Solar Energy Thermionic Electrical Power Supplies

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This article describes the status of solar energy thermionic (SET) electrical power supplies under development by NASA. A system efficiency of 3.3% and a specific weight of 1.5 w/lb was demonstrated in September 1962 in the first prototype system test using solar energy. A thermionic generator tested more recently has produced 82 w with an efficiency of 7.5% using electron bombardment heating to simulate solar energy. SET converters have produced up to 20 w/cm² at 0.8 v output and 1700°C observed emitter temperature. Five SET converters have operated for over 3000 hr at an observed emitter temperature of 1700°C. A 9.5-ft-diam nickel master has been successfully fabricated using an epoxy spincasting process and nickel electroforming. The present development effort is expected to result in SET electrical power supplies possessing advantages of higher conversion efficiency, lower weight, and increased reliability for many of the space missions of interest in the next ten years.

Introduction

PRELIMINARY design analysis and configuration studies of a 500-w solar energy thermionic (SET) conversion system suitable for use as the prime source of electrical power for a Mars spacecraft was undertaken by NASA during the latter part of 1960. The most promising configuration, designated SET II, will employ a 9.5-ft-diam, rigid, parabolic mirror and a multiconverter thermionic generator. A conceptual Mars spacecraft based on such a system is shown in Fig. 1. The 9.5-ft-diam solar concentrator is centrally mounted with a parabolic high-gain earth-oriented antenna at the lower right. A scientific instrument platform oriented in the direction of the target planet is shown at the upper left.

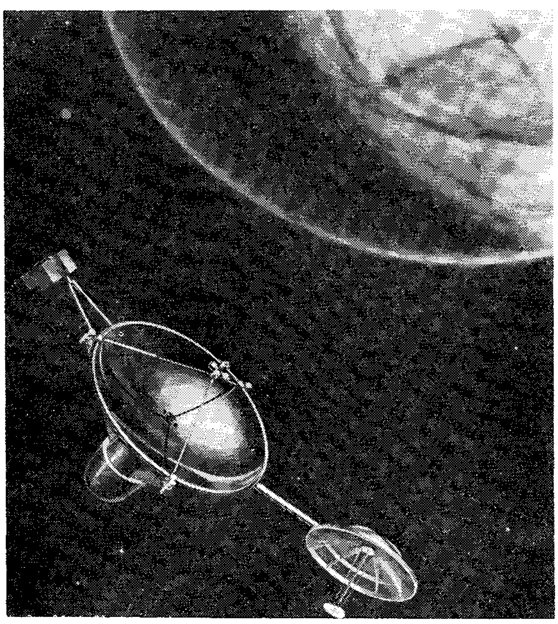

Fig. 1 SET conceptual drawing.

An alternate configuration, designated SET I, incorporates a 5-ft-diam mirror and a 135-w thermionic generator. Four such modules can be clustered to provide up to 540 w of electrical power at Mars (aphelion). The development of a module of the SET I system was undertaken to demonstrate feasibility of the conceptual design.

In May 1961, development of a 135-w module of the SET I solar energy thermionic conversion system was initiated. The first prototype system, SET Ia, was fabricated, assembled, and tested in sunlight in August 1962, 15 months after initiation of detailed design.

Design Goals

The design objectives of the SET I system development include one year service life, 15% system efficiency at Mars, 135 w of electrical power continuously throughout transit from Earth to Mars, and a system weight of 30 lb. Design objectives for the SET thermionic generator are 135 w at 5.35 v output, and 21% conversion efficiency.

The SET I system is designed to operate on a typical Earth-to-Mars mission where the solar flux intensity may vary from a maximum of 138 w/ft² near Earth's perihelion to 44 w/ft² slightly beyond Mars aphelion.‡ The design objectives for the SET I system are summarized in Table 1.

System Description

A prototype of the SET I system is shown in Fig. 2 with the thermionic generator in the operational position. Solar radiation is reflected by the concentrator into the entrance of the generator cavity and absorbed; the resultant heat is converted to electricity by five cesium vapor converters. The flight system will consist of the following basic components:

1) A solar concentrator with a reflective surface of 5-ft frontal diameter supported on its outer rim by a rigid torus.

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‡ The value of the solar constant at the Earth's mean distance from the sun is accepted as 130 w/ft² with an accuracy of ±2%. Using this value, the range of values of the solar constant from Earth perihelion to Mars aphelion is 134.5 to 46.7 w/ft². The values of 138 and 44 w/ft² were selected to insure operation within the known accuracy of the solar constant and to account for the vehicle trajectory extending beyond aphelion-perihelion limits.

Table 1 SET design objectives

Item	Requirement
Power output	135 w (at 5.35 v)
Total weight	30 lb
Cavity temperature	Not specified
Generator efficiency	21.1%
Concentrator-absorber	
Efficiency at 2000°K	
(solar irradiance = 44 w/ft²)	
Perfect alignment	>75%
±6-min misorientation	75%
Service life	1 yr
Power transferred to absorber	640 w
Concentrator size	60-in. frontal diam
Minimum usable projected area	19.0 ft²
Regulation	
Power	±2%
Voltage	±3%

2) Support brackets incorporated into the torus which provide three-point support for the entire system when connected to the vehicle and three points of support for the generator support struts.

3) A support pylon that holds the generator in place during launch.

