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PROPOSED MODEL OF THERMIONICALLY ASSISTED BREAKDOWN AND IMPLEMENTATION ON ELECTROSTATIC THRUSTERS

by

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Proposed Model of Thermionically Assisted Breakdown and Implementation on Electrostatic Thrusters

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

A model for thermionically assisted breakdown is proposed which predicts the voltage reduction experienced in low voltage discharges. This reduction in breakdown voltage has been beneficial to numerous engineering applications of arcs and is explored herein specifically for electrostatic thrusters. Full advantage in employing thermionically assisted breakdown is attained by establishing a continuum of electron emission across the primary discharge gap. These electrons must be independent of the discharge itself, being established prior to ignition. The electron emission is therefore achieved by auxiliary emitters across the gap. Electrons amass in a space charge in the vicinity of the assisting device. The particular processes which induce charge multiplication are proposed to be multistep ionization and neutralization of the space charge by ions. Breakdown criteria and a means of estimating the reduction in breakdown voltage requirement are derived. One proposal for the thermionically assisting emission device is the coiled-coil filament, and a scheme for installing such filaments in ionization chambers for electrostatic thrusters is described. Thermionically assisted breakdown implementation should also pertain to arc applications for various primary electrode geometries as well as certain gases.

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I. INTRODUCTION

A. BACKGROUND

Arc discharges are low-voltage, high-current electrical phenomena used in a wide variety of applications. The ignition of an arc between two electrodes in a gas usually requires reaching high voltages at low current levels before the arc breakdown occurs in which the voltage drops dramatically with a corresponding increase in current. This event is also accompanied by a large increase in current density. The voltage required to cause breakdown is a function of the discharge gap geometry, cathode material and various gas properties. Changes in any of these can reduce or increase the breakdown voltage.

Thermionic assistance is one means of reducing breakdown voltage. By establishing a continuous span of electron emission across the discharge gap which is independent of the discharge itself, the voltage can be reduced by a predictable factor. The ability to surmise the amount of voltage reduction holds promise for engineering exploitation of thermionically assisted breakdown to arc discharge applications.

Thermionically assisted breakdown has been applied to a high-pressure sodium lamps to minimize complexity by allowing the breakdown to occur at line voltage rather than having to boost voltage to higher levels [Ref 1]. Such a voltage reduction scheme is explored herein for electrostatic thrusters.

II. RELEVANT GASEOUS BREAKDOWN PHENOMENA

The present chapter describes conducting gas phenomena to assist the reader with various aspects of gaseous conductivity discussed herein. It is not a comprehensive review of gas processes but primarily a summary of certain mechanisms associated with breakdown. Von Engle [Ref 3], Llewellyn-Jones [Ref 4], Papoular [Ref 5], Brown [Ref 6], Llewellyn-Jones [Ref 7], Nasser [Ref 8], Chapman [Ref 9], and Kunhardt [Ref 10] contain more information relating to gas processes and are the sources of the present discussion.

A. GAS COLLISION PROCESSES

Under normal atmospheric conditions, a gas is a nearly perfect insulator [Ref 4:p 13]. A sufficiently strong change in these conditions leads to electrical conductivity or breakdown. In order for a gas to conduct, it must be ionized meaning that free electrons together with ions must be present mixed along with the neutral atoms [Ref 8:p 54]. A monatomic gas consists of a vast number of freely moving atoms which exhibit two modes of energy. These are translational kinetic energy and internal electron potential energy such as ground state, excitation, or ionization. Changes in these states result primarily from collisions for the neutral atoms.

In the case of a gas which is weakly ionized, the neutrals, ions and free electrons within the gas move continuously and collide frequently. Collisions between the gas particles are either elastic or inelastic based on the energy exchange. Particles in elastic collisions only exchange kinetic energy and do not suffer a change in internal energy. Elastic collisions occur only if the particles' energies are below any threshold energy required to change the internal (electron) energy of either particle. Inelastic collisions, however, alter the internal energy of at least one colliding particle. The collisions also change kinetic energy so as to meet energy conservation requirements. Inelastic collisions are classified, according to the effect on the electron potential energy, into excitation, de-excitation, ionization, and recombination. Inelastic collisions are the more interesting type of collisions because only inelastic collisions result in an increase in the number of charged particles. [Ref 9:pp 23-38] The symbols used to describe the collisions are:

- A -- neutral, ground-state atom
- A^* -- excited atom
- A_m^* -- metastable atom
- A^+ -- positively ionized atom
- B -- other neutral atom
- e -- electron
- $h\nu$ -- photon of frequency ν; energy of the photon (Joules)
- * -- denotes a particle with higher energy. (B^*, e^*, $h\nu^*$ have higher energy than B, e, and $h\nu$.)
- KE -- kinetic energy (Joules)

- eV_{excit} -- excitation potential energy (Joules/atom)
- eV_{ion} -- ionization potential energy (Joules/atom)

1. Excitation and De-excitation

An atom's electrons can fill many discrete energy level combinations. When all electrons of an atom are in the lowest possible potential energy levels, that atom is in its ground state. If an increase in internal energy places an electron in a higher energy level, the atom becomes excited. A free electron is one possible colliding entity for excitation. The outermost electron is more easily excited than the others.

$$e^{*} + A \rightarrow A^{*} + e; \quad KE_{e^{*}} \geq eV_{excit} \tag{1}$$

Relaxation returns the excited atom to a lower energy state and, in the absence of a collision, must produce a photon to maintain conservation of energy. Relaxation may be spontaneous; however, if the relaxation occurs after a significant amount of time (much greater than the time between collisions) the excited atom is in a metastable state:

$$A^{*} \rightarrow A + h\nu; \quad h\nu \geq eV_{excit} \tag{2}$$

2. Ionization

This collisional process is the fundamental source of charged particles for gaseous breakdown. When an increase in internal energy results in loss of the outer electron, the atom becomes ionized remaining positively charged. Two possible ionization scenarios are:

$$e^{*} + A \rightarrow A^{+} + e + e; \quad KE_{e^{*}} \geq V_{ion} \tag{3}$$

$$e^{*} + A_{m}^{*} \rightarrow A^{+} + e + e; \quad KE_{e^{*}} > V_{ion} - V_{excit} \tag{4}$$

3. Recombination

The binding of electrons by positive ions results in charge neutralization. In the case of radiative recombination between an electron and an ion, photon emission resolves energy conservation requirements:

$$e + A^{+} \rightarrow A + h\nu; \quad h\nu = V_{ion} \quad . \tag{5}$$

In other cases another particle assists in meeting the energy balance. This is called three-body recombination:

$$e + A^{+} + B \rightarrow A + B^{*}; \quad \Delta KE_{B} = V_{ion} \quad . \tag{6}$$

Papoular [Ref 5:pp 40-61] offers more detailed information on inelastic collisions.

B. BOUNDARY PROCESSES

Solid objects in contact with an ionized gas have great influence on charged particle behavior. When the weakly ionized gas comes in contact with an object (the container wall or one of the electrodes), the object itself acts as a colliding entity. When a collision occurs with the wall, for instance, the wall absorbs the balance of energy. The result is that the wall's thermal energy rises, the wall may then emit an electron or an atom (called sputtering). [Ref 4:p 42]

1. Cathode Processes

The cathode contributes to charge in a gas primarily by electron emission. This occurs through field emission, photoemission, thermionic emission, or positive ion impact emission. [Ref 3:pp 89-108] The latter two are most relevant to phenomena of concern in this work.

a. Thermionic Emission

All metals emit free electrons when heated. Metals have a conducting band or layer called the Fermi level below the surface. A potential barrier exists between the Fermi level and the surface of the metal so that an electron must have sufficient energy to overcome this potential difference in order to leave the metal and be emitted. High temperature is one method of yielding such an emission in most pure metals. The Richardson-Dushman equation shows the relationship between the emission current density J, the potential difference ϕ and the temperature T:

$$j = A\,T^2\,e^{\frac{-e\phi}{kT}} \tag{7}$$

where A is a constant of the cathode material, k is the Boltzmann constant and e is the unit of charge. The minimum energy necessary to emit one electron is the work function $e\phi$, thus a metal which is described as a low work-function material has good thermionic properties. Thermionic emission is the primary source for thermionic discharges or hot cathode discharges. [Ref 5:pp 62-65]

b. Secondary Emission

Regardless of the method of electron production in the gas, a discharge needs a secondary source to become self-sustaining or independent of the primary source [Ref 8:p 221]. The incidence of a positive ion striking a cathode is a second source of energy for electron emission. Upon collision, the ion recombines with an electron and the balance of energy heats the local area of the cathode to the point that it liberates a second electron. For this to happen, the ion kinetic energy must be about twice the work function of the cathode to yield the two electrons. [Ref 5:pp 70-71] Not all incident ions have this energy so the number of electrons emitted per incident ion, γ, is of the order 10^{-2} to 10^{-1} depending on the gas and electrode material [Ref 11:p 159].

2. Anode Processes

Depending on local conditions, an electron reaching the anode either reflects off the anode surface, causes emission of a second electron, is absorbed to complete the exterior circuit for current flow, recombines with an ion, or collects in a space charge. The primary purpose of the anode is to collect electrons for completion of the exterior circuit.

C. CHARGED PARTICLES IN AN ELECTRIC FIELD

An electric field maintained by two electrodes in a weakly ionized gas elicits important behavior of the charged particles. Without an external field, all particles move randomly throughout the gas regardless of charge. A field exerts a force on the charged particles so that the ions accelerate toward the cathode and the electrons accelerate toward the anode. Collisions prevent continuous acceleration toward the electrodes and result in an average or terminal velocity in the direction of the respective electrode called a drift velocity v_ι. This velocity is related to the electric field $\mathscr{E}$ by a constant μ_ι, the mobility of the particle in the following way:

$$v_\iota = \mu_\iota \mathscr{E} \quad . \tag{8}$$

Because of the mass difference between electrons and ions, the electrons regain their velocity toward the electrode much more quickly with respect to the time between collisions and thus have a greater mobility than the ions in the same system. [Ref 8:pp 155-158] The presence of an electric field and charges in a gas, therefore, results in gaseous conductivity since moving charges form a current density [Ref 5:pp 98-99]

$$\overline{j} = n_+ e_+ \overline{v}_+ - n_- e_- \overline{v}_- \quad . \tag{9}$$

The following section draws together the previously described processes while stepping through the mechanism of gaseous breakdown from the initial introduction of charge to the catastrophic increase in current called breakdown.

