The theoretical application of vacuum and vapor type thermionic converters for a space power supply utilizing solar power is discussed. The characteristics of presently available, commercially produced vacuum thermionic converters are described, and the integration of these characteristics, with those of other system components, is explained. The present characteristics and future application of vapor converters is also discussed. Particular emphasis is placed on the importance of the solar concentrator.

A specific "Solar Thermionic Electric Power System" is described. This system is composed of a reflecting energy concentrator of an automatically unfolding design driven by an orientation subsystem of silicon sensors and mechanical drive elements. At the focus of this concentrator, a thermal to electrical power converter, or generator, is placed. Thermionic converter elements form the basic component of this generator. Electrical energy storage for operating during the dark portion of a satellite orbit will be provided, and a regulation subsystem regulates the voltage between 26 and 29 volts. The report describes hardware development in progress on this system, as well as expected growth possibilities.

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INTRODUCTION

The utilization of thermionic conversion in the generation of power in Space is currently under active development. Of particular interest is the application in which solar power is converted to electrical power. The Solar Thermionic Electrical Power Supply (STEPS) project has as its objective the demonstration of the system feasibility of thermionics for space application, with the use of vacuum converters. Vapor converters are also of interest, and are discussed separately.

There are several functions which must be performed by a thermionic Space Power System. To convert the solar power incident in space on the system, the cathode of a thermionic converter must be elevated to a temperature sufficient to cause thermionic emission, generally above 1400 degrees Kelvin. The solar power density of 0.14 watts per square centimeter is too low to match the required thermionic converter power density of 10 watts per square centimeter or more, and a solar concentrator is necessary. The most efficient concentrator is a parabola since it will focus parallel rays of light to a point. With a parabola however, the axis must be oriented toward the sun, and thus a sun sensing and orientation subsystem is necessary. At the focal point of the parabola the converter generator is located. To match the power density of the generator to the solar intensity at the focal point, and to minimize radiation losses, a hollow cavity generator is used into which the solar energy can penetrate via a small aperture. The thermionic converters are then mounted on the exterior of this cavity and pick up their energy from the cavity interior. In this manner the only reradiating area is the aperture. In addition to the collection, generation and orientation subsystems, there is also a regulation subsystem necessary to maintain regulated voltage under varying conditions of power, since the thermionic converters are not constant voltage devices. A storage subsystem may also be required in order to store energy for operation during the time the satellite is in the dark in the shadow of the earth. There are many types of storage available, but electrical and thermal are the two most promising approaches. For this project electrical storage with nickel cadmium batteries has been selected due to its present advanced state-of-the-art. Thermal or fuel cell storage systems may be utilized later, once thermionic feasibility is established.
SYSTEM DESCRIPTION

With these subsystems in mind the block diagram of the system is shown in Figure 1. In this diagram the solar power is collected by the collection subsystem, and delivered to the generator subsystem which converts the thermal power to electrical power. The electrical energy then passes to the regulation subsystem which maintains the voltage constant with varying load. A storage system is activated by a switching circuit and stores additional energy during the light time for delivery to the load during the dark time while the satellite is in the earth's shadow. Figure 2 is an illustration of the system in a space environment.

The collector is designed to fit within a 9-1/2 ft. diameter cylinder and folds out to 16 feet for operation in orbit, and the vehicle orientation subsystem orients the collector toward the sun. In order to prove the feasibility of the system on the ground, however, a number of minor alterations are necessary in this configuration. The collector will be attached to a simulated vehicle which is attached to a ground mount pedestal. This ground mount pedestal is driven by motors controlled by the orientation sensing system. The ground system is shown in Figure 3.

Although each subsystem of the STEPS is dependent on other subsystems and each subsystem is not truly independent, the problems of each subsystem are separably identifiable. Some of the theoretical and practical problems of the subsystems which are under investigation, design analysis and development follow.

