Thermionic Energy Conversion Plasmas
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Abstract—The history, application options, and ideal basic performance of the thermionic energy converter are outlined. The basic plasma types associated with various modes of converter operation are described, with emphasis on identification and semi-quantitative characterization of the dominant physical processes and utility of each plasma type. The frontier plasma science issues in thermionic converter applications are briefly summarized.

I. INTRODUCTION

THE thermionic energy converter is a nonmechanical gaseous-electronic device for converting heat directly into electric power by thermionic electron emission. In its simplest form—i.e., the diode shown schematically in Fig. 1—electrons are emitted from a hot electrode and collected by a colder electrode at a higher potential energy (lower electrical potential). Part of the heat removed from the emitter by the evaporating electrons is rejected to the collector by the condensing electrons, and the remaining part is converted into electric power in the load as the electrons return to emitter potential.

Although thermionic converter operation usually is described in physical electronic terms (i.e., as a plasma-electron tube), the heat-power engineer may prefer to consider thermionic energy conversion as a thermodynamic heat engine cycle. The thermionic cycle is similar to a modified Rankine (steam engine) cycle that uses electrons directly as the sole working fluid [1]. The emitter is the "electron boiler" and the collector is the "electron condenser," which develop an electrical pressure (potential) difference to produce electrical work rather than a vapor-pressure difference to produce mechanical work. Although the efficiency of the ideal thermionic converter at practical power densities is about 60% of the Carnot thermodynamic limit, the technology on which present applications is based achieves about 25–35% of Carnot efficiency. Advanced thermionic converter types have been investigated that can more closely approach the ideal converter-efficiency limit.

The purpose of this article is to provide a perspective of the nature and scientific characterization of the unique and remarkable plasmas occurring in the various modes of thermionic converter operation associated with different application requirements. Because of the large number and variety of scientific issues addressed, the detailed qualification and documentation required for a comprehensive review is not possible here. Key publications are cited, however, which include comprehensive review of and reference to the supporting detail.

Table I summarizes the variety of technological options and applications associated with thermionic converters. This article is concerned primarily with the physics of the various types of plasma employed to conform to the constraints of particular options and applications. The various plasma types summarized in Table II will be described and their characteristic advantages identified with particular applications.

II. BRIEF HISTORICAL PERSPECTIVE

The history of thermionic energy conversion and its applications is summarized briefly in Table III. The possibility of using electron emission for energy conversion was recognized by several scientists and inventors after the discovery of thermionic emission by Edison in 1885, the discovery of the electron by Thomson in 1897, and the quantitative physical description of thermionic emission by Richardson in 1902. The confluence of high-temperature materials technology, the development of nuclear heat sources, and the emerging need for efficient and compact electrical power sources in space in the mid-1950's led to the first experimental demonstration of practical levels of thermionic power generation by Marchuk in the USSR in 1956, demonstration of the more practical ignited mode of converter operation by Wilson in the U.S. in 1957, and demonstration of converter operation in the core
of a nuclear reactor by Grover et al. in 1959, all apparently acting independently.

Early consideration was given to the use of thermionic converters in solar and radioisotope space-power systems. By 1965 it was clear that the emerging thermionic technology could not displace the well-established photovoltaic and thermoelectric technologies in these applications. By 1965, however, the basic physics of the ignited mode of converter operation was understood sufficiently, and the practical technology was developed sufficiently, to permit initiation of engineering development of in-core thermionic nuclear reactor systems in the U.S., USSR, West Germany, and France. The multiple modular redundancy and high heat rejection temperature capabilities of in-core thermionic space reactor systems give them inherent and decisive advantages over turboelectric systems in reliability, development cost, and system weight.

The U.S. and USSR took substantially different approaches in thermionic reactor development. The former concentrated on perfecting the thermionic technology through iterative development tests of thermionic fuel element (TFE) modules. The USSR essentially froze the thermionic technology at the 1965 level and proceeded immediately to construct full-scale thermionic reactors for testing. By 1973 the U.S. had achieved its thermionic fuel element lifetime and performance objectives and was planning to construct a test reactor. The USSR, however, began ground testing its low-power TOPAZ thermionic reactors in 1970, and ground-tested eight versions by 1983.

In 1973 the U.S. terminated its entire space nuclear-reactor program, including thermionic reactor development. From 1973 to 1983 U.S. thermionic technology development was directed toward application to fossil-fueled terrestrial power systems. Since performance in the ignited mode of operation that had been used in the reactor application was marginal at the lower temperatures required for fossil-fueled applications, basically new types of converter operation were developed during this period, involving advanced electrode and plasma technology.

In 1983 work was resumed in the U.S. on space nuclear-reactor systems in response to the greatly increased electric power requirements of prospective military space-based systems. Major emphasis has been placed on recovering the 1973 thermionic fuel element technology and extending it to meet the 7–10 y lifetime requirements projected for a variety of military systems [2]. Alternate approaches also were explored for applying advanced converter technology to innovative thermionic reactor systems [3], and for applying advanced very-high-temperature nuclear fuels to achieve the high power densities required in multimegawatt applications [4].
In 1987 and 1988 the USSR announced operation and testing in earth-orbit of two of its 6-kW TOPAZ thermionic reactor systems [5]. The USSR identified thermionic reactor systems as the basis for fulfilling its future space electric-power system requirements into the megawatt region [6].

Because of the continuity and central coherence of its scientific support, the basic physical research on thermionic energy conversion in the USSR has been more coherent, more thorough, and much more completely documented in scientific publications than that in the U.S. The U.S.’s basic work, being tied primarily to a variety of transient engineering development programs, has been chaotic and poorly documented, but has been generally more innovative and more directed toward problem solving as a result.

III. THE IDEAL DIODE THERMIONIC CONVERTER AS A REFERENCE CASE

Before discussion of the plasma effects, it is useful to define the ultimate thermionic converter performance limits imposed by electron emission and heat-transfer processes, independent of any plasma effects. This ideal case thereby serves as a basis for quantitative identification of the plasma-imposed characteristics in subsequent descriptions of practical converter operation.

The motive diagram in Fig. 2 shows the potential energy of an electron as it moves from the emitter to the collector. To be moved from the emitter into the gap, an electron must overcome a potential energy barrier known as the emitter work function \( \Phi_E \). A similar barrier, the collector work function \( \Phi_C \), exists at the collector.

If no collisional or space-charge effects occur in the inter-electrode space (e.g., in a very close-spaced diode), an energy
barrier $V + \phi_c$ must be overcome to move an electron from the emitter across the gap to the collector when the electrode potential energy difference (output voltage) $V$ is greater than the contact potential energy difference $V_0 = \phi_E - \phi_C$, as may be seen in Fig. 2. In this article the term “voltage” refers to the potential energy difference per electron, not to the electrical potential (the potential energy per unit charge). Accordingly, the voltage $V$ in electronvolts (eV) is numerically equal to the potential difference in volts.

The total heat that must be supplied to the emitter is

$$q_E = q_e + q_r + q_L$$

where

$$q_e = J(\phi_E + 2kT_E) = \text{heat removed by electron emission},$$

$$q_r = \sigma \epsilon (T_E^4 - T_C^4) = \text{heat removed by thermal radiation},$$

$$q_L = \text{heat conducted down the emitter lead},$$

$\epsilon = \text{net thermal emissivity of the electrode system} \approx 0.1 - 0.2,$

$\sigma = 5.67 \times 10^{-12} \text{W/cm}^2 \text{K}^4 = \text{Stefan-Boltzmann constant}.$

The energy conversion efficiency is therefore

$$\eta = J(V - V_L)/q_E$$

where $V_L$ is the voltage drop across the emitter lead. It can be shown that for maximum efficiency, $V_L \approx V/10$, $q_L \approx q_E/10$, and $q_e \approx \epsilon q_r$. Maximum efficiency and efficiency at a constant typical current density are given in Fig. 4(b) as a function of emitter temperature, and the power density at maximum efficiency is included in Fig. 4(a) for different collector work functions $\phi_C$. 

