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HEAT-SHIELDED MAGNETICALLY
CHANNELED PLASMA HEAT CONVERTER

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ABSTRACT

A design for a highly efficient thermionic converter is described which utilizes a permeable heat shield and a homogeneous magnetic field normal to the cathode and anode surfaces to minimize the radiant power loss without appreciably decreasing the electrical power output. The permeable heat shield consists of thin, close-spaced foils perpendicular to the cathode and anode surfaces. Radiant power transfer is expressed as a function of the spectral emissivities of the cathode and anode surfaces and the interfoil and interelectrode spacings. The heat shield is biased positive with respect to the cathode and anode surfaces to prevent positive ion loss, and, in conjunction with the normal homogeneous magnetic field, channels the electrons and ions to the anode. The required heat-shield positive bias is deduced and given as a function of the parameters of the converter. The energy conversion efficiencies attainable with this converter appear to be close to the Carnot efficiency.

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I. INTRODUCTION

The cathode-anode radiant power transfer causes the major power loss in thermionic energy converters of today¹⁻⁶ and an appreciable reduction of this loss would greatly increase converter efficiency. In Section II is described qualitatively the geometry and operation of the Heat-Shielded Magnetically Channeled Plasma Heat Converter (HC), a design which promises appreciable reductions in radiation losses.⁷ In Section III the radiant power transfer in the HC geometry is derived as a function of converter parameters. Required heat-shield bias, needed for channeling the plasma, is given in Section IV as a function of the parameters of the converter. Converter efficiency evaluation is given in Section V, and an engineering design of the heat shield is presented in the appendix.

II. GEOMETRY AND OPERATION

Many efficient geometric heat-shield arrangements are possible based on the principles presented in this paper. The geometry presented is believed to be the most practical.

Heat shield geometry is shown in Figs. 1 and 2. Separated banks of thin, closely spaced, long, narrow strip foils are aligned with their planes perpendicular to the cathode and anode surfaces. The aperture width or distance between foil planes is D , the interelectrode spacing is L , the average strip spacing or distance between foil edges in banks is g , and the strip width is w . The

ratio g/w is much less than one. The strips can occasionally touch across the gap, g , but total conduction will be sufficiently low so that it can be neglected when compared with the radiant power transfer.

The ratio of the aperture width, D , to the interelectrode spacing, L , has the condition

$$r = D/L \ll 1 \quad (\text{II-1})$$

The radiant power transfer of the heat-shielded system as a function of r and the cathode and anode emissivities, is given in Section III.

A magnetic field channels the electrons from the cathode through the heat shield to the anode. The average cyclotron radii of electrons emitted isotropically from a cathode at 2000°C in magnetic fields of 1000 and 5000 gauss are 2.2 and 0.44 mils, respectively. The magnetic field in a practical device can be obtained from a permanent magnet or an electromagnet. Preliminary calculations show that for an electromagnet only a few percent of the electrical power output need be used for the magnetic field.

The ions in the simple plasma diode are conveniently provided by surface ionization of the ambient vapor at the cathode surface. We assume that the ions in the HC geometry are provided by cathode surface ionization, though the ions may also be provided by auxiliary ion injection, as in the simple plasma diode.

The ambient vapor will also become ionized on the hot heat shield near the cathode. The vapor will coat the anode and the cool portion of the heat shield thereby depressing the work functions of those surfaces. If ions arrive at these low-work-function surfaces they will be re-emitted as atoms.

The surface potential of the cathode and anode are assumed equal for optimum power output. A positive bias placed on the low-work-function surfaces will not allow ions to reach these sections. The necessary positive potential for the coated heat-shield section is calculated in Section IV.

Geometries having hexagonal, circular, or square apertures may be used; the principles discussed in this paper are the same for all the geometries.

III. RADIANT POWER TRANSFER

We have the condition at the cathode and anode surfaces

$$F = (1 - \alpha)G + eCT^4, \quad (\text{III-1})$$

where F = emitted radiant power density at the surface,

G = incident radiant power density on the surface,

C = Stefan-Boltzman constant,

T = absolute temperature of the surface,

α = the absorptivity of the surface,

e = emissivity of the surface.