COLLECTION AND ORIENTATION SUBSYSTEM

The equation of a parabola of focal length \( f \) (see Figure 4) is

\[
y = \frac{x^2}{4f}
\]

(1)

and

\[
\frac{D_c}{f} = \frac{4 \sin \phi}{1 + \cos \phi}
\]

(2)

also

\[
r/f = \frac{2}{1 + \cos \phi}
\]

(3)

and

\[D_c = 2r \sin \phi\]

(4)

The sun's energy impinging on the parabola at a point is reflected in a cone whose total included angle is 32 minutes as is also shown in
Figure 4. In order to collect all of this incident energy an aperture diameter of $D_a$ must be provided in the generator. In addition to the angular deviation of the sun, there are additional deviations of the light rays. These are caused by orientation system inaccuracies and surface defects in the collector. If these angular errors are represented by:

$$\beta_o = \text{orientation system angular deviation from the center line}$$
$$\beta_c = \pm \text{angular deviations of the collector slope.}$$

A total equivalent angle of

$$\beta = \beta_s + \beta_o + 2\beta_c$$  \hspace{1cm} (5)

may be used to estimate the aperture size from Figure 5. The relationships of the variables may be noted, where $r$ equals the distance from the rim to the focal point.

From the geometry of the figure it may be shown that:

$$\frac{R_1}{r} = \frac{\sin \beta}{\cos (\phi + \beta)}$$  \hspace{1cm} (6)

and since

$$r = \frac{D_c}{2} \sin \phi$$  \hspace{1cm} (7)

$$\frac{2R_1}{D_c} = \frac{D_a}{D_c} = \frac{\sin \beta}{\cos (\phi + \beta) \sin \phi}$$  \hspace{1cm} (8)

Which is the ratio of the aperture diameter to the collector diameter. To find the minimum of $D_a/D_c$ with respect to $d$, the first derivative of

(8) with respect to $\phi$ set equal to zero, is:

$$0 = -\sin \beta \left[ -\sin (\phi + \beta) \sin \phi + \cos (\phi + \beta) \cos \phi \right]$$  \hspace{1cm} (9)

Solving for $\phi_m$, where $\phi_m$ is the rim angle for minimum $D_a/D_c$

$$\phi_m = 45^\circ - \frac{\beta}{2}$$  \hspace{1cm} (10)
and substituting this into equation (8)*

$$\frac{D_a}{D_c} = \frac{\sin \beta}{\sin^2 (45^\circ - \beta/2)}$$

which is the equation of the aperture diameter to the collector diameter. For a minimum ratio of aperture diameter to collector diameter, this is the ratio at which the maximum amount of energy may be focused into the aperture area. The analysis assumes that the total amount of energy is collected by the aperture. Due to the fact that the power at the focal point is not constant when the focal plane is traversed, but is a distribution with a greater intensity at the center, the aperture diameter may be reduced below the amount indicated. The exact nature of this wave shape is difficult to predict, and collectors of the foldable type must be built and tested to realistically determine this distribution. If the reciprocal of (11) is squared, the ratio of the collector area to aperture area for maximum energy concentration may be found, or

$$\frac{A_c}{A_a} = \frac{\sin^4 (45^\circ - \beta/2)}{\sin^2 \beta}$$

where $A_c$ = collector area and $A_a$ = aperture area.

A reasonable value of $\beta_0$ (orientation error) is 6 minutes, and for presently manufactured collectors a deviation of the slope of the collector of 8 minutes ($\beta_c$) is a reasonable estimate. This gives a total error of 38 minutes. Thus, substituting 38 minutes into equation (12) a "concentration ratio" of 2,040 is obtained. The maximum possible concentration would be that with no error angle and no angular orientation deviation angle, corresponding to the 32 minutes of arc of the sun. This concentration ratio maximum is shown, by substituting 16 minutes into equation (12), to be 11,300. This illustrates the reduction of concentration due to collector inaccuracies and orientation by a factor of 5.6 to 1.

To examine the effect that the collector would have on the remainder of the system, and to examine interdependence of the generator and the collector combination, it is of interest to calculate the efficiency with which the collector can collect energy. Unfortunately

*Analysis performed by D. L. Kerr
this efficiency is difficult to define since the capability to retain and utilize energy is not only a function of the collector geometry and characteristics but is also a function of the generator cavity characteristics. The predominant characteristics, however, are those of the collector. Of the 130 watts per square foot impinging on the projected surface of the parabola, a certain percentage of this energy is lost in the reflection at the reflector surface. This remaining power is expressed as a percentage $\eta_r$. In addition, only a certain percentage of the solar power after this reflection is absorbed by the aperture opening. This absorptivity is $\sigma_a$.

