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Terrestrial Solar Thermionic Energy Conversion Systems Concept

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To operate thermionic converters using the sun as a primary source of energy, a concentration of insolation is required to achieve the energy density necessary to raise the emitter temperature to 1400°K. Both a parabolic mirror and a Fresnel lens have been investigated for providing a concentration ratio of 2000. A segment of the mirror, which is composed of nine individual mirrors (40cm x 40cm) has been successfully tested. For the reduction of fabrication cost, each mirror is bonded on a low cost substrate. Fresnel lenses, as large as 1140 cm^2 in area have also been tested. Although an optimum concentrator configuration has not been

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

The contents of this Technical Memorandum were presented at the 1975 Thermionic Conversion Specialists Meeting on September 3, 1975, at the Eindhoven University of Technology, Eindhoven, Netherlands, and is included in the Conference Proceedings of that meeting.

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ABSTRACT

Solar thermionic conversion was considered nearly a decade ago for space applications. The solar thermionic technology, which had been developed at that time, has recently been reexamined for potential applications to terrestrial solar power systems. In this paper, unique features and characteristics of solar thermionic power systems will be presented. Those features include high system efficiency, 20 percent with advanced converters, and the potential of operating additional thermal conversion systems utilizing rejected heat from the thermionic system (solar thermionic topping system). Analyses shows that an overall efficiency of approximately 40 percent can be achieved with a topping system.

To operate thermionic converters using the sun as a primary source of energy, a concentration of insolation is required to achieve the energy density necessary to raise the emitter temperature to 1400°K. Both a parabolic mirror and a Fresnel lens have been investigated for providing a concentration ratio of 2000. A segment of the mirror, which is composed of nine individual mirrors (40cm x 40cm) has been successfully tested. For the reduction of fabrication cost, each mirror is bonded on a low cost substrate. Fresnel lenses, as large as 1140 cm^2 in area have also been tested. Although an optimum concentrator configuration has not been defined, a Cassegranian mirror or a "Fresnel mirror", having flat geometry, is also being considered as a possibility.

This paper describes the results obtained from the studies of the (1) solar concentrator, (2) solar energy receiver - thermionic converter system, and (3) solar thermionic topping system. Peripheral subsystems, which are required for any solar energy conversion system, will also be discussed.

I. INTRODUCTION

With the increase in demand for terrestrial power, capabilities of thermionic energy conversion have been reexamined during the last year, to arrive at a viable terrestrial solar thermionic conversion concept.

During the recent years, applications of thermionic energy converters to fossil fuel power systems and to solar power systems have been investigated. Because of the different characteristics of these primary energy sources, there are differences in the thermionic converter configurations and potential system designs depending upon the applications. However, there are requirements which are common with converters to be used in these systems. They are (1) high conversion efficiency, (2) low operating temperatures, (3) oxidation resistance and (4) low cost. Research efforts are currently in progress to develop such converters at various research organizations. Since these advanced converters can operate at lower emitter temperatures (1400°K), an operation of these converters with solar concentrators having a moderate concentration ratio (2000) is feasible for power generation. This paper describes a solar thermionic power system concept which has been investigated to determine its feasibility for terrestrial applications. The approaches taken, the utilization of advanced converters together with a solar concentrator, as well as the advantages and disadvantages will also be presented.

II. SOLAR THERMIONIC SYSTEMS CONCEPT

The basic solar thermionic system concept consists of a thermionic converter array and a solar concentrator. A block diagram of a complete solar thermionic power system is shown in Figure 1. The thermionic converter array is located near the focal point of the solar concentrator as shown in Figure 2. The converter array is enclosed by a thermal insulator (thermionic receiver/module) and backed by a cooling system for removing excess heat from the converter array. An example solar concentrator consists of a 93 m^2 mirror, with a concentration ratio of 2000 for producing a solar energy output of 57 kWt* at a mirror efficiency of 72%. The concentrated energy

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*Solar intensity = 0.085 Wt/cm^2.

will heat the emitter electrodes of thermionic converters at 1400°K with each converter operating at an assumed peak efficiency of approximately 29%, as shown in Table 1. On this basis, the electrical power output from the converter array will be about 16 kWe. The thermionic receiver/module shown on Figures 3 and 4 has an opening area of 0.0465 m^2 and a heat receiving area of 0.182 m^2, of which an area of 0.145 m^2 is occupied by the heat receiving sides of the thermionic emitter. In this design, a mirror concentration ratio of 2000 (= 93/0.0465) and a converter packing factor of 0.8 (= .145/.182) is assumed. If one further assumes that each converter in the array produces 89 We of peak power at an output voltage of 0.7 V (details of the converter technology are discussed in Section III), 180 converters are required in this array. As an example, the 180 converters may be connected to form a 9-parallel connection of series strings of 20 converters each. This connection will result in a net output voltage of 14 V at an output current of 1143 A. The output thus obtained will be further processed for usage by the consumer. An interface unit will be required for matching the voltage, frequency and the phase to tie into an existing commercial electrical power distribution system. On the other hand, if the raw power produced by the thermionic module is stored first in appropriate energy storage devices, a different type of interface unit will be required.

An alternate concept, which has been considered, consists of a Fresnel lens of a relatively small size per unit (≈ 1 m in diameter) and a single thermionic converter per unit. In this concept, the usable thermal power per converter will be 534 Wt assuming the collection efficiency of the lens to be 80%. Therefore, an electric power output from a single converter, which is located at the focal point of the lens, will be 155 We provided that the converter efficiency is 29%. In this concept, 103 similar units will be required to produce the same electric power output (16 kWe) with one 93 m^2 solar concentrator. For small power systems, e.g. 1 to 5 kWe, it appears that the lens concept may be more desirable than a mirror concept.