When the incident radiation has a black body spectrum of temperature T_i , we have

$$\alpha(T_i, T) = \frac{\int_0^\infty e_\lambda(T) J_\lambda(T_i) d\lambda}{\int_0^\infty J_\lambda(T_i) d\lambda} \quad (\text{III-2})$$

where e_λ is the spectral emissivity of the surface at T , and $J_\lambda(T_i)$ is the spectral radiant power density for black-body radiation at temperature T_i .

The radiant power transfer per unit area from cathode to anode, is

$$H_h = (\alpha_c/1 - \alpha_c) \left[\left(e_c CT_c^4 / \alpha_c \right) - F_c \right] \quad (\text{III-3})$$

$$= (\alpha_a/1 - \alpha_a) \left[F_a - \left(e_a CT_a^4 / \alpha_a \right) \right] \quad (\text{III-4})$$

$$= \sigma (F_c - F_a), \quad (\text{III-5})$$

where e_c , α_c , T_c , and F_c , and e_a , α_a , T_a , and F_a are the total emissivity, absorptivity, temperature, and radiant power density of the cathode and anode surfaces, respectively; σ is defined by Eq. (III-5) and is equal to the radiant

power transfer per unit area across the interelectrode space divided by the difference between the emitted radiant power densities of the cathode and anode surfaces.

Using Eq. (III-5) to eliminate F_c and F_a in Eqs. (III-3) and (III-4) we obtain

$$H_h = C \left(\frac{1}{a_c} + \frac{1}{a_a} + \frac{1}{\sigma} - 2 \right)^{-1} \left(\frac{e_c}{a_c} T_c^4 - \frac{e_a}{a_a} T_a^4 \right). \quad (\text{III-6})$$

The radiation incident on the cathode and anode can be characterized by black-body spectra having temperatures T_{ic} and T_{ia} respectively. We then have for Eq. (III-6)

$$H_h = C \left[\frac{1}{a_c(T_{ic}, T_c)} + \frac{1}{a_a(T_{ia}, T_a)} + \frac{1}{\sigma} - 2 \right]^{-1} \left[\frac{e_c(T_c)}{a_c(T_{ic}, T_c)} T_c^4 - \frac{e_a(T_a)}{a_a(T_{ia}, T_a)} T_a^4 \right] \quad (\text{III-7})$$

where $a(T_i, T)$ is given by Eq. (III-2).

In the simple diode T_{ic} and T_{ia} are both approximately equal to T_c , and σ is equal to one. To evaluate H_h in the HC geometry, we must evaluate σ , T_{ia} and T_{ic} .

Let us now determine the radiation transfer from cathode to anode, cathode to heat shield, heat shield to heat shield, and heat shield to anode. Let A be the cross-sectional area of an aperture in the heat shield and P its perimeter. Let S be the distance in units of the aperture-width D between a particular emitter and the region where its radiant flux is intercepted along the aperture. The heat transfer coefficients^{8,9} are: $f_{AA}(S)$ is the fraction of the radiation emitted from one cross-sectional area which is intercepted by another cross-sectional area at a distance SD along the aperture; $f_A(S)$ is the fraction of the radiation emitted from a differential element of area PdS around the wall of the aperture which is intercepted by a cross-sectional area A at a distance SD along the aperture; $f(S)$ is the fraction of the radiation emitted

from a differential element of area PdS intercepted by another differential area PdS at a distance SD along the aperture.

The relationships between f , f_A , and f_{AA} are:

$$f(S) = -f_A'(S) = \frac{D}{2} f_{AA}''(S) , \quad (III-8)$$

$$f_A(S) = -\frac{D}{2} f_{AA}'(S) , \quad (III-9)$$

where the primes designate the first and second derivatives with respect to S .

We assume that Lambert's cosine law holds. The heat transfer coefficient $f_{AA}(S)$ is then

$$f_{AA}(S) = (S^2 + 1)^{1/2} - S , \quad (III-10)$$

which has the value for large S

$$f_{AA}(S) = 1/2S \quad S \gg 1 . \quad (III-11)$$

Using Eqs. (III-8), (III-9), and (III-10), the coefficients f_{AA} , f_A , and f are plotted in Fig. 3.