The ideal diode equation for output current density $J$ is given by

$$J = AT_E^2 \exp[-(V + \phi_C)/kT_E] \quad \text{for } V > V_0$$

$$J = AT_E^2 \exp[-\phi_E/kT_E] \equiv J_0' \quad \text{for } V < V_0$$

where $A = 120 \text{ A/cm}^2 \cdot \text{K}^2$, $k = (11,600)^{-1} \text{eV/K}$ is the Boltzmann constant, $T_E$ is the emitter temperature, and $J_0'$ is the zero-field, saturation emission current density.

Fig. 3. Comparison of ideal and cesium vapor diode thermionic converter electrical output characteristics (transition points circled).

Fig. 4. Performance equivalent to ideal diode thermionic converter ($V_B = \phi_C$ for ideal diode). Solid lines = maximum efficiency; dashed lines are for $J = 10 \text{ A/cm}^2$.

(a) (b)
functions $\phi_C$. More detailed descriptions of the ideal diode, including the effect of collector emission and the conditions for maximum power and maximum efficiency, are available elsewhere [7].

In a real thermionic converter, electron energy losses in the interelectrode space and electron current scattered back into the emitter both cause a reduction in output voltage from that of an ideal diode converter at a given output current density. These effects can be conveniently characterized by defining a quantity $V_B$, which when substituted for $\phi_C$ in (1) defines the ideal diode equivalent to any given output current $J$ and voltage $V$ at emitter temperature $T_E$; i.e.,

$$J = AT_E^2 \exp\left[-(V + V_B)/kT_E\right].$$

(5)

The back-voltage $V_B$ (also called the "barrier index") therefore characterizes the performance of any real thermionic converter relative to tabulated parametric performance data for the ideal diode converter, with $V_B = \phi_C$; e.g., Fig. 4. It is analogous to the back-EMF in electrical machinery or to the back-pressure in mechanical heat engines.

IV. THERMIONIC CONVERTER PLASMAS

A. Nature of Thermionic Converter Plasmas

An inherent aspect of thermionic converter operation is the existence of a high electron current density between the electrodes, corresponding to a minimum electron density of about $10^{13}\text{cm}^{-3}$ for an output current density of 10 amp/cm². The emission-inhibiting electric field of the resultant electron space charge can be suppressed either by making the interelectrode gap approach the associated Debye length ($\sim 1 \mu$m), or by interposing a plasma of this or higher density between the electrodes at much larger spacings (100-1000 $\mu$m).

Because the sole function of the plasma in a thermionic converter is to transport the electron current efficiently between the electrodes, with a minimum of current attenuation and potential drop, it tends to be nearly equipotential within about a tenth of a volt, to be highly energy and charge conservative, and to be only a few electron mean-free-paths thick. As a result, the thermionic converter plasma is primarily one dimensional, and its state and characteristics are determined primarily by its interaction with the bounding electrode surfaces. It is necessary therefore to characterize this interaction in some detail in order to describe the plasma characteristics.

B. Electrode Work Functions and Emission

The electrode work functions determine both the potential at the boundaries of the interelectrode gap, and the flux of ions and electrons into the gap. The practically successful electrodes are those that depend on cesium adsorption to obtain low work functions when immersed in cesium vapor.

By considering the adsorbed layer as a thermal equilibrium between atomic and ionic states of cesium (i.e., a two-dimensional partially ionized plasma), a formulation is obtained [8] that correlates the work function $\phi$ of a surface immersed in cesium vapor at pressure

$$p = p_0 \exp(-h/kT_R)$$

(6)

with the temperature $T$ and "bare" work function $\phi_0$ of the surface, where $p_0 = 7.5 \times 10^6$ torr, $h = 0.75$ eV, and $T_R$ is the temperature of the liquid cesium vapor source. As shown in Fig. 5, the work function is nearly uniquely characterized by $\phi_0$ and the temperature ratio $T/T_R$ in the region of significance for thermionic converter emitters ($\phi_E \geq 2$ eV). In the region of significance for collectors ($\phi_C < 2$ eV), however, basic understanding is inadequate and the database is entirely empirical.

Because transport and ionization in the plasma also depend on the cesium pressure $p$, it is clear that the electrode and plasma properties interact strongly through Fig. 5 and (2) and (6). Furthermore, the work functions given in Fig. 5 have a dependence on plasma density due to the Schottky effect arising from high electric fields in the positive ion sheaths between the plasma and electrode surface. These effects are understood and adequately characterized [9], [10]. There are strong indications, however, that additional electrode/plasma interface processes affect the collector work function in an important but unknown manner.

The electron thermionic emission into the interelectrode gap $J_e$ is given by (2). The positive ion thermionic emission into
the gap is given by the Saha–Langmuir equation:

$$J_{\alpha} = e\mu \left[ 1 + 2 \exp \left( \frac{V_i - \phi_e}{kT_e} \right) \right]^{-1}$$

(7)

where $\mu \approx 1.3 \times 10^{20} \text{ cm}^{-2} \text{ s}^{-1}$ is the arrival rate of cesium atoms at pressure $p$ in torr, and $V_i = 3.9 \text{ eV}$ is the ionization energy of the cesium atom.

For a neutral plasma, the densities and random currents of the electrons and ions are equal, such that at equilibrium, $J_e = \alpha J_{\alpha}$, where $\alpha = (MT_e/mT_i)^{1/2} \approx 500 - 700$, and $M$ and $m$ and $T_i$ and $T_e$ are the ion and electron masses and temperatures, respectively. Equations (2) and (7) can be combined [8] to define the work function $\phi_n$ of an electrode emitting a neutral plasma, which is included in Fig. 5 and also is known as the electrochemical potential of the plasma.

C. Directed Current at Boundaries

The fact that the plasma energy distribution must be asymmetrical and nonequilibrium at the plasma/electrode boundaries significantly affects thermionic converter characteristics and has been examined in detail [11], [12]. A principal effect results from the interaction of the half-Maxwellian energy distribution of particles emitted into or out of the plasma at its boundaries with the full-Maxwellian distribution within the body of the plasma. This effect is adequately described by the “directed current” approach [10] originally developed for description of neutron diffusion near boundaries. At any plasma boundary the total current of particles moving only to the right is

$$J_+ = J_e + J/2$$

(8)

and of the particles moving only to the left is

$$J_- = J_e - J/2$$

(9)

where $J_e$ is the random current, and $J$ is the net (drift) current to the right. This result is obtained because by necessity,

$$J_e = J_+ - J_- = J.$$

Equations (8) and (9) apply to both electrons and ions at both the emitter and collector plasma/electrode boundaries. For electrons at the emitter, for example,

$$J_+ = J_e + J_e \left[ 1 - \exp(-V_E/kT_e) \right]$$

(10)

where $J_e$ is the electron current emitted to the right from the emitter, the second term in (10) is the electron current reflected to the right by an emitter sheath of voltage height $V_E$, and $T_E$ is the temperature of the plasma electrons at the emitter.

D. Alternate Analytical Approaches

Because of the dominance of electrode and boundary effects, two distinct approaches have been taken for analytical representation of the plasma in thermionic converters. The most rigorous or “fundamental” approach is based upon numerical solution of the usual set of differential equations for electron and ion transport and continuity in the plasma, subject to the boundary conditions described in Section IV-B and C. This approach allows the inclusion of the fundamental transport, excitation, and ionization properties, and a first-principle evaluation of their quantitative effect on local and overall plasma properties for experimental confirmation over a wide range of conditions. The numerical integration of these equations across the plasma is quite complex and has been performed by a variety of approaches [13]. Such rigorous calculation of the state of the plasma interior can obscure more significant effects at the plasma boundaries, however.