III. SUBSYSTEM TECHNOLOGY

Thermionic Converter Technology

The investigation of solar thermionic conversion dates back to the 1960's[1]. These early efforts focused exclusively on thermionic power systems for space applications and concentrated on high temperature (emitter temperature = 2000°K) thermionic converters. The development of a solar thermionic power system did not result in flight hardware because of the advancement of solar photovoltaic systems. However, the technologies that are essential to thermionic converters were advanced greatly in the course of these investigations. An output power density larger than 15 W per square centimeter of electrode area was achieved[2] at an output voltage of 0.7 V with a converter operating at an emitter temperature of 2000°K. The efficiency calculated from the converter performance was approximately 12%. Subsequently a solar thermionic converter module, which consisted of multiple converters surrounding a thermal cavity, was fabricated and tested with a solar concentrator at JPL. For space applications, converters were radiation cooled. Because of the requirement to operate at high temperatures, basic electrode materials were refractory metals.

For applications to terrestrial solar power generation, use of oxidation resistant materials that can stand relatively high temperatures is desirable. Moreover, to operate solar thermionic converters in an oxidizing atmosphere, a reduction of operating temperature also becomes necessary. There is an additional advantage for operating at low temperatures, i.e. an increase of the conversion efficiency can be achieved as shown in Table 1.

To improve the converter performance at a reduced emitter temperature (≈1400°K) so that the conversion efficiency is approximately 29%, both the collector work function and the plasma loss have to be reduced. The collector work function can be reduced by making use of a semiconductor electrode or by further developing a metal-oxygen-cesium electrode system. A semiconductor electrode has already shown its ability to achieve low work functions for photo emission electrodes[3] which operate at room temperatures. On the other hand, metal-oxygen-cesium system can operate at temperatures higher than room temperature, however, the work function has never been as low as what was achieved by semiconductor electrode systems.

For the thermionic converter to operate at low temperatures without losing power output, the emitter work function must be reduced to a value, e.g., 2 eV, from a value of 3 eV, typical with high temperature converters. This reduction reflects directly on the output voltage in an adverse manner unless collector work functions can also be reduced. In our laboratory, silicon (100) was selected as a first candidate to produce such a work function. This selection was based upon (1) its proven[4] work function (as a photo emitter) of 0.9 eV and (2) its ability to stand reasonably high temperature (420°C). The investigation of this electrode is being pursued further in both a simulated converter and a LEED/Auger device. The objectives are to (1) demonstrate the feasibility of achieving a low work function in an environment similar to that of a thermionic converter and (2) determine the work function as a thermionic electron collector. The LEED/Auger device is used to determine critical parameters that are required to produce low work functions. In a simulated thermionic converter, the silicon (100) sample was thermally diffusion-bonded on a molybdenum substrate so that the combination simulates a thermionic collector and can be heated to high temperatures (1100°C) for cleaning and annealing purposes. In this test vehicle, a work function minimum of 1.1 eV was achieved with an n-type silicon which was argon sputter-cleaned and cesiated prior to oxygenation. This work function was determined from a threshold wavelength for photo emission. On the other hand, a work function estimated from the thermionic collection was in the neighborhood of 1.5 eV. Although it is not fully understood, this discrepancy is believed to be caused by a back emission (photo emission plus thermionic emission) from this low work function collector producing a space charge sheath adjacent to the collector. Further investigation is being planned at a larger value of collected current in comparison with the back emission current. Although the collector temperature was only 100°C during the above measurements, it is expected that an appropriate amount of cesium arrivals in a practical converter will replenish the desorbing cesium so that a low work function condition can be maintained at elevated temperatures. The stability of the low work function surface is yet to be determined, however.

Among various methods considered for reducing plasma losses, our laboratory is pursuing an introduction of molecular nitrogen gas as a primary scheme for investigation. The intent is to increase the lifetime of excited cesium using an energy exchange between cesium and nitrogen molecules in a higher vibrational state. Until fundamental studies are completed on the effect of molecular nitrogen, which is being investigated at the State University of New York (SUNY), experiments with an actual converter will not be started at our laboratory. Preliminary results obtained at SUNY are encouraging.

The combined effects of reduced collector work functions and plasma losses are tabulated to show the improvement of the converter efficiency in Table 1. This table shows that a barrier index (sum of the collector work function and the plasma loss) should be 1.2 eV to achieve a conversion efficiency of 29%. An explanation of achieving this conversion efficiency follows.

To produce a substantial amount of electric power from thermionic converters by utilizing the sun as a primary source of energy, the emitter electrode of a thermionic converter has to be heated to a temperature of approximately 1400°K. This temperature value was determined so as to achieve maximum power output and conversion efficiency from a converter having an emitter electrode bare work function ϕ_{EO} of 5.0 eV and a cesium reservoir temperature of 500°K. For simplicity of calculation, the output current density is assumed equal to that of the saturated emission which is determined at a given temperature of the emitter electrodes; and the output voltage is equal to the difference between the emitter work function and the barrier index, which is the sum of the collector work function and the plasma drop. The results are plotted in Figure 5, which shows the near maximum power output of 11.6 W/cm^2 at 1400°K for the barrier index of 1.2 eV.

Conversion efficiency η of the thermionic converter is calculated from,

$$\eta = \frac{J_o \, (\phi_E - \phi_C - eV_B)}{\left[J_o \, (\phi_E + 2kT_E) + P_{rad}\right] \times 1.1}$$

where P_{rad} is the thermal power density radiated from the emitter at temperature T_E to the collector. The multiplying factor 1.1 was used to account for an additional input power required for cesium gas conduction and heat conduction through supporting structures. The efficiency of a practical converter will be further reduced, by a factor of approximately 0.9, because of an ohmic loss through the emitter support.

For a converter which is optimized to operate at a temperature of 1400°K ($\phi_{EO} = 5.0$ eV assumed) the maximum conversion efficiency is 29% (Fig. 5). Here the P_{rad} is assumed equal to the total emissive power density from tungsten at $T_E = 1400$°K, and the barrier index V_B ($V_B = \phi_C + eV_P$) is assumed to be 1.2 eV.