The emitted flux density from a point on the wall of the aperture in excess of F_a , is

$$E_S = (F_c - F_a) f_A(S) + \int_0^S E_{S'} f(S - S') dS' + \int_S^{L/D} E_{S'} f(S' - S) dS' . \quad (III-12)$$

The approximate relation for E_S that satisfies Eq. (III-12) is

$$E_S = (F_c - F_a) \left[(1 - \epsilon) - (1 - 2\epsilon) Sr \right] \quad (III-13)$$

where r , is given by Eq. (II-1) and ϵ is a constant. Substituting Eq. (III-13) in Eq. (III-12) and solving for ϵ to third order in r ,

$$\epsilon = r \left[1 - (5/2)r + (13/2)r^2 \right] . \quad (III-14)$$

Now σ , equal to $H_h/(F_c - F_a)$ from Eq. (III-5), in terms of the heat transfer coefficients is

$$\sigma(r) = f_{AA}(r^{-1}) + 2 \int_0^{1/r} \left\{ 1 - \left[E_s / (F_c - F_a) \right] \right\} f_A(S) dS, \quad (\text{III-15})$$

or, using Eq. (III-13),

$$\sigma(r) \approx f_{AA}(r^{-1}) + 2 \int_0^{1/r} \left[\epsilon + (1 - 2\epsilon)Sr \right] f_A(S) dS, \quad (\text{III-16})$$

or to third order in r ,

$$\sigma(r) = r \left[(5/4) + (1/2) \ln(2/r) \right] - r^2 \left[(5/2) + \ln(2/r) \right] + r^3 \left[(105/16) + (5/2) \ln(2/r) \right]. \quad (\text{III-17})$$

In Fig. 4, $\sigma(r)$ is plotted as a function of r .

The heat shield appears to the anode and cathode surfaces as a black body at temperatures T_{ia} and T_{ic} , respectively, or from Eq. (III-1)

$$T_{ia} = \left[\frac{e_a(T_a) T_a^4}{\alpha_a(T_{ia}, T_a)} + \frac{1}{\alpha_a(T_{ia}, T_a)} \frac{H_h}{C} \right]^{1/4}, \quad (\text{III-18})$$

$$T_{ic} = \left[\frac{e_c(T_c) T_c^4}{\alpha_c(T_{ic}, T_c)} - \frac{1}{\alpha_c(T_{ic}, T_c)} \frac{H_h}{C} \right]^{1/4}. \quad (\text{III-19})$$

For condition (II-1), T_{ic} approaches T_c . Setting $T_{ic} = T_c$ in the expression on the right of Eq. (III-19), and in Eqs. (III-7) and (III-18), we obtain

$$\frac{H_h}{C} \approx \left[\frac{1}{e_c(T_c)} + \frac{1}{\alpha(T_{ia}, T_a)} + \frac{1}{\sigma} - 2 \right]^{-1} \left[T_c^4 - \frac{e_a(T_a) T_a^4}{\alpha_a(T_{ia}, T_a)} \right], \quad (\text{III-20})$$

$$T_{ia} \approx \left[\frac{e_a(T_a) T_a^4}{\alpha_a(T_{ia}, T_a)} + \frac{1}{\alpha_a(T_{ia}, T_a)} \frac{H_h}{C} \right], \quad (\text{III-21})$$

where H_h in Eq. (III-21) is taken from Eq. (III-20) and

$$T_{ic} \approx \left[T_c^4 - \frac{1}{e_c(T_c)} \frac{H_h}{C} \right]^{1/4}. \quad (\text{III-22})$$

For numerical evaluation, the cathode and anode surfaces are assumed to have the radiant emissivities of tungsten. Spectral emissivities for various

temperatures were obtained from a curve constructed from data taken from references 10 and 11. For long wavelengths and at a given temperature, the spectral emissivity is approximately inversely proportional to the square root of the wavelength. Spectral emissivities for very long wavelengths were obtained using this approximation. $\alpha(T_i, T)$ given by Eq. (III-2) is plotted in Fig. 5 for T equal to 400°K and 1000°K. The total emissivity, $e(T_i)$ obtained from reference 12, and $e(\sqrt{T_i T})$, an often-used approximation for $\alpha(T_i, T)$, evaluated for $T = 400^\circ\text{K}$, are also plotted on the same figure. It may be noted that $e(T_i, T)^{1/2}$ is a poor approximation to $\alpha(T_i, T)$.

Using Eqs. (III-20), (III-21), and (III-22), T_{ia} , T_{ic} , and $H_h/C(T_c^4 - T_a^4)$ are plotted in Figs. 6, 7, and 8, respectively.

