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THERMIONIC GENERATOR FOR RE-ENTRY VEHICLES

by

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THERMONIC GENERATOR FOR RE-ENTRY VEHICLES*

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ABSTRACT

A novel design of a thermionic generator for use on re-entry vehicles is analyzed analytically and experimentally. Equations are derived for prediction of the output current, output power, and conditions of maximum power for the device.

The electrical power output potential of a typical re-entry vehicle is obtained by solving the temperature history of a thin-walled emitter. Given the wall temperature and the work function, the saturated Richardson current is easily obtained. Other parameters needed for predicting output power are obtained from curves in the literature.

To simulate re-entry conditions, a test model was built and inserted in either a nitrogen or argon plasma jet. Graphite, thoriated tungsten, tungsten and molybdenum were used for the emitter and collector. Of the materials tested, graphite was the only material that met, to some degree, the qualifications needed for operation of the hypersonic plasma thermionic generator

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INTRODUCTION

The study of direct energy conversion has become increasingly important during the last few years. Direct conversion of heat into electrical energy offers many advantages for space applications over indirect conversion methods, the light weight of a direct converter being only one.

Beginning with the well-known assertion that thermionic emission from a metal is accompanied by Peltier cooling of the metal interface¹, and using the converse theory that states the acceptance of electrons by a metal is accompanied by Peltier heating, the interface between a metal and an ionized gas may be treated as a junction between two conductors-- the plasma forming one branch and the remainder of the circuit forming the other.

In just such a fashion, H. W. Lewis and J. R. Reitz² treated the thermionic generator as a thermocouple, using transport theory to calculate the Seebeck emf or open circuit voltage. Their analysis pointed out that any two surfaces separated by a fairly dense plasma with one surface hot enough to emit electrons should operate as a plasma thermionic converter.

A missile re-entering the atmosphere is known to have for a period of time a fairly dense plasma surrounding the body

¹Herwing, C., and M. H. Nichols, "Thermionic Emission", Rev. Modern Physics, Vol. 21, pp. 185-270, 1949.

²Lewis, H. W. and J. R. Reitz, "Thermoelectric Properties of the Plasma Diode," Journal of Appl. Physics, Vol. 30, pp. 1439-45, 1959.

and also a temperature differential on the surface. As long as the vehicle travels at supersonic speeds the affected region is enclosed in the bow shockwave. At sufficiently high shock-layer temperature the air dissociates and ionizes. The highest heating rate occurs at the stagnation point and results in the nose of the vehicle being maintained at a considerably higher temperature than the remainder of the body. The nose can therefore act as an electron emitter, and the body of the vehicle can act as the electron collector. An electrical insulator is inserted between the emitter and collector as shown in Figure 1.

A device very similar to Figure 1 was inserted in an ionized argon plasma jet by T. Cotter³. Although the duration of the run was quite short, the experiment showed a current existing for a short period of time, and also indicated an open circuit voltage of the expected polarity.

This paper describes a study of a hypersonic plasma thermionic generator considered theoretically and experimentally. Electrical parameters of the experimental device were obtained by writing a set of balanced current equations at the emitter and at the collector using a Kirchhoff voltage equation for the complete electrical loop. The current equations were obtained by treating the ionized gas as a fairly dense plasma that tends to emit as well as to accept electrons. The electron current from the metal to the plasma is defined using the familiar Richardson current; the electron current from the plasma to the emitter is

³Cotter, T., "Hypersonic Plasma Thermocouple," Los Alamos Scientific Laboratory, LAMS-2481.

obtained by calculating the flux of electrons emitted from an ionized gas, whereby the electrons have a Maxwellian distribution and have to overcome a barrier equal to the plasma sheath potential existing at the emitter or collector. From these two sets of equations, the output voltage, V , the output current, I , the emitter sheath potential, V_e , the collector sheath potential, V_a , and the output power of the device are calculated. A somewhat similar set of equations was obtained by Carabateas⁴ for a planar diode.

⁴Carabateas, E. N., Pezaris, S. D., and G. N. Hatsopoulos, "Interpretation of Experimental Characteristics of Cesium Thermionic Converters," Journal of Appl. Physics, Vol. 32, pp. 352-358, 1961.

THEORETICAL ANALYSIS OF THE PLASMA MODE

To operate in the plasma mode, the minimum rate at which the ions produced within the bow shockwave must arrive at the emitter should equal the square root of the ratio of the mass of the electron to the mass of the ion times the electron current:

$$J_i = J_e \sqrt{\frac{m_e}{m_i}} ; \quad (1)$$

where

J_i is the ion current density,

J_e is the electron current density,

m_e is the mass of the electron,

and m_i is the mass of the ion.

For argon gas, the mass of an argon ion is equal to $(6.65) (10)^{-23}$ grams, and the mass of an electron is $(.911) (10)^{-27}$ grams. The ion arrival rate should therefore be at least 1/293th the electron emission rate for the elimination of electron space charge. For high temperature air the two main sources of ions are the oxygen and nitrogen ions. The mass of the oxygen ion is $(2.66) (10)^{-23}$ grams, and the mass of the nitrogen ion is $(2.33) (10)^{-23}$ grams, giving an average mass of approximately $(2.5) (10)^{-23}$ grams. The ion arrival rate for air should therefore be at least 1/155th the electron emission rate.