D. BREAKDOWN

> The problem of breakdown is one of identifying the particular [collision] processes predominating in any given case, and of finding the general mechanism by which those processes interact to produce the observed growth of current. [Ref 7:p 15]

The present section describes the contribution of primary and secondary current buildup to gaseous breakdown based on Townsend's theory as described in Kunhardt [Ref

10] and Nasser [Ref 8:p 228]. A gas in a nonvarying electric field bounded by two electrodes initially contains little or no free charge. An existing electron may have been formed within the gas by photoionization from an outside radiation source, or at the cathode by any of the cathode processes except positive ion impact emission. This initial electron travels toward the anode and may ionize an atom thus producing a second electron which may assist in further ionization as it proceeds toward the anode. The production of ions is a function of x the interelectrode coordinates) of the form:

$$e^{\int_0^d \alpha dx} \tag{10}$$

where α is the Townsend-primary-ionization coefficient representing number of ionizations per unit length. Ions which are produced in the gas may eventually strike the cathode and recombine there, possibly leading to secondary electron emission. [Ref 8:p 228]

The development of breakdown criteria requires definition of some self-sustaining condition. A self-sustaining discharge is one in which the current within the gap is independent of any outside electron source [Ref 10:p 132]. Charge multiplication is achieved through ionization and secondary emission processes:

$$i = \frac{i_o e^{\alpha d}}{[1 - \gamma(e^{\alpha d} - 1)]} \quad . \tag{11}$$

Equation (11) expresses the relationship between the emitted current i_o and the total current i in terms of the ionization production function $e^{\alpha d}$ and the secondary emission coefficient γ. [Ref 8:p 228] At breakdown, the current i is independent of i_o; therefore, even when $i_o=0$, the current i is finite [Ref 10:p. 132]. Thus, setting the denominator to zero yields:

$$\alpha d = [1 - \gamma(e^{\alpha d}-1)] \quad . \tag{12}$$

The value of α is well documented and is defined as a function of $\mathscr{E}/p$ which is the average energy gained between collisions with $\mathscr{E}$ being the electric field and p the gas pressure:

$$\alpha = Ape^{-\frac{Bp}{\mathscr{E}}} \tag{13}$$

where A and B are empirical constants of the gas [Ref 8:pp 191-197]. Substituting α and $\mathscr{E}$ = V/d into Equation 17 gives V as a function of the pressure-distance product pd [Ref 8:p 246]:

$$V = \frac{Bpd}{\ln\left(\frac{Apd}{\ln(1+1/\gamma)}\right)} \quad . \tag{14}$$

Specific values of A, B, and γ are given in Appendix A. This is Paschen's law which is graphed in Figure 1 for xenon using A and B coefficients from Von Engle [Ref 3:p 203] and γ = 0.058 [Ref 11:p 159].

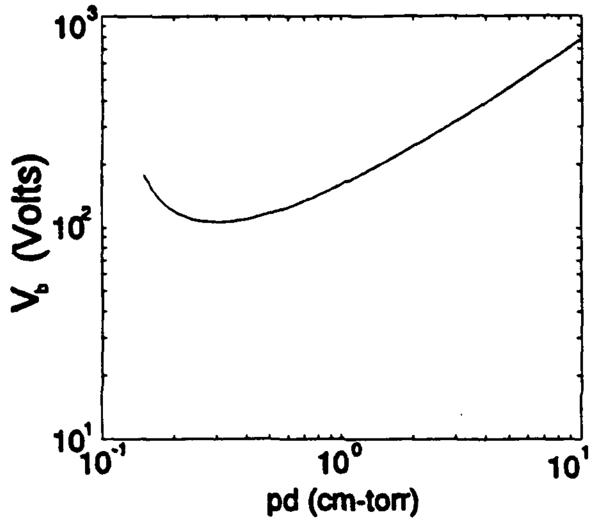

Figure 1 Paschen Curve for Xenon

Figure 1 shows a distinct minimum in the Paschen curve. The derivation for the voltage and pd product at this minimum is described in Nasser [Ref 8:pp 246-247]:

$$V_{min} = 2.718 \frac{B}{A} \ln\left(1 + \frac{1}{\gamma}\right) \quad (15)$$

$$pd_{min} = \frac{2.718}{A} \ln\left(1 + \frac{1}{\gamma}\right) \quad . \quad (16)$$

Since at constant temperature the pressure p is inversely proportional to the mean free path λ, the pd product describes the ratio of gap distance to mean free path. Breakdown voltage increases to the left of the minimum because the distance between electrodes becomes less than the ionization mean free path of an electron within the gap. This reduces the chance of ionization before an electron reaches the anode which directly reduces charge multiplication. To the right of the minimum, an increase in pd results in a decrease in average electron energy gained between collisions (E/p) thus less ions are formed again reducing the charge multiplication. In each case an increased voltage is required to overcome the limitation. [Ref 3:p 196]

The secondary electron emission properties of the cathode material affect the Paschen minimum through the γ term. Material with a high rate of emission per ion collision will shift the minimum down and to the left as shown in Figure 2 for xenon. [Ref 6:pp 190-191]

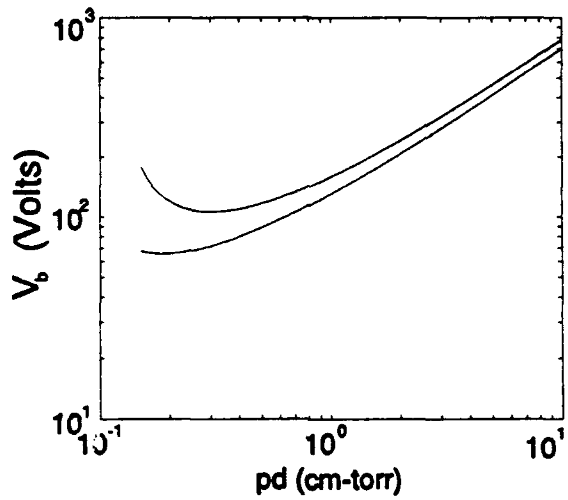

Figure 2 Xenon Paschen Curve for Dissimilar γ

Lebedev [Ref 12] has shown that the cathode temperature also shifts the Paschen curve down and to the left for increasing temperature. The Paschen minimum for the case shifts along a much steeper angle than for the illustration in Figure 2.

E. THE DISCHARGE CHARACTERISTIC

For an external circuit, an increase in voltage from zero yields a very specific progression of current behavior. The solid-lined plot in Figure 3 is a schematic path of

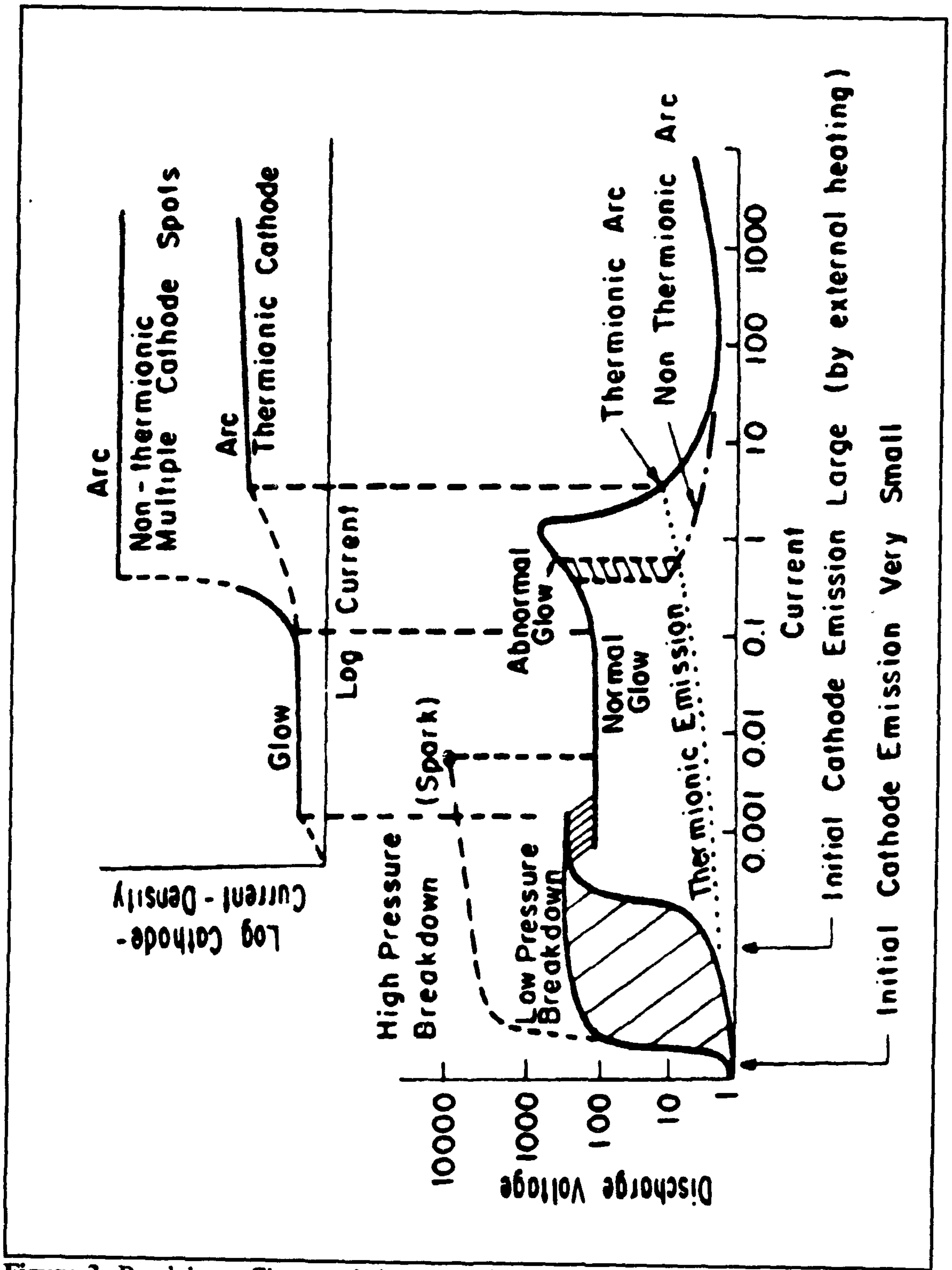

Figure 3 Breakdown Characteristics [Ref 13:p 174]

this behavior for non-thermionic discharges and is dependent on conditions such as pressure and electrode distance within the discharge chamber [Ref 13:pp 173-175]. At first the current increases very slightly for large changes in voltage. During this stage electron collection at the anode is the dominant process and the circuit current eventually reaches saturation. As the voltage increases to the order of 10^2 V, charge multiplication begins and causes breakdown to glow discharge which is characterized by large increases in current independent of voltage and distinct luminous regions between the electrodes. [Ref 5:pp 123-125] Transition to an arc discharge requires a voltage increase to nearly 10^3 V. At the breakdown voltage typically predicted by the Paschen curve, a dramatic drop in voltage is accompanied by an equally dramatic rise in current. The arc is characterized by a voltage of a few Volts, a current of tens of Amps and a bright condensed discharge filament with high current density connecting the two electrodes. [Ref 5:p 141]

Thermionic or hot cathode discharges follow the behavior shown by the dotted line in Figure 3. Arcing takes place without going through the glow processes; therefore, the breakdown voltage is much smaller than the non-thermionic breakdown voltage. The current density in the arc is governed by the external circuit. [Ref 13:pp 173-175]

III. A MODEL OF THERMIONICALLY ASSISTED BREAKDOWN

A. BACKGROUND

This model describes the onset of arcing in which thermionic electron emission reduces breakdown voltage in an electrode gap. A series of very small gaps, called microgaps, spans across the space between the primary electrode pair called the primary discharge gap. The cathode of each microgap emits electrons when heated. Such a system is a good model for a multiply coiled incandescent filament stretched across the primary discharge gap. The resulting breakdown occurs at a voltage value which is substantially lower than the breakdown voltage predicted by the ordinary Paschen curve minimum. The effect results in a non-linear shift in Paschen-like behavior to much lower voltages for breakdown. Such an effect has been known for decades and has been implemented in various discharge devices. It could also be considered for any engineering applications which also utilize arcs.