For this converter, the required power input density is 40 W/cm^2 at an output power density of 11 W/cm^2. Therefore, an energy concentration factor of 470.6 is required for a solar concentrator since the solar energy density at terrestrial condition is typically 0.085 W/cm^2. To achieve the required concentration ratio, a parabolic mirror and a lens have been selected for consideration over a flat or cylindrical concentrator. For a practical concentrator, a nominal concentration ratio (mirror area/ aperture area) of 2000 was selected to allow for mirror losses, pointing errors and fabrication ease. Further discussion of the concentrator will be given in a following section.

Thermionic Receiver/Module

A baseline design of a thermionic receiver/module (shown in Figure 3) has an energy receiving area of 0.182 m^2 on which 180 converters are mounted at a packing density of 80%. Converters are cooled by a cooling channel via a liquid metal loop or an organic liquid which is electrically insulated (e.g. by cermets). Converters that are electrically insulated at emitters and collectors will be connected to form a matrix of 20 in series and 9 in parallel. Assuming that each converter produces 0.7 V of output voltage at 135 A, the output voltage and the current of the module will be 14 V and 1143 A, respectively. Since the packing density is 80%, the remaining 20% should be preferably used to channel the received solar energy to converters but not to the converter support structure, which has to be kept at a low temperature close to that of the collector. The converter array will be located at the bottom of a conical cavity in which solar energy is introduced through an opening of 0.465 m^2. To reduce thermal losses, the cavity and the rim of the cone will be thermally insulated by a high temperature insulator. The protective collar which is required to protect it would be exposed to concentrated solar flux in case of a misalignment caused by a tracking error.

Solar Concentrator Technology

A solar concentrator may be considered as any structure that concentrates energy in the range of the solar spectrum. In the practical aspects, solar concentrators must provide an efficient method for making heat available to an external conversion system with a reasonably low heat loss and at a configuration suitable for the required temperature. Most concentrator systems that meet these requirements can be separated into two main categories; (1) flat plates including all types of panels and roof absorbers[5] and (2) concentrators which include troughs, paraboloids, multiple reflectors, lenses, Fresnel reflectors, etc. The type of a concentrator depends on the output temperature required. Higher temperatures require solar concentration; however, the higher the concentration, the more complex the system. Increased complexity is the result of the need for improved tracking accuracy, closer tolerances, and improved materials to achieve higher output temperatures.

As stated previously, the temperature of interest required for the operation of the thermionic converter is 1400°K. The results of an evaluation of several solar concentrator concepts for this application have shown that the three dimensional parabolic concentrator or a Fresnel lens is suitable for specific concentration ratio requirements. For this concept, the concentration ratio is defined as the projected area of the concentrator divided by the area of the aperture (Fig. 6). The energy collection efficiency of the parabolic concentrator vs. temperature for various concentration ratios is shown on Figure 7. The concentration efficiency is calculated assuming that (1) 15% is lost by the absorption in and the reflection at the mirror and (2) an additional energy is lost from the opening via black body radiation. Figure 7 shows that the predicted collection efficiency is approximately 72% at the collection temperature of approximately 1400°K.

To achieve this efficiency and a temperature of 1400°K, it is mandatory that the combined tracking and mirror figure errors (the angle deviation on the mirror surface from the theoretically perfect shape of the surface), be 0.2 degree or less. Figure 8 shows the allowable tracking and figure errors to acquire a desired concentration ratio. A concentration ratio of approximately 13000 may be acquired if perfect or zero tracking and figure errors were achieved with this concentrator.

The investigation of a cost effective approach for mass production of a parabolic concentrator has been conducted. One of these approaches is to fabricate a mirror on an advanced substrate (40 cm x 40 cm).

Early test results of a mirror utilizing an advanced substrate showed improved physical characteristics that are less than the allowable 0.1 degree figure error. In addition, calorimeter tests have been performed. Figure 9 shows the test setup which included 9 advanced substrate mirrors installed on an existing tracker system. The total panel area is 1.42 m^2. A pyrheliometer (tube) located to the right of the panels was used to measure the solar insolation. This data was recorded in a computer readout unit located below the pyrheliometer. A calorimeter was located at the focal point, 6.6 m from the panels. Another approach, as shown on Figure 10, is to epoxy bond a glass mirror on a stretch-formed aluminum substrate (90 cm x 90 cm). The optimum size and shape of each mirror has not been determined as yet. However, at the present time, evaluation and testing of various substrate and glass thickness combinations are being conducted. Early tests of a mirror that is epoxy bonded on the stretch-formed aluminum substrate (2.1 mm thick) showed a figure error greater than the allowable 0.1 degrees. Indications are that the figure error determined was due to the mismatch of the coefficient of expansion of glass with that of aluminum.

The calorimeter test results are summarized in Table 2 and show an efficiency of 81 percent. The results are in good agreement with the predictions shown in Figure 7 at low receiver temperatures.

The Fresnel concentrator is another concept that is also being investigated for solar thermionic applications. However, since each Fresnel lens cannot, according to current technology, be made for an area larger than 1 m^2, it is envisioned that each Fresnel lens will operate with a single thermionic converter as shown in Figure 11. Thus, the overall system will be considerably different from that of a parabolic concentrator arrangement in that the electrical power output per lens and the converter combination will be considerably smaller (a factor of 100) than the electrical output of the parabolic concentrator arrangement. The present state of the art in fabrication of plastic Fresnel optics offers a good candidate for low cost solar energy collection for small power systems. A Fresnel lens is made by molding prismatic grooves on one surface of a thin plastic sheet as shown in Figure 12. The slope of each groove is designed to provide the desired geometrical characteristics for the complete lens.