In the calculation of the ion arrival rate as compared to the electron emission rate and also of the mean-free path of

the electrons for the hypersonic plasma thermionic generator, it will be seen that it is operating as a plasma converter. The following discussion and derivation will therefore assume this condition to be existing for the device.

The net current at the emitter side can be expressed in terms of the random ion and electron current from the plasma to the emitter plus the Richardson current from the emitter to the plasma. Therefore, one has:

$$I = I_s - I_e + I_{pl} ; \quad (2)$$

where,

I is the net current in the generator,

I_s is the saturated Richardson current,

I_e is the random electron current from the plasma to the emitter,

I_{pl} is the ion current at the emitter.

The random electron current from the plasma to the emitter can be derived by assuming a Maxwellian distribution for the electrons in the plasma and a step potential V_e existing at the emitter boundary:

$$I_e = en_e \sqrt{\frac{kT_e}{2\pi m_e}} A_e \exp \left(-\frac{eV_e}{kT_e} \right) ; \quad (3)$$

where,

n_e is the electron density in the plasma,

T_e is the electron temperature,

and A_e is the area of the emitter.

The positive sheath potential, V_e , is formed when the ion production rate becomes so much greater than that required for space charge neutralization that an ion sheath forms at the surface of the emitter. Near the boundaries of the ionized space, the electrons, with their high value of the coefficient of diffusion, D_e , move away from the point of creation more rapidly than the slower positive ions with coefficients of diffusion, D_i . The diffusion of the negative electronic charge away from the neutral plasma quickly builds up a negative space charge on the surface and leaves a positive ion space charge in the inner volume located right next to the boundary.

The saturated ion current is equal to:

$$I_{p1} = \frac{qN_i \bar{v}_i A_e}{4} ; \quad (4)$$

where $\bar{v}_i$ is the average thermal velocity of the ion. The ion current at the emitter and collector is always at its saturated value and is therefore a constant for a constant ion density and a constant ion temperature.

At the collector side the same net current, I , exists. This current will consist of a random electron current from the plasma to the collector minus the saturated ion current. Therefore, at the collector:

$$I = I_a - I_{p2} ; \quad (5)$$

where,

I_a is the random electron current from the plasma to the collector,

I_{p2} is the saturated ion current at the collector.

The random electron current, I_a , is equal to:

$$I_a = en_e^- \left(\frac{kT_e}{2\pi m_e} \right)^{1/2} A_a \exp - \frac{eV_a}{kT_e} ; \quad (6)$$

where,

A_a is the area of the collector,

V_a is the collector sheath potential.

A voltage equation can be written for the complete electrical loop of the generator:

$$V_t + \varphi_a - V_a - \varphi_e + V_e = 0 ; \quad (7)$$

where,

φ_a is the collector work function,

φ_e is the emitter work function,

V_t is the voltage drop in the plasma plus the voltage drop across the load.

Rewriting equation (2):

$$I_e = I_s + I_{p1} - I, \quad (2')$$

and inserting the definition of I_e from equation (3) into (2'):

$$en_e^- \left(\frac{kT_e}{2\pi m_e} \right)^{1/2} A_e \exp \frac{-eV_e}{kT_e} = I_s + I_{p2} - I. \quad (2'')$$

Rewriting equation (5):

$$I_a = I + I_{p2}, \quad (5')$$

and inserting the definition of I_a from equation (6) into (5'):

$$en_{\tilde{e}} \left(\frac{kT_e}{2\pi m_e} \right)^{1/2} A_a \exp \frac{-eV_a}{kT_e} = I + I_{p2} . \quad (5'')$$

If equation (2'') is now divided by equation (5'') one obtains:

$$\frac{e}{kT_e} (V_a - V_e) = \ln \left[\frac{A_a}{A_e} \left(\frac{I_s + I_{p1} - I}{I + I_{p2}} \right) \right], \quad (8)$$

Inserting the definition of $V_a - V_e$ from equation (7) into equation (8) results in:

$$V = \frac{kT_e}{e} \ln \left[\frac{A_a}{A_e} \left(\frac{I_s + I_{p1} - I}{I + I_{p2}} \right) \right] - Ir + \varphi_e - \varphi_a ; \quad (9)$$

where r is the resistance of the plasma.

In equation 9 the term " T_e " is the electron temperature existing in the boundary layer surrounding the generator. The reason for using this value of T_e is that the emitter surface is relatively cool when compared to the gas temperature surrounding it, and also the accelerating V_e is low enough in magnitude so that the equivalent temperature of the electron as it enters the plasma is still below the gas temperature. With the mean-free path of the electrons much smaller than the spacing between emitter and collector, the emitted electron soon reaches thermal equilibrium with the surrounding gas.