The mechanisms behind the thermionically-assisted breakdown are not well documented. The goal of the present model is to provide a description of the physical process involved in arc initiation with thermionic assistance [Ref 2].

B. PREVIOUS OBSERVATIONS

Small gaps have been used in the form of starter electrodes to initiate discharge in electrostatic thrusters flown on spacecraft. The starter electrode reduces the gap of a 30 cm thruster to 0.10 cm for ignition [Ref 14:p 3]. This is meant to facilitate breakdown across the much larger ionizer radial dimension.

Phenomena behind the thermionic assistance of breakdown have been known since the early development of incandescent lightbulbs. Present day household bulbs use an inert gas such as argon or krypton to increase filament lifetime. These gases have such low excitation/ionization potentials that, even at their relatively low operating line voltages, a gaseous discharge develops during normal use of the bulb. However, manufacturers mix nitrogen with the inert gas; this diatomic molecule quenches the low-voltage ionization of the monatomic gas before large-scale ionization sets in and leads to breakdown. [Ref 15:p 233]

The thermionic power converter has been extensively studied throughout the past several decades since they have benefits of direct production of electric power from heat. The cesium diode has been studied extensively in the "arc-mode." Thermionic discharges in cesium diodes, which result from a single hot cathode emitting electrons into a small gap, use the cathode sheath for an electron source and are not conceptually different from the thermionically-assisted discharge described herein although the gap structure is dissimilar. Literature includes Hernqvist [Ref 16], Lebedev [Ref 12], Gus'kov [Ref 17], Wilkins [Ref 18], Jacobson [Ref 19], Garamoon [Ref 20], and Lawless [Ref 21]. Additional details are included in Appendix B.

It has been observed that the installation of an incandescent filament coil in sodium lamps reduces the breakdown voltage necessary to light a cold lamp from hundreds of volts to line voltage. The alteration has other benefits as well such as allowing hot starts whereas unaltered sodium lamps must cool before being restarted. [Ref 1]

C. DEVELOPMENT

The present model involves a one-dimensional series of very small gaps, called microgaps across the primary discharge gap such that a pair of minute plate electrodes bound each microgap and the primary electrodes bound the multiplicity of microgaps. The cathode of each microgap emits electrons which flow toward the local anode of the microgap represented by a locus of lower potential a short distance away. Figure 4 depicts this geometry, although the actual number of microgaps across the primary discharge gap has been largely reduced.

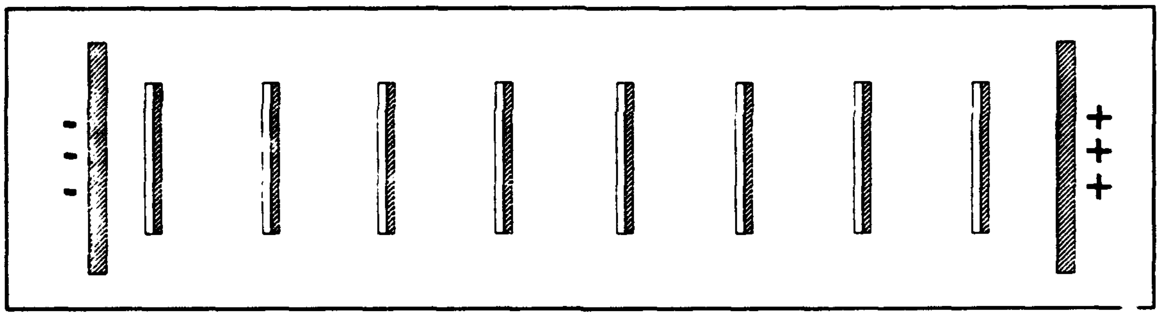

Figure 4 Series of Microgaps Between Primary Discharge Gap

D. BREAKDOWN MECHANISM

1. Assumptions

This model of the breakdown process describes a system of one microgap encompassing a gas with a low excitation threshold. The charged particles of this gas move one-dimensionally with any existent electrons and ions moving with antiparallel velocities relative to each other. Both particle species contribute to current which, by convention, flows from anode to cathode. The electric field is assumed to be uniform and unvarying.

Any electron-ion inelastic collision which contributes to the breakdown results in an excited neutral atom or an ionized excited atom. Because of the low operating voltages, the electrons with energies in the Maxwellian tail contribute most or all of the ionization/excitation energy [Ref 22:p 500]. Therefore, significantly large numbers of electrons are not able to attain the energies necessary for single-step ionization, multiple ionization or negative ion formation; and only positive, singly-charged ions are formed in a multi-step process. Recombination offsets the total ionization rate. Electrons are introduced into the microgap from the cathode sheath or by the ionization process and disappear either in the gap because of recombination or at the local anode.

When a potential difference is applied to the primary electrodes, a small potential difference $V_i(x_i)$ develops across each microgap width $0 < x_i < d_i$ with $V_i(0) = 0$ relative to other points across the microgap. At the same time, the cathode of each microgap begins to heat leading to electron emission.

2. Hot Cathode/Sheath Formation

As the microgap cathode thermionically emits electrons, a cathode sheath or space charge develops which holds the electrons in the low potential region shown in Figure 5. This sheath develops to a dimension d_{sc} which is much smaller than the width of the microgap ($d_{sc} \ll d_i$).

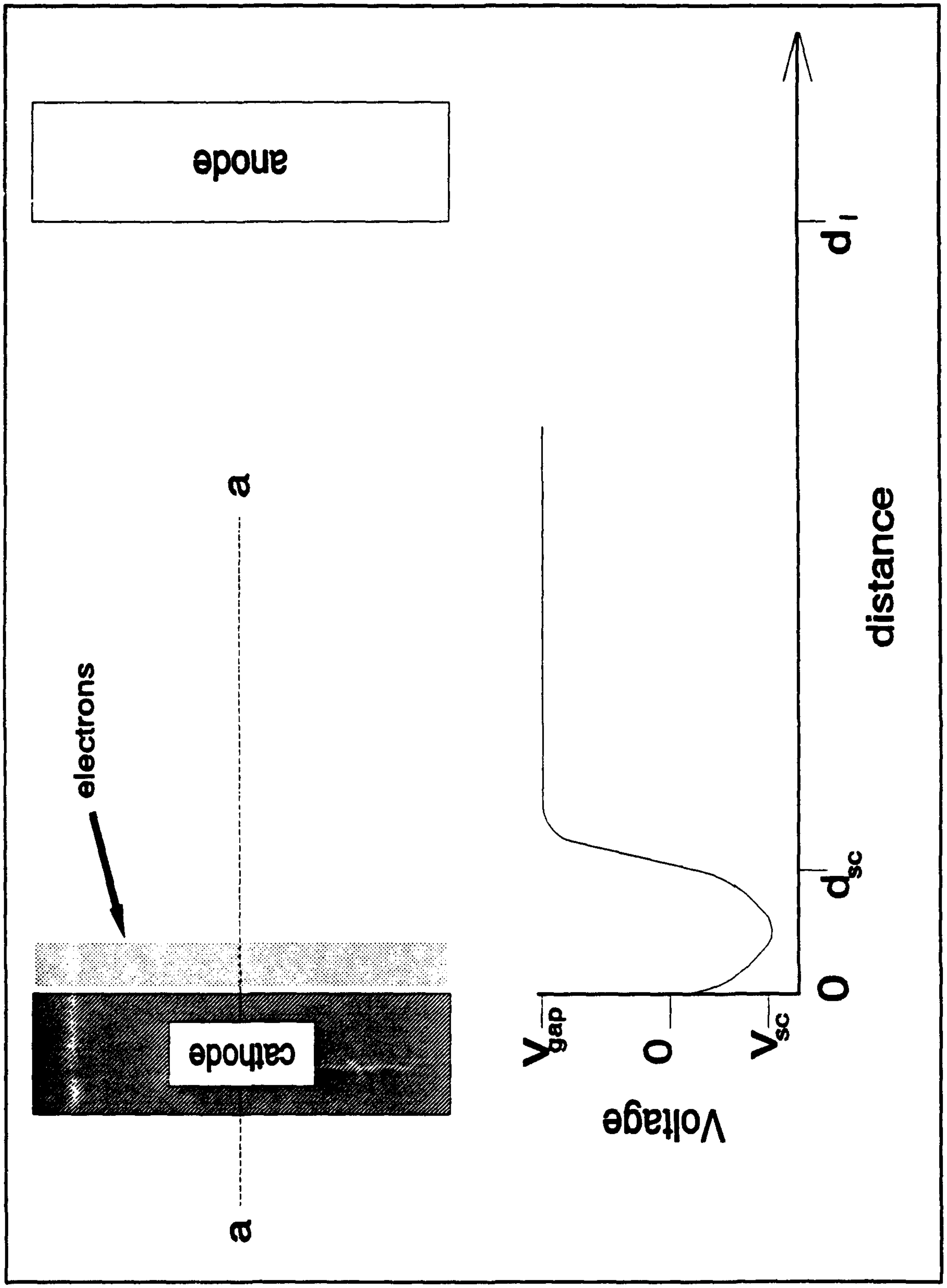

Figure 5 Microgap Cathode Sheath due to Space Charge

3. Current Initialization

As the sheath is formed, an arbitrary electron source produces a small number of initial free electrons that are able to travel toward the local anode and develop an initial current

$$j_- = j_o \tag{17}$$

made of n_- electrons with velocities v_-. These electrons initiate the ionization process. The production of ions is a function of x of the form:

$$e^{\int_0^d \alpha dx} \tag{18}$$

where α is the Townsend primary ionization coefficient. Electrons excite neutrals and ionize excited atoms at lower energies than the energy required for single-step ionization of ground-state atoms. The potential in the microgap can thus be smaller than the ionization potential of ground-state neutrals, $V_{gap} < V_{ion}$, but it is sufficient to provide electrons with the energy to excite the neutrals and ionize the excited atoms ($V_{gap} \approx V_{excit} \approx V_{*ion}$). Therefore, the ionization is a multi-step process:

$$\begin{aligned} e^* + A &\rightarrow A^* + e \\ e^* + A^* &\rightarrow A^+ + 2e \end{aligned} \tag{19}$$

The electron current reaching the local anode j_a is greater than that leaving the cathode sheath j_o according to:

$$j_a = j_o e^{\alpha d} \tag{20}$$

Consequently, the ion current arriving back at the cathode sheath is

$$j_{+} = j_{o}(e^{\alpha d} - 1) \quad . \tag{21}$$

4. Breakdown

The ions impact upon the cathode sheath and recombine. The positive charge neutralizes the local impact area thereby raising the potential so that, at the same overall voltage, more electrons can escape (Figure 6). Once liberated the electrons cause more ionization as they travel toward the local anode. This process continues to enhance the current in the microgap until breakdown occurs. Because the space charge neutralization may release many more electrons compared with Townsend's theory of secondary electron emission (in which ions directly impact on the primary cathode), the microgap cathode need not emit copious amounts of electrons as in a high current density. That is, the cathode temperature need not be extreme in order for an adequate electron reservoir to form at the sheath. Once breakdown develops in a sufficient number of the microgaps, the process expands beyond the microgap geometry and results in a volumetric breakdown across the primary discharge gap.

