traces are plotted in Fig. 4 and show the phenomenon of gain saturation. The following observation is the crux of this study on isolation: Although the over-all driving signal can be "saturable," usually, the first spike of the driving signal is not. The gain for this spike should thus be the small-signal value, indicating that the energy storage in the chain was optimum, i.e., that the isolation provided was adequate. As can be seen in Fig. 4, this was indeed the case.

Thus, when the driving signal is normal-laser and at a power level that can saturate the amplifier-inversion density, amplifier oscillation can be prevented by introducing the driving signal before the amplifier spontaneous emission can self-amplify. The technique is not applicable when a giant-pulse type of driving signal is used; for this case, it is usually desirable to establish and maintain maximum inversion before the driving signal is introduced.

As suggested by these results, no isolators are necessary for the efficient operation of the amplifier chain. The Faraday isolator and the aperture stops were therefore removed. The amplifiers were operated at full aperture, i.e., the entire active chain volume was used.

OUTPUT ENERGY

The energy buildup along the chain was measured, and the results obtained are shown in Fig. 5. The coupling loss for each amplifier is designated by a downward arrow. For about 1.9 J of oscillator input energy (integrated over a 250 μsec normal-laser pulse train), the output energy from the chain was measured to be about 62.5 J. The chain was pumped to yield a total *unsaturated* gain of 66 dB. Note from the figure that starting with the second amplifier, the MOPA output was essentially linear with amplifier length; this is indicative of gain saturation and efficient energy extraction from the amplifiers. The cross section of the output beam was elliptical because of the Brewster bevel on the rod ends. The cross-sectional area was 0.33 cm^2, leading to an output energy density of about 188 J/cm^2.

The coupling loss for the last amplifier could not be determined because of a damaged rod; the dashed line in Fig. 5 for this amplifier is conjecture. Dirt had settled undetected on the end of the rod and caused damage, precluding further testing.

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Experimental Investigation of the Low-Voltage Arc in Noble Gases*

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An experimental investigation of the low-voltage arc mode of the hot-cathode discharge has been carried out in a diode utilizing planar electrode geometry. The investigation consisted predominantly of Langmuir-probe measurements of the discharge in a neon atmosphere. Measurements were also obtained in argon, xenon, and hydrogen and hydrogen–neon and argon–neon mixtures. The probes were of planar, guard-ringed geometry. The volt–ampere characteristic of the hot-cathode discharge in the Torr range of gas pressure was investigated to further define the low-voltage arc. For ample electron emission at the cathode there are two stable high-current, low-voltage discharge modes that occur in the noble gases; these are termed the low-voltage arc and the ball-of-fire modes of the hot-cathode discharge. No low-voltage discharge modes were obtained in hydrogen. The steady-state characteristics obtained for the low-voltage arc indicated peak plasma potentials of approximately 14, 6, and 4.5 V for neon, argon, and xenon, respectively, considerably lower than the first excitation level of the respective gases. There is a minimum value of the product of pressure and electrode spacing for the existence of the low-voltage arc; this condition also yields a minimum value of discharge voltage. The discharge voltage and peak electron densities increase with increasing pressure–spacing product, while the peak plasma potential decreases gradually. Measurements on the discharge in neon atmospheres containing small admixtures of hydrogen indicated that cumulative ionization is important for the generation of the low-voltage arc. It was not possible to detect in the measurements on pure noble gas experimental atmospheres any effects due to the presence of impurities. The study of the Penning impurity effect in the low-voltage arc was limited, but showed that mixtures of less than 0.06% argon in neon do affect the discharge.

I. INTRODUCTION

The low-voltage arc discharge is a mode of the non-self-sustaining, hot-cathode gaseous discharge that can exist at voltages below the first excitation level of the gas. It has been observed in the noble gases, mercury vapor, and the vapors of the alkali metals. Under the proper conditions this mode of the discharge has even been obtained with a negative discharge potential; i.e., the device was operating as a thermionic energy converter.[1] Historically the term low-voltage arc has

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[1] G. Medicus and G. Wehner, J. Appl. Phys. **22**, 1389 (1951).

been applied in general to the independently heated, hot-cathode discharge; the discharge mode here referred to as the low-voltage arc was called the "nonoscillating abnormal low-voltage arc" by Compton and Eckart,[2] the "low-voltage arc" by Druyvesteyn,[3] and the "low-voltage form of the ball-of-fire mode" of the hot-cathode discharge by Johnson.[4]

In this investigation, the term "low-voltage arc" is defined as that mode of the externally heated hot-cathode discharge which exists in noble gases with saturation emission currents at the cathode that are more than sufficient to sustain the discharge. At gas pressures and electrode spacings of the proper magnitude, the discharge voltage of the low-voltage arc is considerably less than the excitation potential of the gas; the average cathode discharge current density is of the order of a few amperes/cm^2.

The low-voltage arc was first unequivocably obtained by Holst and Oosterhuis,[5] who observed discharge voltages of 3.5 and 7.5 V, for the low-voltage arc in argon and neon, respectively. Previous workers[6,7] had reported hot-cathode discharges that existed at voltages below the excitation potential of the gas; however, their work must be viewed critically since it is not clear that their experimental devices were operating in a steady-state condition. The question of steady-state operation in hot-cathode discharges was raised in nearly simultaneous publications by Bär *et al.*[8] and Eckart and Compton.[9] These workers found that experimentally obtained hot-cathode discharges operating at voltages below the excitation potential could actually be undergoing relaxation or circuit-dependent oscillations and that the combined steady-state and oscillating components of the discharge voltage resulted in a peak discharge voltage greater than the excitation potential of the gas.

Compton and Eckart[9] studied the low-voltage arc discharge in helium, argon, and mercury vapor with the then very new Langmuir probe and though their experimental geometry was very distorted they showed that potentials existing within the low-voltage arc were considerably greater than the potential at the anode.

Druyvesteyn[3] published the results of single-probe measurements of the low-voltage arc in argon and neon. His published results for argon indicated a peak in the plasma potential distribution that is near the excitation potential of the gas. The data for neon showed a peak plasma potential greater than the excitation potential of the gas; the electrode geometry of the neon discharge was stated to be distorted. The probe measurements of Druyvesteyn on the low-voltage arc with oxide cathodes were apparently affected by contamination from the cathode[10] because he obtained non-Maxwellian probe characteristics within the discharge plasma. He attributed the nonlinearity of the probe characteristics to inelastic collisions between plasma electrons and barium and strontium atoms evaporated from the cathode.