Equation 9 can be rewritten as:

$$\ln \left[\frac{A_a}{A_e} \frac{(I_s + I_{p1} - I)}{(I + I_{p2})} \right] = \frac{e}{kT_e} V + e \frac{(\varphi_a - \varphi_e)}{kT_e} + \frac{e}{kT_e} Ir, \quad (9')$$

If the resistivity of the plasma is negligible, equation 9' is the equation of a straight line with a slope equal to $\frac{e}{kT_e}$. In an experimental set-up, the current and voltage of the device can be measured. The current " $I_s + I_{p1}$ " is obtained by applying a positive potential on the collector; while the ion current " I_{p2} " is obtained by applying a negative potential on the collector, the net current, I , is varied by means of a resistive load. With a knowledge of these parameters equation 9 can be plotted on a semi-logarithmic paper. The slope of this line should yield T_e and the intersection of the plotted line with the horizontal line $\gamma = 1$ gives $\phi_e - \phi_a$, where

$$\gamma = \frac{A_a}{A_e} \left(\frac{I_s + I_{p1} - I}{I + I_{p2}} \right).$$

The power output of the device is obtained by multiplying equation (9) by I :

$$P = \frac{kT_e}{e} I \ln \left[\frac{A_a}{A_e} \frac{(I_s + I_{p1} - I)}{(I + I_{p2})} \right] - I^2 r + I(\phi_e - \phi_a) \quad (10)$$

The location of maximum power output, P_{max} , as a function of the net current I is obtained by differentiating equation (10) with respect to I and setting the result equal to zero:

$$\frac{dP}{dI} = 0 = \frac{kT_e}{e} \ln \left[\frac{A_a}{A_e} \left(\frac{I_s + I_{p1} - I}{I + I_{p2}} \right) \right] - \frac{kT_e}{e} \frac{I(I_{p2} + I_s + I_{p1})}{(I + I_{p2})(I_s + I_{p1} - I)} \quad (11)$$

$$- 2Ir + \phi_e - \phi_a.$$

Solving equation (11) for $\frac{kT_e}{e} \ln \left[\frac{A_a}{A_e} \frac{(I_s + I_{p1} - I)}{(I + I_{p2})} \right]$ one obtains

$$\frac{kT_e}{e} \ln \left[\frac{A_a}{A_e} \frac{(I_s + I_{p1} - I)}{(I + I_{p2})} \right] = \frac{kT_e}{e} \frac{I(I_{p2} + I_s + I_{p1})}{(I + I_{p2})(I_s + I_{p1} - I)} + 2Ir + \phi_a - \phi_e. \quad (12)$$

Inserting equation (12) into equation (10):

$$P_{\max} = I_\alpha^2 \frac{kT_e}{e} \frac{(I_{p2} + I_s + I_{p1})}{(I_s + I_{p1} - I_\alpha)(I_\alpha + I_{p2})} + I_\alpha^2 r, \quad (13)$$

where I_α is the current corresponding to $P_{\max}$.

To better appreciate the effect of I_s on $P_{\max}$, the ion currents are assumed negligible and equation (13) is rewritten:

$$P_{\max} = I_\alpha \frac{kT_e}{e} \left[\frac{1}{1 - I_\alpha/I_s} \right] + I_\alpha^2 r. \quad (14)$$

In order to increase the maximum power, the saturated Richardson current should be as high as is feasible.

If one now assumes that the current, I_s , is fixed, an interesting observation would be to find the ratio of I/I_s when maximum power occurs. In order to obtain some idea of this value, the resistivity of the plasma is assumed negligible, and the work function of the emitter is assumed equal to the work function of the collector. With these assumptions, equation (12) reduces to:

$$\ln \left[\frac{\frac{A_a}{A_e} \left(\frac{I_s + I_{p1} - I}{I_s} \right)}{\frac{I + I_{p2}}{I_s}} \right] = \frac{I/I_s \left(\frac{I_{p2} + I_{p1}}{I_s} + 1 \right)}{\left(1 + \frac{I_{p1} - I}{I_s} \right) \left(\frac{I + I_{p2}}{I_s} \right)}. \quad (15)$$

The solution of equation (15) has been obtained by graphical analysis and is shown in Figure 2 for various values of I_{p1} and I_{p2} .

Where

$$\lambda = \ln \frac{\frac{A_a}{A_e} \left(\frac{I_s + I_{p1} - I}{I_s} \right)}{\frac{I + I_{p2}}{I_s}} , \quad \text{and} \quad \gamma = \frac{\frac{I}{I_s} \left(\frac{I_{p2} + I_{p1}}{I_s} + 1 \right)}{\left(1 + \frac{I_{p1} - I}{I_s} \right) \left(\frac{I + I_{p2}}{I_s} \right)}$$

One will notice that the ion currents have very little effect in determining the point where $P_{\max}$ occurs. The introduction of $\varphi_e - \varphi_a$ in equation (15) would shift the maximum power point to the left if $\varphi_a < \varphi_e$ and vice versa if $\varphi_e < \varphi_a$. If the resistivity of the plasma is significant its effect would be to shift $P_{\max}$ to the right.

PREDICTING THE ELECTRICAL POWER OUTPUT FOR A RE-ENTRY VEHICLE

To obtain the temperature of the emitter or nose, it will be assumed that the heat sink capabilities of the emitter are negligible in comparison to the total amount of energy involved. For this particular situation, this condition is satisfied by having a very thin material for the emitter. The thermal radiation from the gas to the body will also be neglected. Under these conditions the rate of convective heat transfer rate from the gas to the body, plus the rate of heat added to the body due to electron-ion recombination on the surface must equal the radiated heat from the body to the plasma, plus the rate of electron cooling due to emitted electron current.