From these relationships, the power into the generator aperture may be expressed by the equation

$$Q_i = \eta_r \sigma_a q A_c$$

(13)

$Q_i$ is the incident energy (watts), $A_c$ is the collector area, ($\text{feet}^2$) and $q$ is the solar constant (130 watts/$\text{ft}^2$). The energy which is re-radiated from the generator by the Stefan Boltzman law is

$$Q_i = 5,270 A_a \xi_a \frac{T_c}{1000}$$

(14)

Where $A_a$ is the generator aperture area, ($\text{ft}^2$), $\xi_a$ is the emissivity, and $T_c$ is the temperature of the cathode ($^\circ\text{K}$), assuming no temperature drop across the cathode surface. The total collection efficiency is now defined as the power available for use at the cathode surface divided by the total power input or

$$\eta_c = \frac{Q_i}{Q_c} = \eta_r \sigma_a \frac{A_a}{A_c} \xi_a (T_c)^4$$

(15)

where $Q_c$ is the total energy collected.

From equation (15) it can be seen that the collection efficiency is a function of the generator aperture absorptivity and emissivity, the reflectivity of the collector, the energy incident on a collector, the ratio of the generator aperture to collector area, and the generator interior temperature. The shadow area cast on the collector is not included here, but it also degrades the collector efficiency.

From an analysis by Andre Gouffe (Ref. 1) a plot of the emissivity of an absorber cavity vs the emissivity of the interior surface is shown in Figure 6. From this it is seen that with an emissivity of
about .65, which may be typical of aluminum oxide or a particular coating on the interior of the generator cavity. An effective emissivity of .98 may readily be obtained. A plot of the collector efficiency as a function of the cathode temperature for a space operation is shown in the solid line in Figure 7. This plot assumes $A_c/A_a$ to be 2,040 as shown earlier, a reflectivity of 90%, a $q$ of 130 watts/ft$^2$, and $\alpha_a = \xi_a$.

On the ground, however, the conditions are different than in space. For example, the reflectivity may be lower due to protection against oxidation. The incident energy is also approximately 65 watts per square foot. A plot of the expected collector efficiency on the ground compared to that in space is also plotted in Figure 7. From the shape of the two curves it is obvious that the collector efficiency on the ground is inferior to that in space, thus imposing an additional problem on the development of a ground test power supply unit.

It is also evident that, as the generator temperature increases, the collector efficiency decreases, which precludes, at least with the present state-of-the-art devices, the use of extremely high temperature converters. This effect of cathode temperature on system efficiency is more clearly described in the section on vapor converter application. If light traps or filters are found useful, and collector and orientation accuracies improve, the higher temperature devices may be practical. This collector efficiency combined with the generator efficiency, gives an indication of the optimum system size and may be used as a design tool to pin-point a design point in a space power system.

The efficiency of the system is an artificial method of comparing systems. It is only important in its effects on the total system weight, cost, or reliability. In the eventual design of practical systems, the specific weight or pounds per kilowatt of the system coupled with the cost and the reliability of the system will probably be the determining factors in system selection, rather than efficiency. For example: it may be possible with an extremely light weight and yet low efficiency collector to design a system which is of much lighter weight and much more practical than a higher efficiency but also heavier system. The efficiency is useful, however, in that it gives the engineer a method for interrelating system parameters.

The use of a quartz window light trap, utilizing the greenhouse effect has been considered. If the collection efficiency using a quartz window light trap is calculated the energy into the generator, $Q_1$ now becomes
where \( \eta_t \) is the percentage of light transmitted through the surface of the quartz, the \( \eta_a \) is the percentage of light absorbed in the glass before entering the absorber. Since half of this energy is reradiated out of the aperture only half of it penetrates through into the cavity. The power leaving, by the same reasoning, is now

\[
Q_1 = 5270 \times A_c \left( \frac{T_c}{1000} \right)^4 \eta_t' \left( 1 - \frac{\eta_a'}{2} \right)
\]

where the \( \eta_t' \) and \( \eta_a' \) denote reflectivity and absorptivity efficiencies for the power impinging on the interior of the quartz from the cavity. The new efficiency equation now becomes

\[
\eta_c = \eta_r \eta_t \left( 1 - \frac{\eta_a}{2} \right) - \frac{5270}{q} \left( \frac{A_c}{A_a} \right) \left( \frac{T_c}{1000} \right)^4 \eta_t' \left( 1 - \frac{\eta_a'}{2} \right)
\]