Malter, Johnson, and Webster[4,11–13] published a series of four articles on hot-cathode discharges in noble gases in the Torr pressure range. These articles constituted the first major attempt to classify and analyze the discharges in this range of noble-gas pressures. They did not, however, obtain experimentally the mode of noble-gas hot-cathode discharge here referred to as the low-voltage arc.

Bloss and Krezdorn,[14] as a result of interest in the application of low-energy noble-gas plasmas to space-charge neutralization in thermionic converters, obtained measurements on low-voltage arcs in argon and krypton. Their work used cylindrical geometry and resulted in a discharge which was unstable in its orientation around the axis of the cathode. The problem of probing the discharge was solved by using a weak coaxial magnetic field to rotate the plasma ball circumferentially around the cathode and across the probe. They obtained measurements on the low-voltage arc as a function of the gas pressure and discharge current. Low-voltage arcs were obtained at discharge currents greater than 0.2 A and the plasma potential peak was located very close to the cathode with a value approximately equal to the first excitation potential of the discharge gas.

The purpose of the present investigation[15] was to study experimentally, in detail, the low-voltage arc in noble gases. The objectives of the experiments were to investigate the following:

(1) The various modes of the hot-cathode discharge in the Torr gas pressure range,
(2) The dc characteristics of the low-voltage arc,
(3) The mechanism of ionization in the low-voltage arc, and
(4) The effect of impurities on the low-voltage arc.

Useful data relative to the above objectives were obtained experimentally by generating a low-voltage arc discharge in planar geometry and obtaining Langmuir-probe measurements of the distribution of electron density, temperature, etc., while varying various parameters of the discharge. The experiments were

[2] K. T. Compton and C. Eckart, Phys. Rev. **25**, 139 (1925).
[3] M. J. Druyvesteyn, Z. Physik **64**, 781 (1930).
[4] E. O. Johnson, RCA Rev. **16**, 498 (1955).
[5] G. Holst and E. Oosterhuis, Physica **4**, 42 (1924).
[6] K. T. Compton *et al.*, Phys. Rev. **16**, 282 (1920).
[7] A. C. Davies, Proc. Roy. Soc. (London) **100**, 599 (1922).
[8] R. Bär *et al.*, Z. Physik **20**, 83 (1923).
[9] C. Eckart and K. T. Compton, Phys. Rev. **24**, 97 (1924).
[10] G. Wehner and G. Medicus, J. Appl. Phys. **23**, 1035 (1952).
[11] L. Malter *et al.*, RCA Rev. **12**, 415 (1951).
[12] W. M. Webster *et al.*, RCA Rev. **13**, 163 (1952).
[13] E. O. Johnson and W. M. Webster, RCA Rev. **16**, 82 (1955).
[14] W. Bloss and W. Krezdorn, Proc. Thermionic Conversion Specialist Conference, 81 (1963).
[15] R. J. Martin, Tech. Rept. No. 101, Electron Physics Laboratory, The University of Michigan (1967).

carried out predominantly in a neon atmosphere; other gases used were xenon, hydrogen, tank argon, and hydrogen–neon and argon–neon mixtures.

II. EXPERIMENTAL SYSTEM

2.1. Configuration of the Hot-Cathode Discharge

The configuration of the experimental hot-cathode discharge diode and Langmuir probes is shown schematically in Fig. 1. The hot-cathode discharge diode is of planar geometry and consists of two 4-in. diam electrodes whose separation can be varied. The emitting portion of the cathode is a 0.75-in. diam planar impregnated cathode guard-ringed by a stainless steel annulus. The cathode is heated to emission temperatures by a bifilar-wound tungsten heater supplied by a dc source and is electrically isolated from the cathode in order to ensure a unipotential discharge cathode. As indicated in Fig. 1, one of the cathodes used in the experiment was constructed so that the heater side of the cathode was enclosed and separately evacuated. The purpose of this design was to eliminate any effect upon the low-voltage arc experiment of the heater or heater insulation. No measurable effects were found and later cathodes were installed with the heater environment as part of the discharge atmosphere. The 4-in. diam anode was constructed of arc-cast molybdenum. The temperatures of the hot cathode and anode were continuously monitored by platinum and 10-% rhodium–platinum thermocouples. The cathode thermocouple calibration was compared with the blackbody radiant temperature of the cathode emission surface to ensure that the thermocouple calibration was maintained during the lifetime of the experimental investigation.

Two separate Langmuir-probe systems were used for the study of the low-voltage arc; these were termed the axial and radial probes. The axial probe was used to measure the plasma characteristic of the discharge along the discharge axis. This probe is a ballistic probe; it is inserted into the plasma region through a hole in the center of the anode of the experimental diode only during the time required for measurement of the probe characteristic. The orientation of the active portion of this probe is such that the axial component of the velocity distribution of the plasma electrons is measured.

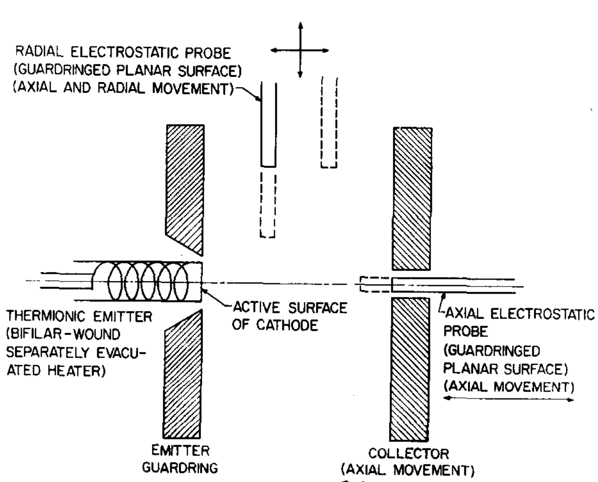

FIG. 1. Schematic of the hot-cathode discharge geometry and Langmuir probes.

