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Investigation of an auxiliary discharge thermionic converter using barium oxide electrodes

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INVESTIGATION OF AN AUXILIARY DISCHARGE THERMIONIC CONVERTER USING BARIUM OXIDE ELECTRODES

by

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INTRODUCTION

A thermionic energy converter is a device which converts heat energy into electrical energy by utilizing the thermionic emission of electrons. It consists of a thermionic emitter electrode to emit electrons and a cold collector electrode whose Fermi level is more negative than that of the emitter electrode to collect them. Thermal energy supplied to heat the emitter is directly converted into electrical energy which may be used in the external circuit connected between the collector and the emitter.

Thermionic converters have a number of potential terrestial and space applications in situations where a very high temperature heat source is available, and a dc power source is needed. The basic physical processes that are responsible for the operation of thermionic energy converter are relatively simple. Fig. 1 shows the essential features of a converter in schematic form. The heat put into the emitter raises the temperature of the electrons, and some of the electrons acquire enough energy to escape the work function barrier of the emitter. The escaping electrons have kinetic energy which is very small in comparison with their potential energy. The electrons with high negative potential energy would give the energy back to the emitter if they fell back into the emitter. If an electron is collected by the

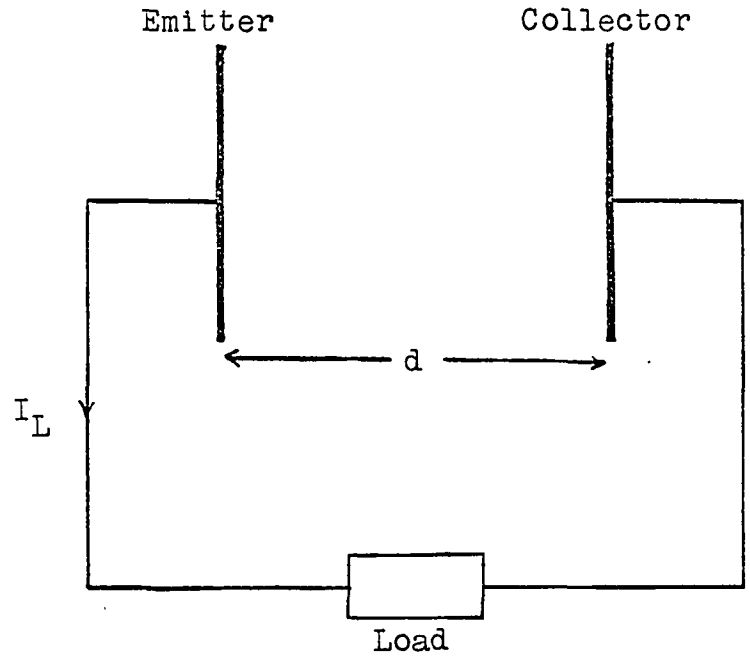


Fig. 1. Basic thermionic converter circuit

collector, it will lose energy proportional to the work function of the collector. If the work function of the collector is lower than that of the emitter, any remaining energy is available for the electron to do work in an external electrical circuit. Therefore it is very important to collect the electron on a surface of low work function.

It should be noted that the lower the work function the higher the electron emission from a surface. If the two electrodes were at the same temperature, the collector would emit more electrons than the emitter. Therefore the collector should be kept cold.

Electrons are charged particles and they produce a space charge in the region between the emitter and collector which limits the current. This effect, called the space-charge effect, is one of the important factors in the performance of vacuum diodes, and presents one of the most challenging problems in the development of thermionic energy converters. Space charge limits the current density to value less than a maximum value which can be computed from the Child-Langmuir equation (8). For planar electrodes this is

$$J = \frac{2.33 \times 10^{-6} V^{3/2}}{d^2} \qquad \text{ampere / cm}^2 \qquad (1)$$

where V is the potential difference between the electrodes and d is the interelectrode spacing.

It is seen from Eq. 1 that the current can be increased by bringing the electrodes extremely close together. It is important to point out that the potential difference between the electrodes is mostly controlled by the difference in the work functions of the emitter and the collector. Typical potential profiles for the converter in different situations are shown in Fig. 2. In all of them the collector Fermi level is negative with respect to that of the emitter. Therefore, they all pertain to power conversion mode of operation.

In Fig. 2 (a), only those electrons having sufficient energy to overcome V_m, the potential maximum, can reach the collector. This situation is likely to occur near open circuit. In Fig. 2 (b) the electrons escaping from emitter have part of their potential energy (eV_1) converted to kinetic energy. In Fig. 2 (c), only electrons having enough energy to overcome V_m, the potential with respect to emitter created by the space charge, will reach collector and will lose eV_1 of their potential energy. This is a situation likely to happen in a practical converter. It should be noted that in the three situations the principle of energy conversion is not affected. However, such matters as current, power, and efficiency would be different.

In order to make an operable vacuum converter Moss (33) showed that the interelectrode spacing must be less than one hundredth of a millimeter. This is impractical; it is not

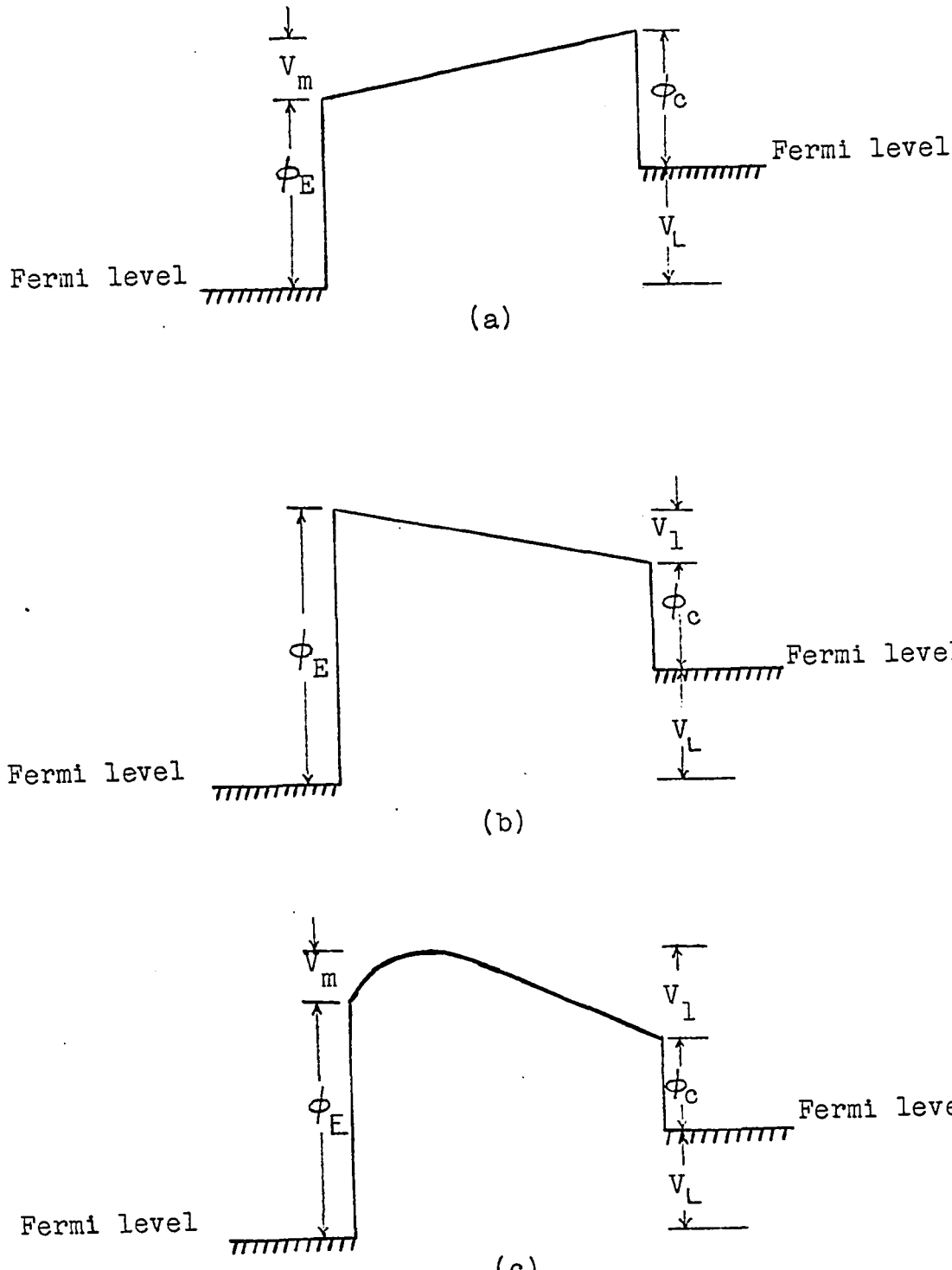


Fig. 2. Some potential profiles of an energy converter (negative potential upward)

possible to overcome the problem of space charge problem. In most cases, this is accomplished by neutralizing the space charge with positive ions. A brief description of each of these systems is given below.