For perpendicular light on a quartz slab \( \eta_t \) is 93% and \( \eta_a \) is 0. For a temperature of 1500° K the value of \( \eta_a' \) obtained by integrating the absorption coefficient across a black body spectral distribution is* .4. Substituting these values in equation 18 efficiencies in space and on the ground are obtained, and are shown on Figure 7. It is therefore evident that a quartz window light trap will degrade the system efficiency.

ORIENTATION SYSTEM

The orientation system consists of two solar sensors which are mounted on the axes of rotation of the parabolic collector. One sensor controls azimuth, and the other sensor controls elevation. As the collector turns light is reduced on one solar cell due to a shadow passing across the cell causing an input to the servo system loop causing the collector to be turned to return it to its zero or null position. This system has been working on a 60 inch collector with excellent results and accuracies of 1/10 of a degree have been obtained. In the ground test case the orientation system drives azimuth and elevation D.C. motors. In the space environment, of course, the vehicle itself would be controlled by the fly-wheel, gas jets, ion drives or other torque producing devices.

*Analysis performed by D.C. Miley
THERMIONIC CONVERTER GENERATOR

A thermionic converter generator consists of a series of thermionic converters which are mounted around the periphery of a cavity as shown in Figure 8, where a spherical cavity is shown. The thermal energy enters the cavity through the generator aperture and is reflected and redistributed by reflection from the interior surface. In this particular application the converters are shown protruding into the cavity and supported by a supporting shell structure. This allows the interior finned cathode to pick up energy from the cavity with a minimum temperature drop from cavity to the cathode face of the converter. Calculations have indicated that conduction heat transfer is not sufficient to cause a uniform temperature distribution from the rear side of the generator cavity to the front side of the generator cavity, and the temperature distribution within the cavity is not uniform if the entire interior surface has the same emissivity and absorptivity. A varying emissivity surface will eliminate this effect.

The generator efficiency is a function of the thermionic converter efficiency, the losses through the insulation between the converters, and the support arms of the generator, as well as pick-off lead wires from the generator.

VACUUM CONVERTERS

The converters to be tested in this project are vacuum converters. Figure 9 is a photograph of a vacuum thermionic converter element and also shows a cross sectional view illustrating the construction of the converter. An integral radiator is mounted on the cool or anode portion of the converter, and rejects the heat directly to space, thus eliminating the need for an additional cooling loop and space radiator.

The theoretical operation of the vacuum thermionic converter has been described in the literature (See Ref. 2, 3, 4) and is based upon emission of electrons which overcome the work function barrier of the cathode, as well as the barrier of the space charge. This is shown in Figure 10. The electron velocity must be sufficient to overcome $\phi_c$ which is the cathode work function potential plus the space charge potential $\phi_k$ to pass to the anode. They then provide electrical power at $V_o$ to the load in returning to the cathode. To obtain an indication of the operation of the thermionic converter generator, coupled with a collector, it is necessary to understand the characteristics of the converter.
The measured volt amperage characteristic of a typical converter is shown in Figure 11 (Ref. 8). The curves are for constant cathode temperature and varying anode temperature. It is evident that the converter acts very similar to a constant voltage and impedance source. The output also varies with the anode temperature. This latter effect is particularly noticeable in Figure 12, where the peak output power at constant cathode temperature is plotted as a function of anode temperature, the maximum power for this particular tube occurring at an anode temperature of 610°C. This effect is important in the sizing of the anode radiator, which radiates the heat lost by the converter to space. It may also cause rapid loss of performance when the converter is operated slightly off its design point value.