In the alternate or “phenomenological” approach [10], [14] the same transport and continuity boundary conditions are applied to the plasma, but the plasma itself is represented algebraically by a simple macroscopic model having the average properties that conform to the boundary conditions. Because of the relative insensitivity of converter characteristics to the details of the local plasma state, this approach characterizes converter operation to the degree required for preliminary converter and system design evaluation. While not as rigorous and versatile as the fundamental approach, the phenomenological approach provides intuitive insight into the physics of the dominant converter processes and is useful for on-line converter diagnostics because of its relative analytical simplicity.

The physics of the converter plasma modes listed in Table II now will be summarized.

V. IGNITED (ARC) MODE

A. Description and Approach

The ignited or arc mode of converter operation is easy to achieve and employ practically, since it occurs spontaneously between elementary electrodes immersed in cesium vapor at practically achievable electrode spacings and temperatures. As a result, it has been the basis for all engineering applications to date. Its physics, however, is relatively complex.

The phenomenological representation will be used here to identify and quantify the various physical processes which characterize operation in the ignited mode and which are relevant to the description of other modes as well. Many simplifying approximations are used in this intuitively tractable representation. The consistency of the results of the phenomenological model with those of the more rigorous fundamental model, however, provides a degree of confidence in the adequacy of those approximations [10].

B. Transition Point

Fig. 6 shows motive diagrams for a plasma diode thermionic converter operating in the ignited mode. In this mode, part of the electric power generated by the converter is dissipated internally in the interelectrode gas by collisional processes, heating the electrons in the gas to a sufficiently high temperature so that they ionize the gas and maintain a neutral plasma. Electrons are retained in the plasma by sheath barriers $V_E$ and $V_C$ at the emitter and collector, but ions freely diffuse to the electrodes and recombine on their surfaces. The voltage drop across the interelectrode space, the arc drop $V_a$, sustains this process. A typical current–voltage output characteristic for the cesium, plasma-diode thermionic converter is shown in Fig. 3.
The transition point \( (J', V') \) identified in Fig. 3—i.e., the point of maximum slope—has both practical and basic significance. It has practical importance, because it is near the points of maximum output power and efficiency. It has basic significance, because it is where the zero electric field occurs at the emitter, as in Fig. 6(b); i.e., where the positive ions neutralized by the ionization rate arising from the resulting arc drop \( V_d \). Accordingly, Fig. 6(a) and (11) give:

\[
V = \phi_E - \phi_C - V_d + \Delta V
\]

and the emission current \( J_E \) from the "virtual emitter" with effective work function \( \phi_E + \Delta V \) is, from (2):

\[
J_E = AT_E^2 \exp[-(4\pi + \Delta V)/kT_E] = J'_e \exp(-\Delta V/kT_E).
\]

2) Particle Transport and Continuity: Rigorous description of the plasma requires solution of the transport equations for the plasma density \( n \), electrical potential \( \psi \), and electron temperature \( T_e \) versus distance \( x \) through the plasma. For electrons,

\[
J = -\frac{e\lambda}{3kT_e} \left[ kT_e \frac{dn}{dx} + n \frac{d\psi}{dx} + Knk \frac{dT_e}{dx} \right]
\]

with a similar equation for the ions, where \( e, \lambda, \bar{v}, \) and \( K \) are the electron charge, mean-free-path, average velocity, and thermal diffusion constant, respectively.

Solution of the ion- and electron-transport equations, with the set of boundary conditions corresponding to (8) and (9) in the presence of the electron-confining sheaths, shows that the random electron current density in the ignited mode plasma is nearly an order of magnitude greater than the output current \( J_e \), corresponding to \( n \sim 10^{14} \text{cm}^{-3} \) for \( J = 10 \text{amp/cm}^2 \). Furthermore, it is found that the potential gradients within the plasma arise primarily from the electric field associated with ion diffusion out of the plasma, rather than from electron transport through it. The electrical and thermal conductivities of this high density plasma are so high and the voltage drop across it is so small \( (V_p \ll 0.1 \text{ eV}, \text{ typically}) \) that, to a very good approximation, the plasma can be treated simply as an equipotential and isothermal region through which the electron current \( J_e \) diffuses. Accordingly, (15) with the \( d\psi/dx \) and \( dT_e/dx \) terms neglected is readily integrated to give the ratio of the plasma densities \( n \) and random currents \( J_r \) at the plasma boundaries, for interelectrode spacing \( d \):

\[
n_E/n_C = J_{rE}/J_{rC} = 1 + \frac{3}{4} \frac{d}{\lambda}.
\]

The mass disparity between the electrons and the cesium atoms and ions is so great that ion currents in the plasma are
negligibly small compared with the electron current $J$, and the energy transfer between them is negligible. The temperature of the atoms and ions is approximately equal to the mean temperature of the electrodes $(T_E + T_C)/2$. The emitted electrons, however, are accelerated across the emitter sheath ($V_E \approx 0.7 \text{ eV}$, typically) and bombarded and heat the electrons at the emitter side of the plasma to a much higher temperature ($T_{EC} = 3300 \text{ K}$, typically). In order for the ignited mode to exist, this temperature must be sufficiently high to produce positive ions by impact ionization precisely as fast as they are lost by volume recombination and by diffusion to and recombinaton at the electrodes. The plasma typically is only about 1% ionized at the emitter and 0.1% ionized at the collector in the obstructed region of the ignited mode.

3) Energy Transport and Continuity: Detailed consideration of the cesium plasma stepwise excitation and ionization process [15] shows that resonance radiation from the first excited state of the cesium atom is almost entirely trapped within the typical ignited mode cesium plasma, and the energy loss from the plasma by escape of other excitation radiation is negligibly small. As a result, the energy delivered to the plasma by the emitted electrons is removed almost entirely by hot electrons reaching the collector or scattered back into the emitter. The heat removed by electron emission from the plasma to the collector must be conducted across the plasma by the electrons, resulting in an approximately linear electron temperature drop across the plasma to about $T_{EC} = 2100 \text{ K}$ at the collector, typically.

4) Volume Recombination and Local Thermodynamic Equilibrium: A plasma cannot appreciably exceed the density at which as many ions recombine locally as are produced locally. In this condition, known as local thermodynamic equilibrium (LTE), the local plasma properties are equivalent to those at the local electron temperature and random current density.

In typical ignited converter operation, only the portion of the plasma adjacent to the collector is near or within LTE and volume recombination has little effect on the output, since most ion production occurs on the high temperature (emitter) side of the plasma. As the cesium pressure, spacing, and current density increase, the LTE portion of the plasma expands toward the emitter and eventually can dominate the entire plasma. Stepwise integration of the transport and continuity equations across the plasma becomes very difficult (unstable) under these conditions, since the local ionization-recombination balance in LTE is exceedingly sensitive to the local density.

5) Summary of Obstructed Region Plasma Physics: The combination of the above-described physical processes is summarized by the phenomenological model in the following complete set of equations defining the state of the obstructed plasma ($V > V'$) [10]:

$$J_E - J = \exp(-V_E/kT_E) \left[ \frac{3d}{4\lambda} J + R_J \right]$$

(17)

$$V_E = V_d + V_C \left\{ \frac{V_d}{2kT_E - T_E} (J_E/J - 1) + \frac{2k(T_{EC} - T_E)}{J_E/J - 1} \right\}$$

(18)

$$V_C = 3k(T_{CE} - T_{EC})$$

(19)

$$T_{EC} = T_{EFF} \left[ \ln \frac{R^3}{1} + 1 \right]$$

(20)

The quantity $R \approx 4.5$ is a dimensionless constant involving the constant ratio of the ion current at the electrodes to the average random ion current, and the ratio of the ion and electron mean-free-paths. Equations (17)-(22), together with the Raozor-Warner formulation for the electrode work functions [8], are the basis of the widely used TECMDL computer model of the ignited cesium diode thermionic converter [16].