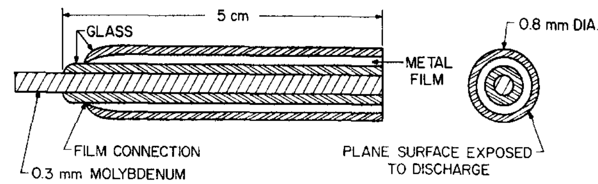

FIG. 2. Schematic of guard-ringed Langmuir probe.

The radial probe is inserted radially into the discharge space and can be moved to measure at any position in the entire r–z plane of the diode geometry; this probe is not ballistically injected into the discharge space. The planar surface of the radial probe is oriented to measure the radial velocity component of the plasma electrons. Probe measurements along the discharge axis by the radial and the axial probes were in good agreement.

The probes were of planar guard-ringed geometry (Fig. 2). The electrically active probe surface consists of the end of a 0.01-in. diam molybdenum wire which is guardringed by a conducting nickel coating. The insulating layers of the probes were of silicate glass. The Langmuir-probe measurements were obtained by using a pulse technique[16] and the probe guard ring was connected to the pulse circuit in order to maintain a potential similar to the probe; the guardring was not a part of the measured probe current. Except for probe measurements very close to the cathode, all measured probe characteristics indicated a Maxwellian electron velocity distribution.

2.2. Experimental Vacuum System

The vacuum system used to control the environment of the hot-cathode discharge experiment was of ultra-high-vacuum quality and was evacuated by an ion pump. During operation of the discharge experiment, a mechanical forepump isolated by a bakeable molecular sieve trap and backed by a liquid-nitrogen-cooled cold trap was used to control the discharge gas pressure. The research-grade gases were in valved containers and metered into the statically sealed experimental vacuum chamber to obtain the necessary atmosphere for the gas discharge.

All movement of the probes and adjustment of the electrode spacing were coupled outside of the vacuum

[16] R. H. Bullis and W. J. Wiegand, Proc. Thermionic Conversion Specialist Conference, 258 (1964).

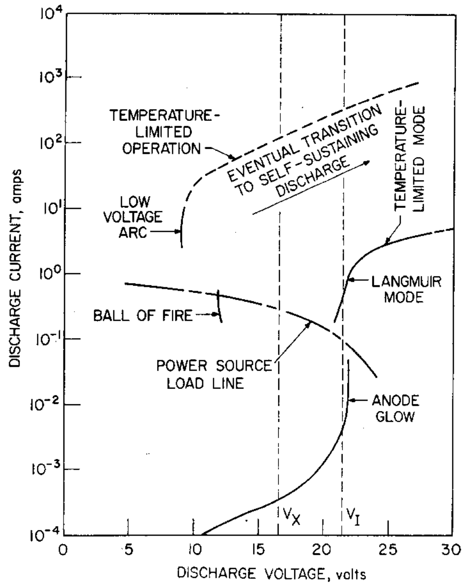

FIG. 3. Representative volt–ampere characteristic of the steady-state, hot-cathode discharge in noble gases in the Torr pressure range, at near-optimum conditions for minimum discharge voltage in the low-voltage arc and ball-of-fire modes. (V_X denotes the excitation and V_I denotes the ionization potential of the gas.)

chamber by means of stainless steel bellows and controlled by external micrometer mechanical drives. The only non-high-vacuum quality component of the experimental vacuum system was the bellows-type manometer used to obtain experimental gas pressure measurements in the Torr range. The bellows-type gauge was isolated from the remainder of the experimental vacuum chamber by means of a long tube in order to maintain it at room temperature during any heat cycle applied to the vacuum system. Pumped pressures of 1×10^{-8} Torr were obtained in the vacuum system, while measurements of the sealed-off vacuum chamber at operating temperatures indicated that the contamination of the discharge chamber due to real and virtual leaks would reach a maximum of approximately 0.05% of the discharge gas pressure over the maximum length of time allowed for a series of experimental measurements.

III. EXPERIMENTAL RESULTS

3.1. Modes of the Hot-Cathode Discharge in Noble Gases

A typical steady-state experimental volt–ampere characteristic for the hot-cathode discharge in planar geometry for noble gases in the Torr pressure range is shown in Fig. 3. This characteristic is representative of near optimum discharge conditions for a minimum value of discharge voltage for the low-voltage arc. The dashed lines denote the values of the ionization potential (V_I) and the first excitation potential (V_x) of the discharge gas. The characteristic shows that there is a continuous transition into the anode-glow mode at low values of current. This mode exists for discharge currents in the range of 1–200 mA; the visible characteristic consists of a thin glowing layer at the anode surface which spreads over the surface as the discharge current increases. In the high-current range of this mode a visible hemispherical ball or tuft may exist at the center of the anode, or one or more of these tufts may be present at some radial distance from the discharge axis. These tufts may also rotate around the discharge axis; however, they are always in contact with the anode surface. No attempt was made to define further the high-current (tufted) segment of the anode-glow mode.

If the hot-cathode discharge current is increased beyond the anode-glow mode, the transition to other steady-state modes is dependent upon the saturation emission capability of the cathode and the load line of the power source. If the emission capability of the cathode is sufficient and the power source load line crosses one of the high-current modes, then the discharge will transfer to that steady-state high-current mode. If the power source load line is incapable of supporting the high-current modes the discharge will undergo relaxation oscillations and a visible discharge will be seen to exist in the discharge space. Such discharges are undoubtedly the low-voltage arcs with abnormally low discharge voltages observed by early workers[6,7] before the discovery of relaxation oscillations in the hot-cathode discharges.[8,9]

With a power source load line as shown in Fig. 3 and sufficient cathode emission capability, the steady-state discharge will transfer to the ball-of-fire mode. The visible discharge consists of a ball midway between the discharge electrodes though not necessarily centered on the axis of the discharge electrodes. Malter *et al.*[11] found that this mode in cylindrical geometry consisted of a ball near the larger anode electrode.

Under the proper conditions of cathode emission and power source load line, the stable discharge mode at currents in the ampere range is the low-voltage arc. This mode consists of a somewhat flattened visible sphere at the discharge cathode but separated from it by an obvious sheath. In neon this sphere is a brilliant red, in xenon a bright white, and in argon the sphere is a muted blue.