The power output curve at the optimum anode voltage of 610°C is shown in Figure 13, and is the product of current and voltage out of the converter. Also shown is the calculated efficiency, based on the measured data. Two efficiencies are shown, the higher one being that efficiency which would be possible with this particular converter if envelope and edge losses could be neglected. The lower curve, of course, is one which is realizable with a practical design which must operate in an earth environment. The calculations have considered electron cooling energy, radiation losses between cathode and anode surfaces, conduction through the insulating spacers, and envelope conduction and radiation losses. The calculations do not include lead losses, which will decrease the overall efficiencies to about 95% of the value shown.

The theoretical calculation of the device characteristic follows very closely the actual measured characteristics. In Figure 14, the measured current voltage characteristic of the converter is compared to a calculated characteristic, with an estimated gap of .000622, approximately that of the converter. Excellent agreement occurs at high currents, with some deviation at lower currents. This is probably due to the assumption of a constant back current from the anode, which will cause a greater effect at low forward currents. With such close agreement between calculated values, it is of interest to examine the effect of reducing the gap spacing from the .0006" to .0002", which is probably the ultimate practical limit. The characteristic of the converter now becomes that shown in Figure 15, with all other parameters such as work functions and cathode and anode
temperatures remaining constant. This characteristic may now be used to plot efficiency, as seen in Figure 16. Again, efficiencies are shown with and without envelope losses. These efficiencies are probably high, since the problem of maintaining a spacing of 0.0002" at an electrode temperature of 1425°K is a formidable one. Other problems occur in the mechanical construction of the converters which places a limit on the size of the device that can be fabricated from two flat surfaces due to warping and thermal distortion, and the limitation on the life of the device due to the failure of the envelope structure by excessive grain growth. Alteration of the work function of the oxide coatings on the cathode and anode surfaces due to higher vapor pressure at high temperature also causes deterioration of performance. Structural limitations are also imposed by oxidation of possible high temperature envelope materials. This illustrates again the difference between a ground type unit which must operate in air and a vacuum type unit designed solely for the vacuum of space, where oxidation is no problem.

Thus a practically realizable efficiency is in the neighborhood of 5-6%, due to the design compromises necessary to make a practicable, manufacturable converter for systems application in a ground environment.

The efficiency discussed previously is the thermionic converter efficiency and not the generator efficiency. The generator efficiency is lower than the thermionic converter efficiency due to thermal insulation losses and thermal losses through the mechanical support structure of the generator. With the particular geometry selected about 30% of the area is covered with insulation and the three support arms cause additional losses. The actual plot of the generator efficiency as a function of converter efficiency is plotted in Figure 17. The degradation of the converter efficiency being due to losses through insulation surrounding the converters, as well as losses through the support arms. This generator efficiency, times the collection subsystem efficiency, will now give the efficiency of the system to produce power output from the converters, or the system efficiency becomes

$$\eta_s = (\eta_c) (\eta_g)$$
This system efficiency is also plotted in Figure 17, and illustrates the effect of converter efficiency on overall system efficiency. Although a system efficiency of 5% is theoretically possible, this efficiency will probably be hard to obtain in a ground test unit, due to the practical manufacturing problems associated with the close spaced vacuum converter. From Figure 17 it can be seen that probably a system efficiency of 3 to 3.5% is a more realistic goal, corresponding to converter efficiencies of 5 to 6%.

VAPOR CONVERTER APPLICATION

The principle of operation of the vapor converter has been well described in the literature (See Ref. 4, 5, 6) and will only be briefly described here. Like the vacuum converter it relies on the work function differences of cathode and anode as illustrated in Figure 10, with the exception that the vapor may perform one or more of several functions within the device.

1. The vapor may provide space charge neutralization, by supplying positive ions to counteract the negative electron space charge. These ions may be generated by surface ionization at the converter electrodes or by collision with high velocity electrons.

2. The vapor provides a low work function anode. All vapor converters rely on this phenomenon.

3. The vapor may provide a lower work function cathode by being absorbed on its surface. The cathode surface may be operated, however, without this covering.