E. BREAKDOWN CRITERIA

To evaluate the current in this process, it is necessary to assume that the current is mobility limited. The space-charge limited current for such a system is found in the conventional manner. For either charged species, the current j_i for charge with a mobility-limited velocity is given by the following relations:

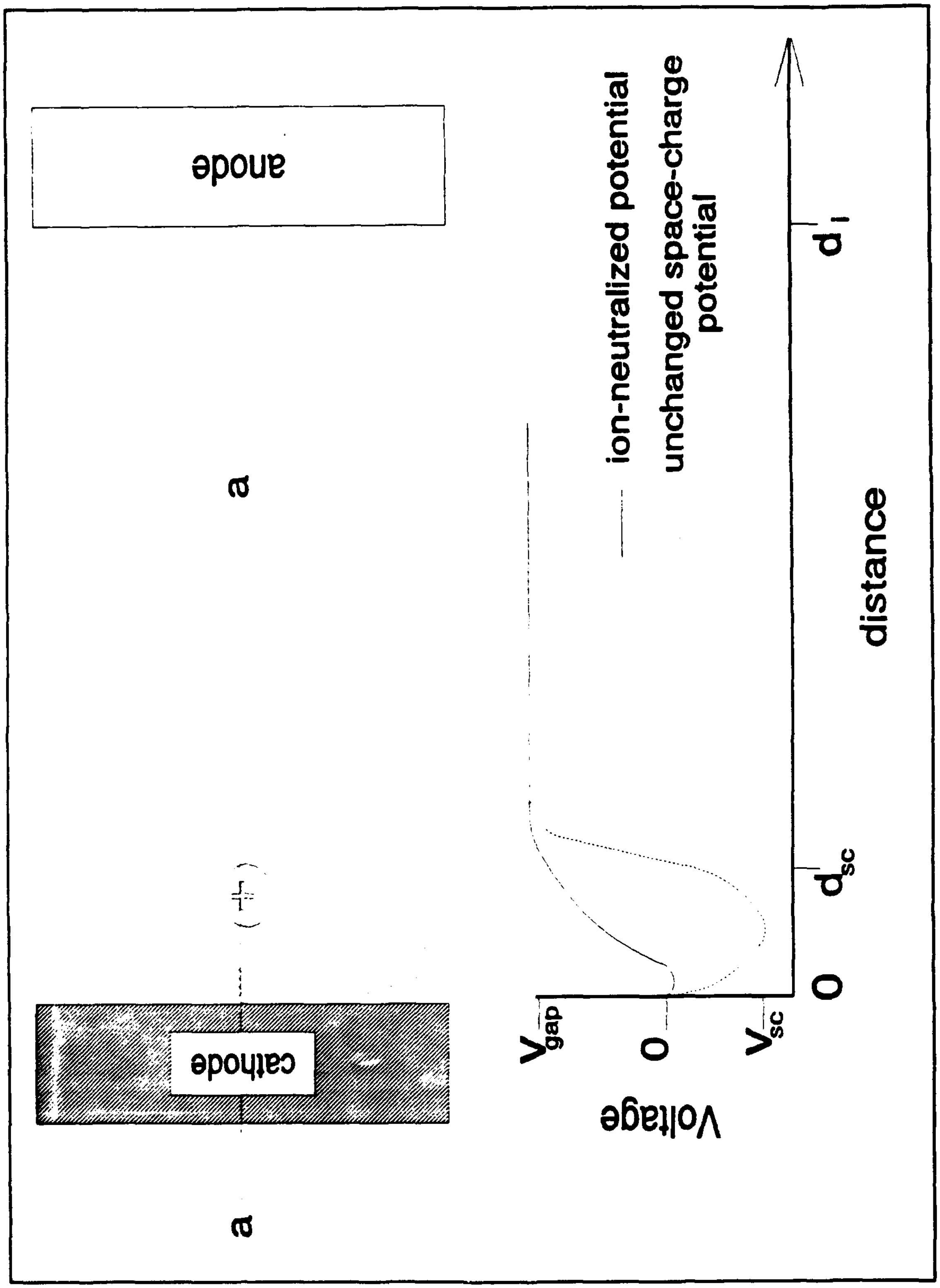

Figure 6 Space-Charge Neutralization by Ion Impact

$$j_\iota = qn_\iota v_\iota = qn_\iota \mu_\iota \mathscr{E} \tag{22}$$

where q is the unit charge, n_ι is the number density of the particle species, v_ι is the particle velocity, μ_ι is the particle mobility, $\mathscr{E}$ is the electric field, and ι represents the particle species (proton or electron). Solving for qn_ι yields

$$qn_\iota = \frac{j_\iota}{\mu_\iota \mathscr{E}} \quad . \tag{23}$$

The problem may be solved by finding a potential V(x) which satisfies the one-dimensional Poisson's equation for the boundary conditions that $V(0)=0$, $V(d_{sc})=V_{sc}$:

$$\frac{d\mathscr{E}}{dx} = \frac{\Sigma qn_\iota}{\epsilon_o} \quad . \tag{24}$$

where

$$-\mathscr{E} = \frac{dV}{dx} \tag{25}$$

and ϵ_0 is the permittivity of free space. Since n_ι is a function of $\mathscr{E}$, substituting Equation (28) into Equation (29) obtains

$$\frac{d\mathscr{E}}{dx} = \frac{1}{\epsilon_o \mathscr{E}} \sum \left(\frac{j_\iota}{\mu_\iota} \right) \quad . \tag{26}$$

The solution for Equation (31) in terms of V_{sc} is

$$V_{sc}^2 = \frac{2}{\epsilon_o}\sum\left(\frac{j_i}{\mu_i}\right)\frac{d_{sc}^3}{\frac{9}{4}} \quad . \tag{27}$$

The current for each charge carrier at the boundary of the space charge is defined by Equations (22) and (26). An expression for j_o is obtained by substituting Equations (22) and (26) into Equation (32):

$$j_o = \frac{9\epsilon_o}{8}\left(\frac{\mu_+\mu_-}{\mu_-(e^{\alpha d}-1)-\mu_+}\right)\frac{V_{sc}^2}{d_{sc}^3} \quad . \tag{28}$$

As the gas in the microgap experiences breakdown, the electron current leaving the space charge becomes very large, so that the condition necessary for breakdown is for the denominator to vanish:

$$\mu_-(e^{\alpha d}-1) - \mu_+ = 0 \quad . \tag{29}$$

By binomial approximation of the exponential term ($\alpha d_i \ll 1$), the breakdown condition is then expressed in terms of αd:

$$\alpha d \approx \frac{\mu_+}{\mu_-} \quad . \tag{30}$$

Considering breakdown in the primary discharge gap without thermionic assistance, Townsend's theory defines the breakdown condition in terms of αd and

γ, the secondary ionization coefficient:

$$\alpha d = \ln\left(1 + \frac{1}{\gamma}\right) \quad . \tag{31}$$

This expression results in Paschen's law [Ref 8:pp 245-246] which relates the breakdown voltage V_b as a function of the pressure-distance product pd for an electrode gap. Combining Equations (35) and (36) shows that the mobility ratio can be used in a similar fashion to determine the voltage necessary for breakdown to occur in the primary discharge gap with the thermionic assistance. This indicates that a thermionically-assisted breakdown will not follow the traditional Paschen's law, although it may exhibit Paschen-like behavior in which V_b is dependent upon the microgap geometry and the pressure. Using the breakdown criteria for thermionically-assisted discharges yields the following Paschen-like minimum values:

$$V_{min} = 2.718 \frac{B}{A} \frac{\mu_+}{\mu_-} \tag{32}$$

$$pd_{min} = \frac{2.718}{A} \frac{\mu_+}{\mu_-} \tag{33}$$

A and B are constants of the gas, and 2.718 is the exponential function of unity. The shift to lower magnitudes predicted from the mobility ratio is similar to the shift due to use of cathode material with a larger secondary electron emission coefficient. The extent of the shift due to the space charge neutralization, however, is much more extreme than a shift by changing the conventional secondary emission properties.

F. MOBILITY RATIO

The mobility ratio which is used in this model to determine the breakdown condition and value of the breakdown potential is given approximately by the kinetic theory of gases.

For either species the mobility can be expressed as a function of mean free path λ, charge q, and mass m of the particle:

$$\mu_i = \frac{|q|\lambda_i}{m_i \bar{c}_i} \tag{34}$$

C-bar is the average velocity of the particle species and is a function of the particle temperature T and mass m:

$$\bar{c}_i = \left(\frac{8kT_i}{\pi m_i}\right)^{\frac{1}{2}} \tag{35}$$

where k is the Boltzmann constant and λ is the mean free path. By substituting Equations (40) into (39), the mobility ratio can be approximated as

$$\frac{\mu_+}{\mu_-} \approx 1.18\frac{\lambda_+}{\lambda_-}\sqrt{\frac{T_-}{T_+}\frac{m_-}{m_+}} \tag{36}$$

which for Xenon is approximately 2.7×10^{-3} [Ref 22:p 528]. A rougher "back of the envelope" estimate of the mobility ratio is

$$\frac{\mu_+}{\mu_-} \approx \sqrt{\frac{m_-}{m_+}} \tag{37}$$

which for xenon is also on the order of 10^{-3} [Ref 16:p 751]. Applying these values to Paschen's law illustrates the expected low voltage breakdown for a thermionically assisted system. By using a series of small gaps with thermionic cathodes, the required voltage for breakdown in the primary discharge gap is decreased beyond the voltage reduction attained by merely introducing a small gap to the system or by using a single thermionic cathode. For lower pd values with monatomic gases, the voltages at which the thermionically assisted breakdown occurs are well below the minimum voltage V_{min} predicted by Paschen's law.