Cesium Thermionic Energy Converters

Cesium vapor can be used as a source of ions needed to neutralize electron space charge and to lower the work function of the collector. Naturally if the density of the positive ions is equal to that of the electrons, complete space charge neutralization is obtained. In the low - pressure cesium - filled converters, positive ions are produced by a process called contact (or resonance) ionization (31). It is found that if cesium vapor at room temperature contacts tungsten a layer of cesium ions forms on the tungsten. This is due to the fact that the ionization potential of the gas is lower than the work function of the tungsten. Cesium atoms lose their valence electrons to tungsten atoms. Cesium ions are held to the surface of tungsten by the negative charge they induce. This is verified by experiment using other materials of work function lower than the ionization potential of cesium (3.89 volts) and it is found that no cesium film is formed on their surfaces.

Cesium ions held at the emitter surface would be useful for space charge neutralization if they could be ejected from the surface. If the temperature of the emitter surface is high enough cesium ions are evaporated and become available in the space charge region. Above this critical temperature every cesium atom that strikes the emitter surface is evaporated as a positive ion and there would be no cesium film formed on the surface. Below the critical temperature, the emitter is partially covered with cesium atoms, and the effective surface work function becomes less than that of the emitter material. Electron emission increases by several orders of magnitude. In this case, more ions for space charge neutralization are required.

Langmuir (31) attributed the decrease in the surface work function to a contact potential between the cesium film and the emitter material. This contact potential depends on the fractional area of surface covered with cesium, which in turn depends upon both the emitter temperature and the partial pressure of the cesium.

If both the emitter and the collector are made of tungsten, and if the collector is at a lower temperature than the emitter, then it will be more completely covered with cesium, and will have a lower work function than the emitter. Thus, the device could be operated in the power mode.

The current density will depend upon the work function of the emitter, the degree of space charge neutralization, and the electrode spacing. The first two factors depend upon the emitter temperature and the partial pressure of cesium. When both the cesium pressure and the emitter temperature are optimized, the emitter temperature is about 2000°K. The electrode spacing must be small in all cases, because of the relatively high plasma resistivity. This in turn produces a high rate of radiative heat transfer.

The high operating temperature of a cesium thermionic converter makes the problems of material, fabrication, and heat radiation loss serious. Internal corrosion can be expected to limit the life of such a system.

The Magnetic Triode Converter

Kaye and Welsh (26) presented an analysis of a device which is supposed to suppress the effect of space charge by controlling the electron flow with a strong electric field and a strong magnetic field. A schematic diagram is shown in Fig. 3. A third accelerating electrode is placed between the emitter and the collector. This electrode produces an accelerating field which causes more electrons to flow than would be possible with wide-spaced electrodes. A transverse magnetic field is used to prevent appreciable

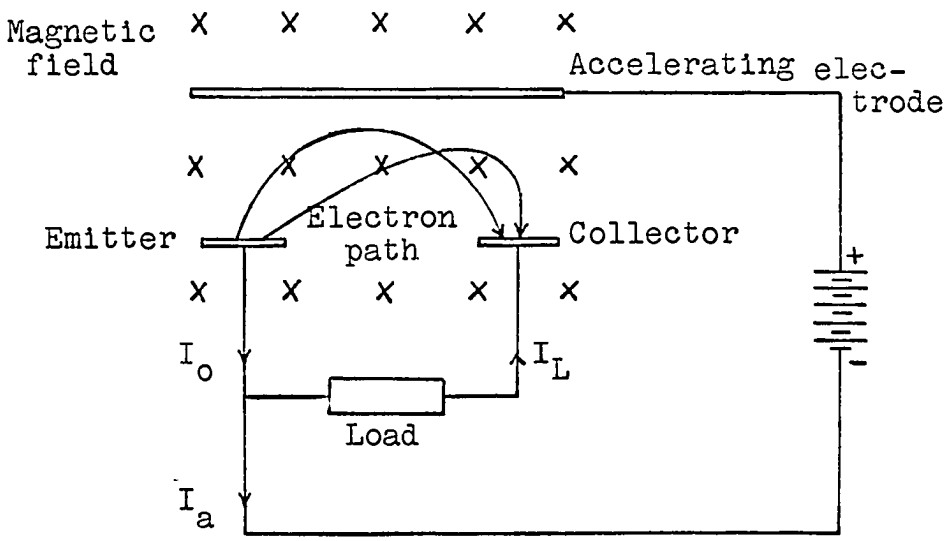


Fig. 3. Schematic of magnetic triode converter

electron collection by the third electrode. The space charge electrons are swept away from the emitter by the applied electric field. In this device, electrons are emitted from the emitter, accelerated toward the positive accelerating electrode and then deflected by the magnetic field until they reach the collector and are collected. In practice, not all the electrons are collected there; a considerable fraction of the electrons are collected at the accelerating electrode. Furthermore, some of the electrons that are deflected from their motion toward the collector will not reach it and will contribute twice to the space charge near the collector as they arrive and then leave. The number of electrons picked up at the collector was substantially lower than the number of electrons theoretically emitted from the emitter. These dissipate more power than is supplied by the electrons to the collector load. As a consequence of these factors, this particular system is not likely to become practical.

The Nuclear Ion Converter

This device uses a Penning mixture (Ne: 0.1 % A) as a filling gas, and space charge is neutralized by introducing fission fragments to produce ions. In an attempt to implement this concept, Jablonski et al. were able to achieve ion density of 10^{17} ions / cm^3 (23).

The converter is filled with a Penning mixture, so the problems of material and containment are at minimum. A suitable emitter material with the best value of work function can be used because there is no restriction on the minimum work function. The operating temperature is about 1500°K. The system should be such that the fission products have a tolerable effect on the operation of the converter during a reasonable life time, which could be estimated by a period as great as the burn-up time of a typical fuel element. Since the fission product content of the device is time dependent many restrictions and design problems may be expected.

The Auxiliary Discharge Converter

Many authors (14, 33) have suggested the possibility of creating the ions in a small auxiliary discharge region adjacent to the main emitter-collector region. Ions for space charge neutralization are produced by impact ionization of an inert gas. The ions can also be injected into the main region (9). This mode of space charge neutralization has many attractive features. Most of them are the same as discussed in the nuclear ion converter. The operating temperature is in the range of 1100°K to 1400°K. The radiation loss which is the most important loss factor is decreased.

The interelectrode spacing which has to be made as small as possible in other converters is not so critical. Usually a spacing of 3 mm to 5 mm is acceptable. The high conductive heat loss encountered with small interelectrode spacing of the cesium converter is eliminated. The additional advantage is that sufficient ions can be produced in a low current auxiliary discharge to allow a much greater electron flow from emitter to collector. Gabor (14) reported that approximately 0.05 to 0.1 watt of auxiliary discharge power is required for each ampere of current reaching the converter collector. However, Gabor did not achieve power mode operation in his experiment because the difference of emitter and collector work functions was not large enough.

Wang (42) seems to have been the first investigator to have achieved power mode operation of a Gabor type converter, but the cost of space charge neutralization was excessively high. This was attributed in part to the following factors:

1. Too large an electrode spacing for both the main discharge and the auxiliary discharge regions.
2. Back emission from the collector, due to excessively high collector temperature.
3. Insufficient space charge neutralization.

The foregoing analyses of the methods of space charge neutralization of different converters together with their

advantages and disadvantages indicate that the auxiliary discharge converter possesses many attractive features. The purpose of this research was to construct a Gabor type converter, and to optimize it for utilization as an energy converter, and, hopefully, to obviate some of the difficulties encountered in Wang's work.

REVIEW OF LITERATURE

The two important topics in the literature that are of special interest in this research are the auxiliary discharge thermionic converter and the oxide coated filaments. This section reviews the existing literature concerning both topics.

Oxide-coated Filaments

Since the turn of the century it has been recognized that the electron emission from a metal cathode can be enhanced by coating the cathode with metallic oxides.

In 1903, Wehnelt as cited in Herrmann and Wagner (19) undertook a detailed examination of various metallic oxides and found that the oxides of the alkaline earth metals are particularly useful for enhancing electron emission. The Richardson's emission equation (35) was also found to be valid for the oxide-coated filaments.

In 1912, Fredenhagen as cited in Herrmann and Wagner (19) found that the emission of an oxide-coated cathode was influenced by gases, such as oxygen, and that his oxide coating was gradually consumed by these gases. He concluded that decomposition of the alkaline earth oxide is necessary for the electron emission.

Improvements in vacuum techniques have made progress in both the physics and manufacture of oxide cathodes possible.

The first large scale use of oxide cathodes in high vacuum tubes was during the first world war. In 1920, Koller (29) and his associates proved that the emission of the cathode is due to the existence of excess metal in the oxide and this excess metal is produced during the cathode activation process. From experiments on barium oxide cathodes, Espe, Rothe, and Detels as cited in Herrmann and Wagner (19) found that a monatomic barium layer rather than a barium island is formed at the surface of the cathode. It is the monatomic layer that decreases the work function of the alkaline earth oxide and produces the good emission of the oxide-coated cathode. Such a layer can also exist at higher temperatures, because the rate of evaporation from adsorbed monatomic layers is considerably smaller than that from the same metals in bulk.

Widell and Hellar (44) reported that the mixed crystal of BaO, SrO, and CaO provides a porous layer which in turn gives good emission. This mixture is the most widely used as the coating material by vacuum tube manufacturers.