The emission characteristics of surfaces in contact with cesium vapor were described by Langmuir, and allow us to obtain an insight into the limiting behavior of a cesium vapor converter. The Langmuir Taylor - "S" curves, shown in Figure 18 extrapolated to higher cesium pressures, can be utilized to calculate the operation of a vapor converter, since these curves define the saturated emission, work function, temperature, and cesium pressure relationships for surfaces in contact with cesium vapor. From these curves, if a specific cesium pressure, and anode and cathode temperature are assumed, the current and voltage may be calculated, assuming no space charge. Thus, if
a tube structure similar to the vacuum converter structure is assumed, an estimate of the limiting efficiency of a practical converter may be obtained. This limiting efficiency includes calculations of conduction losses through the envelope, radiation losses from the electrodes and envelope, electron cooling losses, back emission electron heating, space conduction losses, and lead losses. A number of curves of efficiency vs. cathode temperature at constant anode temperature and constant cesium pressure were obtained in this manner. These curves, when superimposed, then determine a "maximum efficiency" envelope, and is shown in Figure 19. The envelope serves as an indication of the efficiency capability of a device useful in a solar generator. It can be seen that very attractive efficiencies would result if space charge effects could be overcome.

At the present time, however, efficiencies only slightly better than half these efficiencies have been obtained in planar type devices, due to the lack of space charge neutralization as well as losses due to electron cesium collision. The characteristics of such a converter are shown in Figure 20, these characteristics having been obtained by Dr. A. O. Jensen (See Ref. 7) on a planar converter very similar to the design shown in Figure 9, but utilizing refractory metal envelopes, provision for a cesium reservoir integrally attached to the converter, and different braze materials. With known current and voltage characteristics, the electron cooling terms can be added to losses due to structure, radiation, and leads in a practical tube design to provide the converter efficiency. Lead and envelope geometry has been optimized. This design point is shown in Figure 19 @ 1603°K with lead and envelope geometry optimized. Additional data on a high temperature converter has been obtained by Dr. V. C. Wilson, (Ref. 6) in which a power of 7.5 watts/cm² at 1.33 volts output was obtained. This data can be utilized to determine an efficiency at 2105°K, and is also shown on Figure 19. These calculations thus enable a currently realizable efficiency curve to be drawn. N. S. Razors (Ref. 5) observed efficiency data is in close agreement in the 1700°K to 1900°K range with this efficiency.

From the converter efficiency and power density data used to calculate the currently obtainable curve, the generator losses may be added to the converter losses as was done for the vacuum converter generator. Since presently available vapor converters, however, will only operate in a vacuum or inert atmosphere, the
losses are less than one would expect in air. The system may also only be tested in vacuum. This complicates the testing, but simplifies the generator and converter design by an order of magnitude. The curve of generator efficiency is now shown in Figure 19. It is noticeable that the generator efficiency is degraded by a larger amount at higher cathode temperatures, due to the fact that the ratio of the converter anode radiator to cathode area has increased, and hence insulation losses have proportionately increased, and because the insulation is less effective at higher cathode temperatures. With the generator and collector efficiency known as a function of cathode temperature, the total system efficiency may be calculated. The generator and collector efficiencies are again shown in Figure 21, coupled with their product, the generator efficiency. It is significant to notice that system intereffects cause the optimum efficiency point of the converter to steadily move down, until the optimum system efficiency of presently realizable vapor converters occurs at approximately 1750° Kelvin. This point would move to higher cathode temperatures if the slope of the generator efficiency curve should increase, which is probably to be expected with increased converter development, and the expected advance in converter state-of-the-art.

REGULATION AND STORAGE

With the selected light-dark cycle of 55 minutes in light and 35 minutes in the dark, a battery charging efficiency (the ratio of the power output of the battery divided by the power input to the battery) of 68%, and a system efficiency of 5%, the area required for 500 continuous watts in space is 160 sq. feet.

With the collector sized to deliver 500 watts in space of continuous power, a 14.75 foot collector would be required. This 14.75 foot collector will deliver to the storage and regulation system on the ground an amount of power equal to the efficiency of the collection and generation systems times the total power input, or 540 watts. Of this 540 watts, 250 of it will be delivered to the load, and 290 watts will be delivered to the storage system. The reduced power, of course, is due to the reduced solar constant at the earth's surface.