IV. SURFACE POTENTIAL OF THE HEAT SHIELD

The surface potential of the heat-shield foils is kept at cathode potential when the ratio, R , of ions to neutrals emitted from the surface, is very much less than one. The foils are biased to a potential $(V_p - V_c)$ positive with respect to the cathode surface when $R \gg 1$, where V_c is the work-function depression of the surface. This bias, which will be calculated shortly, is the minimum necessary to make the potential everywhere inside the apertures of the heat shield always positive or equal to zero. The surface potential of the cathode and anode are assumed equal for optimum power output.

Further, we assume that collisions are negligible and that the temperature of the ions is approximately T_c . The average electron cyclotron radius is taken to be much less than D , while that of the ions is much greater than D . Hence, the electrons are strongly collimated by the magnetic field while the ions are negligibly affected. In the region of the heat shield where $R \ll 1$, all ions of energy greater than eV_p are absent, since they have reached the heat shield and have become neutralized.

Let x be the distance from the midplane of the aperture in a region where $R \ll 1$. The minimum potential occurs for $x = 0$, which is equal to the cathode surface potential for minimum positive bias.

$$\text{Let} \quad \eta(x) = eV(x)/kT_c \quad (\text{IV-1})$$

where e and k have their usual designations.

We assume for this derivation that the electron charge density is entirely due to cathode emission. When anode emission is appreciable, this charge density may be approximated as due to the sum of the cathode and anode electron current densities.

For the electrons channeled by a magnetic field, the electron current density, $\rho_e(x)$ as a function of x , for $V \geq 0$, is

$$\rho_e(x) = -\rho_e(C) \left[1 - (\text{erf } \eta^{1/2}) \right] (\exp \eta), \quad (\text{IV-2})$$

$$\rho_e(C) = J_c (\pi m_e / 2kT_c)^{1/2}, \quad (\text{IV-3})$$

where $\rho_e(C)$ is the electron density at the cathode surface, J_c the cathode current density, and m_e the electronic mass.

The ion density is given by

$$\rho_i(x) = \rho_i(0) \exp(-\eta), \quad (\text{IV-4})$$

where $\rho_i(0)$ is the ion density at the middle of the aperture.

The ion density $\rho_i(0)$ differs from the ion density at the cathode surface, $\rho_i(C)$, by the factor $\left[1 - \exp(-\eta_p) \right]$ as a result of ion interception, and a factor h , comparable to unity, as a result of ion reflection and focusing.

We have then

$$\rho_i(0) = h \left[1 - \exp(-\eta_p) \right] \rho_i(C) = a \rho_i(C), \quad (\text{IV-5})$$

$$a = h \left[1 - \exp(-\eta_p) \right]. \quad (\text{IV-6})$$

We assume at the cathode surface that $\rho_i(C) = -\rho_e(C)$. We then have for the total space charge ρ at the position x

$$\rho = \rho_i + \rho_e = \rho_e(C) \left\{ a \exp(-\eta) - \left[1 - (\operatorname{erf} \eta^{1/2}) \right] (\exp \eta) \right\}. \quad (\text{IV-7})$$

The potential distribution is given by Poisson's equation,

$$\frac{d^2 V}{dx^2} = - \rho(x)/\epsilon_0. \quad (\text{IV-8})$$

We use the normalized distance,

$$\zeta = x \left[2e\rho_e(C)/\epsilon_0 kT \right]^{1/2}. \quad (\text{IV-9})$$

Using Eq. (IV-8) and the fact that dV/dx is equal to zero at x equal to zero,¹³⁻¹⁵ we obtain

$$d\eta/d\zeta = \left[G(\eta, a) - (1 + a) \right]^{1/2}, \quad (\text{IV-10})$$

where

$$G(\eta, a) = (\exp \eta) \left[1 - \operatorname{erf}(\eta^{1/2}) \right] + 2(\eta/\pi)^{1/2} + a(\exp - \eta). \quad (\text{IV-11})$$

The finite ratio of the electron cyclotron radius to the aperture width, the lack of complete homogeneity of the magnetic field and planarity of the foils, cause interception of electrons located a fractional distance $q/2D$ away from the aperture wall. The result is that only ions exist in this laminar volume.