Auxiliary Discharge Thermionic Converter

Techniques which have been used to reduce electron space charge effects include close emitter-collector spacing, crossed electric and magnetic fields in a three electrode device, and

the introduction of positive ions into the interelectrode space. The possibility of neutralizing space charge by ions was first suggested by Hertz as cited in Angrist (1). The idea of using an auxiliary discharge for space charge neutralization was utilized by Johnson and Webster (25) in their continuously controllable gas tube called a Plasmatron. In this tube a source of auxiliary electrons is used to generate ions and these ions serve to neutralize space charge. The auxiliary power required for space charge neutralization was about 0.3 watt / ampere.

Two types of auxiliary discharge converters have since evolved. They are the single electron emitter introduced by Gabor (14), and the double electron emitter, of Plasmatron mode type, introduced by Bernstein and Knechtli (2). Since then Bloss (3), and Cook et al. (9) have presented papers dealing with their works on the Plasmatron mode converter.

An experimental thermionic converter employing the plasmatron auxiliary mode was first constructed by Bernstein and Knechtli (2). A schematic of the system considered is shown in Fig. 4. It consists of an emitter, a collector and three heated tungsten wires, which supply the auxiliary electrons for impact ions formation. The system was filled with argon at 1 mm Hg and operated at 1500^{o}K. They achieved a cost space charge neutralization of 0.2 watt/ampere. The value of the ratio of electron current to ion current was as large as 120.

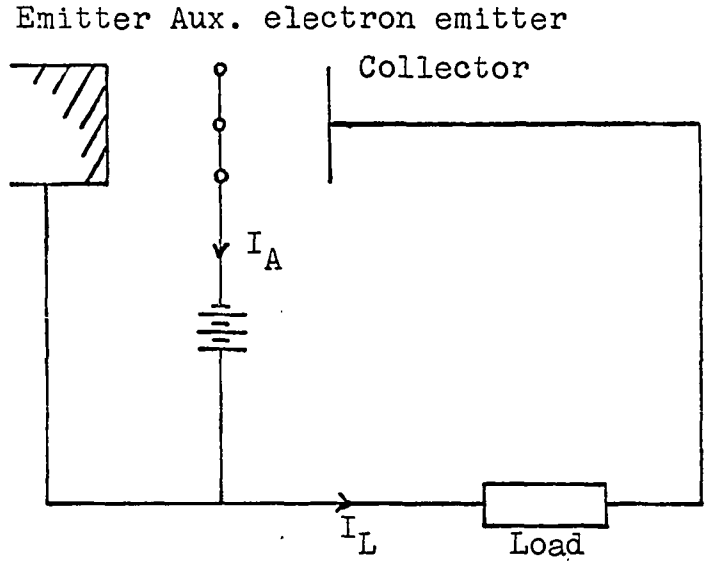


Fig. 4. Schematic of the auxiliary discharge thermionic converter - Plasmatron mode

According to Langmuir's theory (30), the main body of a discharge contains equal number of electrons and ions per unit volume, while excess charges of either kind tend to exist at the electrodes. The theory also predicted that the ratio of electron to ion currents is equal to $\sqrt{\frac{M}{m}}$ at the emitter, where M and m are the ion and electron masses respectively. Thus, in effect, each ion neutralizes $\sqrt{\frac{M}{m}}$ electrons. For argon this ratio is 270. This prediction is based on the following assumptions:

1. Each auxiliary electron has an ionizing collision.
2. No ions are lost from the plasma.
3. All ions pass through the emitter sheath only once.

These assumptions do not seem to be justified in the plasmatron mode thermionic converter because a considerable loss of ions due to drift and ambipolar diffusion occurs. Therefore the ratio of electron to ion currents of 120 seems rather high and raises questions about the validity of direct application of Langmuir's sheath theory in this case. However, Houston (20) reported that in the cesium converter at low cesium pressure the ratio of electron to ion currents was as predicted by Langmuir, while at higher cesium pressure deviation from this value was observed. In auxiliary discharge thermionic converters many reports indicate that the ratio is larger than the predicted value.

Bloss (3) used a barium oxide emitter and a CsAgO collector in an experiment on a noble gas filled thermionic converter. He claimed an efficiency of 10%. However, there was an inherent disadvantage of cesium in the system.

In 1962, Cook et al. (9) investigated an auxiliary discharge thermionic converter with ion injection as shown in Fig. 5. Both main electrodes were of the same material and heated to the same temperature. Xenon was used as a filling gas. The system was operated at 2000°K, so the advantages of low temperature operation of the auxiliary discharge converter did not exist. Also, a very small spacing between the auxiliary electron source and the accelerating cathode was required. This distance must be less than the electron mean free path to achieve sufficient ion production. This limits the size of the converter.

In the Gabor type auxiliary discharge thermionic converter (14), no auxiliary electron source is required; a small fraction of the main discharge electrons are drawn off and accelerated in order to produce the ions. Fatmi (10) discovered the mode of operation while working on an experiment about the possibility of slow ion reflection. In 1961 Gabor suggested a converter using the single electron emitter mode of auxiliary discharge. In his 1963 paper, Gabor (15) concluded that the low energy ions are reflected several times

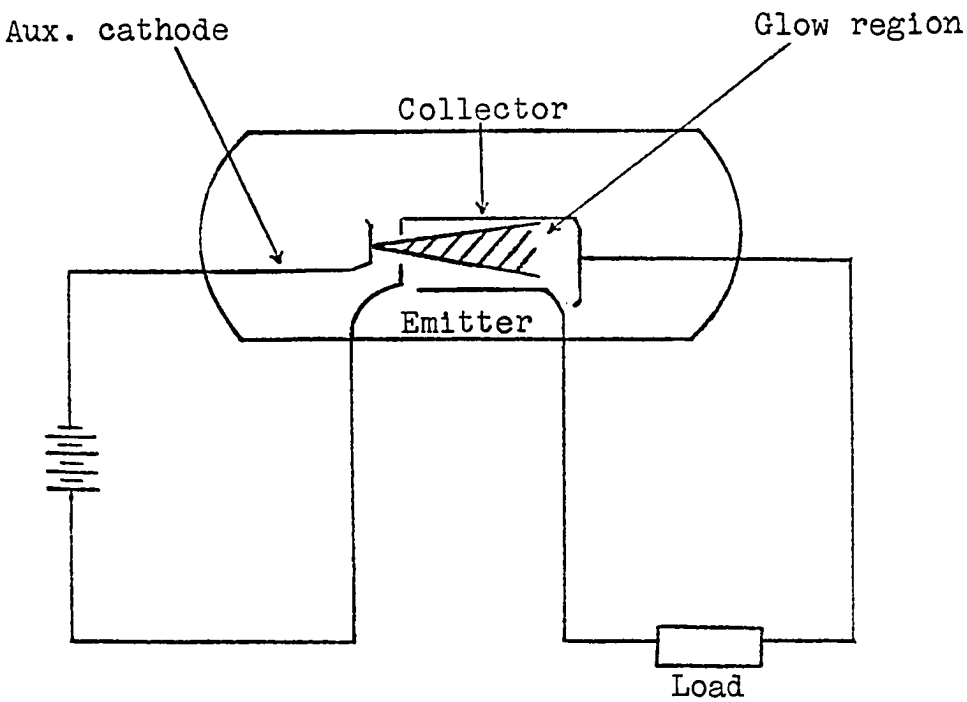


Fig. 5. Diagram of a converter with an injection system

before being absorbed by the emitter. It was also found that more than one half of the ions produced in the auxiliary discharge region lost their energy during the repeated passages through the emitter sheath, partly by collisions with gas molecules, and were trapped there. Therefore, less than one half of the ions oscillate in the emitter sheath. It is apparent that this causes the space charge neutralization to be much more effective than it is in the case where the positive ions pass through the emitter sheath just once. This phenomenon of slow ion reflection also explains the discrepancy between the ratios of electron to ion currents obtained from experiment and from Langmuir's theory.

Gabor modified Langmuir's theory by postulating that an ion has a probability, R, of reflecting at the emitter sheath, then ions on the average make $1 + 2R + 2R^2 + 2R^3 + - - - - - =$ $\frac{1 + R}{1 - R}$ passages through the emitter sheath before being neutralized. Then $\sqrt{\frac{M}{m}} \frac{(1 + R)}{(1 - R)}$ electrons will be neutralized by each ion.

In 1965 a cyclic analysis of a Gabor type auxiliary discharge converter was presented in a paper by Fouad and Walsh (12). This analysis took into account the phenomenon discovered by Gabor of the reflection of slow ions at the emitter. Later they developed an expression for the cost of ion production in terms of system parameters by applying the

results they discussed in their previous paper (13). They showed that a cost of space charge neutralization in the range of 0.01 to 0.18 watt/ampere is achievable.