4) Three support struts for the generator, two rigid and one telescoping, which support the generator during space operation. The two rigid struts are also the power leads for the generator.

5) An erection mechanism consisting of two damped spring drives located at the base of each rigid strut.

6) The thermionic generator, mounted on a support ring, consisting of five thermionic converters mounted in a cubical pattern on a support block. The converters form a cavity into which the solar flux is concentrated. Each thermionic converter incorporates individual radiators and cesium reservoirs.

7) A solar flux control system that controls the amount of sunlight entering the cavity by means of flaps mounted on the thermionic generator support ring near the cavity entrance.

The system will be launched in a folded position, with the generator held close to the concentrator for packaging. The initial system start-up begins after the vehicle support structure unfolds into proper position, the generator supports are placed in operating position by the spring drives, and the vehicle is oriented toward the sun. As the solar flux heats the cavity and the converters begin to operate, the solar flux control will regulate the amount of energy entering the cavity according to temperature sensors on the generator structure. As the vehicle moves further from the sun toward Mars, a greater percentage of solar radiation reflected from the concentrator would be allowed into the generator cavity to provide constant power during the interplanetary journey.

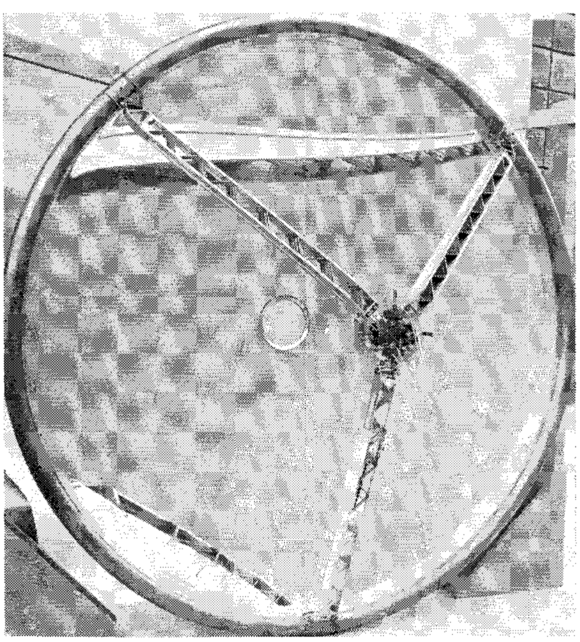

Fig. 2 Prototype of SET I system.

Component Status

Major program efforts to date have emphasized the development of the 5-ft SET concentrator, thermionic converter, the three-legged generator support system, generator assembly, and test facilities for these components. In addition, the design of a solar flux control mechanism has been initiated, and many support efforts in generator development have been accomplished.

After a series of experimental models, two flight prototype SET concentrators designated JM-1-1 and JM-1-2 were fabricated in September 1961. These concentrators consist of a nickel electroformed paraboloid mirror with aluminum coating supported by a torus rim-mounted on the front of the concentrator. Both concentrators met or exceeded the mirror efficiency goal of 82.5%with a geometric concentration ratio of 14,884.

Several types of thermionic converters are being developed for use with SET power supplies. Converters are now available which generate from 25 to 40 w of electrical power at 0.8 v with an observed emitter temperature of 1700° C. Typically, converters weigh 200 g and have an overall length of 4 to 5 in. Converters have been operated at temperature for over 3000 hr with less than 10% degradation.

To date three SET thermionic generators have been assembled. The first generator, designated JG-1, was tested with solar energy in August and September 1962 using concentrator JM-1-2 as a heat source. The second generator was assembled in August 1962 and has been tested in the laboratory using electron bombardment heating to simulate solar energy. The third generator was assembled in August 1963 and tested in the laboratory using electron bombardment heating.

With 1080 w of solar radiation entering the cavity, generator JG-1 produced a power output of 41 w at 2.5 v with four converters in series and the fifth converter disconnected electrically. With 1100 w of electron bombardment power, generator JG-2 produced 82.4 w at 2.9 v with all five converters in series. The third generator to be assembled utilized three type B converters and produced 53.7-w output with 1210-w electron bombardment heat input.

A prototype generator support system has been fabricated and is shown supporting generator JG-2 in Fig. 2. The rigid and telescoping struts have been tested for erection characteristics; tests demonstrated that the basic design functioned as expected. The prototype system used aluminum, and the total weight of the three arms is about 5.2 lb. The electrical resistivity of each rigid arm is such that only 0.15% of the design power output of the generator (135 w) is dissipated through I^2R losses. The area of the mirror obscured by each arm is about 0.3 ft², and the stiffness of the strut cross section is such that the lowest resonant frequency is 400 cps.

The preliminary design of the solar flux control has been completed. It incorporates a series of bimetallic elements

Table 2 Constitution of system weight

Component	Weight, lb
Generator	3.5
Strut supports	5.2
Concentrator	11.0
Vehicle attachments	2.0

that use the solar flux intensity as the basic parameter to regulate the position of flaps, which obscure the cavity entrance. The actual cavity temperature provides an adjustment by heat conduction to a vernier bimetallic element. The present design concept is based upon a system that provides continuous control on an Earth-to-Mars mission with flux intensities ranging from 138 to 44 w/ft^2.

Using the latest concentrator design, the system weight of about 22 lb would be constituted as shown in Table 2.