Early test results of a Fresnel lens with an area of 1140 cm^2, not designed specifically for this application, are summarized in Table 3. At the conditions shown, a collection efficiency of 61% was obtained. Note that this lens, which did not have the required optical characteristics, was used because of its immediate availability for the present testing.

If the lens were optically perfect, the collection efficiency would have been better than 85% according to the manufacturer's estimate in which the only losses considered were the reflection and transmission losses, and the actual energy available at the focal spot would become comparable to that of the parabolic mirror.

Additional Systems Components

In addition to the basic solar concentrator and thermionic receiver module, there are components such as the tracking and pedestal unit, power processing elements and energy storage devices. For the tracking unit, the present tracking and pedestal technology is similar to that of the Deep Space Network (DSN)[6]. Tracking antenna technology was considered as a starting point for adoption to a solar concentrator. Tracking accuracies of the DSN antennas are more stringent than those required for solar thermionic concentrator tracking. Several configurations using the above technology have been investigated. These included an azimuth-elevation mount with the concentration backup structure suited for the mirror panels described previously. Another approach uses the same basic structure, but is installed on an equatorial mount with no declination counterweight. The declination bearings are closely coupled to the concentrator and are supported by a wide tubular yoke structure, which is supported by a polar bearing and polar wheel. A third approach uses a conventional lightweight truss type structure on an equatorial mount. The primary structures are thin-wall light tubular trusses, four fly counterweights which balance both the coincidental declination and hour angle axles, and a lightweight tilted tubular tower support structure.

Because of the low voltage (14 to 28 vdc) and high current output of the solar thermionic power system, methods must be provided to make this output more acceptable by the user. One approach studied consists of utilizing voltage boost circuitry with each solar thermionic unit connected in parallel with a centralized line commutated inverter. In this concept, higher input voltages are required for high efficiency (≈95% at full load) operation of the inverters. A typical inverter output voltage would be 277/480 Vac, 4 wire, 3 phase, 60 Hz, with a power output of 1/2 to 1 MWe depending on the number of solar thermionic units to be employed. Transformation to even higher voltages will be required for a long distance power transmission. The power processing elements which consist of solid state devices of present day technology[7,8] can be utilized for individual modules or large power plants.

As in the case with all solar systems, energy storage is required for "flattening" energy variations of the solar insolation. Candidate devices include lithium sulfur batteries, fuel cells etc.[9,10,11]. The final selection of these components depends on plant size, costs etc. In particular for the application of fuel cells, the inherent low voltage high current characteristics of thermionics lends itself to providing power to an electrolysis plant for the on-site generation of hydrogen which may be used as the fuel cell reactant. Several types of fuel cells are being developed, at the present time, for terrestrial applications. For example, the hydrocarbon fuel cell developed jointly by United Technologies (Pratt & Whitney) and the gas utility industry may lend itself to this type of application since hydrocarbon fuels are reformed to a hydrogen output. Lithium sulfur batteries are also being developed for bulk energy storage on electrical utility networks. Their use is envisioned as a peaking device when a maximum energy demand exists.

Solar Thermionic Topping Concept

As was indicated in the basic concept, the rejection of excess energy occurs at a temperature (700°K ≈ 430°C) which is effectively usable in operating additional heat engines, thus forming a thermionic topping system (Fig. 13). An advantage of such a topping system is that it can increase the overall system efficiency. Since the total power output P_o of a topping system is

$$P_o = \left[P_i \, \eta_c + P_i(1 - \eta_c) \, \eta_h\right] \eta_s$$

where P_i is the input power available from the sun, η_c is the conversion efficiency of the thermionic converter, η_h is the efficiency of the heat engine, and η_s is the solar concentrator efficiency. Therefore an overall efficiency η_o is given by

$$\eta_o = \left[\eta_c + (1 - \eta_c) \, \eta_h\right] \eta_s = \left[\eta_c \, (1 - \eta_h) + \eta_h\right] \eta_s$$

As it can be seen in Fig. 14, an overall efficiency of the topping system with $\eta_h = 0.4$, $\eta_c = 0.3$ and $\eta_s = 1.0$, as an example, is 0.58. The resulting gain in the overall efficiency is 43% over a system which does not have the thermionic topping cycle. Since losses in a solar concentrator are unavoidable and since η_s equals 0.72 for a concentrator having a concentration ratio of 2000, the practical conversion efficiency will become 41%. This efficiency is still considerably larger than what is obtainable from a solar thermal engine system which would result in an overall efficiency of about 29% (= .72 x .40 x 100). Note, a sharing of the output power between the thermionic system and the thermal system varies depending on the efficiency of each system. For example, the output power will be equally shared by two systems if $\eta_c = .29$ and $\eta_h = 0.4$ and an increased amount of power is produced by a thermionic system if $\eta_c > .29$ and vice versa.

Candidate thermal systems include organic Rankine, steam turbine and Stirling cycles[12,13] with appropriate heat exchangers. A choice of a thermal system has to be made by considering its compatibility with a thermionic system, system efficiency, and cost effectiveness. In any event, a thermionic topping system can offer higher conversion efficiency than what is available from an individual system. One obvious advantage of high conversion efficiency is that an area required for the collection of solar energy can be considerably small. For example, an area of 93 m^2 at 350 W/m^2 of incident energy will produce 32 kWe of combined electric power using the above topping system with a solar concentrator efficiency of 72%.

A complete solar thermionic topping system will be composed of not only a solar concentrator, a thermionic power system, and a heat engine, but also a concentrator tracking system, energy storage system, and a power processing system for consumer use.

IV. CONCLUSION

A feasibility study of terrestrial solar thermionic energy conversion systems indicated that such systems can efficiently convert solar energy to electrical energy. A topping system, consisting of a basic solar thermionic power system and a thermal power converter system would have an efficiency as high as 40 percent. The development of components, which are essential in the system, has progressed in thermionic converters and solar concentrators. The test results of these components indicate that further development is required to demonstrate the feasibility. Moreover, it was found that a considerable amount of work is required to arrive at an optimum system configuration and a cost estimate. A cost goal of the order of a few hundred dollars per kW would be attainable when the component technology matures and the system is fully optimized.