The following equation can therefore be written:

$$q_s + \frac{q_{i-e}}{11380} = \frac{\sigma \epsilon_h T_w^4}{11380} + \frac{I_R (\phi_e + 2kT_w)}{11380} ; \quad (16)$$

where,

- q_s is the convective heat transfer rate from the plasma to the body,
- q_{i-e} is the rate of heat added to the body due to electron-ion recombination on the surface,
- σ is the Stephan-Boltzmann constant,
 $(5.67)(10)^{-8} \frac{\text{watts}}{\text{meter}^2 (\text{deg K})^4} ,$
- ϵ_h is the emissivity of the heat sink surfaces,
- T_w is the wall temperature or the temperature of the emitter in degrees Kelvin,
- I_R is the Richardson electron current in $\frac{\text{amperes}}{\text{meter}^2} ,$

ϕ_e is the work function of the emitter in electron-volts,
11380 is the conversion constant from watts/meter² to
BTU/sec-ft².

The equations for obtaining the convective heat transfer rate have been formulated exactly and solved numerically by a computer.⁵ A correlation of the numerical results was then made which produced the following formula for computing convective heat transfer rates at the stagnation point:

$$q_s = 20800 \left(\frac{\rho}{R\rho_o} \right)^{1/2} \left(\frac{V}{V_e} \right)^{3.25} \left(1 - \frac{h_w}{h_e} \right) \frac{\text{BTU}}{\text{ft}^2\text{-sec}} ; \quad (17)$$

where,

R is the nose radius in the meridional plane,
 ρ_o is the mass density at standard atmosphere,
 h_w is the enthalpy at the wall per unit mass,
 h_e is the enthalpy at the edge of the boundary layer per unit mass.

To obtain the re-entry velocity as a function of altitude, the vehicle is assumed to be subjected only to a drag force. With this condition existing, the flight path angle during entry will remain constant. In actuality, however, the trajectory is slightly curved. This problem has been computed several times before⁶ and the equation that results is:

⁵Kemp, N. H., and F. R. Riddell, "Heat Transfer to Satellite Vehicles Re-entering the Atmosphere," Jet Propulsion, vol. 27, part 1, February, 1957, pp. 132-137, 147.

⁶Wagner, C., "The Skin Temperature of Missiles Entering the Atmosphere at Hypersonic Speed," TR 60, Ordnance Research and Development Division, Sub-office, Fort Bliss, Texas, Sept., 1949.

$$V = V_e e^{-Be^{-Y/H}} ; \quad (18)$$

where,

V_e is the initial velocity at re-entry,

$$B = \frac{H\rho_e g C_d A}{2W \sin \theta} ,$$

Y is altitude in ft.,

H is 21400 ft.,

ρ_e is .00363 slugs/ft³,

C_d is the hypersonic drag coefficient,

A is the area on which the drag coefficient is based in ft².

W is the weight of the re-entry vehicle, lb.

θ is the entry flight path angle, measured from the horizontal,

g is 32.2 ft/sec².

The density as a function of altitude can be approximated by an exponential, that is:

$$\rho = \rho_e e^{-Y/H} ; \quad (19)$$

where according to Sutton⁷ for $\rho_e = .00363$ slugs/ft³ and $H = 21400$ ft. the maximum error in ρ is six percent compared to standard atmosphere.

Substituting equation (18) and (19) into equation (17) one obtains the convective heat transfer rate as a function of altitude:

⁷Sutton, G., "The Temperature History in a Thick Skin Subjected to Laminar Heating During Entry into the Atmosphere," Jet Propulsion, pp. 10-45, January, 1958.

$$q_s = 20800 \left(\frac{\rho_e}{\rho_o} \right)^{1/2} \left(\frac{V_e}{V_s} \right)^{3.25} \left(1 - \frac{h_{\omega}}{h_e} \right) e^{-(y/2H + 3.25Be^{-y/H})}; \quad (20)$$

where V_s is the sea level satellite velocity in ft/sec.

The heat transfer due to ion-electron recombination at the emitter surface is the product of the ion flux into the sheath and the energy of recombination per ion. Thus:

$$q_{i-e} = \frac{1}{4} \frac{h_{i-e} (n_i \bar{v}_i) (3.28) (1728) (16.39)}{(1054.8)} \frac{\text{BTU}}{\text{ft}^2 \text{-sec.}}; \quad (21)$$

where

h_{i-e} is the energy of ionization,

$\bar{v}_i$ is the average thermal velocity in meters/sec.

The assumption was made that recombination occurred to the ground state. The ionization potential of oxygen is 13.62 e.v., while that of nitrogen is 14.55 e.v., giving an average value of 14.36 e.v. The average value was obtained by assuming 80% nitrogen and 20% oxygen.

By definition, the saturated Richardson current is equal to:

$$I_R = \frac{A_o T_{\omega}^2}{11380} \exp \frac{-e\phi_e}{kT_{\omega}}; \quad (22)$$

where A_o is a constant involved with electron emission, amps/meter² -(degree K)².