THEORY OF OPERATION

Physically a Gabor type auxiliary discharge thermionic converter consists of three parallel electrodes, separated by two regions. Fig. 6 shows the arrangement schematically, and provides designations for the two regions between the electrodes. The emitter is the electrode which is heated externally and emits electrons. The collector collects most of the electrons from the emitter, but a small portion is allowed to pass through from the main discharge region into the auxiliary discharge region. The third electrode, called the auxiliary anode, is maintained at a relatively high potential with respect to the collector and accelerates the penetrating electrons which in turn ionize the filling gas molecules by impact ionization.

The purpose of this design is to provide an adequate supply of positive ions at the emitter for space charge neutralization. The operation can be explained as follows. When the emitter is heated, electrons are emitted thermally from the surface of the emitter into the main discharge region. Most of these are collected by the collector, but a small fraction passes through the collector and comes under the influence of the auxiliary anode accelerating potential. These electrons ionize the filling gas by impact if the

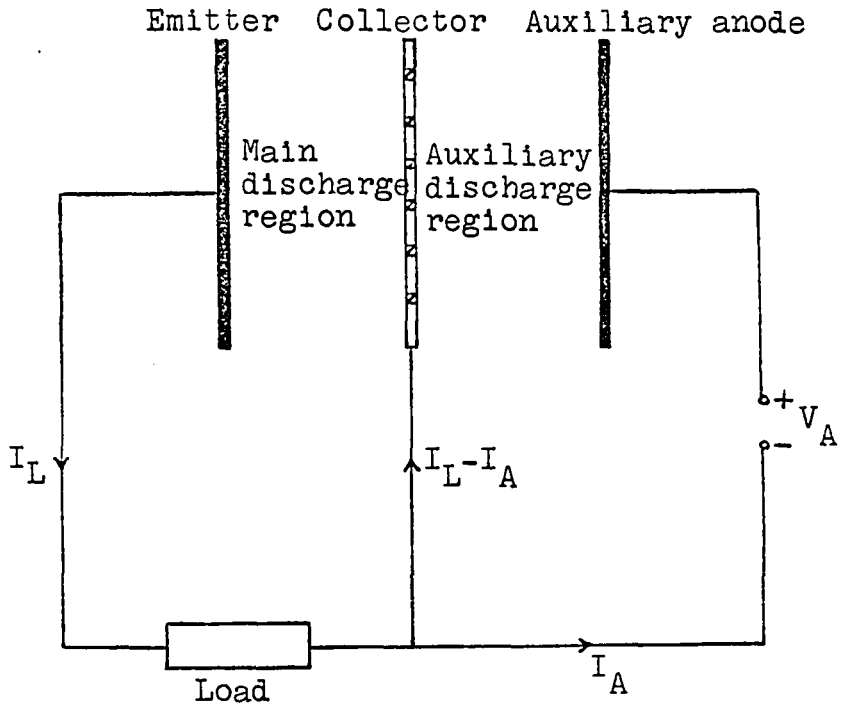


Fig. 6. Schematic representation of auxiliary discharge converter

auxiliary anode potential is higher than the first ionization potential of the filling gas. A luminous plasma can be observed in the auxiliary discharge region.

Potential Profile in the Main Discharge Region

The positive ions formed are accelerated toward the collector and many of them pass through into the main discharge region while the electrons are approaching the auxiliary anode. In the main discharge region, the potential drop due to the plasma resistivity is too small to cause internal ionization or excitation. Therefore this region contains a dark plasma which depends on the emitter for its electrons supply and on the auxiliary discharge for its positive ions supply.

A typical potential profile for the complete inter-electrode system is shown in Fig. 7. V_p is the plasma resistivity drop in the main discharge region. V_{Ef} and V_{cf} are the emitter and collector sheath potential drops respectively, which arise from the difference of electron and ion mobilities. In other words, potential gradients build up at the surfaces of the electrodes, these retard the electrons but accelerate the positive ions until the rates of arrival are equal. Charge equilibrium at the sheath edges is thus maintained. It is important to point out that when

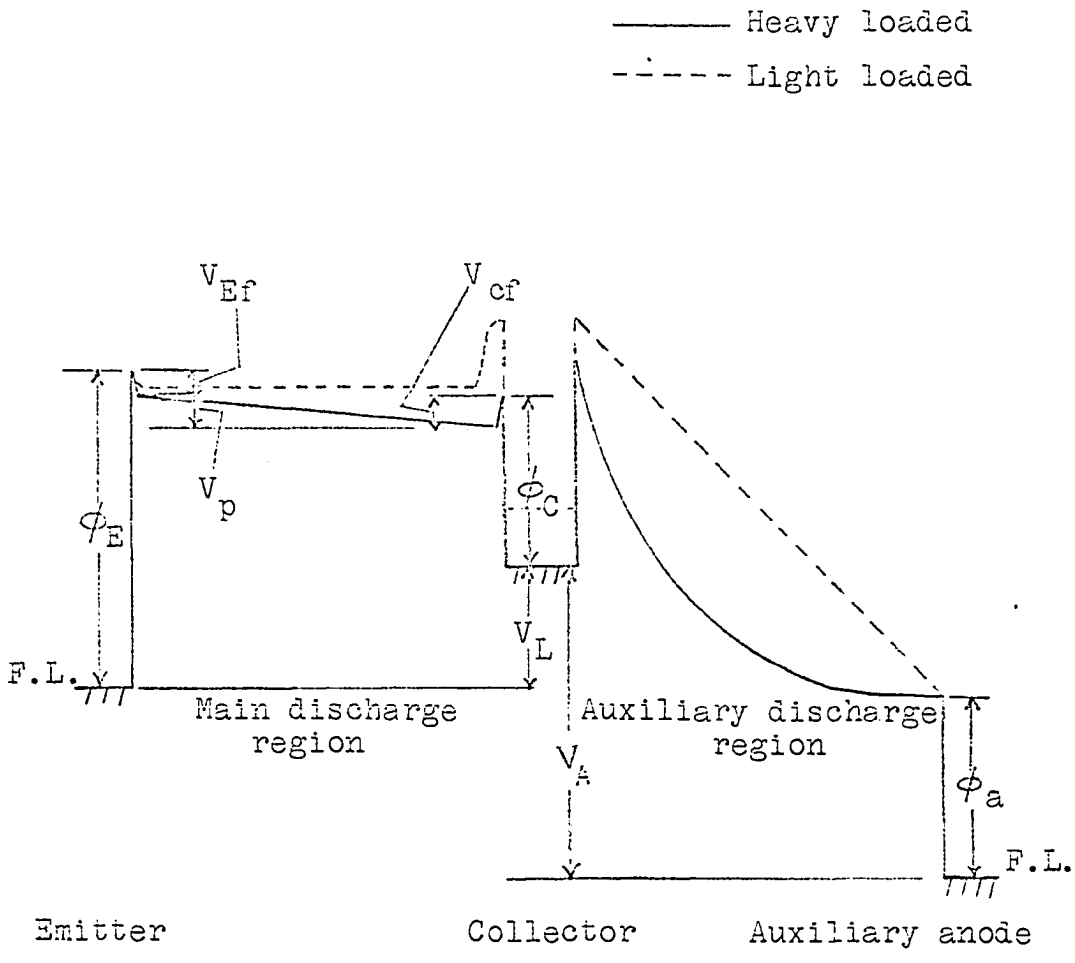


Fig. 7. Potential profile between emitter, collector, and auxiliary anode

the potential of the emitter is positive relative to the collector, the emitter potential drop will change very slightly as the collector potential is varied. In the case where the collector is positive with respect to the emitter, the emitter potential drop depends on the load condition. The collector potential drop, V_{cf}, is affected by the load current; when the load is light, V_{cf} is large, and as more load current is required V_{cf} decreases, permitting an increased flow of electrons.

The plasma resistivity potential drop in the main region varies with the load current. Under an open circuited or lightly loaded condition the plasma is equipotential and under heavy loaded condition a potential gradient exists in the plasma. This causes preferential drift of electrons from the emitter to the collector and therefore a preferential drift of positive ions from the collector to the emitter. This is illustrated in Fig. 7.

When the emitter emits a number of electrons greater than the number capable of being neutralized by the positive ions, a double sheath will exist at the emitter. The potential profile of such a condition is shown in Fig. 8. V_{min} is the potential minimum at the emitter. It depends on the rate of electron emission from the emitter and rate of arrival of positive ions for space charge neutralization.