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Table 1. Performance Comparison of High and Low Temperature Thermionic Converter

VARIABLES		HIGH TEMP CONV	LOW TEMP CONV	
			ADVANCED	IDEAL
T_E	(°K)	2000	1400	1400
T_C	(°K)	1000	700	700
T_{CS}	(°K)	600	400	400
ϕ_E	(V)	3.0	2.0	2.0
ϕ_C	(V)	1.7	1.0	1.0
V_P	(V)	0.6	0.2	0
V_O	(V)	0.7	0.8	1.0
I_O	(A/CM^2)	12	14	14
P_{OUT}	(W/CM^2)	8.4	11	14
P_{IN}	(W/CM^2)	70	40	40
η	(%)	12	29	35

Table 2. Solar Concentrator Calorimeter Test Results

Total Area (9 Panels):	1.42 m^2
Energy Input Density:	856 W/m^2
Energy Input:	1215 W
Efficiency:	81%

Table 3. Fresnel Lens Test Results

Lens Area	1140 cm^2
Pyroheliometer	60.8 W (Clear Sky)
Power Collected	37.1 W
Collection Efficiency	61%

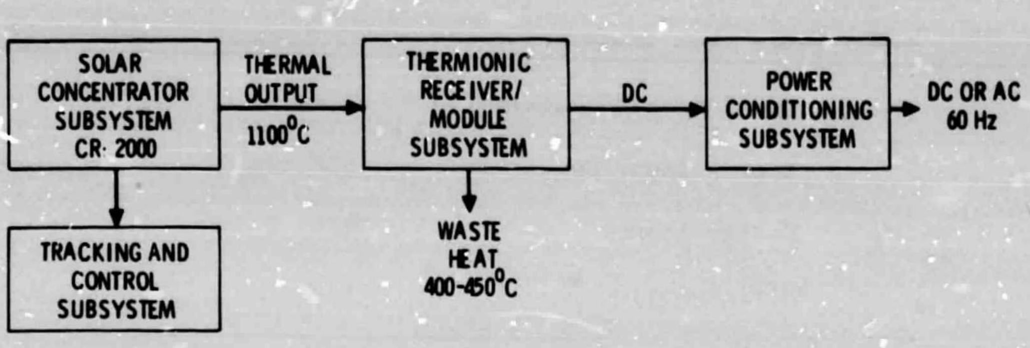

Fig. 1. Block Diagram — Basic Solar Thermionic Power System

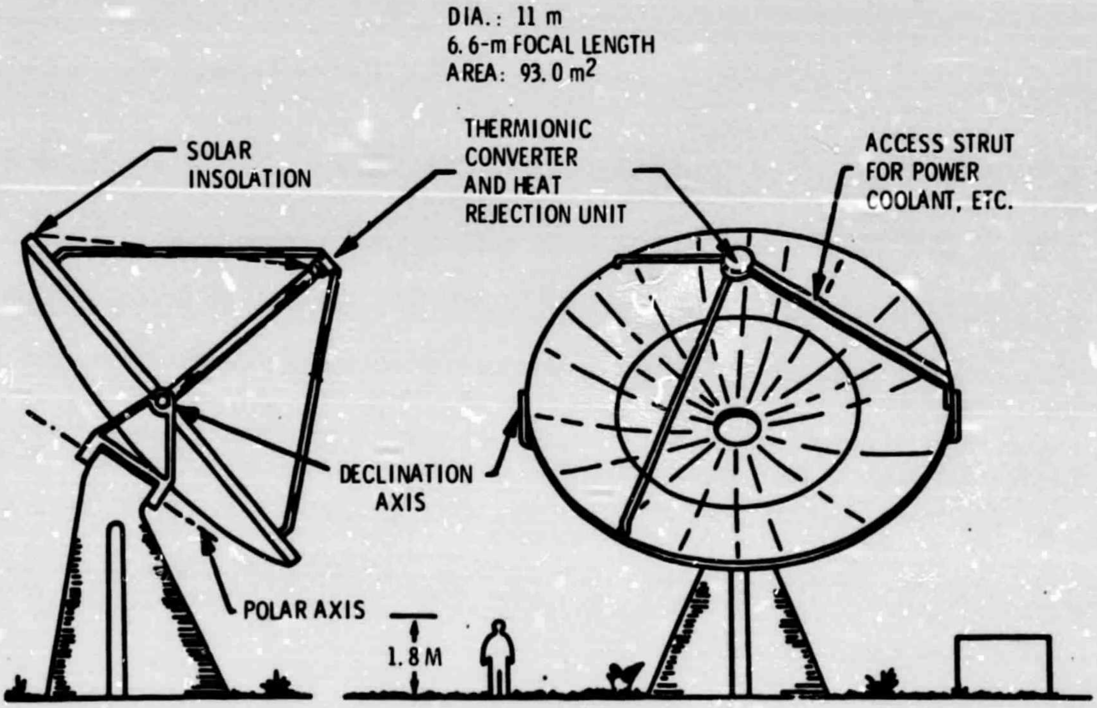

Fig. 2. A Solar Thermionic Power System Configuration

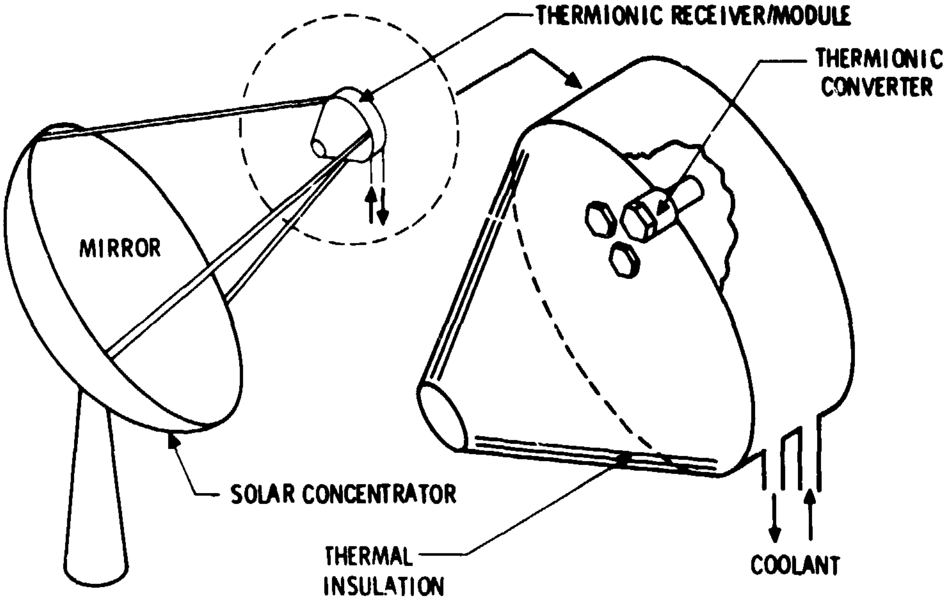

Fig. 3. Solar Thermionic Power System Schematic

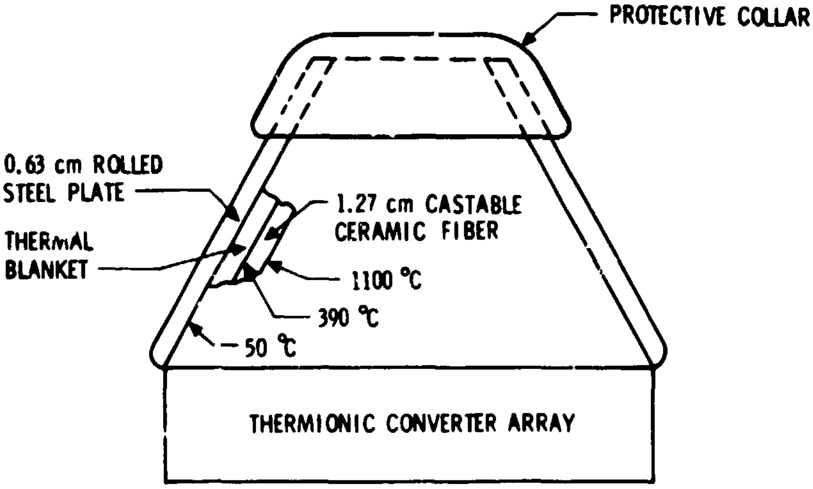

Fig. 4. Solar Thermionic Receiver/Module Enclosure

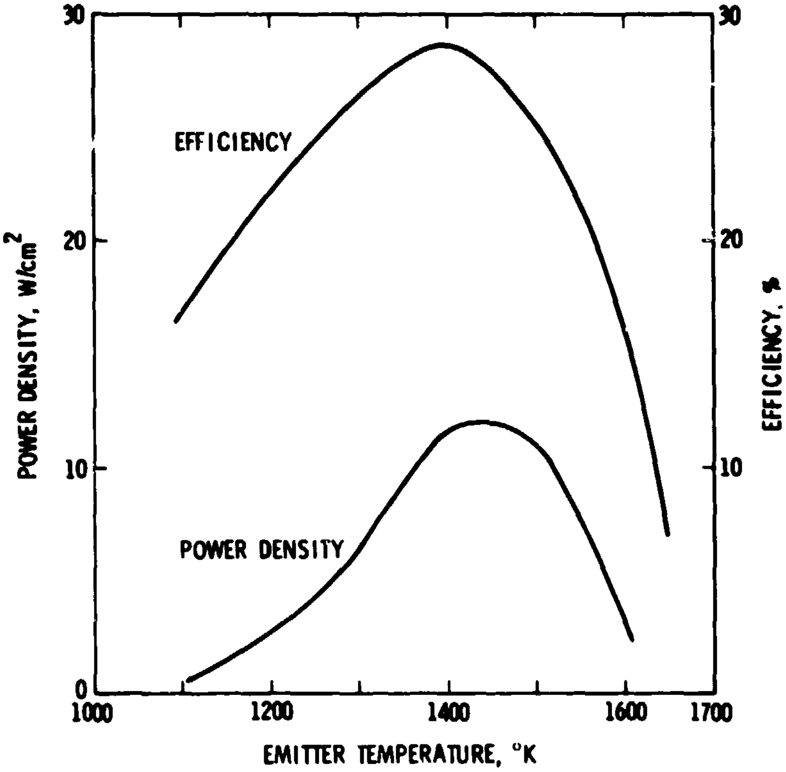

Fig. 5. Output Power Density and Conversion Efficiency vs. Emitter Temperature for a Converter