Current Development Effort

Further electron bombardment heater tests of generator JG-2 are planned. Assembly of JG-2 into a vacuum chamber for sunlight testing will take place in the near future at Table Mountain, Calif. The third generator using three converters will be further tested using electron bombardment heating, and this will be followed by tests using solar energy.

Two additional SET thermionic generators each using four converters are being developed. A generator output of 100 w is expected for each of the generators with an efficiency of 10%. The incorporation of thermal energy storage into the SET converter is being studied with plans to initiate actual converter fabrication in the near future.

A 9.5-ft-diam nickel electroformed mirror master has been completed, and a nickel electroformed replica has been obtained. The availability of 9.5-ft-diam mirrors will make it possible to accelerate the development of the 500-w SET II system.

Concentrator Developments

The SET system design requires that a 5-ft-diam concentrator place sufficient energy into a 2000°K cavity absorber to allow 640 w to be absorbed by the cavity walls when the solar constant is 44 w/ft^2. The cavity entrance diameter was determined by balancing the increased thermal radiation losses with larger entrance sizes against the ability to gather more energy from the concentrator (allowing also for a ±6-ft misorientation requirement). A $\frac{1}{2}$-in.-diam aperture was selected for the first generator design. Assuming the cavity to be a perfect blackbody, 115 w would be reradiated from the generator aperture at 2000°K cavity temperature.

The mirror efficiency used in this paper refers to the ratio of sunlight entering the cavity aperture divided by the sunlight incident on the reflective surface of the concentrator. The mirror efficiency would be lowered further by consideration of the obscuration of the generator and generator support arms, that portion of the front surface of the concentrator which is nonreflective, and other similar factors. After consideration of mirror obscuration, it was calculated that a mirror efficiency of 82.5% was required to meet system goals.

To achieve design specifications, it was necessary to fabricate a concentrator that would maintain a near-perfect optical figure. Consequently, it was decided to use the electroforming, because it is the only process that appears capable of providing a sufficiently accurate concentrator surface. An all-metal structure, without adhesives or other organic components, was selected to minimize dimensional changes after exposure to the space environment.

Physical characteristics of the SET concentrator are summarized in Table 3. The total weight of the first prototypes (JM-1-1, JM-1-2) using the front-mounted support torus shown in Fig. 2 is 19.5 lb, 10.5 lb of which comprise the torus and support brackets. The concentrator is a single-skin nickel structure, integrally bonded to the torus during the electroforming process. The nickel torus is also electroformed; brackets are stainless-steel welded structures.

Concentrator JM-1-2 was used in the systems test described herein. Further developments have produced 60-in.-diam concentrators weighing 11–14 lb using a rear-mounted torus.

Table 3 Physical characteristics of SET concentrators

Concentrator with front support torus, JM-1-1, JM-1-2
Diameter of useful reflecting surface, 61 to 61.26 in.
Over-all diameter (including torus rim support), 66 in.
Diameter of center hole, 6 in.
Useful projected area of mirror (including area obscured by generator support), 20.09 ft^2
Rim angle (useful reflecting surface), 62°
Skin structure, rim-supported paraboloidal shell
Support structure, Rim torus with support brackets
Fabrication technique (skin and torus), electroforming
Specular reflectivity (estimated by calorimeter measurements) 87 to 90%
Skin and torus material, nickel
Bracket material, stainless steel
Total weight, ~19.5 lb
Concentrator with rear support torus
Diameter of useful reflecting surface, 60 in.
Over-all diameter, 60 in.
Diameter of center hole, 6 in.
Useful projected area of mirror, 19.63 ft^2
Rim angle, 61°
Skin structure, rim-supported paraboloidal shell
Support structure, rim torus with support brackets
Fabrication technique (skin and torus), electroforming
Specular reflectivity (estimated by calorimeter measurements), 87 to 90%
Skin and torus material, nickel
Bracket material, aluminum
Total weight, ~11 lb

Weight reduction was due to the use of thinner skinned structures and reduction of bracket weight. The 60-in. rear supported concentrator features a skin of variable thickness, heavy toward the rim and light toward the center. A further advantage of the rear supported structure is that the entire front surface of the mirror is reflective.

A vibration test was performed on solar concentrator JM-1-1. The test consisted of 2–15 g rms white, gaussian noise superimposed on a sinusoid input swept from 40–1500 cps at levels up to 4.5 g rms. The concentrator successfully passed this test.

The prototype 5-ft SET concentrators, designated JM-1-1 and JM-1-2, met or exceeded the mirror efficiency goal when used with a cavity of $\frac{1}{2}$-in. aperture diam. The measured performance of these concentrators is shown in Fig. 3. The data were obtained using a cold calorimeter, and no corrections

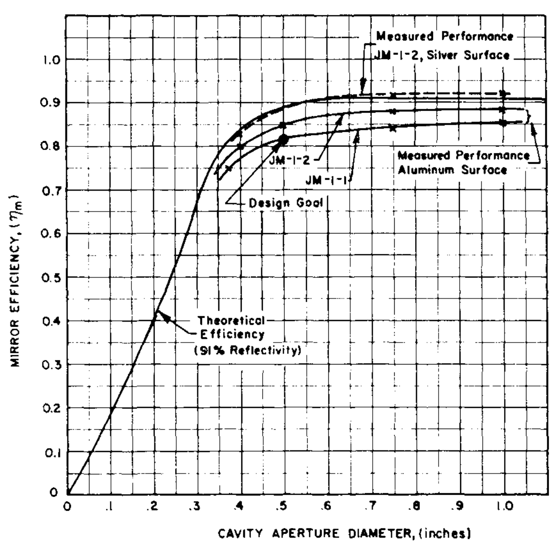

Fig. 3 Measured mirror efficiency SET generator.