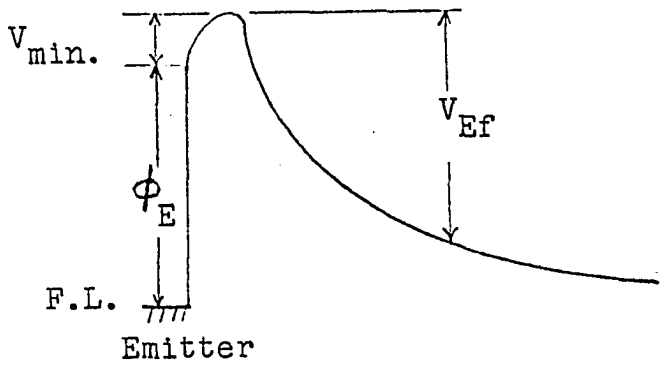


Fig. 8. Double sheath potential profile at the emitter

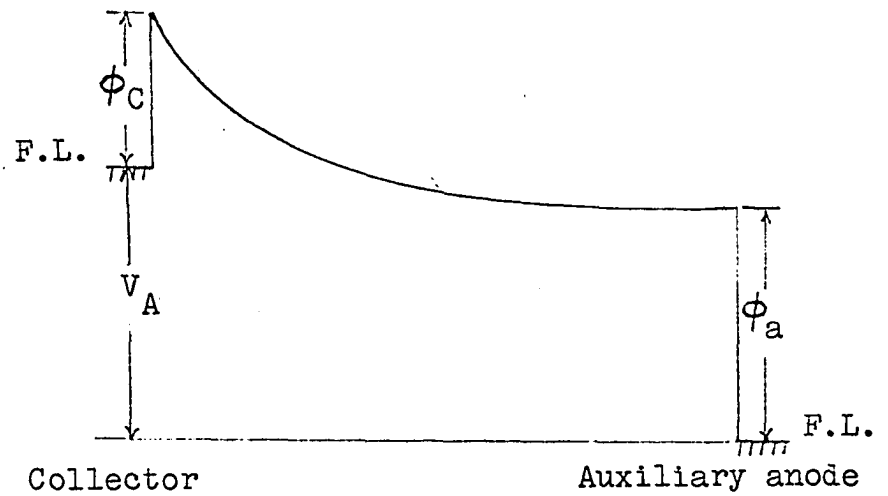


Fig. 9. Potential profile in the auxiliary discharge region

Potential Profile in the Auxiliary Discharge Region

In practice, the accelerating voltage V_A is adjusted to be slightly above the first ionization potential of the filling gas so that the probability of inelastic electron-gas atom collision is high. The potential profile in the auxiliary discharge region may be assumed to be linear initially. As soon as ionization occurs, a depression in the potential profile will be developed due to the presence of the positive ions. This causes a high potential gradient to build up at the collector. Thus, most of the collisions take place close to the collector and cause a glow to be observed above the surface of the collector. It is seen that almost all of the accelerating potential V_A is across the narrow collector sheath. Since a low potential gradient exists in most of the region, it only serves as a conducting path between the two electrodes. If its dimension is properly selected the ion loss due to ambipolar diffusion and recombination will be minimized. The potential profile is shown in Fig. 9.

Slow Ion Reflection

The phenomenon of slow ion reflection was discussed briefly in a previous section. This is the most important

factor in the theory of operation of the auxiliary discharge converter. Gabor (15) observed this while he was investigating the characteristics of the auxiliary discharge converter. He obtained very interesting results which strongly indicate the possibility that the slow ions which reach the emitter sheath are not immediately collected by the emitter with a high probability. This concept is based on the low ratio of auxiliary to main discharge currents achieved in experimental auxiliary discharge system. Gabor also reported a ratio of electron to ion plasma drift currents of 24,000. According to Langmuir's theory (30) this ratio should be 270 for argon as discussed before. The discrepancy between these two values corresponds to the probability of ion reflection R = 0.98 in the modified formula proposed by Gabor (12).

Characteristics of the Filling Gas

Rare gases are used for the filling gas in the auxiliary discharge converter because they are chemically inactive, they have comparatively high ionization coefficients and low recombination coefficients under normal operating conditions. Several single gases such as neon and argon are acceptable. However, both gases have relatively large excitation probabilities. Some power is wasted in exciting these atoms without causing any ionization. It was found that by mixing

proper amounts of each gas together, the ionization coefficient of the mixture is increased (17). This is called the Penning effect, and mixtures of this kind are called Penning mixtures. Another Penning mixture that has some very special theoretical advantages is helium gas containing small admixture of mercury vapor.

The Penning effect can be explained as follows. In certain atoms, such as Hg, He, and Ne, there are energy levels, called metastable levels, from which the selection rules prohibit radiative transitions to lower levels. Once an electron is in a metastable level, it must remain there until the atom has an accidental encounter with another particle. An electron of sufficient energy may collide with a metastable atom and raise it to a higher energy level from which it may undergo a radiative transition to the ground state.

A metastable atom may also revert to the ground state via an inelastic collision with another atom. This is a collision of the second kind. Kinetic energy may be interchanged in such a collision so that the atom is either raised to a higher energy level or dropped to a lower level. Only relatively small amounts of kinetic energy can be interchanged in this way so that the normal excited levels must be very near the metastable level. When atoms of other elements are present, the excess energy of the metastable atom may be given up in exciting or ionizing one of these other atoms.

Since such encounters are relatively unlikely to occur, the life of a metastable state is very long. The average life of a metastable state is of the order of 10^{-3} second compared with the average life of a normal excited state which is of the order of 10^{-8} second.

From the energy level diagram of neon and argon in Fig. 10, it can be seen that neon has an ionization potential of 21.5 volts, and the first ionization potential of argon is 15.7 volts. Two of the three energy levels of neon are metastable levels. A collision between a metastable neon atom and a normal argon atom results in the ionization of the argon and the return of the neon to its ground state. The energy which would be lost in exciting the neon atom is available then for ionization of the argon atom.

Mixtures of argon and neon, showing some of these effects, are depicted in Fig. 11. The symbol η and E represent, respectively, the ionization coefficient, and the electric field intensity. The numbers on each curve give the ratio of the argon pressure to the total pressure of the mixture. A ratio of 10^{-3} parts of argon is optimum.

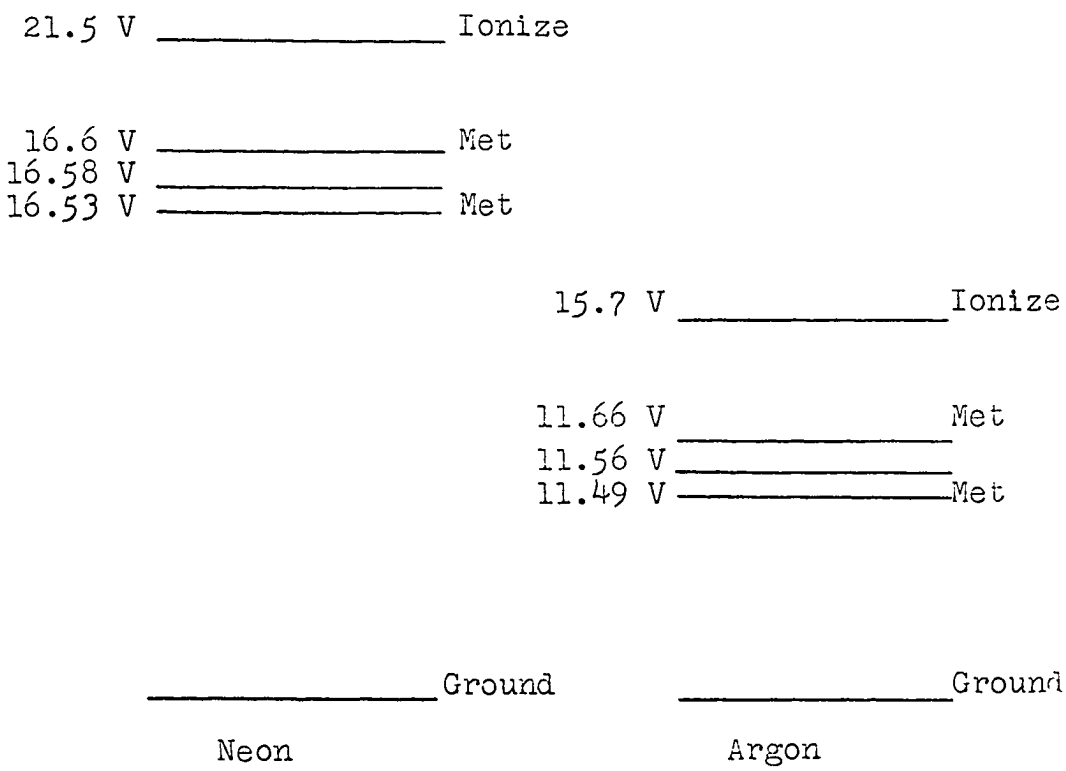


Fig. 10. Energy level diagrams of Ne and A

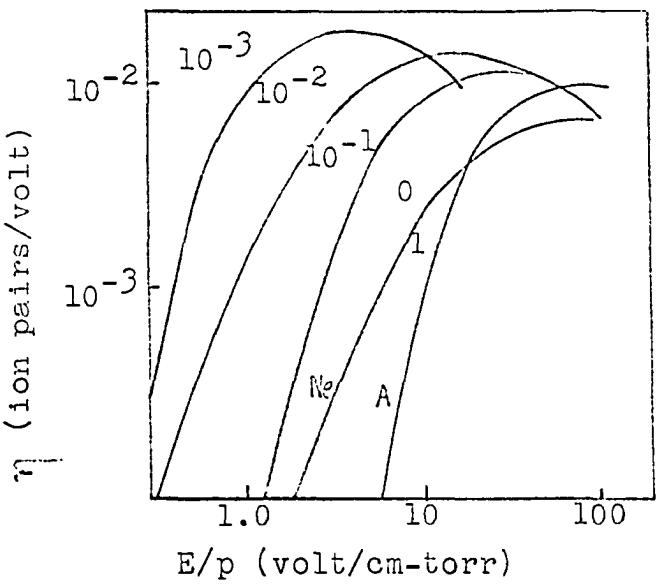


Fig. 11. Illustration of the Penning effect (ionization per volt per torr at 0^{o} C for Ne-A mixtures)