G. AN EXAMPLE

The theoretical shift in Paschen-like behavior is shown in Figure 7 and Figure 8 for argon to demonstrate Waymouth's observation [Ref 15:p 233] that an incandescent bulb filled with pure argon breaks down at line voltage which is a much lower voltage than expected. Assuming the argon pressure is one atmosphere (760 torr) and the gap which contains the incandescent filament is a set of parallel plates one centimeter apart, the unassisted breakdown voltage plotted on the conventional Paschen curve (curve 1 of Figure 8) is approximately 16,000 volts using A and B from Nasser [Ref 8:p 203] and $\gamma = .058$ [Ref 11:p 159]. Thus, the voltage required for breakdown without a thermionically assisting filament is far above line voltage. Substituting $\mu_+/\mu_- \approx 4 \times 10^{-3}$ for the $\ln(1+1/\gamma)$ term in Paschen's law *shifts* the Paschen *minimum* along the slope

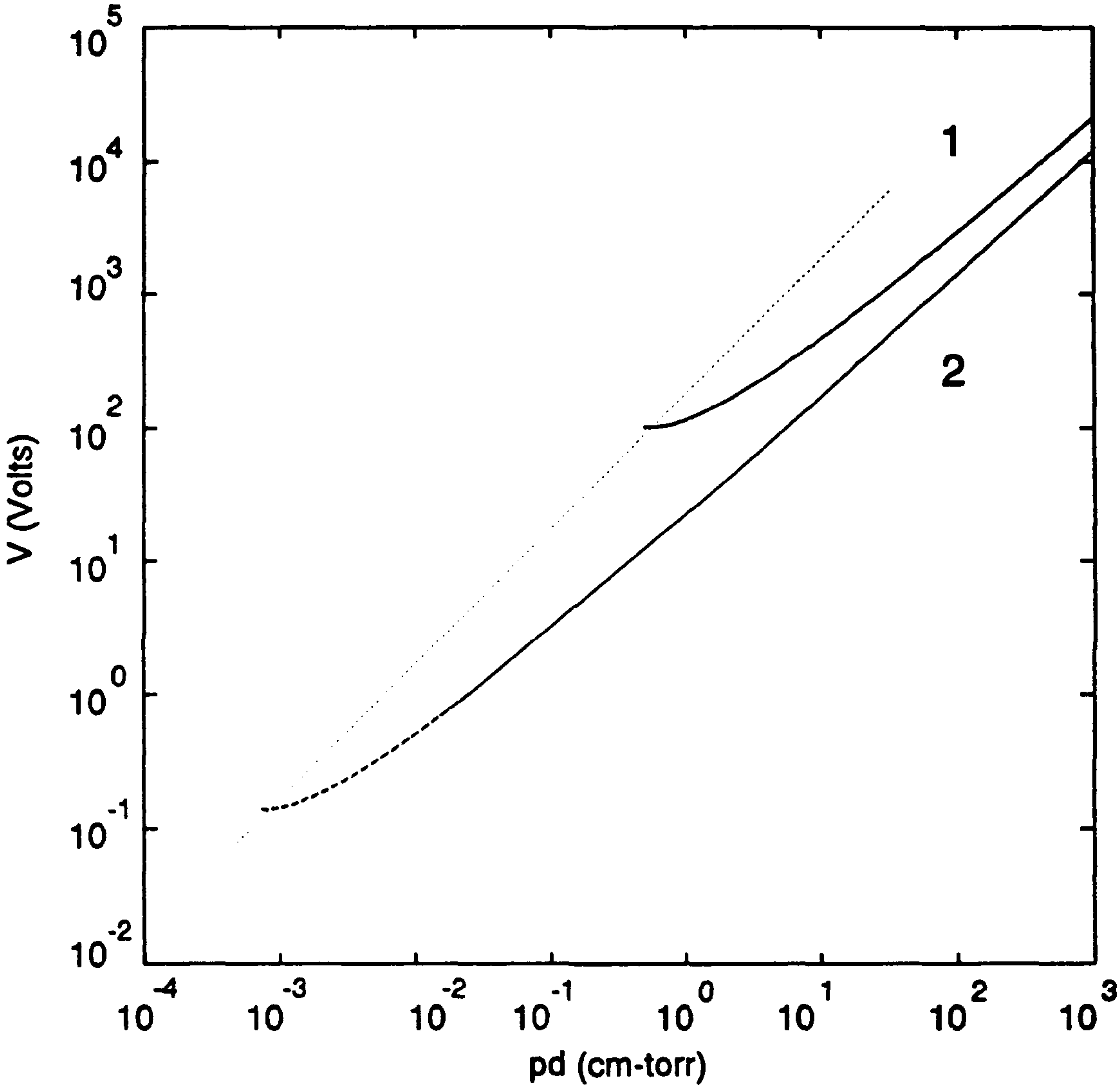

Figure 7 Paschen Minimum Shift for Argon

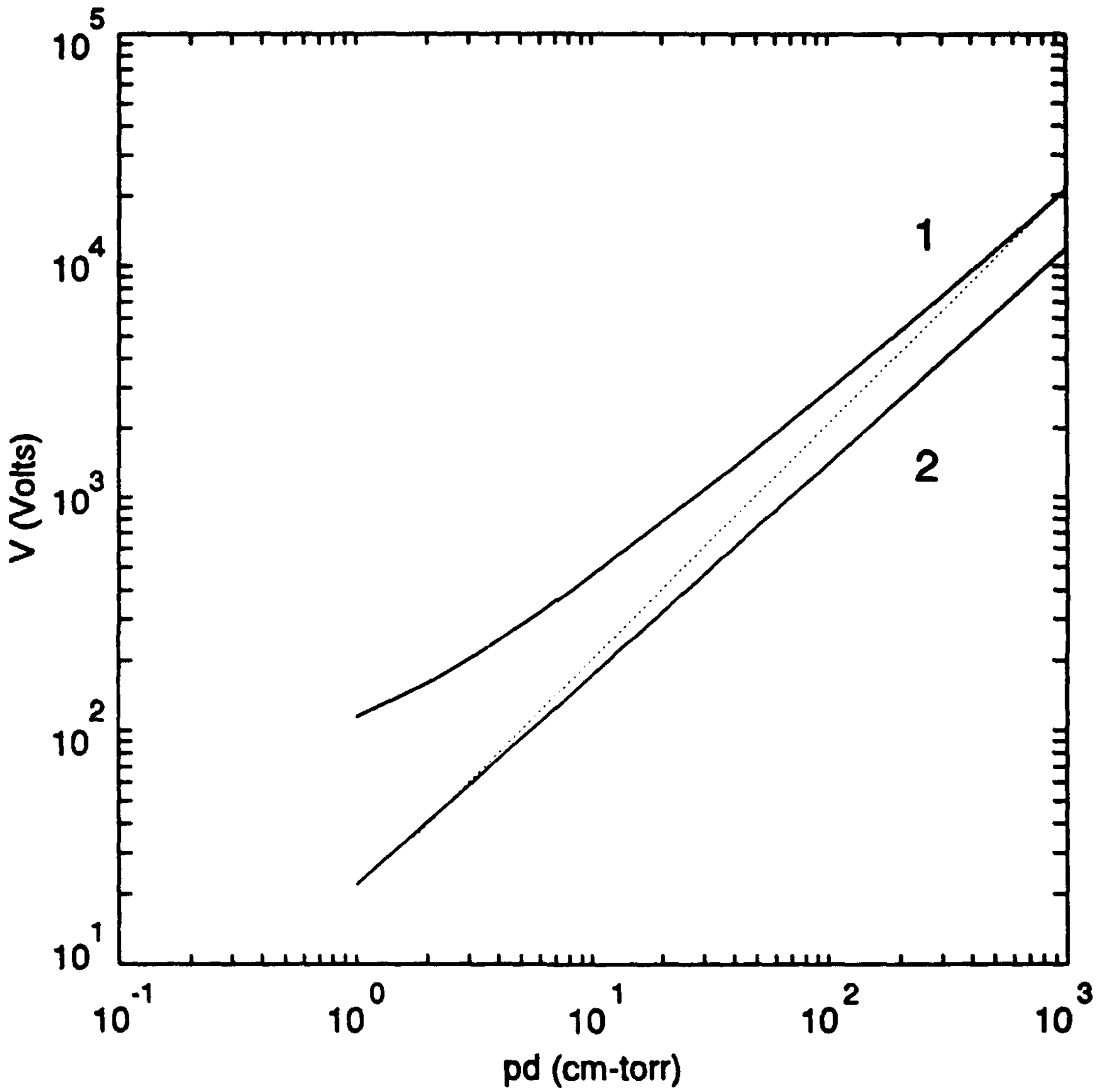

Figure 8 Operating Point Shift for Argon Lamp

shown by the dotted diagonal line in Figure 7. The operating point of the argon is expected to shift in the same manner as shown by the dotted line in Figure 8. The intersection at curve 2 of Figure 8 is the voltage required for breakdown with a thermionically assisting filament in the gap. Therefore, the assisted breakdown voltage is 35 volts which is below line voltage indicating that pure argon is not practical for household incandescent bulbs! Adding nitrogen increases the breakdown voltage; however, this cannot be indicated on Figure 7 or Figure 8 because the Paschen law A and B constants change and are undocumented for a mixture of argon and nitrogen.

The dashed portion of Curve 2 in Figure 7 indicates the probability of a limiting value in the neighborhood of the quantum-driven ionization potential. Electrons from the high-energy tail of the Maxwellian distribution are likely to allow a voltage which is below the voltage value of the ionization potential to some extent, but the results predicted by the model are too great to be tenable in the dashed-curve region.

Nasser makes a noteworthy point that Paschen's law does not yield realistic values due to the simplifications used in its derivation. The behavior depicted in the Paschen curve, however, is accurate and has been confirmed by numerous experiments. [Ref 8:pp. 246-247] Therefore, the values quoted from Curve 1 of Figure 7, which were generated directly from Paschen's law, are different from experimental values of breakdown voltage. Von Engle [Ref 3:p 201] gives a good example of an experimental Paschen curve for argon. It is expected that the behavior predicted by the model would still hold for the experimental values.

H. MODEL SUMMARY

A model has been proposed describing the thermionically-assisted breakdown process for an electrode pair in a monatomic gas. In the model, a series of microgaps is spanned across the primary discharge gap to thermionically emit electrons uniformly across the gap. The breakdown voltage is much less than that predicted by Paschen's law. This voltage reduction is a result of two conditions:

- Ions interacting with a negative space charge developed near the microgap thermionic cathode liberate far more electrons than the conventional model of secondary electron production by direct impact of ions upon a primary cathode, and
- A series of thermionic cathodes across the primary discharge gap to create a uniform distribution of free electrons across the primary discharge gap. The electrons in the high-energy tail of the Maxwellian distribution participate in multi-step ionization leading to charge multiplication

The breakdown criterion becomes

$$\alpha d \approx \frac{\mu_+}{\mu_-} << 1 \tag{38}$$

which, when applied to the development of Paschen's law, shows a dramatic reduction in breakdown voltage.