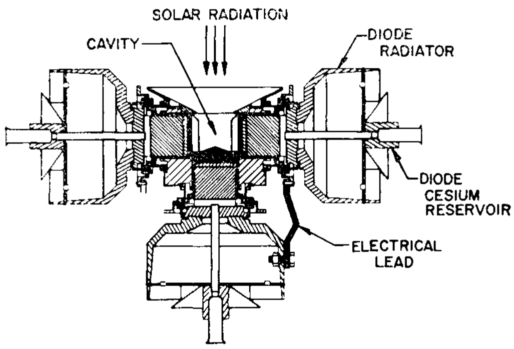

Fig. 4 Cross section of 5-converter SET generator using type A converters.

for possible heat losses from the calorimeter entrance have been applied.

Mirror efficiency is the amount of solar radiation entering the calorimeter entrance divided by the amount of radiation that strikes the usable reflective face of the concentrator. The amount of radiation entering the calorimeter is detected by the measured increase in temperature (20° to 40°F) in a known flow of water through the calorimeter. The inlet water temperature is approximately 70°F.

As shown in Fig. 3, concentrator JM-1-1, using an aluminum overcoat for the reflective surface, exhibited 83% efficiency using a $\frac{1}{2}$-in. cavity aperture diam, and 86% using a 1-in. diam. It should be noted that with a surface reflectivity of 91% the theoretical maximum efficiencies are 89 and 91%, respectively, indicating that the concentrator surface approximates a perfect paraboloid.

The measured mirror efficiency of concentrator JM-1-2, using an aluminum reflective surface, is 85% with $\frac{1}{2}$-in. and 88% with 1-in. cavity aperture diameter. Therefore, at these diameters, the performance of concentrator JM-1-2 exceeds design goals. A comparison with the maximum efficiency theoretically obtainable for a concentrator surface of 91% reflectivity is also shown in Fig. 3.

The measured loss in surface reflectivity which occurred when the basic silver surface of the concentrator was overcoated with aluminum was 3 to 4% as demonstrated by the results of concentrator JM-1-2.

The measured performance characteristics are summarized in Table 4. The estimated performance of the prototype concentrators JM-1-1 and -2 is given for Mars operation for a cavity opening of $\frac{1}{2}$ in. The estimated energy balance for the operation of a 2000°K cavity at Mars and Earth is also presented; estimated mirror-absorber efficiency at Mars is 75.9% and at Earth it is 80.4%. Mirror-absorber efficiency is defined as the total radiation energy absorbed by the cavity walls (after subtracting losses by thermal reradiation from the cavity entrance) divided by the sunlight energy incident on the reflective surface of the concentrator. A smaller cavity opening would probably increase mirror-absorber efficiency at Mars due to a better balance between thermal reradiation losses and mirror efficiency. For example, a cavity opening of about 0.37 in., resulting in a mirror-absorber efficiency of about 79.4%, appears optimum for Mars operation.

The use of a flux trap other than the conical entrance on the cavity is not being considered because of the highly accurate surface obtained on the SET concentrator.

Table 4 Performance characteristics of prototype SET concentrators

Performance characteristics
Earth, measured
Mirror efficiency at $\frac{1}{2}$-in. aperture (energy collected by calorimeter divided by energy incident on 61-in. reflective surface, 82–85%
Mirror efficiency at 1-in. aperture, 85.5–88%
Geometric concentration ratio ($\frac{1}{2}$-in. cavity aperture), 14,884
Mars, estimated
Mirror efficiency at $\frac{1}{2}$-in. aperture, 87–90%
Mirror efficiency at 2-in. aperture, 87–90%
Estimated energy balance for 2000°K cavity operation at Mars
Total power incident on useful area of mirror (0.92 ft² is subtracted for generator support; solar constant = 44 w/ft²; diameter of useful reflecting surface = 61 in., 846.5 w
Loss due to radiation not entering cavity, negligible
Misorientation loss (±6 ft), negligible
Mirror reflectivity loss (90% reflectivity), −84 w
Blackbody radiation from cavity loss (2000°K—$\frac{1}{2}$-in. entrance diameter), −115 w
Cavity efficiency loss (deviation from ideal blackbody), −7 w
Net power retained by absorber, 640.5 w
Mirror-absorber efficiency, 75.9%
Estimated energy balance for 2000°K cavity operation at Earth
Total power incident on useful area of mirror (0.92 ft² is subtracted for generator support; solar constant = 130 w/ft²), 2492 w
Loss due to radiation not entering cavity, −125 w
Misorientation loss (±6 ft), −50 w
Mirror reflectivliy loss (90% reflectivity), −249 w
Blackbody radiation from cavity (2000°K; $\frac{1}{2}$-in. entrance diameter), −115 w
Cavity efficiency loss (deviation from ideal blackbody), −21 w
Net power retained by absorber, 1932 w
Mirror-absorber efficiency, 80.4%

Generator Developments

A total of three thermionic generators have been fabricated and tested. Only one has been tested in sunlight, whereas the other two have been tested in the laboratory using electron bombardment heating to simulate solar energy. The first two generators incorporated five cesium-vapor-filled thermionic converters, whereas the third generator incorporated only three converters.