TABLE I. Critical potentials of experimental gases.

Gas	Ionization potential	Resonance potential	Lowest metastable potential
Ne	21.559	16.84	16.62
Ar	15.755	11.83	11.55
Xe	12.127	8.44	8.31
H_2	15.4		

No consistent measurements were obtained for the Langmuir and temperature-limited modes of the hot-cathode discharge because of poisoning of the impregnated cathode. The location of these modes in the volt–ampere characteristic is dependent upon the state of the emissivity of the cathode. These modes occur when the saturation cathode emission capability is insufficient to support an increase in discharge current and thus electric fields must be generated at the cathode in order to enhance the cathode electron emission. These modes are shown to occur in Fig. 3 as a transition from the anode-glow mode. Malter *et al.*[11] obtained the ball-of-fire mode before the discharge transferred into the Langmuir mode, while Kitrilakis *et al.*[17] apparently obtained the low-voltage arc in the ignited (arc)-mode cesium energy converter before the transition to the cathode emission-limited discharge modes. Application of voltages greater than the ionization potential of the gas was always necessary in order to obtain breakdown to the low-voltage arc and ball-of-fire modes of the discharge.

3.2. dc Characteristics of the Low-Voltage Arc

The majority of the Langmuir-probe studies were made in neon gas because the critical potentials of neon are relatively high (see Table I). The error caused by influences external to the discharge is minimized by the use of a gas with high critical potentials.

The characteristics of the neon low-voltage arc along the axis of the discharge are shown in Fig. 4. This figure

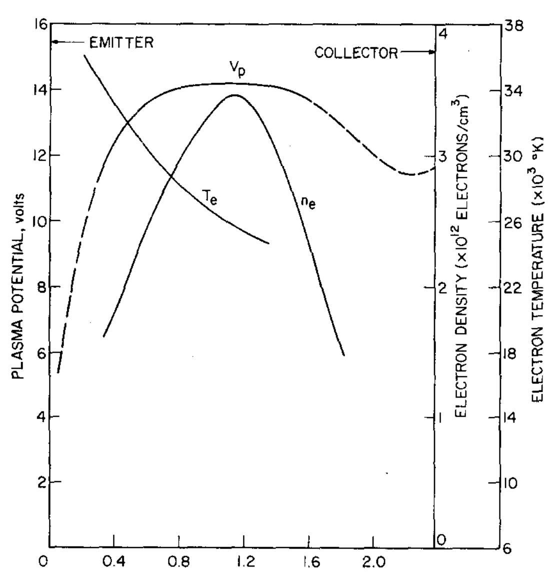

FIG. 4. Axial distribution of the electron density, temperature, and plasma potential of the low-voltage arc in neon for a 4-A discharge at 2-Torr neon for 2.37 cm electrode spacing (first metastable excitation level of neon is 16.6 V).

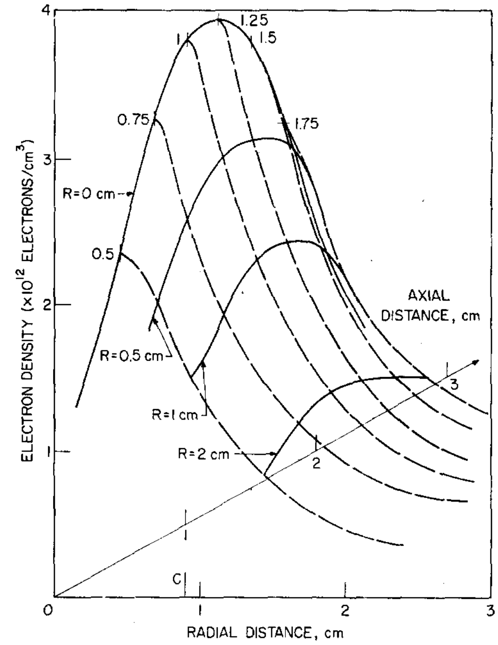

FIG. 5. Spatial distribution of the electron density in the neon low-voltage arc for a 4-A discharge at 2-Torr neon and 2.37 cm electrode spacing.

is representative of the axial characteristics of the low-voltage arc obtained in the noble gases. The discharge can be divided into three regions: the cathode sheath, the plasma, and the anode sheath. In the cathode sheath the space potential rises rapidly to the plasma potential, while the electron temperature drops rapidly. In the plasma region the potential remains relatively constant, the electron temperature tends to level off and the electron density reaches a maximum. Within the anode sheath the potential characteristically is determined by the necessity of obtaining random anode sheath currents which are sufficient to maintain the discharge current. In general, at higher pressure–spacing products the cathode sheath and the plasma occupy a smaller fraction of the interelectrode spacing, the electron temperature falls off rapidly with electrode spacing to a minimum value, the electrode density maximum moves toward the cathode, and the anode sheath occupies a larger portion of the interelectrode spacing. Within the anode sheath the potential falls off to a minimum value before rising to attain the higher discharge voltage that is obtained at larger pressure–spacing products. Generally, probe measurements were not obtained within the anode sheath.

For the low-voltage arc (Fig. 4) in neon at 2 Torr with a discharge current of 4 A and electrode spacing of 2.37 cm, the peak electron density is 3.4×10^{12} electrons/cm^3; the electron temperature is 36×10^3 °K near the cathode and falls off to 24×10^3 °K near the plasma–anode sheath boundary. The peak plasma potential is 14 V, a value lower than the 16.6-V lowest metastable

[17] S. Kitrilakis *et al.*, Thermo Electron Engineering Corp. **1**, IX-35 (1965).

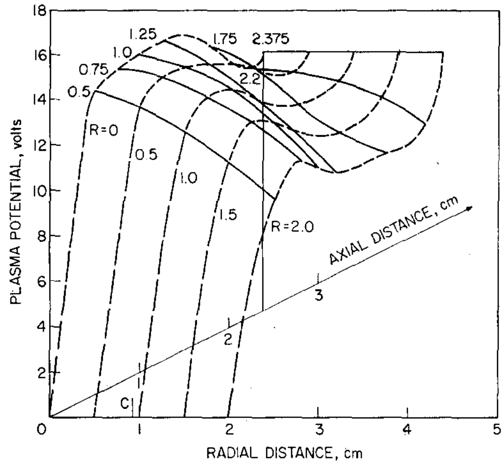

FIG. 6. Spatial distribution of the plasma potential in the neon low-voltage arc for a 4-A discharge at 2-Torr neon and 2.37 cm electrode spacing.