The value of ζ at $x = D/2$, $\zeta_p/2$, is given then by

$$\left[1 - \frac{q}{D} \right] \zeta_p = 2 \int_0^{\eta_1} \left[G(\eta, a) - (1 + a) \right]^{-1/2} d\eta, \quad (\text{IV-12})$$

$$\frac{q}{D} \zeta_p = 2 \int_{\eta}^{\eta_p} \left[K(\eta, a) \right]^{-1/2} d\eta, \quad (\text{IV-13})$$

where

$$K(\eta, a) = a \left[\exp(-\eta) - \exp(-\eta_1) \right] + G(\eta_1, a) - (1 + a). \quad (\text{IV-14})$$

In Fig. 9, ζ_p is plotted as a function of η_p for $h = 1.0$, and $q/D = 0.1$ and 0.

V. CONVERTER EFFICIENCY

We use the previous assumptions that (a) there is a collisionless plasma in the interelectrode volume; (b) the anode and cathode surface potentials are equal; and (c) the electron and ion charge densities are equal immediately in front of the cathode surface. The ratio of the efficiency of the converter to the Carnot efficiency neglecting all external losses, is

$$E' = \frac{(\phi_c - \phi_a)(J_c - J_a)/(1 - \theta)}{\phi_c(J_c - J_a) + (2k/e)[T_c J_c - T_a J_a] + H_h + (2k/e)(R^{-1} + 1)(m_e/m_i)^{1/2}[T_c J_c - T_a J_a]}, \quad (V-1)$$

where ϕ_c , J_c , and T_c , and ϕ_a , J_a , and T_a are the cathode and anode work functions, emitted current densities, and temperatures, respectively; θ is equal to T_a/T_c ; H_h is the radiant power transfer given in Section III; R is the ratio of ions to neutrals emitted from the cathode, and (m_e/m_i) is the electron to ion mass ratio.

R , the ratio of ions to neutrals emitted from a surface where there is negligible ion or atom reflection, is given by the Saha equation for an alkali vapor

$$R = (1/2) \exp[(\phi - V_c - I)/kT], \quad (V-2)$$

where ϕ_c is the work function of the bare surface,

V_c is the work-function depression of the surface due to adsorption,

I is the ionization potential of the alkali vapor,

and T is the temperature of the surface.

The numerator of (V-1) is the net electrical power output and is equal to the net voltage output, $(\phi_c - \phi_a)$, times the net current output, $(J_c - J_a)$. The denominator contains the power inputs.

The energy loss due to the interception of electrons by the heat shield is approximately $(J_c + J_a)qV_p/D$ where q/D is the fraction of the electrons emitted from the cathode and anode which are intercepted by the heat shield, and V_p is given in Section IV. For $q/D = 0.1$, $(J_c + J_a)qV_p/D$ is on the order of a few tenths of one percent of the total power input and can thus be neglected.

The significant power inputs are then:

$\phi_c(J_c - J_a)$ the net power used by the electrons to surmount the cathode work function,

$(2k/e)[T_c J_c - T_a J_a]$ the power contained in the kinetic energy of the electrons,

H_h the radiant power transfer, and

$(2k/e)(R^{-1} + 1)(m_e/m_i)^{1/2} [T_c J_c - T_a J_a]$ the net power contained in the ions and neutrals.

We have from Richardson's equation:

$$\begin{aligned} J_c &= 120 T_c^2 \exp(-e\phi_c/kT_c) \text{ amp/cm}^2, \\ J_a &= 120 T_a^2 \exp(-e\phi_a/kT_a) \text{ amp/cm}^2. \end{aligned} \quad (V-3)$$

Let

$$\eta_c = e\phi_c/kT_c \text{ and } f = J_a/J_c, \quad (V-4)$$

then

$$e\phi_a/kT_a = \eta_c - \ln(f/\theta^2). \quad (V-5)$$

Multiplying numerator and denominator of (V-1) by $e/kT_c J_c$ and rearranging, we obtain

$$\begin{aligned} E' &= \frac{\eta_c(1-f)}{(\eta_c+2)(1-\theta)} \\ &\times \left[1 - \theta + \frac{\theta}{\eta_c} \ln\left(\frac{f}{\theta^2}\right) \right] \left[1 - \frac{f}{(\eta_c+2)}(\eta_c+2\theta) + \frac{\eta_c}{\eta_c+2} \frac{H_h}{J_c \phi_c} + 2(R^{-1}+1)(m_e/m_i)^{1/2} (1-f\theta) \right]^{-1} \end{aligned} \quad (V-6)$$

E' is plotted in Fig. 10 as a function of T_c for $T_a = 1000^\circ\text{K}$, $\phi_c = 3.5$ volts, $r = 0.02$, and for the value of f maximizing E' . The ambient vapor is taken as cesium. The corresponding ϕ_a of the f maximizing E' is given in Fig. 10 for a number of temperatures.