Equation (17) describes the attenuation of the emitted current $J_E$ by the plasma for electrode spacing $d$ and electron mean-free-path $\lambda \approx 0.006/p$ cm for cesium vapor pressure $p$ in torr. The term in the square brackets is the current arriving from the interior of the plasma on the emitter side, which is the sum of the current scattered back by the plasma and the current $R_J$ reflected from the collector. This arrival current times the Boltzmann exponential in emitter sheath height $V_E$ and electron temperature $T_{EC}$ is equal to the current returning to the emitter from the plasma $J_E - J$. The current attenuation $J/J_E$ obtained from (17) is shown in Fig. 7(a) as a function of the degree of electron scattering $d/\lambda$.

Equation (18) describes the dependence of the arc drop $V_d$ (the net energy loss in the plasma per electron) on the emitter temperature $T_E$ and the plasma boundary electron temperatures $T_{EC}$ and $T_{EF}$. The first term represents the net energy lost from the plasma via the hot electrons backscattered to the emitter. The second term represents the net energy lost via hot electrons reaching the collector. Fig. 7(b) shows that the arc drop decreases at large $d/\lambda$ as the increased collisional ionization probability results in a colder, more efficient plasma until ion recombination in LTE is encountered.

Fig. 7(c) shows, however, that the back-voltage $V_B$ or “barrier index” (12) has a minimum value, giving maximum converter performance via (5) and Fig. 4, at about $d/\lambda = 8$, or pressure-spacing product $pd = 0.06d/\lambda \approx 0.5$ torr-mm. This minimum results from the competition between the decrease in $V_d$ (Fig. 7(b)) and the increase in $V_n$ (Fig. 7(a)) as $pd$ is increased. Remarkably, the decrease in $V_d$ resulting from the energy added by electrons emitted at higher $T_E$ is nearly balanced at all $pd$ by the increased loss of electrons backscattered over a lower emitter sheath barrier $V_E$, resulting in a nearly constant $V_B = 0.05 + 0.45 \text{ eV}$ over a wide range of $pd$ and emitter temperature $T_E$.

Equation (20) shows that the electron temperature at the collector $T_{EC}$ is about $0.64 T_{EFF}$, so the collector sheath
height by (19) is \( V_C \approx 1.09kT_{eE} \). It can be shown that the collector back emission current \( J_C \) increases \( V_d \) by an amount

\[ 2k(T_C - T_E)J_C/J \]

due to the energy absorbed in the plasma by the cold collector electrons [10].

The electron temperature \( T_e \) required to sustain a non-LTE cesium plasma, given by (21), is characterized by two plasma parameters, \( V_I \) and \( B \), that are derivable from the detailed kinetic analysis of the multistep excitation/ionization process [15]. The “effective ionization energy” \( V_I \) is found to be about 3.1 eV, i.e., at the energy level “bottleneck” above which excitation is equivalent to ionization in a Maxwellian plasma. The “ionizability factor” \( B \approx 30 \) is a dimensionless constant that includes the ionization cross section and the electron/ion mean-free path ratio, and is a measure of the ability of the plasma to produce and retain ions.

A number of concepts have been proposed to improve the properties of the ignited mode plasma, including cavities or grooves in the electrodes to modify the ion production mechanism and additive gases to modify the scattering processes. None of these has been successful due to the relative insensitivity of the minimum \( V_B \) to the disposable quantities included in the plasma characterization factors \( R, I?, \) and \( V_I \). Similarly, the use of state-dependent fundamental properties to describe the plasma in the detailed fundamental model does not give results significantly different from those obtained by the use of constant values of these three plasma characterization factors.

Although both analytical models satisfactorily characterize ignited converter behavior in most respects, it can be seen in Fig. 8 that both models fail to describe the experimental volt-ampere characteristics properly in the obstructed region. The models predict a constant back-voltage \( V_B \) below the transition point, when in fact the back-voltage increases with decreasing current density. This discrepancy is important,
since the practical operating point typically is in this region, and this and related anomalies pose an uncertainty in what basic processes actually dominate the important quantity \( V_B \). Because of the relative insensitivity of \( V_B \) to the detailed state of the bulk plasma, several hypotheses have been advanced to explain this discrepancy as arising from the plasma/surface interaction, including energy loss to the electrodes by resonance radiation, incomplete thermalization of the electrons in the presheath region, positive ion trapping in the nonmonotonic emitter sheath, discharge constriction, and an anomalous Schottky effect at the collector. At present, this issue is unresolved. A complete kinetic simulation model that eliminates the artificial division of the interelectrode space into nonmonotonic emitter sheath, discharge constriction, and the presheath region, positive ion trapping in the sheath and plasma regions might be required if the discrepancy is a sheath effect, or a detailed model of sheath field effects on the adsorbed layer is required if it is an anomalous Schottky effect.

D. Saturation Region

For the conditions in the obstructed region and at the transition point—i.e., for \( V \geq V' \) as in Fig. 6(a) and (b), the arc drop \( V'_E \) is automatically that required for production of precisely sufficient positive ions to neutralize the electron emission current. For \( V < V' \), as in Fig. 6(c), however, an arc drop \( V'_E = V'_d - \Delta V \) is imposed across the plasma that is greater by \( \Delta V \) than that required for plasma neutrality. Accordingly, this "excess" energy \( \Delta V \) cannot be transferred to the plasma electrons, since this would increase \( T_{TE} \) and produce an excess of positive ions. The details of the ionization and scattering processes in the emitter sheath are highly complex [12], but experimental data indicate that essentially all of the excess energy \( \Delta V \) is expended on production of positive ions within the emitter sheath that are immediately swept into the emitter instead of entering the plasma. To accomplish this the electron temperature at the emitter edge of the plasma rises to a value sufficient to approach a fully ionized plasma there in the saturation region.

Since the body of the plasma accepts only the electron energy required to maintain a neutral plasma, the remainder of the plasma is essentially unchanged. Equations (17)-(22) therefore remain valid for that region, except that the emitter sheath is now:

\[
V_E = V'_E - \Delta V \quad \text{for} \quad \Delta V < 0
\]

(23)

which with (13) and (17) gives for the output characteristics in the saturation region,

\[
J = \frac{J_s}{1 + \left[ \frac{J'_s}{J_s} - 1 \right] \exp \left[ \frac{-\phi_Y}{kT_{TE}} \right]} \quad \text{for} \quad V < V'
\]

(24)

with \( T_{TE} \) equal to the temperature that approaches complete ionization at cesium pressure \( p \) (~4500 K). The large positive ion current into the emitter \( J_{E} \approx J_s \Delta V/V_E \) produces an intense electric field at its surface that lowers the emitter work function \( \phi_E \) and increases the saturation emission current \( J_s > J'_s \) via the Schottky effect [9], [10].

The initial rapid increase in output current for \( V < V' \) in Figs. 3 and 8 is dominated by the emitter Schottky effect. For \(- \Delta V \geq kT_{TE} \), the output current increases primarily because the increase in emitter sheath height \( V_E \) reduces the back-scattered electron current. For \(- \Delta V \gg kT_{TE} \), the approximately linear increase in output current is mostly ion current.

VI. UNIGNITED PLASMAS

A. General Description

The ignited or arc mode plasma just described is internally maintained by impact ionization in a collisionally self-heated "hot" electron gas \( (T_e \gg T_{CE}) \). The arc drop and current attenuation associated with this inefficient process typically absorb nearly half the electrical power generated, increasing \( V_B \) by 0.4-0.5 eV, whereas less than 0.01 eV per electron is required to produce the plasma-sustaining ions themselves. Alternate means exist for maintenance of more efficient unignited or "cold" plasmas \( (T_e \approx T_{CE}) \) by energy sources outside the plasma, without dependence on collisional processes, such that \( V_a + V_d \leq 0.1 \) eV (equations (12) and (18)).