EXPERIMENTAL INVESTIGATION

Vacuum System

It was pointed out earlier that decomposition and activation of the oxide coated electrode is necessary for good electron emission. These processes must be carried out under high vacuum. Accordingly, a vacuum system had to be designed that was capable of producing a sufficiently high vacuum for decomposition and activation, that would hold the pressure to 10^{-3} torr during the outgassing of the filament, and that would allow for certain mechanical adjustments during the processes. The vacuum system in its final form is shown in Fig. 12. A mechanical pump is used to pump the system to the 1 micron range. A liquid nitrogen cold trap is placed in line with the pump to condense vapors, particularly water vapor, which are detrimental to the operation of the pump. This also increases the density of the exhaust gas and consequently augments the pumping rate. Valve A serves to isolate the roughing pump. A thermocouple pressure gauge together with the control unit measures the pressure effectively between 1 and 10^{-3} mm Hg. Copper tubing and rubber hose are used between the roughing pump and valve A since very low pressure is not expected there. Valve B is a Varian stainless steel valve which isolates the high vacuum operating

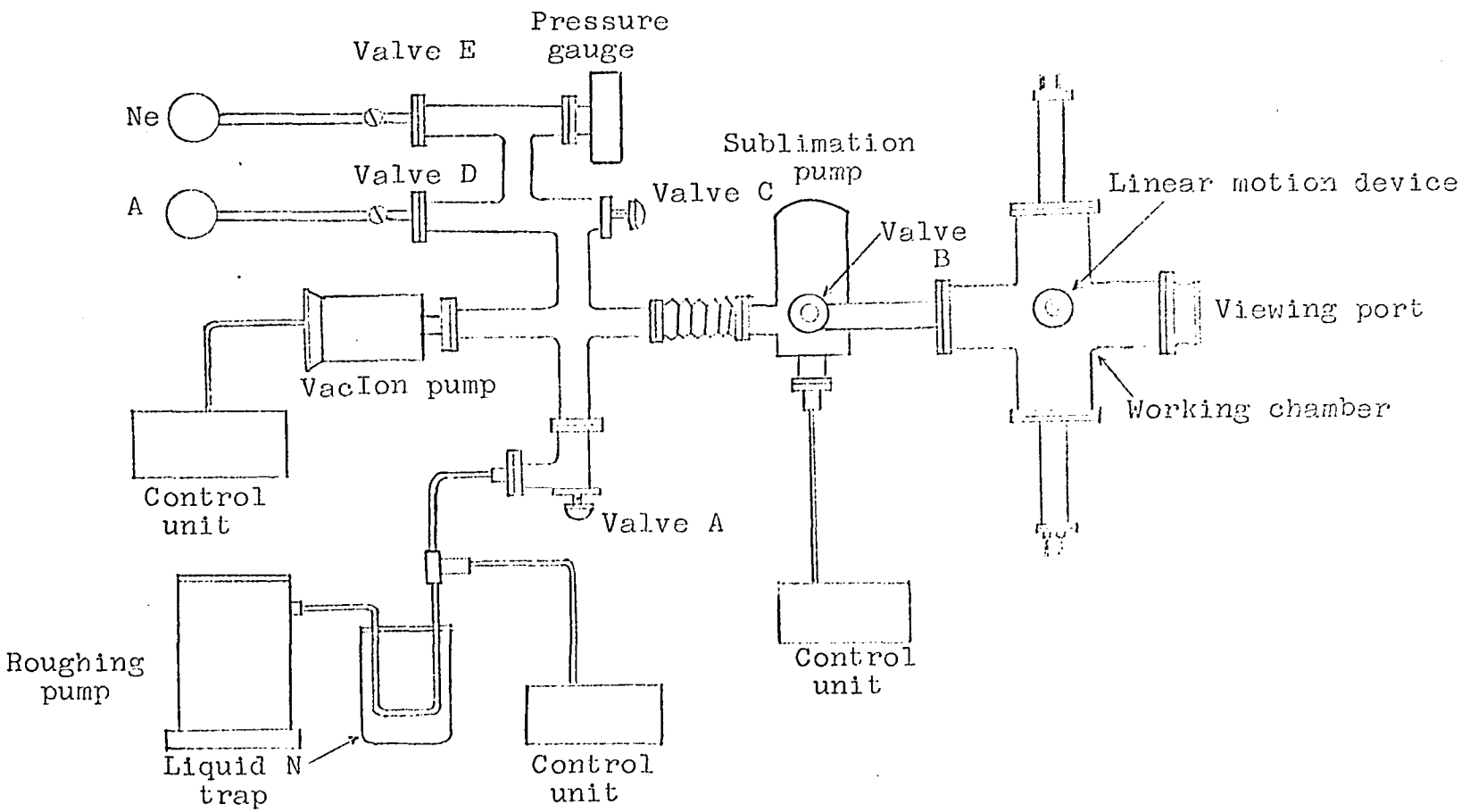


Fig. 12. Vacuum system

Fig. 13. Vacuum system

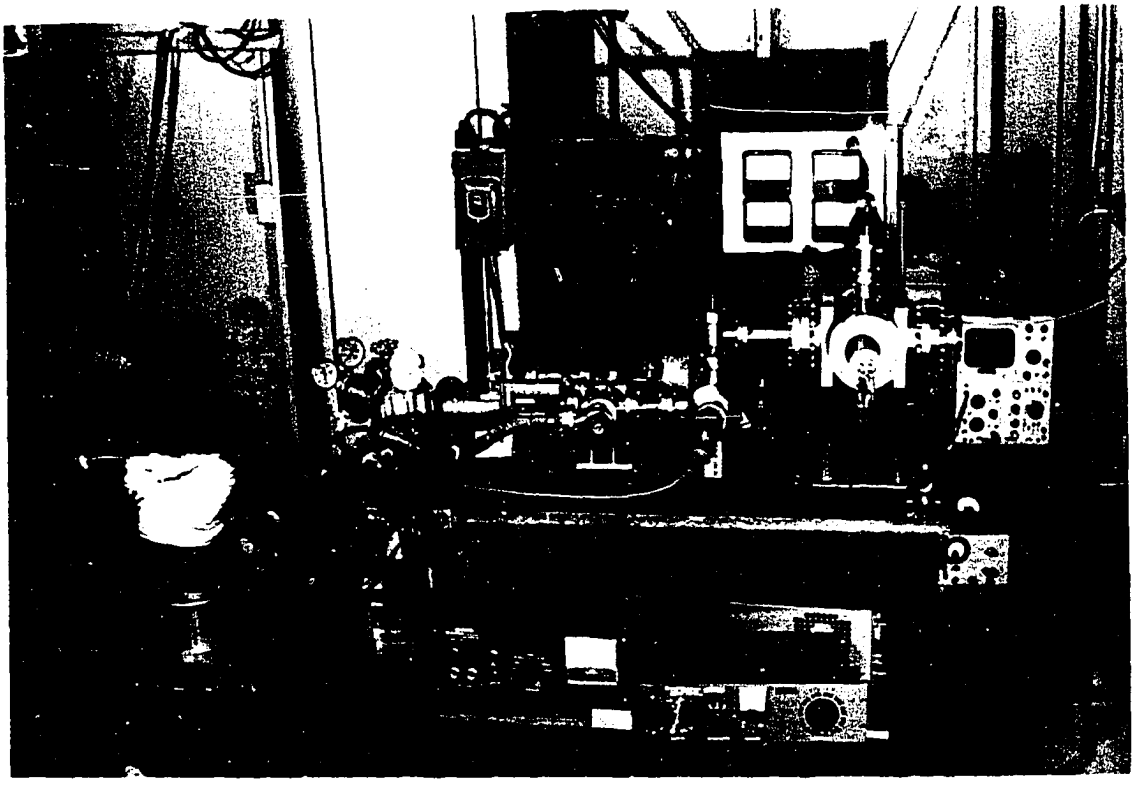
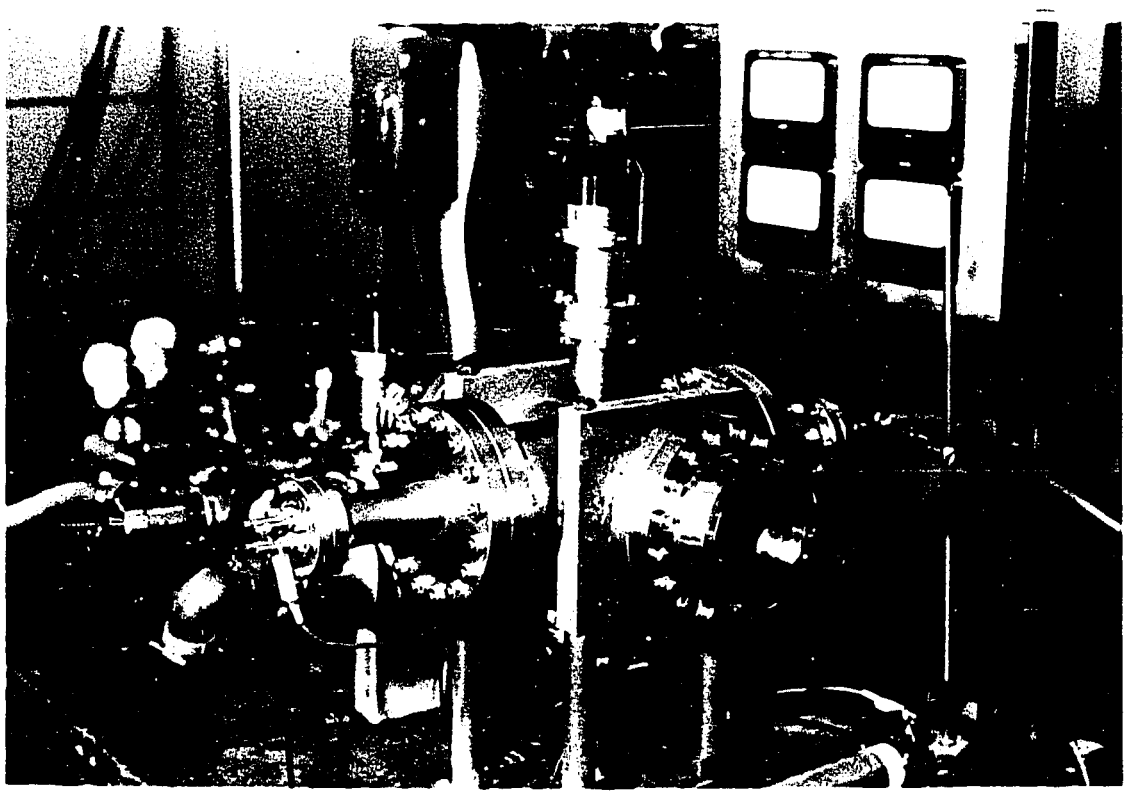