A cutaway drawing of the 5-converter SET thermionic generator is shown in Fig. 4. The converters are incorporated into a hollow molybdenum support block in a cubical configuration; the sixth side contains the opening for solar radiation. The sides of the converters form a cavity that traps the solar radiation. The cavity entrance is a 120° angle cone cut into the molybdenum block. During space operation, the converters would be electrically connected in series. The maximum dimension of the generator is about 8 in. and weight is about 3.5 lb.

The second prototype of the SET I thermionic generator, designated JG-2, was tested using electron-bombardment heating. These tests were performed to verify satisfactory operation and to provide a means of equating the output of the generator as measured in the laboratory with that obtained using solar energy. The results of tests performed on JG-2

Table 5 SET generator JG-2, test data

Parameter	Total power input, w		
	800	900	1100
Total voltage output, v	2.75	2.80	2.90
Current output, amp	11.90	18.80	28.4
Power output, w	31.50	52.65	82.40
Efficiency, %	3.93	5.85	7.5
Molybdenum block temperature, °C	597	627	686
Cesium reservoir temperature (average), °C	350	359	386
Radiator temperature (average), °C	560	593	638
Power input to cesium reservoir (average), w	1.8	2.73	3.10

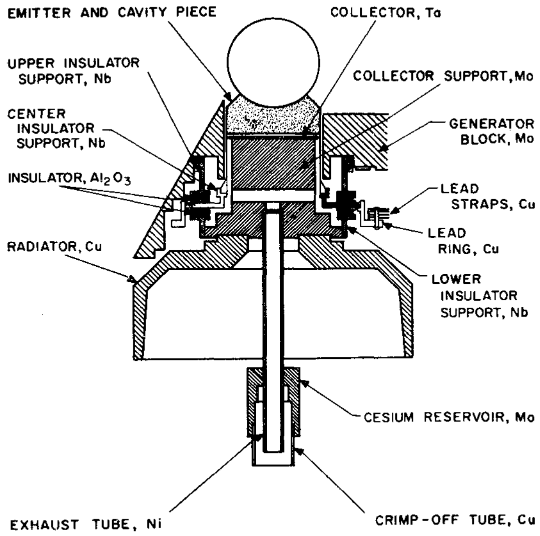

Fig. 5 SET converter, type A.

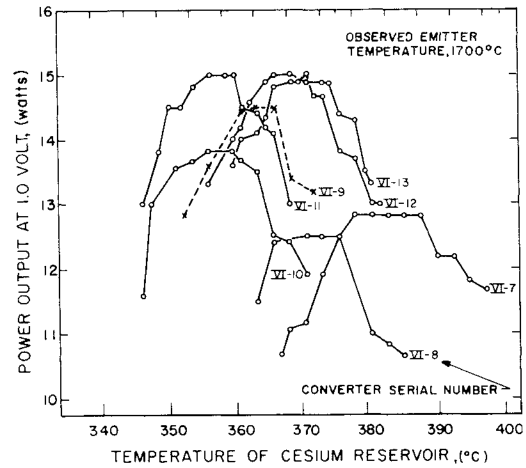

Fig. 7 Effect of cesium temperature on converter output, type A converter at 1 v.

are tabulated in Table 5. The most significant result was the measured conversion efficiency of 7.5%.

A cross section of the converter used in JG-2 is shown in Fig. 5. Typical curves of power as a function of voltage for the converter are shown in Fig. 6. Similar converters have operated at rated temperature for periods of time in excess of 3000 hr and have withstood repeated thermal cycling from room temperature to 1700°C. The effect of cesium reservoir temperature on output power for such converters is shown in Fig. 7. The observed emitter temperature refers to a micropyrometer measurement of the radiation from a four-to-one cylindrical hole located in the emitter structure; no corrections were made other than belljar losses.

Solar Test Results

During August and September 1962, SET generator JG-1 was installed in the SET solar test facility and tested for approximately 120 hr using solar radiation as the heat source. Tests were conducted at Pasadena and Table Mountain, Calif. During this time, considerable data were accumulated concerning performance of the generator with estimated solar power inputs to the generator cavity ranging up to about 1130 w; these data are given in Ref. 1. The performance of each individual converter was obtained along with the performance of a series circuit composed of four of these converters. Cesium reservoirs were optimized to obtain maximum performance within the limits dictated by converter thermal mass and auxiliary heaters. For solar test, the electrical leads for each of five converters were brought to the test console to allow either independent or series operation.

Solar Test Facility Description

The major components of the solar test facility are shown in Fig. 8. The concentrator is mounted on a tracking platform and suitable electronics and drive mechanisms are incorporated so that the platform automatically tracks the sun with an accuracy of better than $\frac{1}{2}$ min of arc.

In front of the concentrator is located a vacuum chamber in which the thermionic generator is placed during test. The chamber incorporates a vac-iron pump, hemispherical front window through which the radiation enters the cavity, and sufficient feedthroughs on the vacuum chamber wall for generator instrumentation. During the generator test, pressures in the range of 10^{-6} to 10^{-5} mm Hg are maintained at all test conditions.