The motive diagram for the unignited plasmas in Fig. 9(a) shows that in the region of greatest interest for thermionic converter operation, ions typically are retained in the plasma by sheath barriers \( V_E \) and \( V_c \) at the emitter and collector, and electrons freely diffuse to the electrodes; i.e., the opposite condition from that for the ignited plasma. The conditions in Fig. 9(b) and (c) are of interest also for converter diagnostics. Fig. 9(b) represents the condition at the transition point \( (V''_E, V'') \), where \( V_c = 0 \), and Fig. 9(c) represents the condition at \( V > V'' \), where the collector limits the converter output, both of which are identified as regions in the electrical output characteristics in Fig. 3. A rigorous description of unignited plasmas can be obtained by applying the appropriate boundary, transport, and continuity conditions described in Section V [16]. An approximate description by the intuitively tractable phenomenological approach [17] is described below.

For the general case of plasma maintenance, the net rate at which ions are supplied to the plasma is

\[
J_{ip} = J_{io} - J_{ib}
\]

(25)

where

\[
J_{io} = J_{i\alpha} + J_{i\beta} - J_{io} - J_{i\gamma}
\]

(26)

is the sum of the ion sources and sinks that are independent of the sheath heights, \( J_{i\alpha} \) is the thermionic emission current of ions into the plasma given by (7), \( J_{i\beta} \) is the ion current injected into the plasma by other external means, \( J_{i\gamma} \) is the ion current lost from the plasma by volume recombination, and \( J_{i\gamma} \) is the ion current lost by transverse diffusion to the plasma edge. \( J_{ib} \) is the ion current lost from the plasma over the bounding electrode sheath barriers, which is exponentially dependent on \( V_E \) and \( V_c \). Computation of \( J_{ip} \) using the boundary and transport conditions described in Sections IV-C and V-C gives, for the practically important condition of equal sheath heights \( (V = V_c) \),

\[
J = \alpha(J_{i\alpha} - J_{ip}) \left[ \frac{J}{J_{ip}} \right]^{1.2}.
\]

Note that \( J_{ip} = 0 \) for steady-state operation.
RASOR: THERMIONIC ENERGY CONVERSION PLASMAS

converters with efficiently maintained unignited plasmas is understandably proportional to the strength of the plasma—unignited plasmas. It is a measure of the effectiveness of the scattering factor $s$ sustaining ion source $J_s$, and inversely proportional to the important in all types of advanced converters employing unignited plasmas. Recently, cesium adsorption. This dilemma inhibited the prospects for are contradictory requirements for electrodes that depend on sheath barrier $d$ needed for advanced unignited converters at temperature $T_i$. However, it has been found that use of an equilibrium mixture of cesium oxide and cesium vapors permits $J_s$, increasing the adsorption energy for cesium on the electrodes to be obtained at very low cesium pressures, $10^{-10}$ torr. By adsorbed layer and thus lower cesium pressure is required to maintain the and cesium vapors [19]. Adsorbed barium lowers the emitter work function without cesium adsorption, but unfortunately it also gives a high collector work function ($\phi_C \geq 2.0$ eV). A description of various other vapor mixtures for obtaining high $J_s$ at low cesium pressures is given in [20, chap. 5].

A comparison of (17) and (27) shows that output current attenuation by electron scattering is much greater in unignited plasmas, because of the absence of the large electron-retaining sheath $V_E$ at the emitter. As a result, converters with unignited plasmas operate typically with $d/\lambda \leq 1$ compared with $d/\lambda \leq 8$ for ignited converters. Furthermore, the greater sensitivity to electron scattering in the unignited plasma causes Coulomb (electron–ion) scattering to be significant at high output current $J$ and low electron temperatures $T_e \approx T_i$, as summarized by

$$\frac{1}{\lambda} = \frac{1}{\lambda_{ea}} + \frac{1}{\lambda_{ei}}$$

where $\lambda_{ea} \approx 0.006/\rho$ cm and $\lambda_{ei} \approx 3 \times 10^{-9} T_e^{5/2} / J_e$, cm are the respective electron–atom and electron–ion scattering mean free paths for $p$ in torr, and $J_e = env/4$ is the random current density at the local plasma density $n$.

In fact, the dependence of $\lambda$ on current density in (16) and (28) implies a basic upper limit on attainable current density in unignited plasmas; i.e.,

$$J < J_{\text{max}} = 4 \times 10^{-9} \left(1 + T_i / T_e \right) T_e^{5/2} / d.$$  \hspace{1cm} (29)

For $d = 1$ mm, (29) suggests that $J_{\text{max}}$ is 2, 5, and 10 A/cm$^2$ at $T_e = T_i = 1000, 1500, \text{and} 2000$ K, respectively.

Similarly, the effect of self-generated magnetic fields can be significant in unignited plasmas due to the large $\lambda$ and absence of electron-reflecting sheaths [11]. As shown in Fig. 10, the magnetic field arising from the output current is transverse to the current flow through the plasma. To a good approximation, the effect of a transverse magnetic field $H$ on output current density for $d \geq \lambda$ (cm) is

$$J \approx \frac{J_o}{1 + 0.4(\lambda H)^2}.$$  \hspace{1cm} (30)

where $J_o$ is the current density in the absence of a magnetic field. For a converter with coaxial cylindrical electrodes of length $L$ cm and total field-free output current $I_o$, the attenuation of the total current $I$ by the self-generated magnetic field is

$$I \approx \frac{I_o}{1 + 0.14(J_o L)^{3/2}}.$$  \hspace{1cm} (31)

If electron–atom scattering is dominant (i.e., $\lambda_{ei} \ll \lambda_{ea}$ in (28)), the magnetic current attenuation is $I/I_o = 75\%$ for a current density $J_o = 3$ A/cm$^2$ in a cylindrical converter having length $L = 10$ cm and cesium pressure $p = 0.1$ torr. If Coulomb scattering is dominant, the magnetic attenuation is independent of $J_o$ for $J_o \ll J_{\text{max}}$, and is 80, 40, and 20% at $T_e = 1000, 1500, \text{and} 2000$ K, respectively, for $L = 10$ cm. It is clear, therefore, that both Coulomb scattering and magnetic effects must be considered in unignited plasmas.

In fact, the strong interaction of these effects for $J$ near $J_{\text{max}}$ gives rise to a potential for instabilities in the unignited discharge. A further factor in such instabilities is the Lorentz ponderomotive force on the plasma by the magnetic field. As shown in Fig. 10, this force tends to drive the plasma toward the end opposite the current lead in a cylindrical converter, producing a pressure drop along the length of the converter of

![Fig. 9. Motive diagrams for general unignited thermionic converter plasmas. (a) Plasma saturation region ($V < 1/e^n$), ion-retaining sheaths. (b) Transition point ($V = 1/e^n$). (c) Boltzmann region ($V > 1/e^n$); $\phi_C$ measured via (1).](image-url)
magnitude \( \Delta P = 4.8 \times 10^{-5}(JL)^2 \) torr for \( JL \) in A-cm [11]. For \( JL = 30 \) A-cm, the resultant \( \Delta P = 0.04 \) torr becomes comparable to the total gas pressure employed in unignited plasmas. The possibility for electrical coupling to acoustic waves is apparent. Various types of converter operation with unignited plasmas, associated with different means for providing the ions in (26), will be described.