Fig. 14. Vacuum system



chamber. A large XYZ stainless steel cross was chosen as the operating chamber and a high vacuum linear motion device was introduced to support the collector assembly. In addition, a powerful titanium sublimation pump was connected to the system as a getter during decomposition and activation. It also absorbed all contaminating gas molecules and thus purified the Penning gas mixture when admitted to the system.

All fittings of the system are Varian 300 Series stainless steel with Con-Flat flanges and copper gaskets. The cross fitting forms a junction for the roughing line, the gas filling line, the working chamber line and the ion pump line. The ion pump is a Varian 15 liters/second VacIon pump which removes gaseous molecules and atoms by formation of chemically stable compounds and by ion burial. The major components of the VacIon pump system are a control unit, a permanent magnet, and a pump. The pump consists of an enclosure containing an anode grid sandwiched between two cathode plates. The pump current has a linear relation to the density of the gas molecules, ionic current flow being proportional to the rate of electron-atom collisions. The milliammetter in the pump control unit can be calibrated to read directly in pressure. Consequently, the same device serves as a pump and a pressure gauge.

A bottle of argon and a bottle of neon are connected via the regulator valves and valves D and E. The proper

amount of each gas has to be admitted to the system to form the Penning mixture (neon - 0.1% argon). A diaphragm gauge operating in the 1-760 mm Hg range serves to indicate the filling gas pressure in the system.

Converter Design

Selection of the core material

Materials with low work functions are suitable for use as core materials for the electrodes. Other factors such as evaporation rate, melting point, thermal conductivity, chemical stability and tensile strength at high temperatures are also important. The work functions of some pure metals are listed in Table 1. It is to be noted that the work functions listed are for illustrative purposes only, because the work function will generally depend on how the material is prepared (35). From the work function point of view, Li, Na or K would be acceptable; however due to their low melting points they are rejected.

The nickel base alloy has been used widely by tube manufacturers. The more active metals are added to nickel to serve as aids in the chemical reduction of the nickel compound surface where electron emission is to occur. However, pure nickel is also found to be a suitable base metal for

Table 1. Work function of pure metals

Material	Work function in eV
Li	2.48
Na	2.28
K	2.22
Cs	1.93
Ba	2.51
Ca	2.84
Ni	5.0
Mo	4.2
Ta	4.2
Cu	4.5
W	4.6
Nb	4.0
Re	5.0

oxide-coated electrodes. Nickel sheet and nickel mesh gauzes were therefore selected to use for the emitter and the collector cores respectively.

Configuration

Planar electrodes were used in the first design of the converter because the electrode spacings could be easily

varied during testing. For auxiliary discharge systems the emitter-collector spacing is generally between 2 mm and 5 mm. Fig. 15 shows the schematic of the planar electrode converter. The emitter rested on a cylindrical heat shield, and a heating element inside it was supported by the bottom feedthrough of the vacuum system.

The collector assembly consisted of the fine wire nickel mesh, a slotted quartz tube and a nickel cap which served as the auxiliary anode. This assembly was connected to the linear translation device in order to adjust the spacing between the emitter and the collector. One inch of linear translation was achievable. The activating electrode had to be inserted in between the emitter and the collector assembly during decomposition and activation and subsequently it had to be withdrawn completely. It was therefore connected to the side linear translation device.

The collector heater was supported by the nickel tube welded to the mesh. All the leads used in the system were tantalum wire to avoid the problem of metallic evaporation.

The disadvantage of the planar electrode system is that there is no practical and efficient way of cooling the collector. The experiment on the planar electrode system was performed for the purpose of finding the optimum values of some parameters such as interelectrode spacings, pressure

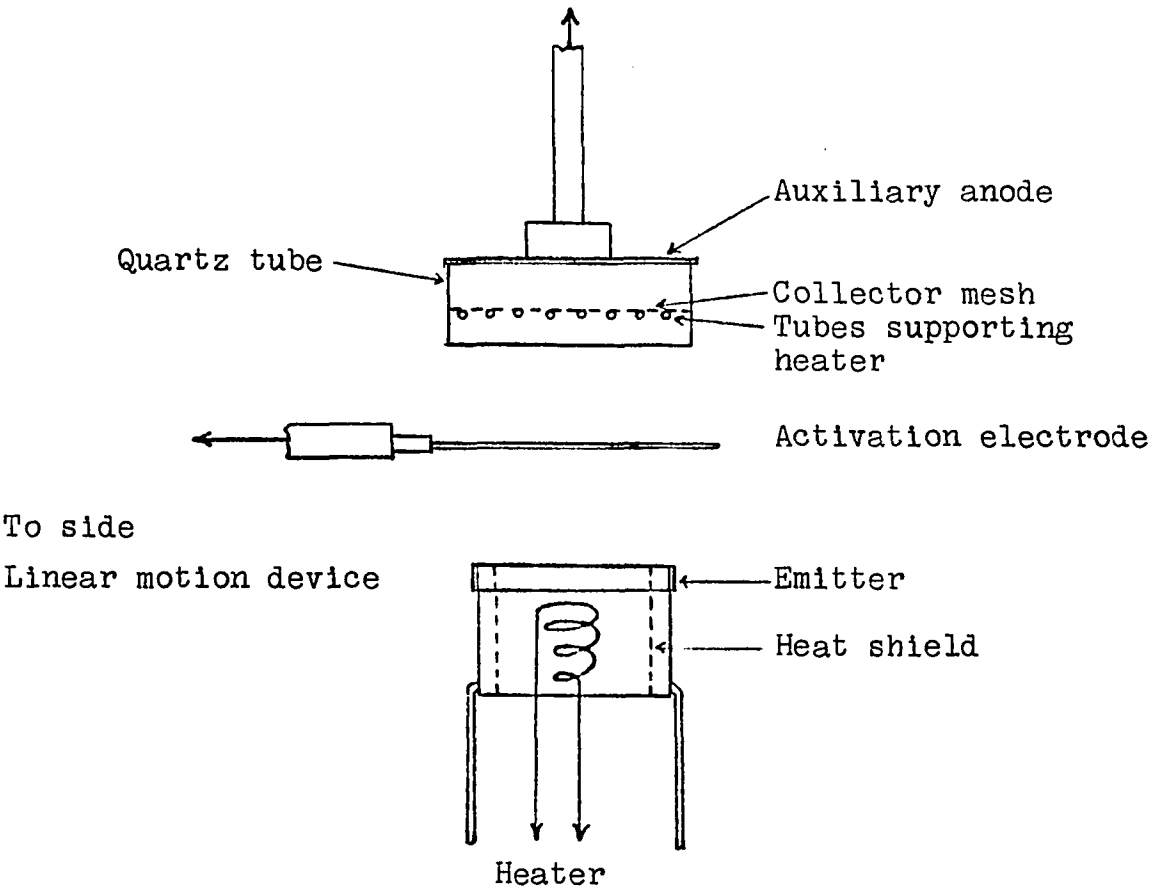
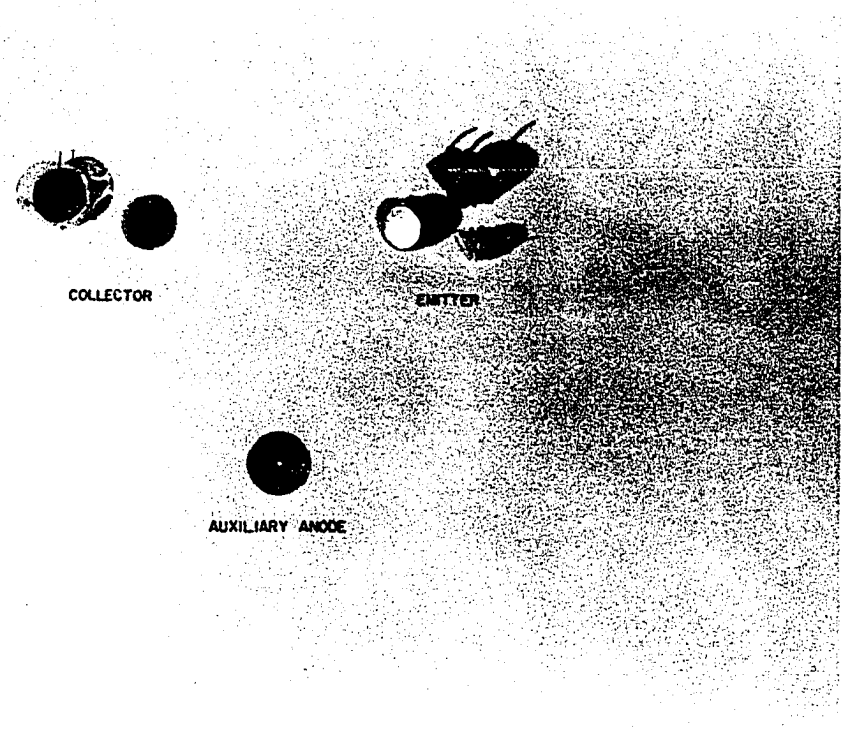