IV. PRINCIPAL ELEMENTS OF ELECTROSTATIC PROPULSION

This chapter describes the basic aspects of electrostatic propulsion which pertain to the following chapter for the reader who is unfamiliar with electrostatic thruster technology. Electrostatic thrusters are low-thrust propulsion devices which accelerate ions through an electric field to attain a propelling force [Ref 23:pp 464-506]. They consist of the principal elements and supporting devices shown in Figure 9. The electron source, accelerator and neutralizer are closely integrated as shown in Figure 10.

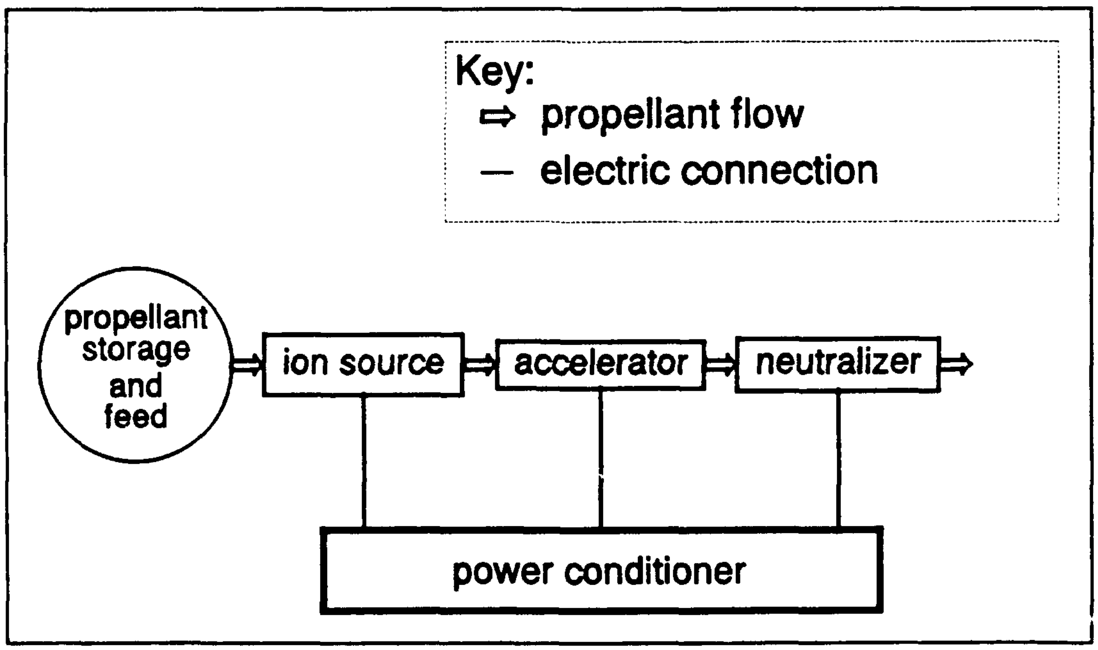

Figure 9 Schematic Diagram of an Electrostatic Thruster

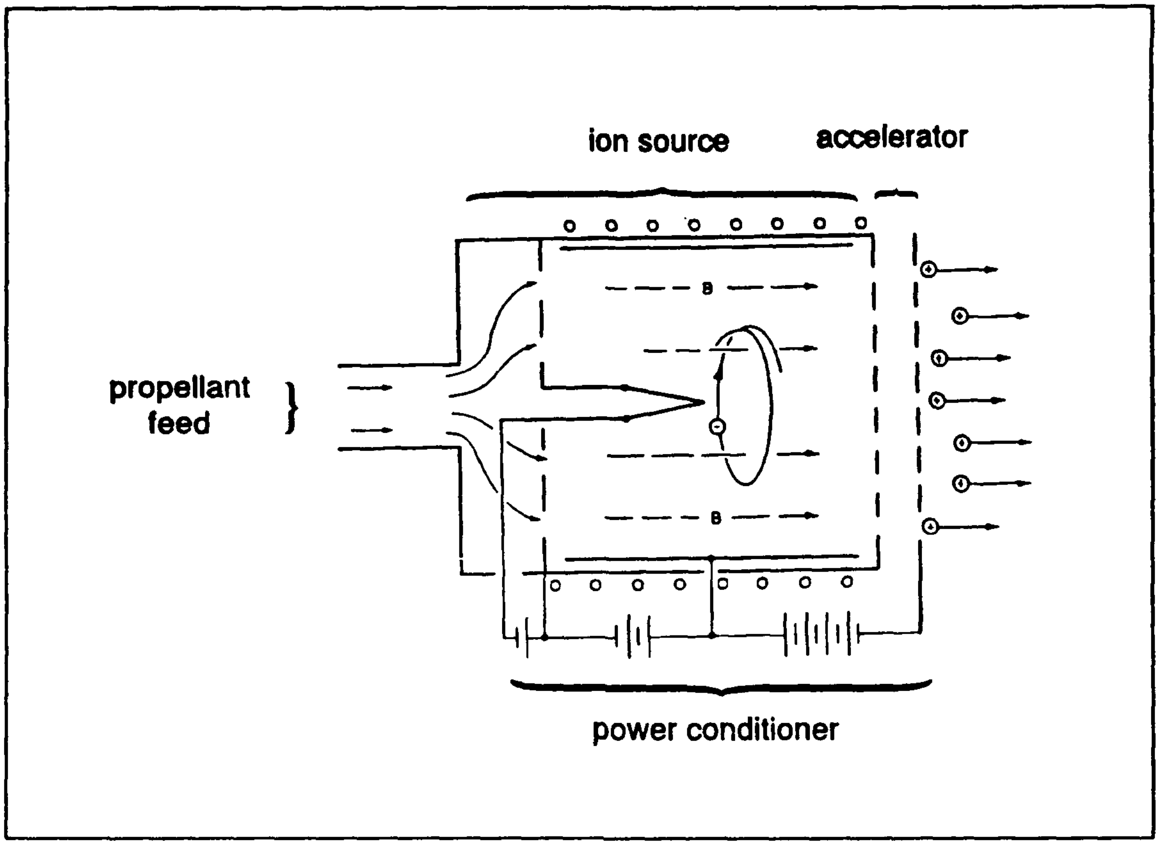

Figure 10 *Principal Elements of an Electrostatic Thruster*

A. Ion Source

The ion source is the most pertinent thruster element for the following discussion on implementation especially the type of ion source which uses electron bombardment. The primary components of an electron bombardment ion source include an electron source, or cathode, an anode, a magnetic field source, and propellant feed outlets. This ion source depends on the electron-atom gaseous collisions for ionization. The electron source is a thermionic cathode which is usually aligned with the axis of the cylindrical thruster. Originally, filaments were used, but in the late 1960's hollow cathodes replaced filaments [Ref 24:p 12] to overcome what was seen as disadvantages to using filaments.

The electrons are attracted toward the anode and collide with the propellant atoms along the way. Magnetic coils or permanent magnets establish a cross field which extends the path of the electrons by approximately one order of magnitude to increase the probability of an ionizing collision [Ref 25]. The electrons are collected at the anode which forms the circumferential inner wall of the cylindrical thruster.

The present thruster generation uses hollow cathodes with a starting electrode to facilitate arc initiation [Ref 14:p 13] although recent research at NASA-Lewis [Ref 26] appears to refute the necessity of a starting electrode. The hollow cathode consists of a tungsten insert which is heated by an external heating coil to about 1100° C to emit thermal electrons. The outer casing of the cylindrical cathode is closed except for a small orifice on the end which protrudes into the chamber. Electrons are emitted through this orifice to ionize the propellant. [Ref 27]

B. PROPELLANT

Cesium and mercury were the original propellants for electrostatic thrusters because of their extremely low ionization potentials. Handling difficulties with these propellants, however, necessitated the shift to alternatives such as the noble gases. [Ref 24:p 4] Xenon is the preferred propellant for missions to date, however argon would most probably be used for missions such as solar system exploration due to availability and cost.

C. POWER CONDITIONER

The power conditioner supplies the required voltage level at the required time to the various electrodes and heaters. The power conditioner composes more than 50% of the thruster-dedicated dry mass [Ref 28:p 4].

D. OTHER

The remaining ion engine elements include the neutralizer and accelerating electrodes. The ion beam which provides the thrust is formed by the accelerating electrodes which operate at high voltage and high current levels. The accelerator therefore consumes most of the power during steady-state operation of the thruster. The neutralizer is a thermionic device which emits the balance of electrons stripped from the atoms during ionization. These electrons neutralize the ion beam and prevent spacecraft charging.

V. IMPLEMENTATION OF THERMIONICALLY ASSISTED BREAKDOWN

A. THE EMISSION CONTINUUM

The implementation of thermionically assisted breakdown is not difficult and has been amply demonstrated. Exact knowledge of the microgap geometry is not necessary for implementation because the concept of a microgap is an abstraction used to explain the processes contributing toward breakdown with thermionic assistance. What is necessary is a means of establishing a continuum of electron emission across the primary discharge gap which is independent of the gaseous discharge. For this reason, the parallel plates which form the microgaps are not necessarily rigid or tangible parallel plates, and the establishment of an emission continuum by other similar geometries is suitable and may be preferable. Thermionic assistance, furthermore, is independent of primary discharge gap geometry. Application of the thermionic assistance to various primary discharge geometries (such as coaxial or parallel-plate) is feasible as long as the emission continuum can be established across the primary discharge gap in a practical manner.

B. ASSISTING DEVICES

1. Filament

One alternative to the parallel-plate microgap geometry is a multiply-coiled filament electrically linked to both primary electrodes and stretching across the gap. This configuration has succeeded for thermionically assisted breakdown in the high-pressure sodium lamp [Ref 1]. The filament geometry should be a multiply-coiled wire-filament construction which is extensively used in the lighting industry. The multiply-coiled form increases the emission surface area above that of singly-coiled or straight-wire filaments. Furthermore the coiled coils approximate the parallel plate geometry to some extent. A potential applied across the gap causes resistive heating in the filament which leads to electron emission. This fulfills the basic requirement for an emission continuum. The filament is suitable for diverse primary discharge gap geometries including parallel plate and coaxial.

2. Ribbon

A narrow corrugated ribbon is another possible geometry for the assisting thermionic device. This device is most suitable for a coaxial system and should be spiraled out from the cathode. Gallagher [Ref 29] discusses a similar geometry used as a cathode in electrostatic thrusters.

C. APPLICATION TO ELECTROSTATIC THRUSTERS

Thermionically assisted breakdown is expected to benefit the electrostatic thruster. The most apparent means of implementation is with a multiply-coiled assisting filament attached to a wire-filament cathode although incorporation with a hollow-cathode thruster is also conceivable.