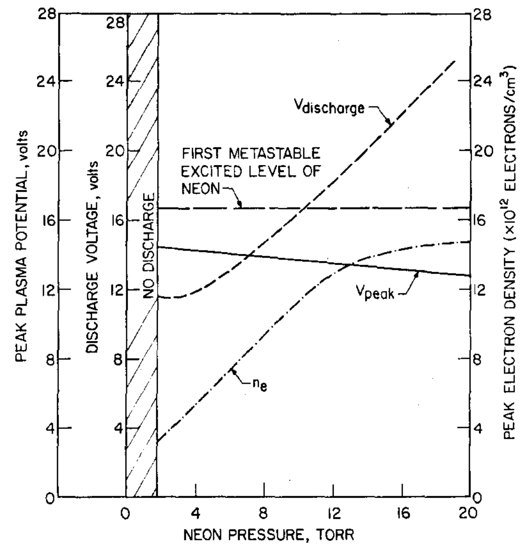

FIG. 8. Characteristics of the neon low-voltage arc; peak electron density, peak plasma potential, and discharge voltage as a function of neon pressure for a 4-A discharge with 2.37 cm electrode spacing.

excitation potential of neon. Data derived from Fig. 4 have been used by Salinger[18] in his analysis of the low-voltage arc by Monte Carlo techniques.

Figures 5 and 6 show the spatial distribution of the electron density and plasma potential of the low-voltage arc for the same conditions as Fig. 4. The symbol *C* located on the radial axis denotes the radius of the emitting cathode. Probe measurements for greater than twice the cathode radius were obtained in the radial direction. Within experimental error the measured electron temperature was independent of radius.

In Fig. 5 the electron density is seen to fall off very rapidly in the radial direction and the random electron current density is quite high at the center of the plasma. The plasma potential distribution curve (Fig. 6) shows very little change with radius at the cathode sheath–plasma boundary. Also, the cathode sheath–plasma boundary does not undergo much change in its axial position; this is in good agreement with the distinct demarcation of this boundary observed in the experiments. The plasma–anode sheath boundary is spherical and moves toward the cathode with increasing radius, again in good agreement with the flattened spherical shape of the visible discharge. The curve (Fig. 6) shows very clearly the potential minimum in the anode sheath which occurs in the low-voltage arc at larger pressure–electrode spacing products.

The effect of electrode spacing upon the low-voltage arc is illustrated in Fig. 7. Shown are the effects of electrode spacing upon the peak plasma potential, the

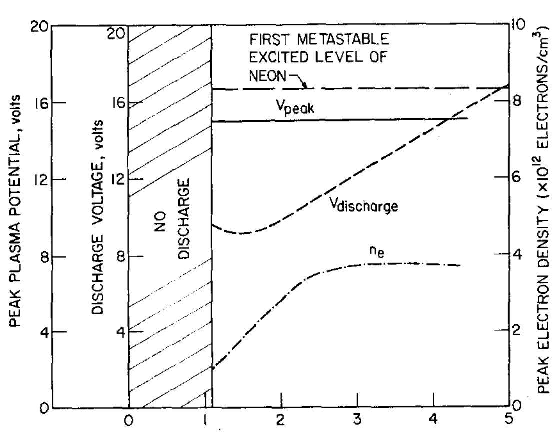

FIG. 7. Characteristics of the neon low-voltage arc; peak electron density, peak plasma potential, and discharge voltage as a function of electrode spacing for a 4-A discharge at 2-Torr neon.

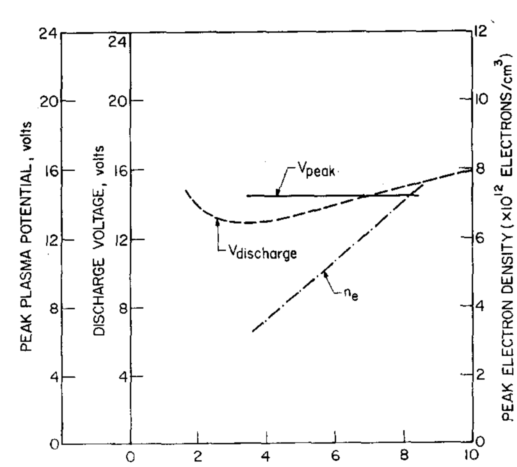

FIG. 9. Characteristics of the neon low-voltage arc; peak electron density, peak plasma potential, and discharge voltage as a function of discharge current at 1.9-Torr neon and 2.37 cm electrode spacing.

[18] S. N. Salinger, Tech. Rept. No. 99, Electron Physics Laboratory, The University of Michigan (1967).

peak electron density, and the discharge voltage for a 4-A low-voltage arc discharge in neon at 2 Torr. There is a minimum spacing for the existence of the low-voltage arc and, for the range of electrode spacings measured, the peak plasma potential remains nearly constant at approximately 15 V. The discharge voltage is at its lowest value of 9 V at 1.5 cm electrode spacing and increases for increasing electrode spacings. The peak electron density in the low-voltage arc is 1×10^{12} electrons/cm^3 at the minimum electrode spacing, increases to 3.5×10^{12} electrons/cm^3 at 2.5 cm electrode spacing, and remains relatively constant for larger spacings. The visible characteristics of the discharge as a function of the electrode spacing are outlined below in reference to Fig. 7. At shorter electrode spacings the plasma ball increases in size with increasing spacing. For larger spacings the peak electron density levels off, the plasma ball also ceases to increase in size, and at approximately this same electrode spacing the discharge voltage begins to increase rapidly with electrode spacing. As indicated by the constant value of the peak plasma potential, the increased discharge voltage is appearing across the anode sheath, which is itself occupying an increasing portion of the discharge electrode spacing. The constant peak plasma potential indicates that the energy input required to generate the plasma has remained constant.