Reinserting the definition of q_s , I_R , and q_{i-e} into equation (16):

$$\begin{aligned} & 20800 \left(\frac{\rho_e}{R\rho_o} \right)^{1/2} \left(\frac{V_e}{V_s} \right)^{3.25} e^{-(y/2H + 3.25Be^{-y/H})} + \frac{1}{4} \frac{h_{ie} n_i \bar{v}_i}{11380} \\ & = \frac{\sigma \epsilon_h T_{\omega}^4}{11380} + \frac{A_o T_{\omega}^2}{11380} \left(\exp \frac{-e\phi_e}{kT_{\omega}} \right) (\phi_e + 2kT_{\omega}). \end{aligned} \quad (23)$$

Since the equation for convective heat transfer rate applies only at the stagnation point, the nose of the vehicle was assumed to be blunt thereby giving a better indication of the emitter temperature. With the emitter confined to the blunt part of the vehicle, the convective heat transfer rate, as well as the density, temperature, and ion density, can be approximated as being nearly equal to the stagnation value. With the convective heat transfer rate known, it is also possible to determine the wall or emitter temperature through the use of equation (16). As previously mentioned, the equation neglects the heat capacity of the material.

An indication of the magnitude of q_s was obtained by assuming the following constants:

$$R = 10 \text{ ft.}$$

$$\rho_e = .00363 \text{ slugs/ft}^3$$

$$\rho_o = .002375 \text{ slugs/ft}^3$$

$$V_e = 25000 \text{ ft/sec.}$$

$$V_s = 5000 \text{ ft/sec.}$$

$$H = 21400 \text{ ft.}$$

$$g = 32.2 \text{ ft/sec}^2.$$

The correction factor $(1 - h_w/h_e)$ was obtained from a Mollier diagram⁸. Since the temperature of the wall is considerably lower than the surrounding gas temperature, the ratio h_w/h_e did not exceed 0.2. When the convective heat

⁸Korobkin, A., and S. M. Hastings, 'Mollier Chart for Air in Dissociated Equilibrium at Temperatures of 2000° K to 15000° K', NAVORD Report 4446, May 23, 1957.

transfer rate exceeded the maximum radiated heat rate plus electron cooling, the factor $1 - h_\omega/h_e$ was neglected, since the correction did not affect T_ω .

The heat transfer due to ion-electron recombination at the emitter surface was obtained from equation (21). The average thermal velocity was calculated from temperature measurements as obtained by Sisco and Fiskin⁹ for equilibrium air near the stagnation point.

The calculation of the saturated Richardson current was divided into two main regions. In the first region, the convective heat transfer rate plus the heat rate due to electron-ion recombination was less than the sum of radiated heat rate and electron cooling. As long as this condition existed, it was possible to use equation (23) for predicting the wall temperature. This equation was solved by an iteration process on T_ω ; knowing the wall temperature, it was then possible to calculate the expected saturated Richardson current. In the second region, the sum of convective heat transfer rate plus the heat rate due to electron-ion recombination was sufficiently larger than the radiated heat rate plus the electron cooling to permit assumption that the wall temperature would remain constant at its ablation value.

To obtain the output voltage and output current, equation (9) was utilized. In these calculations, the resistivity of

⁹Sisco, W. B., and J. M. Fiskin, "Basic Hypersonic Plasma Data of Equilibrium Air for Electromagnetic and Other Requirements," Planetary and Space Science, Vol. 6, p. 47-73.

the plasma was neglected. The difference in work functions, $\phi_e - \phi_a$, was obtained for graphite from experimental data to be in approximately -0.4 e.v. The current, I , was based on generator operation near the region of maximum power. For graphite, the current ratio, I/I_s , for this condition was 0.1748. The low value of this ratio as compared to the theoretical value of 0.21 was mainly due to the effect of the negative term $\phi_e - \phi_a$.

A typical set of the computed results for $\theta = 30^\circ$, $W/C_D A = 100$, $\phi_e = 4.7$ e.v., $A_o = (60.2)(10)^4$ amps, and $\phi_e - \phi_a = -.4$ e.v. are shown in Table 1.

Spatial Configurations

The requirements of maximum power output per unit volume and minimum collector heating can be satisfied by means of a hemispherical shell attached to a cylindrical body. Figure 2 shows a cross-sectional view.

The radius of the hemispherical shell in the meridional plane should be large when compared to the diameter of the cylinder. This is needed in order to have a high convective heat transfer rate and a high ion density at the emitter. The length of the separator should be made as short as possible. This assumes the insulator to be a poor heat conductor. By decreasing the length, the resistivity of the plasma near the collector can be near enough the forward end of the re-entry body to permit the electron density to still be sufficiently high.

From the graphs given by Lees, the heating rate is practically a constant along the cylindrical portion of the body. Therefore, even though the length of the separator is short, the convective heat transfer rate to the collector should not increase.

To assure that the emitter is operating at or near its ablating temperature, the nose shell should be very thin. This will decrease the heat capacity of the emitter as well as decrease the total weight of the generator. The collector, however, should have a high enough heat capacity to prevent any back current.

Experimental Models

Due to the large number of problems that arise in construction of the hypersonic plasma thermionic generator, it was decided that a large portion of the research program would be devoted to a feasibility study. In addition to showing feasibility, the experimental results would be used to verify to some degree the fundamental assumptions used in the foregoing analysis.