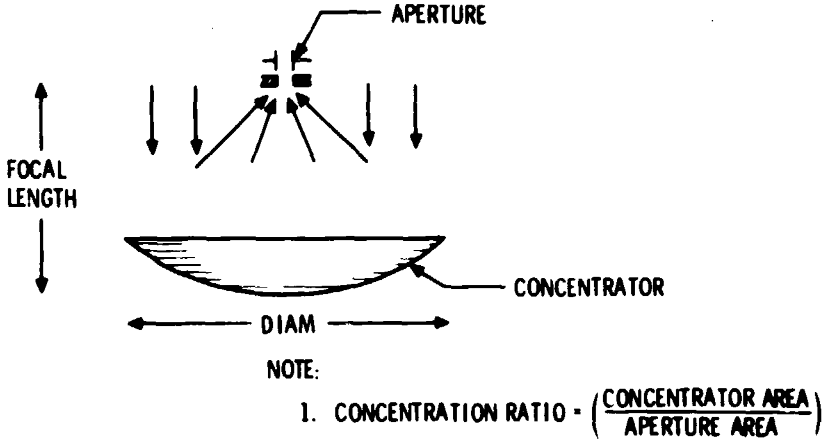

Fig. 6. Solar Concentration Parameter Definition

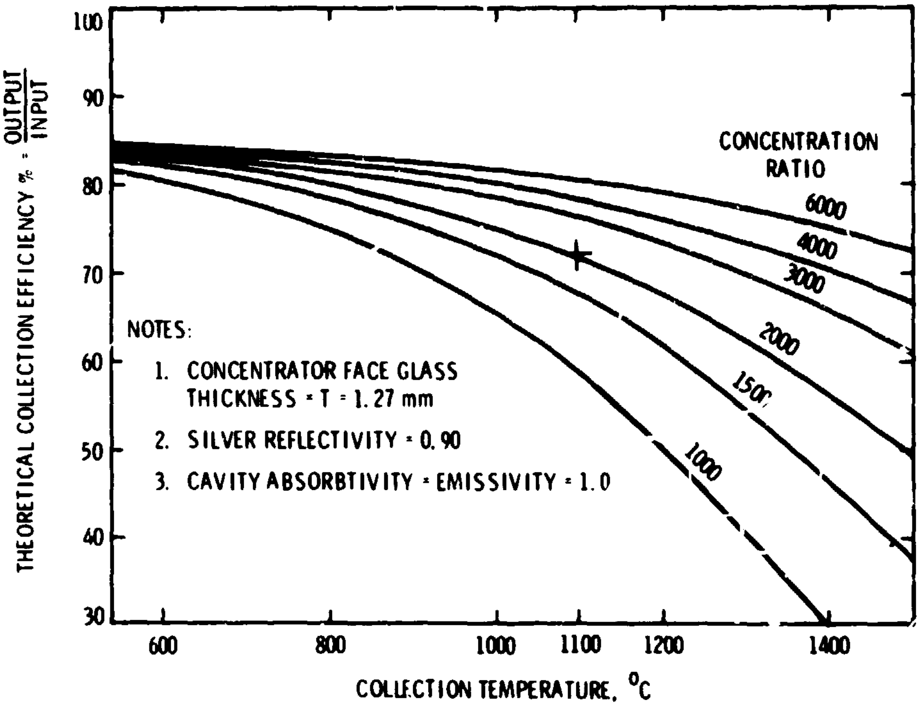

Fig. 7. Theoretical Collection Efficiency vs Collection Temperature

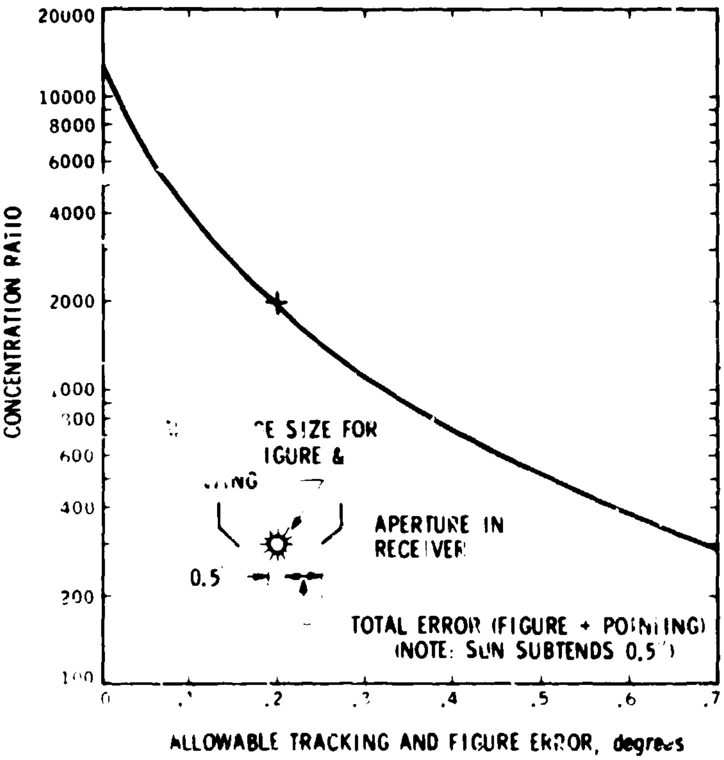

Fig. 8. Concentration Ratio vs. Allowable Tracking and Figure Errors

Fig. 9. Solar Concentrator Test Setup

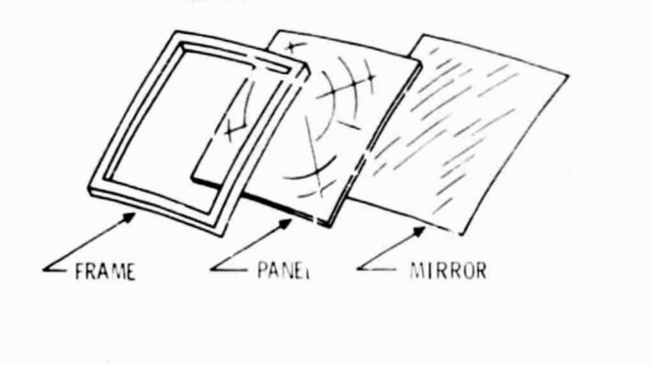

Fig. 10. Schematic of Mirror on Stretch-Formed Aluminum Substrate

