generation systems are evaluated for the range of 1.0 to 0.1 AU distance from the Sun. Performance estimates are based on a four-converter generator-solar concentrator system sized to produce 200 watts of electrical power at design point. The results of the study are as follows:

1. A solar thermionic system designed to produce 200 watts at 0.1 AU will have a specific weight of about 20 pounds per kilowatt electric (9.1 kg/kWe) at design point, while a system designed to produce 200 watts at 1.0 AU will have a specific weight of about 100 pounds per kilowatt electric (45.4 kg/kWe).

2. Severe variations in output power occur as the system changes position relative to the Sun, unless solar flux control is employed.

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

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