The characteristic of the storage device is such that to deliver between the 26 and 29 volts, which is a regulation
requirement, the storage battery must charge at 34 volts. Since the converter elements are sized for 34 volts, they cannot be placed in series or in parallel with the load supply, and a separate switching arrangement is required. A suggested system is shown in Figure 22. The battery charging converters are placed directly across the battery circuit, and when in the light the battery converters deliver their energy to the batteries, and the load converters deliver their energy to the load at 28 volts. During this period, the light control switch is open and the battery does not effect the load. When the system enters the dark, the control switch is closed. The load converters cool down, and become a very large impedance. The battery converters do likewise and the battery now supplies the load. A regulator for the load varies a series of load resistances by use of transistor variable impedances. These impedances are controlled depending upon the voltage, and provide a constant impedance load for the converters. For example: if the load decreases the current through the converters will decrease. This decrease in current will cause an increase in voltage. The increasing voltage will be sensed by the regulator and the transistor impedances will decrease, increasing the current flow from the converters and again reducing the voltage to within the controlled range. One of the major problems is the matching of the impedances of individual converter elements in series with the battery and with the load. This results in a series paralleling problem which, at a particular power level, may force the converters to operate off their best design point.

This type of a regulation system has high reliability, with no moving parts. The design approach is particularly valid for a solar system since the system must be designed to provide the maximum power output and conservation of energy (which is free from the sun) is of no value.

CONCLUSIONS

The interdependence of the various subsystems in a thermionic space power supply have been theoretically identified. The collection subsystem must concentrate its energy into as small an aperture as possible, commensurate with orientation accuracy and collector manufacturing tolerances. The generation system in turn must operate at as high a temperature as possible, commensurate with thermionic converter life. There are two effects which limit this peak temperature operation. The first is the
increased loss of power by reradiation of power out of the generator aperture, which causes a rapid decrease in collection efficiency at high temperatures. The second is the limit placed on temperature by thermionic converter cathode deterioration, coupled with deleterious effects of oxidation and grain growth of the converter foil envelope. The vacuum and vapor converter characteristics important in a space power system have been discussed.

For regulation and storage a static regulator circuit coupled with a nickel-cadmium battery electrical storage unit and a dark-sensing switch should provide proper regulation.

Although there are still many problems to be overcome, none seem insurmountable, and the present development of a ground operation unit is expected to prove practically what appears possible theoretically. In addition the testing of a complete system will pave the way for future, more refined space power systems.
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Fig. 1. Solar thermionic electric power system
Fig. 2. Space configuration
Fig. 3. Ground operation facility
Fig. 4. Collector geometry

Fig. 5. Focal plane geometry
Fig. 6. Emissivity of a cavity (sphere) vs emissivity of interior coating
Fig. 7. Collection subsystem efficiency as a function of generator interior temperature

Fig. 8. Thermionic converter generator
Photograph of Converter

Cross Section of Converter

Fig. 9. Vacuum thermionic converter

Fig. 10. Thermionic converter energy diagram
Fig. 11. Output voltage vs current (measured) - vacuum converter (Ref. 8)
Fig. 12. Vacuum converter power output vs anode temperature
Fig. 13. Calculated efficiency and measured power output of a vacuum thermionic converter
Fig. 14. Calculated and measured vacuum converter characteristics

- Output Voltage (Volts)
- Output Current (Ampères)

Assumed Values for calculation:
- $\phi_C = 2.15$
- $\phi_A = 1.6$
- $T_C = 1150°C$
- $T_A = 610°C$
- Spacing = 0.00622"
Fig. 15. Calculated power output and voltage vs current for a vacuum thermionic converter.

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Fig. 16. Calculated efficiency vs converter current - vacuum converter.
Fig. 17. Generator and system efficiency vs vacuum converter efficiency.
Fig. 18. Langmuir-Taylor curves for cesium-on-tungsten
Fig. 19. Vapor converter and generator efficiencies vs cathode temperature
Fig. 20. Volt-ampere characteristic for arc-mode vapor thermionic converter No. 30 (Ref. 7)
Fig. 21. Collector, generator and system efficiency vs cathode temperature for vapor thermionic converter system
Fig. 22A. Block diagram, electrical power

Fig. 22B. Schematic, regulator