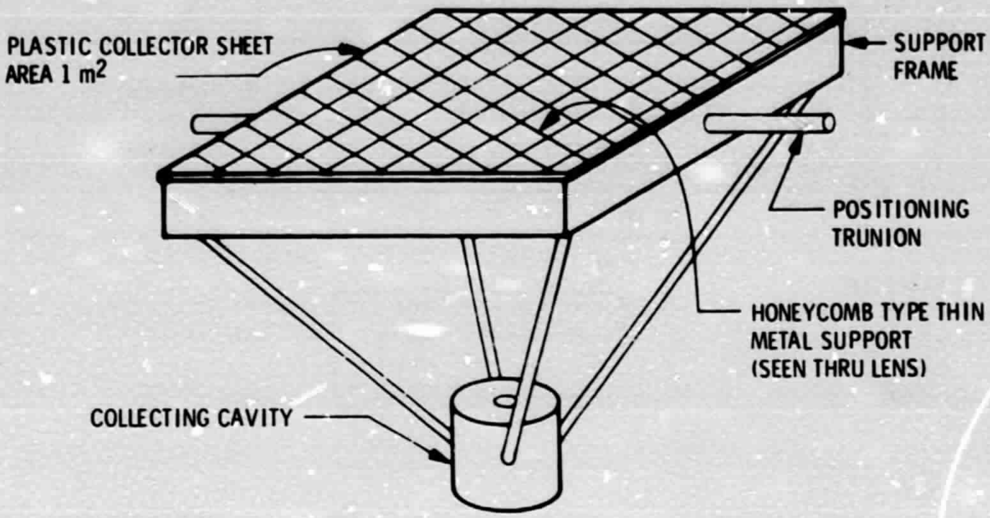

Fig. 11. A Fresnel Solar Concentrator Configuration

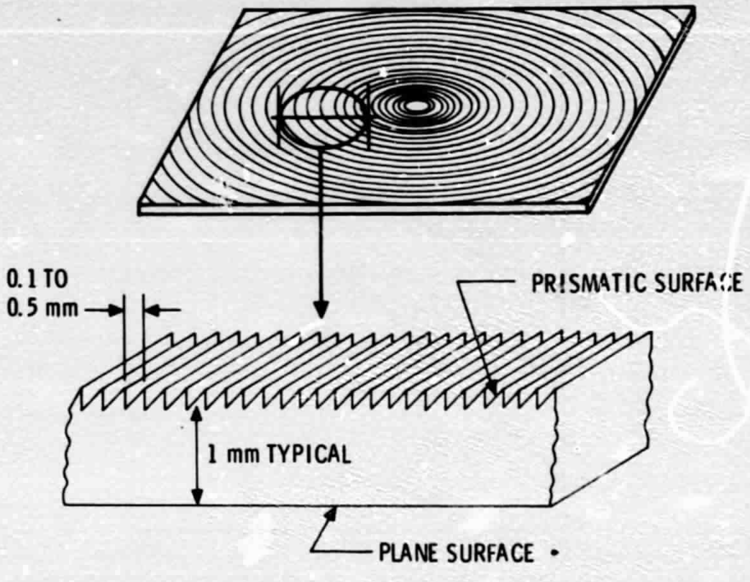

Fig. 12. Fresnel Lens

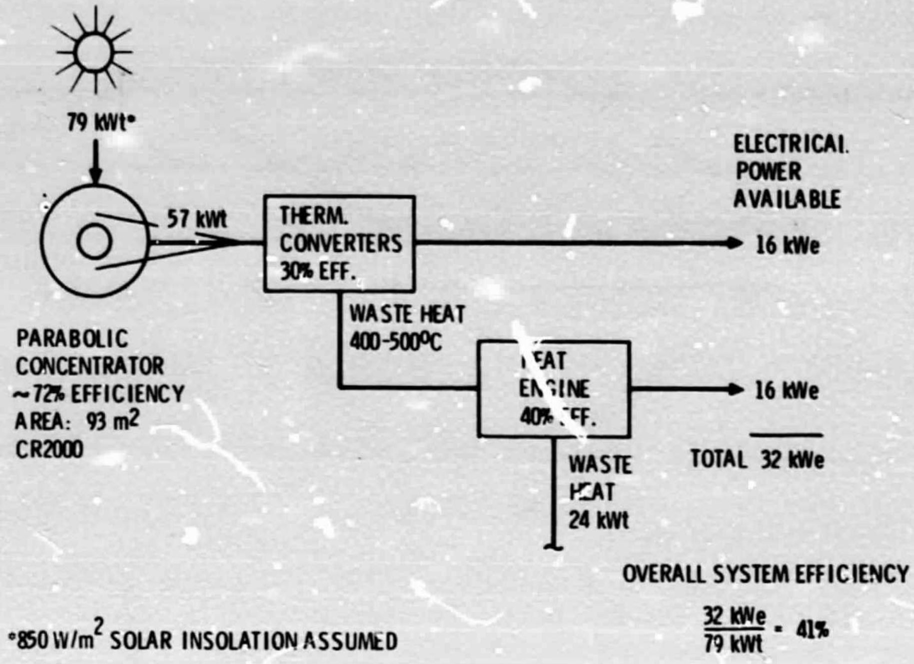

Fig. 13. Thermionic Topping Concept

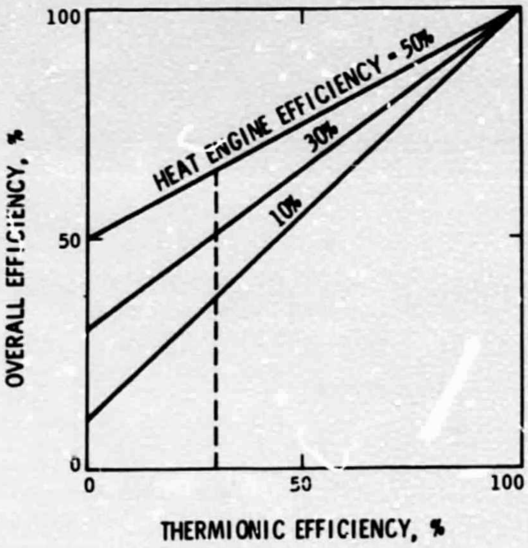

Fig. 14. Overall Efficiency of a Solar Thermionic Topping System

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