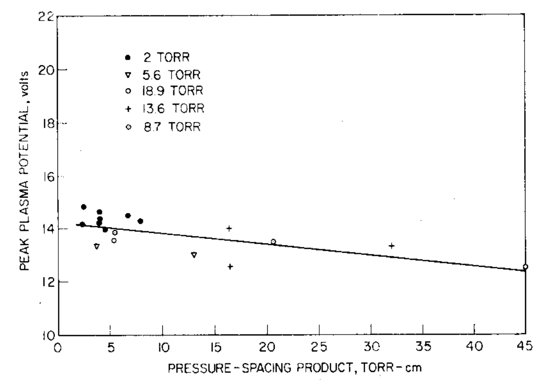

FIG. 10. Peak plasma potential of the low-voltage arc in neon as a function of the pressure–spacing product for various neon pressures (4-A discharge current).

The effect upon the low-voltage arc of changes in gas pressure is shown in Fig. 8, where the peak plasma potential, the peak electron density, and the discharge voltage for a 4-A low-voltage arc in neon with an electrode spacing of 2.37 cm are shown as functions of the neon pressure. Again there is a minimum condition for obtaining the low-voltage arc: In this example the discharge was not obtained at pressures below 1.8 Torr. The discharge voltage is at a minimum of 11 V near the pressure minimum and increases with increasing pressure. The peak electron density is also at its lowest value of 3.8×10^{12} electrons/cm^3 at the 1.8-Torr minimum pressure. It increases linearly to approximately 13×10^{12} electrons/cm^3 at 12 Torr and then becomes constant for higher gas pressures. The peak plasma potential is also shown to be decreasing gradually with increasing pressure.

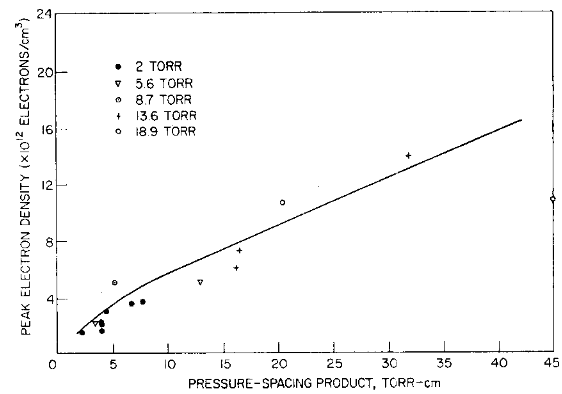

FIG. 11. Peak electron density of the low-voltage arc in neon as a function of the pressure–spacing product for various neon pressures (4-A discharge current).

Figure 9 indicates the effect of variation of discharge current on the low-voltage arc. Shown are the peak plasma potential, the peak electron density, and the discharge voltage for a low-voltage arc in neon at 1.9 Torr with an electrode spacing of 2.37 cm. Measurements were obtained only in the range of 4 to 8 A discharge current. At lower currents measurements were limited because there was a tendency for unstable operation, while limited cathode emission capability prevented measurement of higher-current low-voltage arcs. The discharge voltage is similar to that indicated in the volt–ampere characteristic of the low-voltage arc shown in Fig. 3. The peak plasma potential is seen to remain constant over the measured range of discharge current, indicating that the necessary energy input to generate the plasma is approximately proportional to discharge current. Accordingly there is a proportionate increase in the peak electron density for increasing discharge currents as shown in Fig. 9.

The peak plasma potential, peak electron density, and discharge voltage of the neon low-voltage arc as functions of the product of gas pressure and electrode spacing are shown in Figs. 10, 11, and 12, respectively.

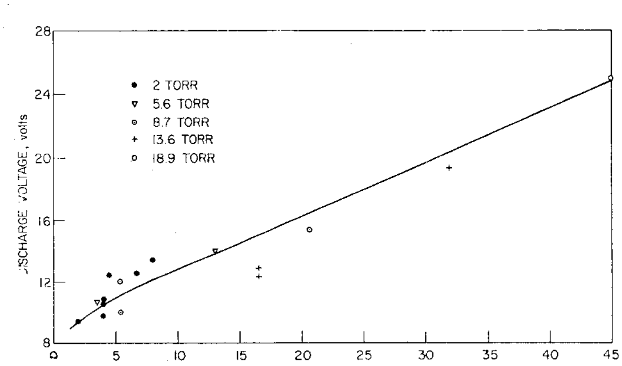

FIG. 12. Discharge voltage of the low-voltage arc in neon as a function of the pressure–spacing product for various pressures (4-A discharge current).

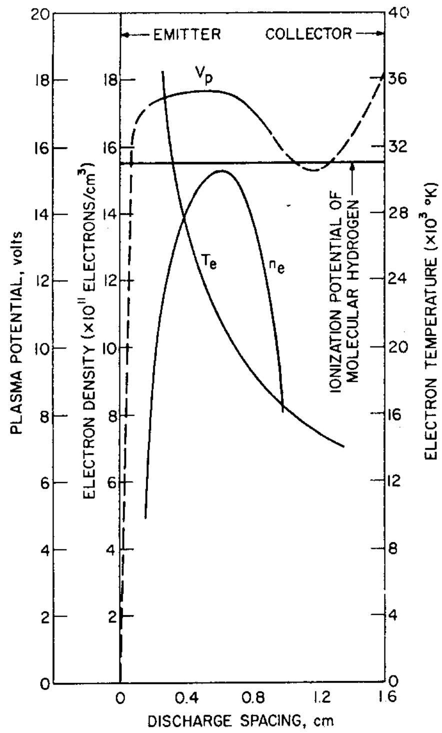

FIG. 13. Axial distribution of the electron density, temperature, and plasma potential of the Langmuir mode of the hot-cathode discharge in hydrogen (4-A discharge at 0.35-Torr hydrogen and 1.63 cm electrode spacing). (The electronic ionization potential of molecular hydrogen is 15.4 V.)

The pressures for which data were obtained range from 2 to 18.9 Torr. At lower pressures the obtainable data were limited by the available range of experimental electrode spacing. The limit of the low-voltage arc mode at the high end of the pressure–electrode spacing product resulted in a transition of the discharge to a higher-voltage mode consisting of the low-voltage arc with tufts at the anode surface. For small electrode spacing, measurements were also difficult at high pressures because the plasma ball became too small to be constrained by the cathode; any attempt to insert the probe into the plasma would result in movement of the ball over the cathode surface and away from the region where the perturbing effects of the probe are significant.