For simplicity, it was decided to construct models for which hypersonic flow characteristics had been either solved analytically or obtained experimentally. The basic problem was to study the device from an electrical point of view.

The emissive materials used in the models were thoriated tungsten, tungsten, molybdenum, and graphite. The same group of materials was utilized for the collector. The insulators were composed of 96% alumina. This material possesses a very high resistivity and very poor ablating characteristics.

Experimental Apparatus

The apparatus used to study the hypersonic plasma thermionic generator is built around an evacuated chamber. The chamber was fitted with a large reinforced window which permitted detailed viewing of the generator in operation. The enclosure of the model in the chamber allowed one to control, to some degree, the environmental conditions.

Plasma Generator

A Giannini Plasmadyne arc plasma generator model M-4 was utilized for all tests. This generator has a maximum capacity of 120 kilowatts.

Hypersonic Nozzle

A conical nozzle with an area ratio of 3.88 from outlet to throat was utilized for all tests. The nozzle was theoretically designed for a mach number of 3.4. In actual operation, the mach number was closer to 2.

Experimental Procedure

The arc plasma was turned on without the model in the jet. This was felt necessary since a considerable amount of copper vapor was contained in the plasma when the power was first turned on. The power was then brought up to the desired value and the model lowered into the stream.

The short circuit current was the first parameter to be measured. Approximately 20 seconds would elapse before the generator and lead-in wires reached thermal equilibrium. After reaching equilibrium, the current would reach a steady state value. A variable resistive load was then utilized for obtaining the volt-ampere curve of the model.

The saturated Richardson current plus ion current at the emitter was obtained by applying a variable positive potential on the collector. This measurement was quite sensitive due to the fact that, if the potential was too high, an arc would form between emitter and collector. When this condition occurred,

excessive currents would flow. The ion current at the collector was measured by simply reversing the battery potential and current switch. All measurements were made with the system in a floating condition.

The following quantities were measured:

1. The net current existing with a variable resistive load.
2. The saturated Richardson current plus ion current at the emitter.
3. The ion current at the collector.
4. The potential difference between emitter and collector.
5. The potential difference across the battery.
6. The arc chamber pressure.
7. The test chamber pressure.
8. The input power to the arc plasma.
9. The flow rate of the gas.
10. The elapsed time for a complete operation at one input power level.
11. The water temperature at the input and output.
12. The water pressure at input and output.
13. The flow rate of water.

Experimental Results

Table 2 shows experimental results obtained with a graphite emitter and graphite collector. Table 3 shows the corresponding calculated results. Figure 4 shows the output voltage versus current and Figure 5 shows a plot of power versus current.

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picked up this increase in energy from the acceleration of the emitter sheath potential, V_e , or else it was obtained from the collision process in the gas.

The difference in work function, $\phi_e - \phi_a$, was negative for all graphite emitters and collectors except one. This would seem to indicate that the work function of this material decreases as the temperature increases. Graphite, being a semiconductor, will have an increase in the number of electrons in the conduction band as the temperature rises. The Fermi level will therefore move toward the conduction band, resulting in a lower work function.

The one exception occurred at a very high input power to the plasma. The difference in work function for this case was zero. A possible explanation of this condition is the rise in temperature of the collector. This temperature increase, which was observable by the glow of the collector body, results also in a decrease of the work function.

Tables 4 and 5 show the results of a thoriated tungsten emitter and graphite collector. Two rather surprising facts occurred when the $\ln I$ versus output voltage curve was plotted. The first was a drastic drop in electron temperature, and the second was the difference, $\phi_e - \phi_a$, as a positive number.

A possible explanation of this condition would be the decrease in the accelerating emitter sheath potential. Another factor which could decrease the electron temperature is the large number of tungsten atoms in the gas. As previously indicated, tungsten was deposited on the insulator as well as

on the collector. Since the tungsten atoms are coming from the emitter, their temperature is considerably lower than the surrounding gas. Their effect should then be to cool the plasma. The cooling effect did in fact increase the resistivity of the gas. This was observable to some degree by the tendency of the $\ln \gamma$ versus output voltage plot to curve upward at low values of load impedance.

The value of the ion current at the emitter was obtained by first calculating the ion density at the collector from I_{p2} . The ion density at the stagnation point was assumed to be approximately 1% the argon density existing at that point. This percentage was obtained by spectographic means.¹¹ An inspection of the theoretical values of ion density existing along the body, as obtained by various authors revealed that the average value was smaller by a factor of 10 over the emitter surface relative to the value at the stagnation point. This was fairly consistent for the emitter areas of 10 cm² utilized in this experiment. Knowing the density and temperature, it was then possible to calculate the ion flux.

The highest saturated current density attained was 1.423 amps/sq cm for an emitter temperature of 2288.5° K. Correspondingly, the highest power density obtained was 0.45 watts/ sq cm. Due to the melting of set screws utilized for holding the graphite emitters, it proved impossible to attain the current density corresponding to the ablating temperatures.

¹¹See reference 10.