Figure 10 shows that the Heat-Shielded Magnetically Channeled Plasma Heat Converter may attain a conversion efficiency close to that of Carnot.

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APPENDIX. A PRELIMINARY DESIGN OF THE HEAT SHIELD

A. Description

As shown in Fig. 11, the heat shield consists of thin refractory metal ribbons lying in closely spaced parallel planes perpendicular to the cathode surface (views B and C). Ceramic rods, extending through the heat shield, constrain the ribbons to their proper planes.

Spring tension holds each ribbon taut to compensate for the thermal expansion (views A and B). Ribbons are subassembled into frames which are thermally and electrically isolated.

B. Design Details

Ribbons of width, w , and thickness, t , are formed from a wire of diameter, d . A spring whose outer diameter is less than, w , is coiled at each end of the ribbon.

The ceramic rods (views B and C) are supported at their ends such that their axes are parallel and coplanar.

Ribbons strung between two support plates constitute a frame. The ribbons are mechanically spaced and joined to the support plates by a resistance welding machine. An aluminum-oxide layer is sprayed on the support plates by a plasma jet. This layer insulates the frame and controls the frame spacing. At assembly, the frames are accurately indexed and rigidly clamped.

C. Representative Dimensions and Materials

<u>Dimensions</u> (in inches)	Aperture width, D	= 0.030
	Ribbon thickness, t	= 0.00065
	Ribbon width, w	= 0.030
	Wire diameter, d	= 0.005
	Spring outer diameter	= 0.020
<u>Materials</u>	Tantalum	- ribbons, springs, and support plates
	Aluminum oxide	- rods and insulation.

MUL-14036

Fig. 1. Cross section of the HC geometry.

MUL-13864

Fig. 2. View of heat shield and anode from the cathode.

Fig. 3. The heat transfer coefficients f_{AA} , f_A , and f as a function of $1/S$.

Fig. 4. The radiant power transfer, σ , divided by the difference of the cathode and anode emitted radiant surface power densities, plotted as a function of r .

Fig. 5. The absorptivity $\alpha(T_i, T)$, the total emissivity $e(T_i)$, and $e(T_i, 400)^{1/2}$ for tungsten, as a function of T_i for $T = 400^\circ\text{K}$, and 1000°K .

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Fig. 6. T_{ia} , the effective black-body temperature of the radiation incident on the anode as a function of T_c for $r = 0.1$ and 0.02 at $T_a = 400^{\circ}\text{K}$, and $r = 0.02$ at 1000°K .

Fig. 7. T_{ic} , the effective black-body temperature of the radiation incident on the cathode as a function of T_c for $r = 0.1$ and 0.02 at $T_a = 400^{\circ}\text{K}$, and $r = 0.02$ at 1000°K .

Fig. 8. $H_h / C(T_c^4 - T_a^4)$, the radiant power transfer in the HC geometry divided by the radiant power transfer for a black cathode and anode in a diode geometry, as a function of T_c , for $r = 0.1$ and 0.02 at $T_a = 400^\circ\text{K}$, and $r = 0.02$ at $T_a = 1000^\circ\text{K}$.

Fig. 9. η_p , the reduced surface potential difference between the cathode and the heat shield, as a function of ζ_p , the reduced aperture width, for q/D equal to 0.1 and zero for h equal to unity.

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Fig. 10. E' , the efficiency of the converter in the HC geometry divided by the Carnot efficiency, as a function of T_c for $T_a = 1000^\circ\text{K}$, $\phi_c = 3.5$ volts, $r = 0.02$, and the value of f maximizing E' . The anode work function, ϕ_a , for the f maximizing E' , is given in parentheses for a number of temperatures.

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Fig. 11. Preliminary design of heat shield.

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