**B. Diffusion Regime**

In the diffusion regime of the unignited cesium vapor diode converter the ion emission current \( J_\text{i} \), is the dominant ion source \( J_\text{i0} \) in (27), and \( J_\text{e} = 0 \) at steady state. The plasma potential is such as to give a net neutral electron and ion emission into the plasma, whereupon \( \phi_E = \phi_n \). Accordingly, \( V_E \) is essentially constant, unlike that in the ignited diode, and is equal to the difference between the curves for \( \phi_E \) and \( \phi_n \) in Fig. 5. Furthermore, for the condition in Fig. 9(b), the location of the transition point \( (J'', V'') \) identified in Fig. 3 is given by \( V'' = \phi_c - \phi_n \) and \( J'' \approx J_\text{i} \), where \( J_\text{i} \) is given by (2) with \( \phi_e \) substituted for \( \phi_E \).

The basic thermodynamic constraint that the emission current can be no greater than \( J_\text{n} \) limits the performance in this mode to less than that in the ignited mode, except at very small electrode spacings and very high emitters temperatures \( T_E \geq 2200 \) K). Because of its unique dependence on plasma properties, however, the diffusion regime of the unignited cesium diode often is used for converter diagnostics; e.g., for inference of emitter temperature, spacing, cesium pressure, or collector work function whenever one of these quantities cannot be measured independently. The most accurate diagnostics are obtained through comparison of the full experimental \( J \) versus \( V \) curve with that computed using the detailed fundamental approach. As can be seen in Fig. 11, the MASTERPC computer model [16] for the unignited mode precisely represents the experimental converter characteristics, including the approach to the ignited mode as the plasma electrons are heated above the emitter temperature. Accordingly, the discrepancy that occurs in modeling the ignited mode (Section V-C.5 and Fig. 8) is uniquely associated with the fully developed ignited plasma.

**C. Knudsen Regime**

The fundamental and phenomenological approaches using the conventional macroscopic diffusion transport equations are in surprisingly good agreement with experimental data, even when the electrode spacing \( d \) is as small as one electron mean free path, presumably due to multiple traverses of the gap by particles trapped in the plasma between the electrode sheaths. Nevertheless, for the essentially collisionless plasma regime \( d \ll \lambda \), as known as the Knudsen regime, the diffusion equations fail and the plasma is nearly homogeneous; i.e., there are essentially no electric fields or particle density gradients in the body of the plasma.

The physics of the Knudsen plasmas has been explored and described in substantial detail [11], [21]. At first it might seem a converter operating in the Knudsen regime would be highly attractive, since when \( d \ll \lambda \) and \( \phi_E \approx \phi_n \), nearly the full emission current is obtained as output \( J \approx J_\text{d} \), and the arc drop \( V_d \) and scattering loss \( V_\text{s} \) are nearly zero, giving \( V_E \approx \phi_n \), as in the ideal diode converter. At the cesium pressures required to obtain \( \phi_E \approx \phi_n \), and a sufficiently low \( \phi_n \), however, the requirement \( d \ll \lambda \) requires impractically small electrode spacings and operation at very high temperatures. Also, at the very high current densities \( J \) required for efficient high temperature operation, Coulomb scattering (\( \chi \) in (28)) tends to preclude efficient operation in the Knudsen regime, even with no electron-atom scattering (\( \chi_{\text{e-\text{a}}} \)).

Similarly, interest has arisen from time to time in the potential utilization of the spontaneous oscillations (typically near 1 MH) associated with the ion transit time across the plasma that occur in converters operating in the Knudsen regime. Aside from the interesting physics involved [11], [21], these oscillations apparently have no practical value for converter output, since they occur with amplitudes comparable to the dc output only at impractically low output currents and at the expense of a substantial arc drop \( V_d \).

Although operation in the Knudsen regime with a plasma sustained by ion emission apparently has no practical application, applications exist for Knudsen plasmas under conditions known as the Knudsen arc. At sufficiently high output currents...
and arc drops \( (V_d \leq 1 \text{ eV and } J \geq 0.4 \text{ A/cm}) \), the rate of ion production by electron impact becomes sufficient to produce a high-density electron-trapping plasma, even for \( d/\lambda \ll 1 \) [11]. The Knudsen arc has been applied as a plasma switch, the Tacitron [22], and as a fault current limiter, the Terma-tron [23]. These devices utilize the low arc drop (~1 V) at practically high current densities (0.5–5 A/cm²) and the practically high standoff (inverse) voltages (30–200 V) attainable with the cesium-vapor Knudsen arc. In addition, an arc in the quasi-Knudsen (quasi-collisional, \( d/\lambda \approx 1 \)) regime is used to generate the injection plasmas for advanced types of thermionic converters discussed below.

VII. INJECTION PLASMAS

A. General Description

The plasmas in the ignited and unignited modes of the cesium diode converter are maintained by energy sources within the converter itself. The multiple constraints associated with these spontaneous internal processes limit converter performance and versatility of application. Advanced converter types utilize external energy sources to efficiently maintain the plasma by injection of electrons or ions into it under more optimum conditions. In addition, by modulation of the external energy source, such converters can be made to act as a switch or otherwise condition their own power output without a separate output power conditioner.

It must be recognized that the simplified description here of unignited plasmas using (27) neglects the effects of volume recombination \( J_{iv} \) and plasma edge losses \( J_{it} \). In practice, the converter design and operating regime are chosen to minimize these and other performance-limiting effects. For example, the output current of converters using injection plasmas is limited to only a few A/cm² due to the importance of Coulomb scattering (29) at the relatively low electron temperature \( T_e \) and large spacings \( d \) inherent to the injection process. Also, ion losses at the edges of the electrodes \( J_{iv} \) can severely limit converter performance if the plasma is efficiently contained by electrode sheaths, particularly for small-area planar diode converters.

B. Triodes

1) Electron Injection Triode: As shown schematically in Fig. 12(a), a small auxiliary electron emitter can be placed within the interelectrode gap to maintain the plasma. This type of converter often is called the “plasmatron” type, named after the electron tube having this configuration. The electrons from the auxiliary emitter are accelerated into the plasma by the applied voltage \( V_r \) at an energy sufficient for a high probability of producing an ion; i.e., several volts as in the Knudsen arc. The auxiliary ion current \( J_{iv} \) in (26) thereby is generated by an auxiliary electron current \( J_e = J_{iv}/f \), where \( f \) is the ionization probability per auxiliary electron. The auxiliary power required is \( P_{e} = J_e V_e = J V_e^* \), where \( V_e^* \) is the “equivalent arc drop” across the external power supply required to provide \( P_{e} \), as shown in Fig. 12(a). If \( J_{iv}, J_{it}, \) and \( J_{ip} \) are negligible in (25) and (26), (27) gives,

\[
V_e^* = \frac{V_r}{j\alpha} \left[ 1 + \frac{3}{8} \frac{d}{\lambda} \frac{f}{f^*} \right] \frac{T_e T_i}{J_{iv}}.
\]  

Fig. 12. Schematic and motive diagrams for converters with injection type plasmas. \( P_{e} \) is a power supply that generates the auxiliary voltage \( V_r \) and current \( J_{iv} \) from a potential drop \( V_e^* \) in the load circuit. (a) Electron injection triode. The auxiliary electron emitter \( i \) emits an ionizing electron current \( J_{iv} \) into the plasma. (b) Ion injection triode. The auxiliary ion emitter \( i \) emits a positive ion current \( J_{it} \) into the plasma. (c) Pulsed diode. A pulse of voltage \( V_r \) and current \( J_{it} \) injects ionizing electrons from the emitter into the plasma.