1. Filament Location

First-generation thrusters used a filament for a primary cathode and implementation on such a configuration would be simple, as shown in Figures 11 and 12. Several assisting filaments may be installed radiating from the primary cathode element to the anode, at even intervals, and should not interfere with propellant flow paths from the feed to the accelerator electrodes. The position of the assisting filament may depend upon the location of high-energy ions (induced by the accelerating electrode) to limit sputtering. The filament should consume a certain fraction of the discharge power which is a "loss" of efficiency. The sizing of the filament requires a certain hot resistance to maintain its temperature at the gap voltage.

2. Expected Results

The expected primary benefit from installing thermionic assistance on an electrostatic thruster is a reduction of power-conditioning equipment complexity resulting from the reduction in breakdown voltage requirements. The power processing unit mass is more than 50% of the total thruster-dedicated mass and more than 80% the total thruster cost. [Ref 24:p 10] The reduction in power conditioner complexity would reduce the thruster-associated mass. Payload fraction (payload-mass to initial-mass ratio) is the ultimate performance criterion, thus a reduction in the power conditioner mass, increases payload fraction. [Ref 30:p 4-2]

Present electrostatic thrusters use a hollow cathode with a starter electrode forming a small gap (1 mm) from the cathode orifice plate to initiate breakdown [Ref 14:pp 2-3]. Both of these components require power conditioner circuits for power

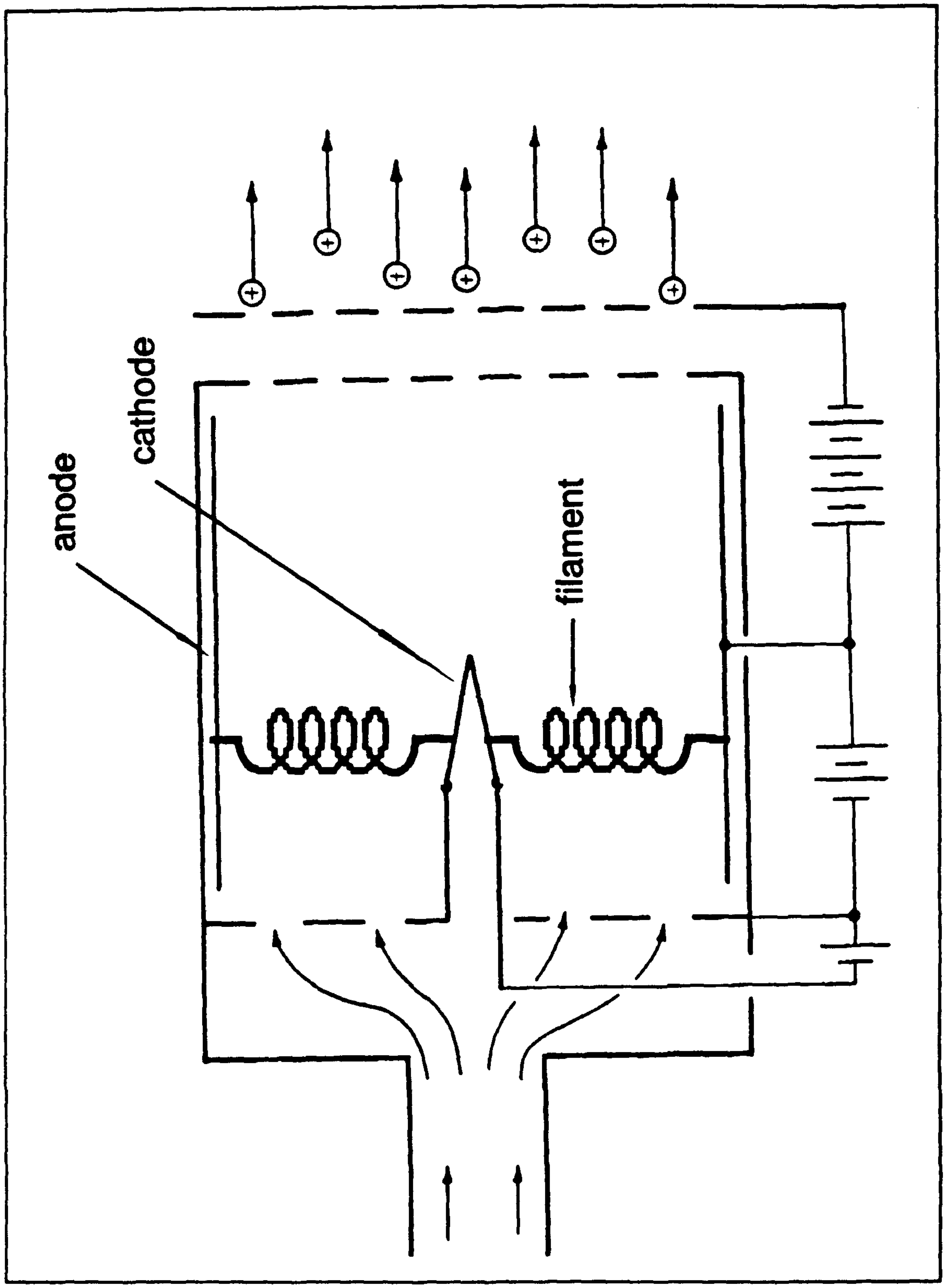

Figure 11 Schematic of Thermionic Filament Installation

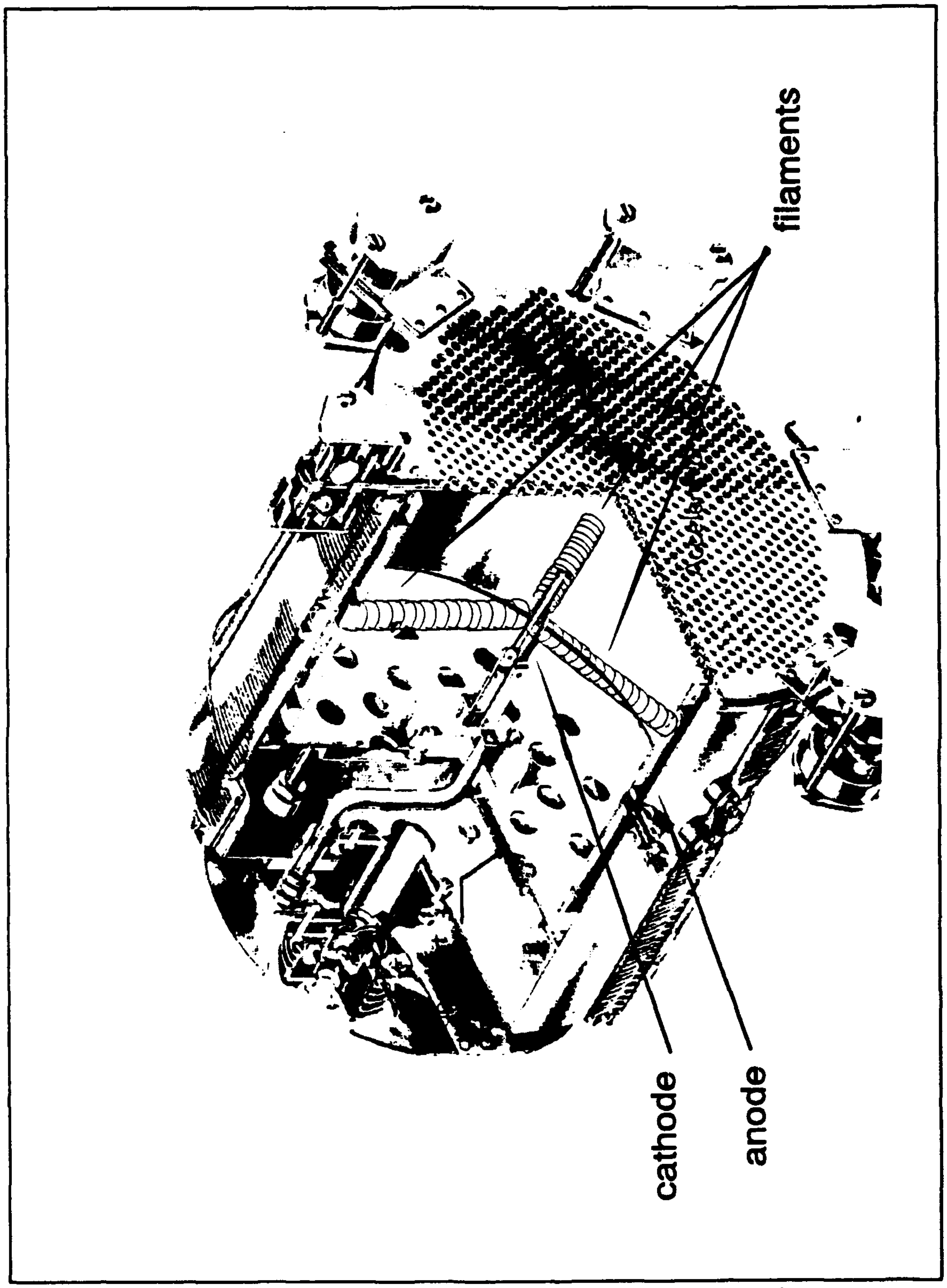

Figure 12 Three Dimensional View of Thermionic Filament Installation

supply and switching during startup operations. The starter electrode uses high-voltage/low-current power supply while the heater uses a 22 W power supply [Ref 14:p 24].

The starter electrode and its supporting circuitry may be eliminated completely. The hollow cathode insert heater and supporting circuitry would be replaced by the thermionic filament. Supporting circuitry for the filament would not be necessary because the filament draws power directly from the primary electrodes which already have their own circuitry. The steady-state discharge is a low impedance (low voltage and high current) component of the circuit [Ref 31], and the present design places the filament coil and discharge in parallel so that the filament becomes a shunting device with very little power being consumed by the coil after ignition.

The shift in Paschen-like behavior for xenon is depicted in Figure 13. The conventional Paschen curve foı xenon is plotted on Curve 1. Curve 2 is the plot of the Paschen-like behavior for thermionically assisted breakdown using the mobility ratio (μ_+/μ_-) equal to 2×10^{-3} for xenon gas. Electrostatic thrusters presently operate to the left of the Paschen minimum because of the extremely low operating pressures [Ref 32:p 489] and [Ref 26] where the thermionically assisted voltage reduction appears to be most dramatic. Because of the geometric and thermionic nature of the hollow cathode, electrostatic thrusters also do not operate exactly on the Paschen curve [Ref 25]. The operating point is shown as an "o" in Figure 13.

Additionally, the presence of electron emission continuously across the primary discharge gap may reduce the magnetic field requirements partially or completely.