A solar flux control, consisting of a louvered window with provision for adjusting blade position, screens the concentrator and automatically regulates the amount of energy entering the cavity.

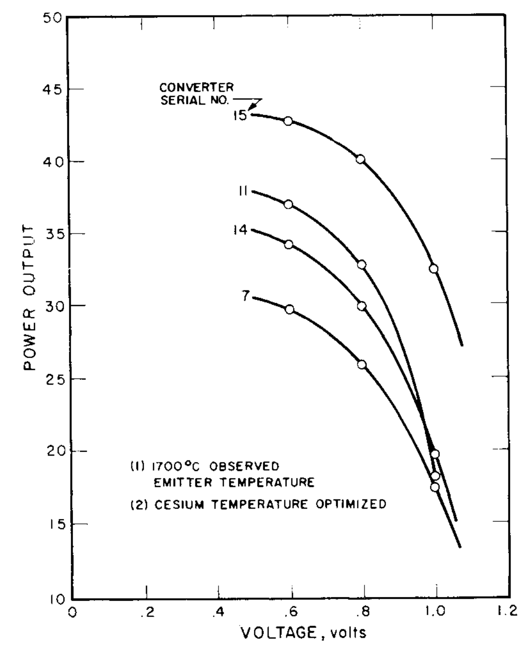

Fig. 6 SET converter output, four type A converters.

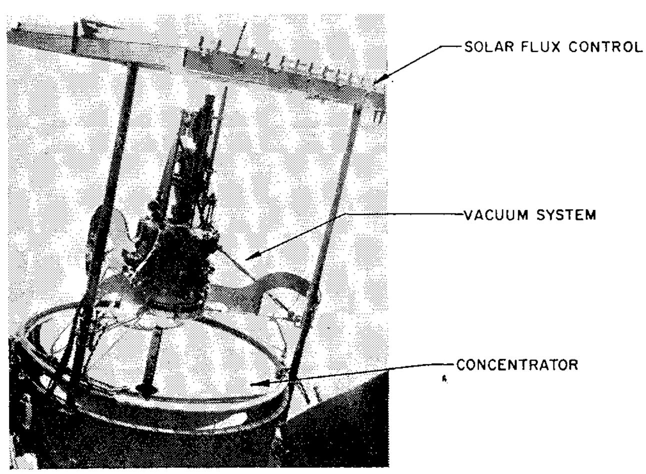

Fig. 8 Solar test facility for thermionic generator test.

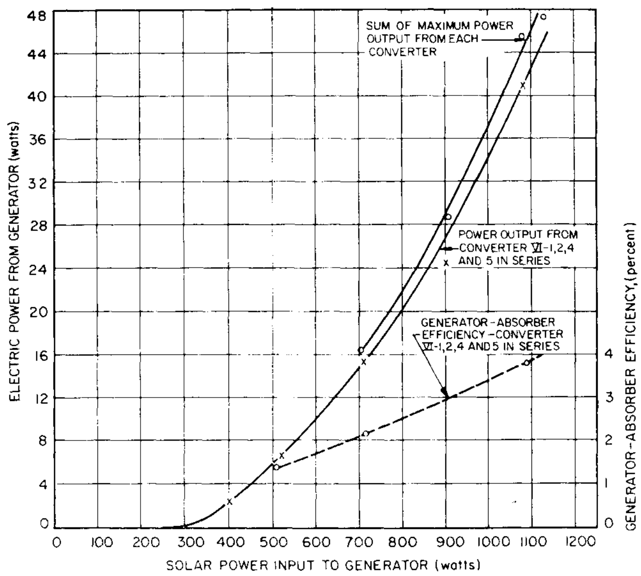

Fig. 9 Maximum power output obtained from generator JG-1.

For the JG-1 generator test, 16 thermocouples, 10 heaters, and the output from each of 5 converters was monitored. Five variable loads were used so that each converter could be operated independently while heated by solar radiation. A system of switches allowed any combination of parallel or series operation of two to five converters. Individual heaters (10) were used for the cesium reservoir and radiator heaters of each diode. A dynamic load circuit was also used to trace the current-voltage characteristics of the diodes.

Electrical Performance

The maximum electrical power obtained from generator JG-1 is shown in Fig. 9 with three curves. The upper curve shows the sum of the maximum power output from each converter as a function of the solar power into the generator cavity. At an input of 1080 solar w, the maximum power sum was 47.5 w. Some mismatch was evident between converters; furthermore, the rear converter (opposite the generator entrance) of the generator appeared to be significantly colder (less than 1 w output) and could not be placed efficiently in a series string with the four side converters. Consequently, for most tests, the rear converter was not placed in series with the four side converters. The next lower curve in Fig. 9 shows the power output when the four side converters (VI-1, -2, -4, and -5) in the generator were placed in series; a maximum of 41 w was obtained with 1080 w entering the cavity.

The generator-absorber efficiency corresponding to the series output of the generator is also shown in Fig. 9. Generator-absorber efficiency is defined as electrical power output divided by the solar power input to the generator cavity. At 1080 w input, a generator-absorber efficiency of about 3.8% was obtained. Combined with concentrator JM-1-2 mirror efficiency, an over-all system efficiency of 3.3% results.