APPARATUS, METHODS AND CONCLUSIONS

Emissive Materials

In choosing the emissive materials, the following factors were considered:

1. The emitter should be a material producing a high saturated Richardson electron current. The large emitted current gives an increase in power output as well as an increase in electron cooling. Since the ion density surrounding the emitter must be sufficient to overcome the electron space charge cloud caused by electron emission, a lower limit is imposed on the work function of this material.
2. The emitter should have good ablating properties since the convective heat rate is normally well above the heat capacity of a thin sheet material and the heat radiated from the nose.
3. The material should be reasonably machinable.
4. The material should possess a high coefficient of emissivity, a high heat capacity per unit weight, and be a poor heat conductor.
5. The material should be chemically stable when exposed to high temperature air.
6. The extremely low resistivity of the generator means that the emitter and collector material should be good electrical conductors.

Of the materials tested, graphite was the only one which met to some degree the required properties. This material, however, does possess two fairly serious drawbacks, namely:

1. Low emitting capabilities.
 2. Lowering of the work function with respect to temperature.
- Both conditions seriously limit the power output.

Thoriated tungsten and tungsten are chemically unstable in high temperature air. This instability was pronounced during the experiment. With the use of either a thoriated tungsten or a tungsten emitter or collector, a bluish compound would cover the surface of these materials. If the oxygen content was high enough, a yellowish deposit would then plate itself on top of the first deposit. The bluish material was always present after the generator had been in operation. The yellowish deposit was accidentally discovered when an air leak occurred in the chamber. The leak evidently caused a sufficient increase in the oxygen content to precipitate this compound. A chemical analysis of these compounds indicated that both were tungsten trioxide. The yellowish material possessed a very high resistivity, and therefore seriously affected the operation of the generator. The bluish material performed more like a semiconducting compound in that its resistivity was higher than the tungsten metal but was not high enough to be considered as an insulator. The main effect of this particular compound seemed to be in a slight increase in the work function of thoriated tungsten and a decrease in the work function of tungsten.

Thoriated tungsten and tungsten also possess another serious drawback. As the temperature of the nose approaches

2000° K, both of these materials vaporize at a fairly high rate. The insulator, being considerably cooler, has a thin film of tungsten deposited on its surface. After two or three minutes of operation, an insulator of 1/2 inch in length is sufficiently covered so as to cause a low impedance path between emitter and collector.

Another factor is that these materials lose their shape as the temperature begins to exceed 2500° K.

Molybdenum, which was also tried as an emitter and collector, proved to be chemically unstable. This material has a very high chemical reaction rate. After five or ten seconds of operation, the collector was sufficiently covered with an insulating compound to completely prevent any electron flow.

Table 1

Y (ft)	V(ft/ sec)	q_s (BTU/ sec ft ²)	q_{i-e}	$T_g^{\circ}K$	n	J_i (amps/ sq ft)	I_s (amps/ sq ft)	I (amps/ sq ft)	V(volts/ sq ft)	P(watts/ sq ft)
300000	24999	1387	.607	5700	(4)(10) ¹²	45.5	12.25	0	.117	0
290000	24998	1751	.61	5800	(4)(10) ¹²	46.0	50.9	8.89	.121	1.08
280000	24998	2211	.914	5800	(6)(10) ¹²	68.7	200.0	35.0	.197	6.89
270000	24997	2792	1.22	5800	(8)(10) ¹²	92.0	667.0	116.3	.290	33.7
260000	24996	3525	1.535	5900	(1)(10) ¹³	115.7	5500.0	960.0	.365	351.0
250000	24994	4452	3.09	6000	(2)(10) ¹³	233.0	6300	1100	.374	412.0
240000	24990	5621	6.3	6200	(4)(10) ¹³	475	6300	1100	.375	413
230000	24985	7096	9.6	6400	(6)(10) ¹³	723	6300	1100	.372	410
220000	24977	8955	12.9	6500	(8)(10) ¹³	971	6300	1100	.362	398.5
210000	24964	11294	16.25	6600	(1)(10) ¹⁴	1225	6300	1100	.354	390
200000	24944	14230	16.4	6700	(1)(10) ¹⁴	1235	6300	1100	.365	402
190000	24911	17901	16.4	6700	(1)(10) ¹⁴	1235	6300	1100	.365	402
180000	24859	22462	32.3	6500	(2)(10) ¹⁴	2440	6300	1100	.267	294
170000	24777	28072	65.4	6700	(4)(10) ¹⁴	4920	6300	1100	.205	225.5
160000	24647	34859	100.5	7000	(6)(10) ¹⁴	7550	6300	1100	.182	200.5
150000	24440	42846	170.5	7300	(1)(10) ¹⁵	12870	6300	1100	.152	167.2
140000	24114	51810	347.0	7500	(2)(10) ¹⁵	26100	6300	1100	.114	125.3
130000	23602	61039	668.0	7000	(4)(10) ¹⁵	50400	6300	1100	.054	59.4
120000	22807	68982	1003.0	7000	(6)(10) ¹⁵	75600	6300	1100	.043	47.2
110000	19992	62741	1307.0	6700	(8)(10) ¹⁵	98500	6300	1100	.037	40.7
100000	17923	54807	307.0	5900	(2)(10) ¹⁵	23100	6300	1100	.006	6.6
90000	15219	40675	119.5	5600	(8)(10) ¹⁴	9000	6300	1100	.057	62.7
80000	11902	23821	.814	4600	(6)(10) ¹²	61.0	6300	1100	.209	230.0

Table 2

Experimental Results Hypersonic Plasma Thermionic Generator

Run No. 174

Date: August 6, 1962

Δr : .05 μ

Insulator length: 1/2 inch

Model located 1 inch from the nozzle.