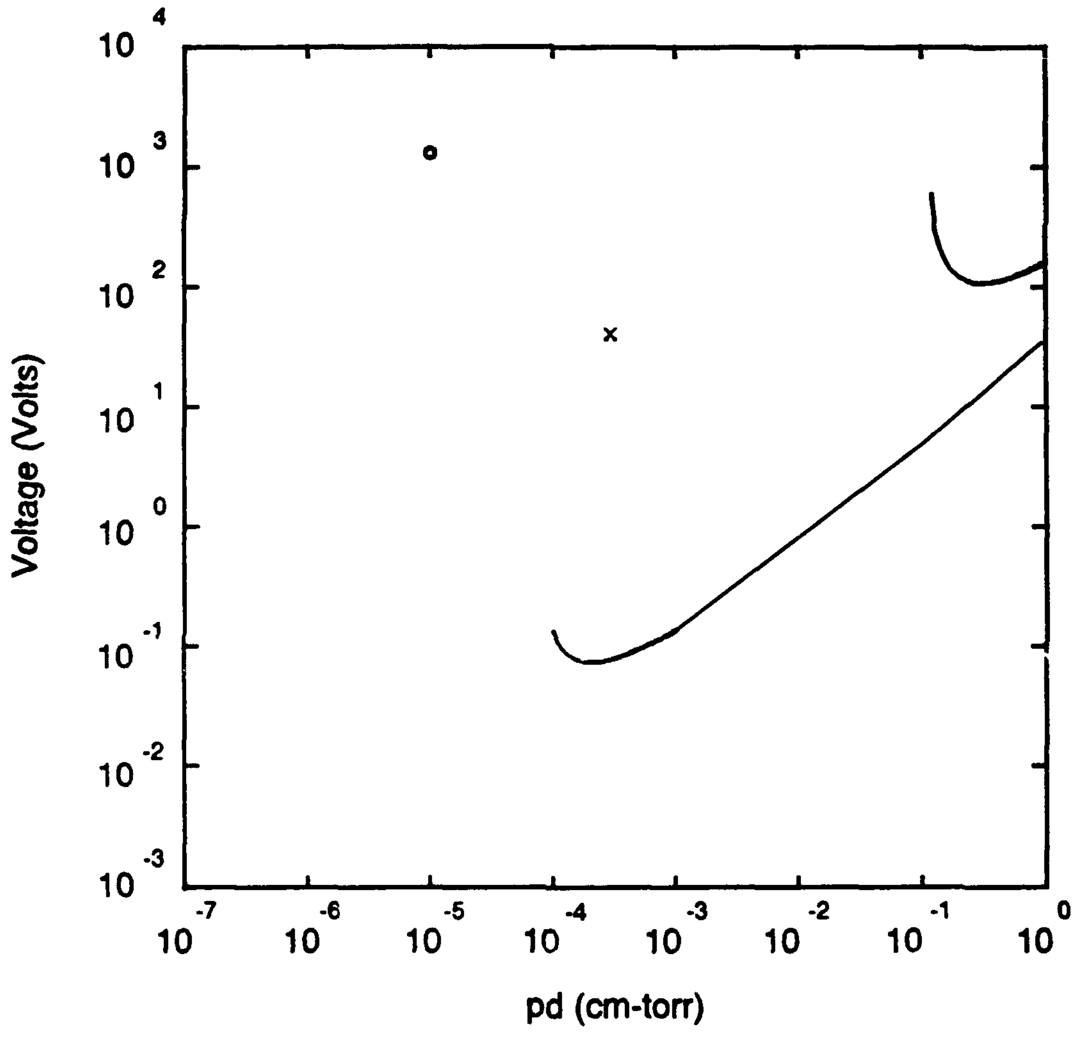

Figure 13 Paschen Behavior Shift for Thermionically Assisted Breakdown in Xenon in the Operating Vicinity of an Electrostatic Thruster

3. Industry Response

Presently, the electric propulsion industry appears to have some reservation about the introduction of wire filaments as a means of inducing thermionically assisted breakdown to electrostatic thrusters. During a telephone conversation with Dr. John R. Beatty [Ref 33] he felt that filaments might be too brittle for the thruster environment and that filament lifetime would be finite due to evaporation and sputtering of the filament material. Dr. Beattie, who tracks ion propulsion for the AIAA, had no knowledge of our work prior to the telephone conversation referenced above.

Numerous telephone conversations with Jim Sovey and Vince Rawlin, Low Thrust Propulsion Branch, NASA-Lewis Research Center, Cleveland, Ohio, indicate that their research has uncovered the possibility that removal of the starter electrode does not require a high-voltage breakdown across the much larger primary discharge gap. "Discharge ignition would occur immediately upon turning on the 80 V open circuit discharge supply voltage to the anode, under normal propellant flow conditions" using a pre-heated hollow cathode [Ref 14:p 13]. This operating point is indicated as "x" in Figure 3. It is unclear that the results reported by NASA are a consequence of the same mechanisms described previously in the model, but Figure 13 indicates that the strong possibility exists. The preliminary experimental results reported above pertain to a single primary discharge gap using a thermionic cathode in an environment where the electron mean free path is about 0.1 times the electron path to the anode [Ref 25]. The thermionically assisted breakdown criterion is derived from mobility-limited (high-pressure) conditions in which a microgap uses a thermionic cathode and the mean free path is less than the distance to the microgap anode. In Figure 13, the operating point "x" appears to fall below the conventional Paschen behavior as thermionically assisted breakdown would normally do.

Additionally, separate research at NASA Lewis concludes that "heaterless ignition of inert gas ion thruster hollow cathodes was consistently achieved" [Ref 34:p 5] using a keeper at high voltages.

Several points must be considered before ruling out the implementation of thermionically assisted breakdown on electrostatic thrusters:

- Development of alternatives to filamentary assisting devices is expected. Possibilities include a multiplicity of parallel plates, corrugated ribbon, or multiple hollow cathodes.
- Filaments, if used, can be designed for lifetimes on the order of 10000 hours. Long-life filaments are presently used in vacuum bulbs without problems with evaporation.
- The low-voltage environment resulting from thermionic assistance may inhibit sputtering by eliminating high-energy ions or multiply-charged ions.
- Sputtering of assisting filaments may be further inhibited by filament position relative to the location of high-energy ions within the thruster.

As in other cases, the actual answers will only be found after a prototype is built and tested under the required ionizer conditions.

VI. CONCLUSIONS

A model has been proposed with which to explain the use of thermionic emission to assist in breakdown. The model illustrates thermionic breakdown by assuming a profusion of parallel plates across the primary discharge gap which form numerous microgaps (Figure 4). Upon the application of a potential across the primary discharge gap, the cathode of each microgap heats which causes electron emission. The electrons collect in a space charge near each microgap cathode (Figure 5). Ions neutralizing this space charge release more electrons than conventional secondary electron emission (Figure 6). Because of this thermionic assistance, the primary discharge potential required for breakdown is much less than otherwise by a factor equal to μ_+/μ_- (Equation 30). This results in a shift of the Paschen curve along a slope which travels down one decade along the abscissa for every decade decrease along the ordinate (Figure 7 and Equations 32 and 33). This shift is much more extreme than the similar shift for different cathode materials and different cathode temperatures depicted in Figure 2.

A design to induce thermionically assisted breakdown is explored herein for electrostatic thrusters (Figures 11 and 12), one of the numerous applications of arc discharges. The thermionically assisted breakdown should be pertinent to arc applications for various primary electrode geometries as well as various gases.

APPENDIX A

TABLE 1 PASCHEN LAW VARIABLES (A, B, γ)

Gas (A, B)[a] ↓	Secondary Emission Coefficient (γ) for Various Cathode Materials[b] (Number electrons/ion impact)									
	Al	Ba	Cu	Fe	Hg	K	Mg	Ni	Pt	W
Air (15, 365)	0.035		0.025	0.02		0.077	0.038	0.036	0.017	
Ar (14, 180)	0.12	0.14	0.058	0.058		0.22	0.077	0.058	0.058	
CO_2 (26, 466)[c]										
Kr (17, 240)										
H_2 (5.1, 138.8)	0.095		0.05	0.061		0.22	0.125	0.153	0.02	
He (3, 34)	0.021	0.1		0.015	0.02	0.17	0.031	0.019	0.01	
Hg (20, 370)[c]										
N_2 (12, 342)	0.1	0.14	0.066	0.059		0.12	0.089	0.077	0.059	
Ne (4, 100)	0.053			0.022		0.22	0.11	0.023	0.023	0.045
Xe (26, 350)										

a. *[Ref 8:p 203] unless otherwise noted*
b. [Ref 11:p 159]
c. [Ref 3:p 181]

TABLE 2 EXPERIMENTAL PASCHEN MINIMA FOR VARIOUS GASES AND CATHODE MATERIALS

Gas (Cathode)	V_{min} (Volts)[d]	pd_{min} (cm-torr)[d]
Air (Fe)	330	0.57
Ar (Fe) (Cu)	265 220[e]	1.5 1.3[e]
CO_2 (n/a)	420	0.5
Kr (Cu)	200[e]	0.5[e]
H_2 (Pt)	295	1.25
He (Fe)	150	2.5
Hg (W) (Fe)	425 520	1.8 2.0
N_2 (Fe)	275	0.75
Na (Fe?)	335	0.04
Ne (Fe) (Cu)	244 244[e]	3 3[e]
O_2 (Fe)	450	0.7
Xe (Cu)	270[e]	0.7[e]

d. [Ref 3:p 196]
e. [Ref 35:p 558]

APPENDIX B

TABLE 3 CESIUM BREAKDOWN MINIMA FOR INCREASING TUNGSTEN CATHODE TEMPERATURE [Ref 12]

Temperature (°C)	V_{min} (Volts)	pd_{min} (cm-torr)
400	520	.05
500	130	.05
600	35	.05
700	9	.05
800	~4	.02
>800	~4-5	n/a

TABLE 4 CESIUM BREAKDOWN MINIMA FOR INCREASING STEEL CATHODE TEMPERATURES [Ref 17]

d = .003 cm

Temp (°C)	V_{min} (Volts)	pd_{min} (cm-torr)
430	274	0.003
450	216	0.003
500	43	0.003
550	18	0.003
600	10	0.001
650	7	0.0003

d = .011 cm

Temp (°C)	V_{min} (Volts)	pd_{min} (cm-torr)
430	225	0.011
450	120	0.0011
500	28	0.0011
550	10	0.0011
600	8	0.00011
650	9	0.00011

d = .03 cm

Temp (°C)	V_{min} (Volts)	pd_{min} (cm-torr)
430	130	0.003
450	33	0.003
500	8	0.0003
550	8	0.00003
600	6	0.00003
650	7	0.00003

TABLE 5 CESIUM BREAKDOWN MINIMA FOR INCREASING RHENIUM CATHODE TEMPERATURE [Ref 19]

Temp (K)	V_{min} (Volts)	pd_{min} (cm-torr)
1796	.53	.065
1598	.475	.063

Temp (K)	V_{min} (Volts)	pd_{min} (cm-torr)
1994	0.38	0.21
1895	0.39	0.17
1796	0.395	0.11
1697	0.39	0.11
1598	0.40	0.13

Temp (K)	V_{min} (Volts)	pd_{min} (cm-torr)
1994	0.22	0.13
1895	0.21	0.14
1796	0.24	0.06
1697	0.25	0.12
1598	0.30	0.12

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