The ionization probability \( f \) and scattering factor \( d/\lambda \) both increase with the pressure-spacing product, leading to an optimum pressure near \( d/\lambda \approx 1 \) if the scattering and ionization cross sections are comparable in magnitude. Unfortunately, cesium has an electron-scattering cross section, at typical unignited plasma electron energies \( (p\lambda \approx 0.006 \text{ torr-cm} \) at 0.1–0.3 eV), that is much larger than its ionization cross section, because of resonance scattering by its loosely coupled valence electron; i.e., a partially ionized cesium plasma tends to be opaque to the low-energy output current electrons (large \( d/\lambda \)) and transparent to the ion-producing high-energy electrons (small \( f \)), the opposite of what is desired. The heavy noble gases, however, have this opposite property, tending to be transparent to low-energy electrons \( (p\lambda \approx 1 \text{ torr-cm}) \) because of the Ramsauer electron diffraction effect, and opaque to the high-energy ionizing electrons. For this reason, argon, krypton, and xenon are favorable for production of the electron-injection plasma, because \( V_e^* \) is much less for them than for cesium vapor in spite of the higher \( V_r \) required (ionization energies 16, 14, and 12 eV, respectively,
versus 4 eV for Cs). However, cesium vapor at low pressure (10^{-2} – 10^{-1} torr) usually is added to the plasma to obtain the low electrode work functions required so that production of the electron-injection (plasmatron) plasma is an exceedingly complex quasi-Knudsen discharge.

Using the reasonably obtainable or near-optimum values $f = 0.1 - 0.3, d/\lambda \approx 1, V_2 \approx 15$ eV, $\alpha = (MT_e/mT_d)^{1/2} \approx 500$, and $J/J_0 = 0.2$, (32) gives $V_2^* \approx 0.1$ eV. The noble-gas electron-injection type of converter therefore potentially can have substantially higher performance than the ignited mode converter ($V_2^* \approx 0.4$ eV), especially at low emitter temperatures. To obtain the assumed values of $f$, however, it is necessary to distribute auxiliary emitters over the entire electrode area no more than a few gap-widths apart. Since the gap width typically is less than 1 mm and the auxiliary emitter must be heated by the emitter but electrically insulated from it, the triode type of converter is structurally and technologically quite complex compared with the elementary diode.

C. Pulsed Diode

A type of converter that combines an injection plasma with the much simpler diode structure is the pulsed diode. The plasma is maintained by applying to the diode electrodes a continuous series of short (<1 µs) pulses at a high enough voltage to efficiently ionize the interelectrode gas. During a negative pulse to the emitter, as shown in Fig. 12(c), the high-energy electron beam from the emitter produces a high density plasma by impact ionization in a quasi-Knudsen arc. Between pulses, if ion loss is sufficiently inhibited by diffusion and ion-retaining electrode sheaths, the plasma decay time can be much longer than the pulse repetition period, providing nearly continuous output power with a cold injection plasma.

In the previously described steady-state plasma, the net rate at which ions were supplied to the plasma was zero; i.e., production rate equaled loss rate, such that $J_{ip} = 0$. If $J_{ip}$ is not zero, the average density $\bar{n}$ of the plasma must change at the time rate

$$\frac{dn}{dt} = J_{ip}/ed. \tag{33}$$

It can be shown [17] that the average density for a sheath-contained quasi-collisionless unignited plasma is, to a good approximation,

$$\bar{n} \approx \frac{J}{eV} \left(1 + \frac{3d}{8\lambda}\right). \tag{34}$$

Accordingly, (27), (33), and (34) together can be solved for the time dependence of the electrical output characteristics. If there are no ion sources ($J_{ip} = J_{io} = 0$), and ion losses other than to the electrodes are negligible ($J_{il} = J_{io} = 0$), (33) is readily integrated to give the output current decay at constant output voltage $V = V_0$:

$$J = J_o/(1 + t/\tau) \tag{35}$$

where

$$\tau = 2\tau_i T_i \left[\frac{2J_{ip}/J_o}{1 + \frac{3d}{8\lambda}}\right] \tag{36}$$

$\tau_i = v_i d = \text{ion transit time at average velocity } v_i$ and $J_o = \text{initial value of } J$.

The pulse power requirement is $P_e = J_x V_x \tau_x / \tau_d = J V_x^*$, where $J_x, V_x, \text{ and } \tau_x$ are the pulse current, voltage, and width, and $J$ is the average output current over the pulse repetition period $\tau_d$. For $J_x = J_o$, therefore, the equivalent arc drop is

$$V_x^* = J_o V_x \tau_x / \tau_d. \tag{37}$$

For a cesium vapor diode with typical values $d = 1$ mm, $d/\lambda \approx 1$, $J_x/J_o = 2$, $V_x = 6$ eV, and $\tau_x = 1 \mu$s, (35) and (36) give a pulse repetition period $\tau_d = 47\pm150 \mu$s for $J/J_o \approx 0.5$, and (37) gives $V_x^* \approx 0.16$ eV, which is significantly superior to the ignited mode $V_2^* \approx 0.45$ eV.

Several means are available to substantially decrease this $V_x^*$, however. When several torr of a noble gas such as Xe or Kr is added to the cesium vapor, additional electron scattering is negligible, but the resulting diffusion gradient for the ions causes the average plasma density to be several-fold greater than that given by (34). This effectively increases $\tau_i$ and therefore $\tau_d$ by the same amount, resulting in $V_x^* < 0.1$ eV. Also, since the plasma formation time is less than 0.1 µs, the pulse width $\tau_x$ could be substantially less than 1 µs if shorter
pulses can be employed in practical configurations, further reducing $V_i$.

It has been experimentally demonstrated recently in the USSR [24] that metastable vibrational states of nitrogen gas added to the cesium vapor can be excited during the pulse, and the plasma sustained long after the pulse by cesium ionization via collisional de-excitation of these states. The observed plasma decay times reported are an order of magnitude greater than those for cesium vapor alone, but the nitrogen pumping (excitation) time is similarly increased. Accordingly, the ratio $\tau_d/\tau_{\text{eq}}$ in (37) is not substantially improved by this process. The auxiliary electrode voltage required for the $N_2$ excitation $V_{Z} \approx 1 \text{ V}$ is much less than the 6 V required for cesium ionization, however, such that $V_i \ll 0.1 \text{ eV}$ might be possible. Furthermore, the much greater pulse width and lower pulse-repetition frequency required might substantially improve the practical application of pulsed diodes to large systems.

Attempts in the U.S. to verify these results have not been successful [25], suggesting that this approach may be dependent on conditions not yet identified. For example, $N_2$ de-excitation must not occur at the electrode surfaces, so that the different surfaces employed (adsorbed cesium in the U.S. and barium oxide layer in the USSR) may be responsible for the different results.

It is informative to note that the addition of nitrogen gas to the ignited cesium diode increases its arc drop [26]. Excitation of the nitrogen by the high-temperature electron gas in the ignited plasma is a parasitic effect that adds another electron energy-loss term to (18) for $V_d$ without significantly increasing the total ion production rate.

VIII. APPLICATIONS

A. Space Nuclear-Power Systems

In-core thermionic nuclear reactor systems have an inherent advantage over other systems, because the high-temperature heat source, the nuclear fuel, is suspended like the filament in a light bulb, isolated from the entire remainder of the system which operates at conventional reactor coolant temperatures. Because the thermionic energy conversion cycle can operate at the highest temperature attainable by the nuclear fuel, a high heat rejection temperature can be used to minimize the radiator weight that dominates high-power space systems. Also, as shown in Fig. 13, development of the basic cell and thermionic fuel element (TFE) enables production of a family of static space-power systems having high redundant reliability over a wide range of power levels.