I (amps)	V (volts) Measured	V (volts) Corrected	Power (watts)
33.3	-5.63	-3.97	
31.3	-4.75	-3.19	
29.14	-3.75	-2.30	
25.8	-2.875	-11.583	
9.24	.075	.536	4.95
8.40	.30	.720	6.05
7.21	.55	.91	6.57
5.80	.775	1.065	6.18
4.72	1.00	1.236	5.84
3.58	1.26	1.44	5.16
2.90	1.41	1.555	4.52
2.32	1.565	1.685	3.91
1.78	1.655	1.744	3.10
1.00	1.855	1.905	1.905
.7	1.940	1.975	1.383
0	2.15	2.15	0

Table 3

Computed Results Hypersonic Plasma Thermionic Generator

Material: Graphite Emitter and Graphite Collector.

$I_s + I_{p1} : 33.3$ amps

NOTE: Corresponds to run No. 174

$I_{p2} : 6.5$ amps

I			$\frac{kT_e}{e}$	$\phi_e - \phi_a$	I_r	V
33.3	3944	-8.25	-10.35	0	0	-10.35
31.3	-19.0	-2.94	-3.69	0	0	-3.69
29.14	-8.6	-2.15	-2.7	0	0	-2.7
25.8	-4.32	-1.465	-1.84	0	0	-1.84
9.24	-1.521	.42	.527	0	0	.527
8.40	1.67	.513	.645	0	0	.645
7.21	1.9	.641	.806	0	0	.806
5.80	2.26	.802	1.008	0	0	1.008
4.72	2.55	.937	1.176	0	0	1.176
3.58	2.95	1.082	1.36	0	0	1.36
2.90	3.22	1.17	1.47	0	0	1.47
2.32	3.51	1.253	1.576	0	0	1.576
1.78	3.82	1.34	1.685	0	0	1.685
1.00	4.35	1.47	1.845	0	0	1.845
.7	4.53	1.51	1.895	0	0	1.895
0	5.16	1.64	2.06	0	0	2.06

To obtain T_e

$$\frac{e}{kT_e} = \frac{4.35 - 2.55}{1.905 - 1.236} = .798;$$

$$T_e = 14520^\circ K ,$$

Table 4

Experimental Results from Group 3

Run No. 132

Date: July 23, 1962

$\Delta r = .043$

Insulator length: 1/2 inch

Model located 1 inch from the nozzle.

I (amps)	V (volts) measured	V (volts) corrected	Power (watts)
6.15	-2.45	-2.19	
5.30	-1.32	-1.092	
3.78	- .3	- .138	
3.56	.05	.203	.722
2.95	.43	.557	1.645
2.15	.865	.958	2.06
1.80	1.00	1.0774	1.942
1.27	1.25	1.305	1.61
.82	1.375	1.410	1.157
.3	1.565	1.578	.473
.17	1.64	1.647	.280
0	1.73	1.73	0

Table 5

Computed Quantities Hypersonic Plasma Thermionic Generator

Material: Thoriated Tungsten Emitter and Graphite Collector

$I_s + I_{p1}$: 6.15 amps

NOTE: Corresponds to run No. 132

I_{p2} : .98 amps

I		ln	$\frac{kT_e}{e}$ ln	$\varphi_e - \varphi_a$	I_r	V
6.15	-99	-4.6	-2.225	.83	0	-1.395
5.30	-7.39	-2.0	-.967	.83	0	-.137
3.78	-2.02	-.703	-.339	.83	0	.49
3.56	-1.752	-.562	-.2715	.83	0	.56
2.95	-1.228	-.2055	-.0980	.83	0	.74
2.15	1.28	.247	.1192	.83	0	.95
1.80	1.565	.4475	.216	.83	0	1.046
1.27	2.17	.775	.3745	.83	0	1.2045
.82	3.875	1.352	.653	.83	0	1.483
.3	4.57	1.52	.734	.83	0	1.564
.17	5.2	1.65	.796	.83	0	1.626
0	6.27	1.835	.886	.83	0	1.716

To obtain T_e :

$$\frac{e}{kT_e} = \frac{\ln 6.27 - \ln 4.57}{1.73 - 1.578} = 2.07 ;$$

$$T_e = 5600^\circ K .$$

FIGURE 1

FIGURE 2

INTERSECTION POINTS

Curve 1 $I/I_s = .218$

Curve 2 $I/I_s = .24$

Curve 3 $I/I_s = .242$

Curve 1 $I_{p1} = I_{p2} = 0$

Curve 2 $I_{p1} = I_{p2} = .2I_s$

Curve 3 $I_{p1} = I_{p2} = .4I_s$

Model 3

Output Current

vs

Output Voltage

FIGURE 4

FIGURE 5

FIGURE 6