The peak plasma potential (Fig. 10) is 14 V at 2.5 Torr·cm and decreases gradually to 12.5 V at 45 Torr·cm. The spread in data is approximately ±1 V. The peak electron density of the low-voltage arc (Fig. 11) is approximately 2×10^{12} electrons/cm³ at 2.5 Torr·cm, and it increases to 12×10^{12} electrons/cm³ at 45 Torr·cm. The discharge voltage (Fig. 12) is 10 V at 2.5 Torr·cm and increases to 25 V at 45 Torr·cm.[19]

Considerable difficulty was experienced in obtaining a sufficient electron current density from the cathode for generation of the low-voltage arc in xenon for the range of gas pressures of this experimental study. The experimental data obtained on the characteristic of xenon along the discharge axis are consistent with that for neon. The measured peak plasma potential is 4.5 V and the characteristic dimensions of the discharge compared to the neon low-voltage arc were considerably smaller, consistent with the larger inelastic collision cross section in xenon.

One set of axial characteristics of the low-voltage arc in tank argon was also obtained. Again the characteristic is consistent with that of neon. The measured peak plasma potential in argon is 6 V.

No low-voltage arc was obtained in hydrogen even though a considerable pressure range was surveyed and the temperature of the cathode was increased beyond normal operating temperatures in order to ensure an ample electron emission from the cathode. The high-current discharge obtained was the Langmuir mode (see Fig. 13) with a peak plasma potential of approximately 17.5 V, higher than the ionization potential of molecular hydrogen.

3.3. Mechanism of Ionization

Addition of small percentages of hydrogen to an electrical discharge in neon will deactivate atoms in the metastable excited states of neon.[20] Such an experiment

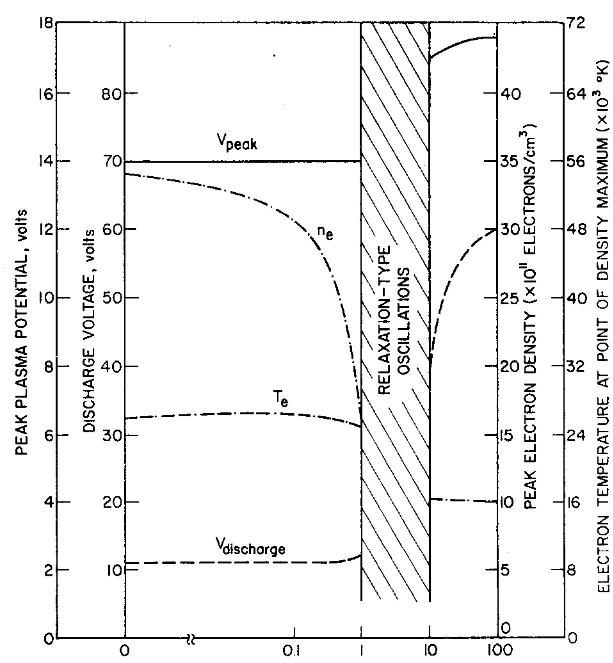

FIG. 14. Peak plasma potential, peak electron density, electron temperature at the peak density, and discharge voltage as a function of the percentage of hydrogen for a 4-A hot-cathode discharge at 2-Torr total hydrogen–neon pressure and with 2.37 cm electrode spacing.

[19] Note that at the larger pressure–spacing products the discharge voltage is considerably higher than the ionization potential of the discharge gas.

[20] T. C. Marshall, Rept. No. 8, Plasma Laboratory, Columbia University (1964).

on the low-voltage arc was undertaken for the purpose of investigating whether the cumulative ionization mechanism is of importance in the noble-gas low-voltage arc discharge. The results of measurements on the discharge for mixtures of neon and hydrogen are represented by Fig. 14, which shows the peak plasma potential within the discharge, the peak electron density, the electron temperature at the position of peak electron density, and the discharge voltage for a 4-A discharge as a function of the percentage of hydrogen in neon with a total pressure of 2 Torr. For gaseous mixtures of less than 1% hydrogen, a low-voltage arc is obtained. In mixtures containing 1%–10% hydrogen the power source could not support a steady-state discharge, and a Langmuir-mode discharge was obtained with gaseous mixtures containing more than 10% hydrogen. The measurements of interest for the purposes of this study were on gaseous mixtures containing less than 1% hydrogen. In this region the peak density of the plasma electrons decreases with an increasing percentage of hydrogen, with increasing deactivation of the neon metastable levels until the low-voltage arc can no longer exist. This behavior indicates that the cumulative ionization mechanism is an important factor in the generation of the low-voltage arc.

3.4. Effect of Impurities in the Low-Voltage Arc

The consistency of measurements on the low-voltage arc in the noble gases (neon, argon, and xenon) indicated that the experimental atmosphere was of sufficient purity to obtain a true noble-gas low-voltage arc; even the measurements on the discharge in tank argon were in good agreement. The probe measurements of the low-voltage arc discharge plasma did not indicate any distortion of the plasma electron energy distribution by contaminants evaporated from the cathode as discussed by Druyvesteyn.[3] Linear-probe characteristics were obtained over more than three orders of magnitude of probe current at the center of the plasma.

An investigation on the effect of a Penning impurity on the low-voltage arc was limited in scope, but did show that mixtures of less than 0.06% argon in neon do affect the electron density and electron temperature of the discharge.

IV. DISCUSSION AND EVALUATION OF RESULTS

Unless specifically stated, the experimental data were obtained under steady-state discharge conditions. The steady state is defined as the condition for which there are no detectable oscillations as measured by an oscilloscope connected across the discharge electrodes; whenever probe measurements were obtained, the definition of the steady state also includes the stipulation that no oscillations could be detected by the Langmuir-probe measurement circuit. Because an impregnated cathode was used in this investigation it was impossible to control the saturation emission of the cathode, and in order to insure that the low-voltage arc discharge was operating properly, discharge experiments were generally repeated; the criterion for proper operation of the cathode was that reproducible data should be obtained.