Figure 9 indicates that system efficiency and power output would continue to increase as the solar power input to the generator increases. However, it is estimated that emitter temperatures of 1700° to 1800°C were obtained on several converters with 1100 w entering the generator. Furthermore, several seal temperatures were on the order of 600° to 700°C. Therefore, it is possible that further increase in solar power input could raise converter temperatures beyond tolerable limits.

Series Circuit Performance

Figure 10 shows the typical current-voltage characteristics obtained when the four converters were placed in series. The current-voltage characteristic is dependent on the cesium reservoir temperature. Thus, it is possible to obtain a higher series output power with lower solar power input with correct adjustment of cesium reservoir temperature. This is illustrated in Fig. 10, which shows that the series output power for 1080-w solar power input is higher than for 1128-w input over most of the voltage range. Data obtained during the solar test demonstrated many times that the individual current-voltage characteristics for each converter could be used to estimate the series current-voltage characteristic by simple addition of voltages at the same current level.

Misorientation Effects

The effect of misorientation on solar-thermionic power system performance is an important parameter in determining the usefulness of such a system for a space vehicle. If vehicle orientation must be maintained within extremely close tolerances, the weight of the attitude control system may become prohibitive.

For several days during the solar test of generator JG-1, data were accumulated regarding the effects of system misorientation with respect to the Earth-sun axis on the performance of both individual converters and a series circuit consisting of the four side converters. Misorientation angles of 5, 10, 15, and 20 min of arc in azimuth and elevation were investigated. Tests were conducted in most cases by deliberately misaligning the tracking sensor on the solar test facility a prescribed amount. This procedure enabled the generator to come to thermal equilibrium while in a given misoriented position.

The power output from a solar-thermionic system will generally decrease with misorientation for several reasons:

1) The total amount of energy entering the generator cavity will decrease, i.e., mirror efficiency will decrease. Consequently, the average amount of energy absorbed by each converter will tend to decrease with a resultant decrease in emitter temperature.

2) The distribution of energy within the cavity will change, i.e., one converter will have a higher emitter tempera-

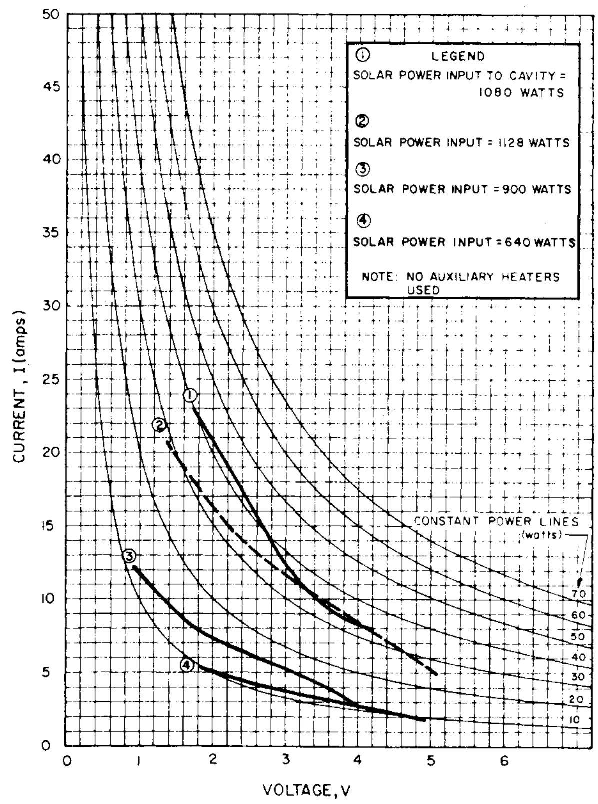

Fig. 10 Typical current-voltage characteristics obtained during solar test, converters VI-1,2,3,4,5 in series.

ture than another. Consequently, the match between converters will not be optimum and the resultant voltage from a series circuit will decrease.

3) The equilibrium temperatures within the converter will change. For example, the cesium reservoir and radiator temperature will be different and probably nonoptimum for the new emitter temperature.

It should be noted that the misorientation data discussed here refer to a system in equilibrium. Transient and temporary effects will also occur, for example, when a vehicle momentarily loses and then regains orientation.

Figure 11 contains a chart of typical power loss and voltage loss due to misorientation with the four side converters in the generator in series. For each case, 900 w were entering the cavity entrance. The optimum position was used as coordinate origin and not necessarily the beginning location for solar test. At 5 min of arc misorientation, relative power output ranges from 94 to 98%; at 10 min, 73 to 88%; at 15 min, 51 to 68%; and at 20 min, 30 to 49%.

The voltage drop is less precipitous as a function of misorientation; i.e., for one case, beginning with 4 v at optimum position, the voltage drops to 3.9 v at 5 min, 3.4 v at 10 min, 2.8 v at 15 min, and 2.2 v at 20 min. The contribution to power loss from current and voltage decreases seems about equivalent.

During misorientation, changes in the equilibrium temperature of each converter did occur. For example, the maximum change in reservoir temperature as misorientation ranged from 0 to 20 min of arc varied from 4° up to 17°C.