Because of this inherent advantage and modular versatility, use of the elementary, ignited-mode, cesium vapor thermionic converter has been adequate to develop competitive thermionic space-power systems for past needs in spite of the performance limits on the primitive ignited-mode converter (circa 1965). Accordingly, most work on thermionic space reactor systems to date has been concerned with the engineering development of components and integration of conventional ignited converters into various reactor designs [2], instead of research on improving the plasma characteristics of the converter. Improved understanding of the basic physics of the plasma has provided analytical models for design evaluation and diagnosis of engineering test data, but has tended to show that substantial improvements in the characteristics of the ignited plasma are not likely, as was concluded in Section V-C. Basic improvement of ignited converter performance has been and probably will be obtained further through advances in the surface physics of the electrodes, however.

A recent study [3] examined the potential for substantially improving the in-core thermionic reactor through use of converters with the injection plasma described in Section VII. As shown in Fig. 14, the Thermionic Reactor with Inductive Coupled Elements (TRICE) concept employs core-length pulsed diode converters that are coupled to the external load via electromagnetic induction, rather than by series connection of dc cells. In addition to potentially increased system performance, this greatly reduces the complexity of the cells and eliminates the need for electrically insulating them from the liquid-metal coolant. The experimentally demonstrated inductive coupling requires cycling the converter plasma through four sequential states: ignition pulse (quasi-Knudsen arc, Fig. 12(c)), unignited plasma decay phase (35), plasma quench pulse ($V - V_q \gg kT$),
as in Fig. 9(c), and stand-off phase \((V \ll 0)\). The quench pulse rapidly reduces the plasma density to a sufficiently low value that significant current cannot flow during the subsequent magnetic flux reversal (inverse voltage standoff) phase required in an inductive coupling cycle.

Emitter temperatures in thermionic reactor designs have been limited to about 1800 K, because of intolerable swelling of the nuclear fuel at higher temperatures during the 5–10 y full-power lifetime and high fuel burnup required in previous applications. Recently, however, applications have emerged which require much higher power densities for their feasibility, but for much shorter periods and much less fuel burnup. These include power systems for military space systems, for elevation of spacecraft from low earth orbit to high or translunar orbits by electrical propulsion, and for cargo transport in the manned Mars mission. As shown in Fig. 15, the analytically projected power density attainable by thermionic converters at much higher temperatures is an order of magnitude higher than that in the conventional temperature regime, and at up to twice the efficiency [4]. Nuclear fuels developed for nuclear rockets, both UC-ZrC and W/UCO cerments, have operated for hours at 2800 K, and potentially are stable for many months at 2400 K. Fig. 16 summarizes the revolutionary increases in power density and the efficiency potentially achievable; i.e., 1 hp from a cell the size of an AA flashlight battery, at efficiencies approaching those of terrestrial power plants.

As indicated in Fig. 15, ignited-mode performance is projected analytically to be superior to the zero-arc-drop unignited-mode performance up to about 2500 K. This somewhat surprising result occurs, because as the emitter temperature approaches and then exceeds the plasma-maintaining electron temperatures (i.e., as \(T_E < T_{E,L} \) and \(T_{E,C} \) in (18)), the arc drop \(V_d \) in the ignited mode approaches zero and possibly becomes negative, as in Fig. 7(b). Furthermore, the existence of the electron-reflecting sheath \(V_g \) in the ignited mode (17) reduces the effect of electron backscattering compared with that in the unignited mode (27) at practically large electrode spacings. It should be recognized, however, that there are as yet very limited experimental data for evaluation of the validity of the present analytical models in this very high-temperature regime.

**B. Terrestrial Power Systems**

Terrestrial thermionic power systems differ from space power systems primarily in the availability of a low heat-rejection temperature and in the much greater importance of costs. The conventional ignited thermionic converter has been unable to utilize the low heat-rejection temperature as do other heat engines, because this requires a collector work function much lower than that attainable in ignited converters. Furthermore, practical output at the present \(V_d \geq 2.1 \text{ eV} \) is obtained in ignited converters only for high emitter temperatures \(T_E \geq 1600 \text{ K} \), which requires expensive refractory materials and high-temperature heat sources. For these reasons the conventional ignited thermionic converter is submarginally competitive for terrestrial applications.

Detailed system studies have shown, however, that achievement of \(V_d \leq 1.6 - 1.8 \text{ eV} \) would make terrestrial thermionic systems cost-effective and superior to alternative systems in several applications. These include the topping of fossil-fueled steam power plants and cogeneration of electric power in
process heat or gas turbine combustors [27], the efficiency of which would be substantially increased, thereby reducing their fuel requirements and pollutants. While part of this reduction in $V_B$ can be achieved by decreasing the collector work function $\phi_C$ (12), it probably is necessary also to employ converters using the advanced injection plasmas described in Section VII for two reasons: first, the effective arc drop $V_d^*$ in the injection mode of operation can be significantly less than $V_d^*$ in the arc mode (12); secondly, the much lower cesium pressure in the injection mode is required for achievement of the low collector work function at low collector temperatures $T_C$, since necessarily $T_R < T_C$ (6). Inductive output coupling using the switchable injection plasmas also could decrease thermionic module and power-conditioning costs.

Similar considerations apply to terrestrial thermionic nuclear reactors. Utility power plants probably require the use of low-cost, low-temperature thermionic fuel elements without expensive refractory metal emitters, especially if the entire TFE must be reprocessed upon refueling. The cost constraint might not be as severe for naval reactors, however, permitting utilization of both the high-power-density ignited plasma at high temperatures for full power operation, and the low-temperature injection plasma with a low heat-rejection temperature to maintain high efficiency for low-power operation.

IX. CONCLUSION

A. Dominant Plasma Issues

There are still many peripheral issues that need to be addressed for complete physical understanding and description of thermionic converter plasmas. The following are felt by the author, however, to be dominant frontier issues for substantial advancements in the field via plasma physics:

1) Surface/Plasma Interaction

There is substantial empirical evidence in the form of experimentally observed anomalies that $V_d^*$ and $\phi_C$ in (12) are coupled by as-yet unidentified surface/plasma interaction processes at the collector which inhibit lowering $V_B$ by decreasing $\phi_C$ [28].

2) Injection Plasma Properties

The physical description of injection plasmas is incomplete, especially in the details of the ionization process and of the output current limitation and instabilities arising from interaction of Coulomb and magnetic effects.

3) Plasma Properties at Very High Emitter Temperatures

The properties of both the ignited and unignited plasmas at very high power densities need to be defined both experimentally and analytically for emitter temperatures at which the temperatures and densities of the emitted electrons and ions approach those in the ignited plasma.

B. Projections

Projections are hazardous, especially to the degree that they involve speculation. Whereas the detailed means for accomplishing the following projections are not yet defined, there already are indications that they might be achievable, and no fundamental or practical limitations are known at present that make the following impossible:

1) Thermionic converters operating with injection-type plasmas in cesium-oxygen vapor eventually may operate with steel or superalloy emitters at temperatures of 1100–1300 K and collector temperatures of 500–600 K, giving efficiencies of 15–20% at power densities of a few W/cm$^2$. Externally triggered, self-driven, inductive ionizing oscillations might sustain the plasma and permit either dc or inductive ac output coupling. Applications: large and small fossil-fueled terrestrial power systems.

2) Thermionic converters operating with ignited plasmas in cesium-oxygen vapor eventually may operate with refractory metal emitters at temperatures of 1800–2000 K, and with low thermal emissivity collectors at temperatures of 600–800 K, giving efficiencies of 20–25% at power densities of 10–20 W/cm$^2$. Applications: long life (5–10 y) space and terrestrial nuclear power systems.

3) Thermionic converters with ignited or unignited plasmas in cesium-oxygen vapor eventually may operate with known nuclear fuels at emitter temperatures of 2400–2800 K and collector temperatures of 1100–1400 K, giving efficiencies of 25–30% at power densities of 30–80 W/cm$^2$. Applications: short duration (<1 y) multimegawatt nuclear power systems for high-power density military and electric propulsion systems in space, and for compact silent naval propulsion.

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REFERENCES


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