In this investigation the discharge voltage is measured using a digital voltmeter that is separately connected to the discharge anode in order to minimize error in voltages due to the lead resistance. Except for the use of tank argon, all measurements were taken using research-grade gases and the cathode temperature was maintained at 1100°±20°C for all studies. The amount of perturbation of the low-voltage arc plasma by the probe was calculated following the suggestion of Waymouth.[21] The error in measurement of the electron density in the neon plasma was determined to be at most a factor of two and the calculations yield a minor perturbation of the plasma potential. A correction for the electrode work function has been applied to the experimental data. The work functions of the Langmuir probe and anode surface relative to the cathode were obtained experimentally by the retarded field method described by Waymouth.[22]

The investigation of the volt–ampere characteristics of the hot-cathode discharge indicates that there are two low-voltage modes that exist for high currents where the emission of the cathode is more than sufficient to maintain the discharge current (space-charge-limited operation). Considerable confusion has resulted from lack of separation of these two modes and from the lack of application of a common system of nomenclature to the various modes of the noble-gas hot-cathode discharge in the Torr pressure range. The nomenclature applied to the modes shown in Fig. 3 appears to be most appropriate and consistent with the literature. In this work the peak plasma potential of the low-voltage arc was determined to be approximately 14, 6, and 4.5 V in neon, argon, and xenon, respectively. This peak potential does undergo some change with gas pressure; however it is readily apparent that the peak potential within the plasma of the low-voltage arc is well below the first excitation level of the discharge gas. This is also observed in cesium. A minimum peak plasma potential of 0.6 V for cesium vapor was obtained by Bullis and Wiegand[16] in an ignited-mode cesium thermionic converter.

The experimental measured peak plasma potentials in noble gases are not in agreement with the values determined by Druyvesteyn,[3] or Bloss and Krezdorn.[14] These workers obtained measurements of the low-voltage arc in cylindrical or nonplanar electrode geometry and obtained peak plasma potentials of the order of the potential of the first excited levels of the discharge gas. Bloss and Krezdorn[14] obtained a peak plasma

[21] J. F. Waymouth, Phys. Fluids **7**, 1843 (1964).
[22] J. F. Waymouth, J. Appl. Phys. **30**, 1404 (1959).

TABLE II. Peak plasma potential and discharge voltage for gases investigated.

Gas	Lowest metastable potential (V)	Measured peak plasma potential (V) at $pd \approx 2.7$ Torr·cm	Discharge voltage (V) at $pd \approx 2.7$ Torr·cm
Ne	16.62	14	11
Ar	11.55	6	7
Xe	8.31	4.5	6
H_2		17.5	11.5

potential of approximately 9 V in krypton, whereas extrapolation of the data obtained here for the low-voltage arc in planar electrode geometry indicated that the peak plasma potential in krypton should be approximately 5 V.

The study of the low-voltage arc discharge in mixtures of neon and hydrogen[20] is significant because this is direct experimental evidence that cumulative ionization is of importance in noble-gas low-voltage arcs. The result of the hydrogen–neon experiment is also consistent with the further result that no low-voltage arc is obtainable in pure hydrogen. If direct impact ionization produced the low-voltage arc in noble gases, then there is no reason to expect that a similar discharge would not be produced in the hydrogen hot-cathode discharge. The question then arises as to why the low-voltage arc occurs in vapors of the alkali metals, because these metals do not have metastable first excited levels. Apparently imprisonment of resonance radiation increases the effective lifetime of the resonance levels of alkali vapors sufficiently that these levels can then serve as the intermediate step in the ionization process.

V. CONCLUSIONS

Results of an experimental investigation of the low-voltage arc discharge in noble gases have been described. The low-voltage arc exists in a hot-cathode discharge and can exist at potentials below the first excitation level of the discharge gas. It has been observed in the noble gases and vapors of mercury and the alkali metals. Two stable low-voltage discharge modes were obtained when the cathode emission was more than ample to supply the discharge current. These are called the low-voltage arc and the ball-of-fire modes.

The characteristics of the low-voltage arc were measured by planar guard-ringed Langmuir probes in planar electrode geometry. The measurements were predominantly in neon atmospheres, although argon and xenon low-voltage arcs were also investigated. Neither of the low-voltage discharge modes were experimentally obtained in hydrogen. Measured peak plasma potentials for the low-voltage arc were approximately 14, 6, and 4.5 V for neon, argon, and xenon, respectively, as indicated in Table II. These peak plasma potentials are considerably lower than the first metastable excited levels of the respective gases. The low-voltage arc has a minimum value of the pressure–electrode spacing product for which the discharge can exist. This least value of pressure–spacing product also yields the minimum discharge voltage. With increasing pressure–spacing product, the peak electron density and discharge voltage increase but the peak plasma potential decreases slightly. At the upper limit of the pressure–spacing product for the existence of the low-voltage arc, the discharge transfers to a low-voltage arc with tufts or aureoles at the anode. Over the measured range of discharge currents the peak plasma potential remains constant and the peak plasma electron density increases approximately in proportion to the discharge current. At higher gas pressures, the decrease in size of the plasma of the low-voltage arc was sufficient so that the plasma was not constrained to one position on the cathode and would move due to the perturbing effects of the probe.

An experimental study of the low-voltage arc in neon containing small admixtures of hydrogen indicates that cumulative ionization is of importance in the generation of the low-voltage arc. The admixture of molecular hydrogen deactivates the metastable excited levels of atoms of neon; an addition of 1% hydrogen to the low-voltage arc in neon prevented the generation of this low-voltage form of the hot-cathode discharge.

No measurable effects were noted upon the low-voltage arc by contamination of the noble-gas discharge atmosphere or by products of evaporation from the hot cathode. This conclusion is based upon the fact that consistent data were obtained in the gases neon, argon, and xenon and that Langmuir-probe measurements indicated a Maxwellian electron velocity distribution within the plasma. A few measurements of the effect upon the low-voltage arc of a Penning impurity were made. The available data indicate that the peak electron density and electron temperature of a low-voltage arc in neon were increased by the addition of less than 0.06% argon. The discharge voltage was not affected by less than 1% argon.