The seal temperature of the converter is relatively sensitive to the amount of heat absorbed by the emitter structure. Also, at the higher misorientation angles, the seal structure itself might begin to absorb some of the solar radiation of the outside edges of the focal image. During tests, seal temperatures showed wide variation in temperature as a function of misorientation.

Generator Warm-Up Characteristics

The rate of warm-up and cool-down of the generator as a function of power input is of interest to the systems designer. The time necessary to achieve power output after a shutdown can be of critical importance in satellite design.

Several times during solar test the generator was allowed to warm up and cool down by abruptly allowing a large amount of solar radiation to enter the cavity or abruptly cutting off the incoming radiation.

Figure 12 illustrates a typical thermal response of the four side converters (VI-1, -2, -4, -5) connected in a series circuit when solar radiation was abruptly cut off from the cavity and

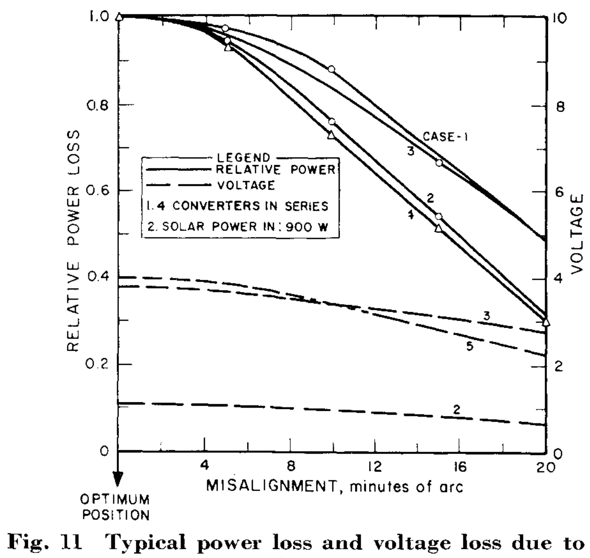

Fig. 11 Typical power loss and voltage loss due to misalignment.

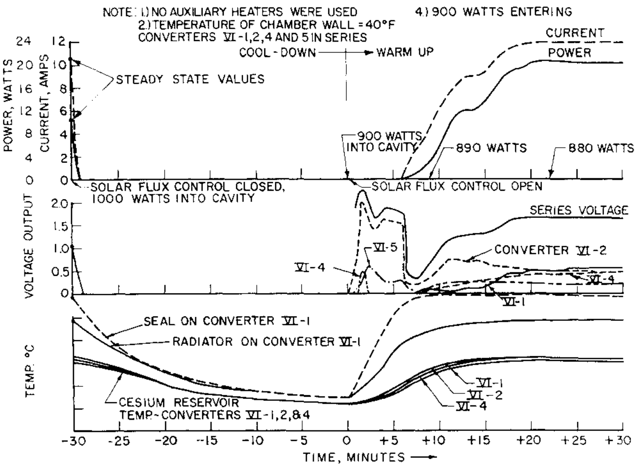

Fig. 12 Typical thermal response of generator JG-1.

then abruptly allowed to enter again. No auxiliary heaters were used during this test. Curves are given which show the output of the series circuit, voltage output of the series circuit and individual converters, cesium reservoir temperatures of converters VI-1, -2, and -4, and the seal and radiator temperatures of converter VI-1 as a function of time.

With 1000 w entering the cavity, the system was abruptly taken off track. As shown, power was completely lost within 1 min after shutdown. Generator temperatures began to come down, with an initial cool-down rate on the seal of converter VI-1 of about 75°C/min. After 30 min, an equilibrium temperature of 110°C on the cesium reservoirs and 145°C on the radiator and seal of converter VI-1 was obtained. Thirty minutes after shutdown, 900 w were allowed to enter the cavity by placing the test system on automatic track and allowing the solar flux control to open, consuming about 45 sec. Converter temperatures began to rise immediately, with a maximum warm-up rate on the seal of converter VI-1 of about 75°C/min. Converters VI-1 and VI-5 displayed voltage (but no current) almost immediately, whereas converter VI-4 took 1 min to display any voltage and converter VI-1 took 7 min. Converter VI-2 obtained a maximum open circuit voltage of 2 v about $1\frac{1}{2}$ min after start-up. Converters VI-2, VI-5, and VI-4 all indicate by their voltage characteristics that the spacing between emitter and collector may have changed in a damped oscillatory manner until current output from the series circuit was achieved.

Current from the generator was first observed about 6 min after start-up. Corresponding with the first indication of current, the voltage on converters VI-2 and VI-5 dropped precipitously. Current and power output from the series circuit steadily rose with some perturbations until steady-state output was achieved about 20 min after start-up.

Temperature equilibrium on the seal of converger VI-1 was achieved about 10 min after start-up, whereas the radiator on VI-1 and the cesium reservoirs of the converters took 20–25 min to reach equilibrium. It is probable that the time required to obtain full power from the generator is governed by the rate at which the cesium reservoirs can obtain operating temperature. The converters open up almost immediately after start-up, and the emitter structure probably reaches equilibrium temperature much faster than the reservoir or radiator structure as evidenced by the quicker warm-up of the seal region.

It is probable that auxiliary heating of the cesium reservoir would result in more rapid start-up characteristics for the entire generator.

Reference

[1] "Solar energy thermionic conversion system," Jet Propulsion Lab. Contract 950109, NASA Rept. 7-100 (November 15, 1962).