Fig. 15. Schematic of planar electrode converter

Fig. 16. Planar electrode converter components


COLLECTOR
EMITTER
AUXILIARY ANODE

of filling gas, the operating temperature, the life-time of the electrodes and heaters and the effective areas of the electrodes. This information can be used in the design of other electrode configurations in which the collector can be cooled more efficiently.

Since the preparation of the oxide-coated electrodes, their decomposition and activation, the evacuation of the system and the operating procedures are the same for any electrode configurations, the results obtained from the tests on the planar electrode system will be shown later for the purpose of comparison with those obtained from a cylindrical electrode system with a collector cooling device.

The optimum values of some parameters obtained from the experiments are given below.

Emitter work function, ϕE	2.25	eV
Collector work function, ϕc	1.72	eV
Emitter surface area	3.82	cm^2
Collector surface area	1.91	cm^2
Penning mixture pressure, p	2.5	mm Hg
Emitter temperature, T_E	1250	^oK
Emitter - collector spacing, d	2.5	mm
Collector-aux. anode spacing	5	mm

The design and fabrication of the cylindrical electrodes will be discussed in detail in the following sections.

Electrode design

The emitter is a pure nickel cylinder with diameter of 7 mm, and an effective working area is 2.35 cm^2. The emitter is connected to the terminals on the bottom feedthrough of the system after being coated with the barium oxide coating compound.

A 20-mil tungsten wire is used as a heating filament for the emitter. The electrical source is a 125 V dc power supply. It is necessary for the filament to last for long periods of time. Due to the physical configuration of the emitter the heater was constructed to have the shape of reverse coils. This is the most effective shape to provide efficient heat generation and transfer to the emitter sleeve. The tungsten wire is brittle, therefore one should be careful while working with it. To prevent the turns and legs from shorting to one another and to the emitter sleeve, the heater is coated with alundum. The schematic of the emitter is shown in Fig. 17.

In the cylindrical configuration the spacing between emitter and collector cannot be adjusted. It is fixed at the optimum value of 2.5 mm as obtained from the experiments on the planar electrode converter. Due to this small spacing it is impossible to insert the activating electrode between them without touching either one of them. This problem is solved by using separated activating electrodes for emitter and

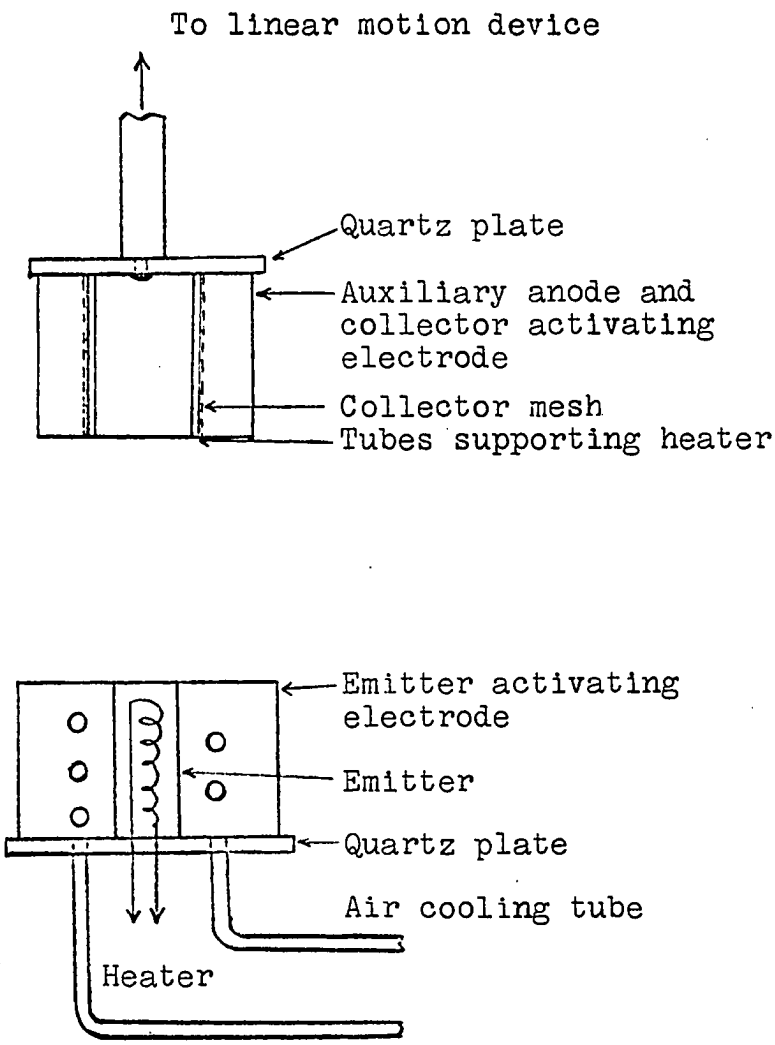
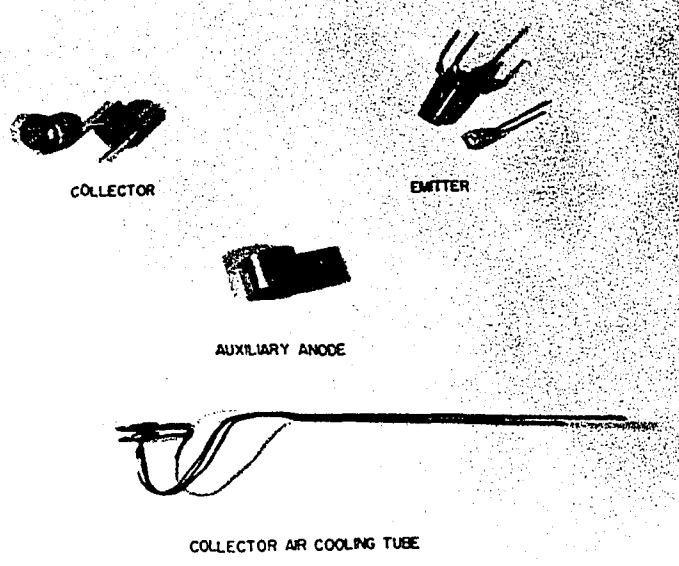


Fig. 17. Schematic of cylindrical electrode converter

Fig. 18. Cylindrical electrode converter components


COLLECTOR
EMITTER
AUXILIARY ANODE
COLLECTOR AIR COOLING TUBE

collector. The emitter's activating electrode is a larger nickel cylinder built encircling the emitter in the lower assembly.

The lower assembly components rest on the 3 mm thick quartz plate which insulates them from one another. The collector cooling tube is also inserted in the quartz plate and helps to support the lower assembly together with the emitter. The cooling tube is a seamless nickel tube of about 1 mm O.D. from the Uniform Tubes, Inc. It was fabricated to form a cylinder, encircling the emitter, large enough for the collector cylinder in the upper assembly to fit in. The 20-mil tantalum wire is used as a lead for the activating electrode and is connected to the terminal of the bottom feed-through. The height of each electrode is about 1.3 cm above the quartz plate.

The production of a suitable collector is a major problem in the development of all thermionic conversion systems. A low work function collector can be realized by using an oxide-coated surface. In the case where the collector work function is not low enough, a bias voltage supply will be needed to compensate for work function deficiency. This is an external factor and in no way changes the conditions pertaining to the potential profile and plasma which would be observed if a low work function collector were used. The collector is fabricated from a

35/0095 nickel mesh. The diameter of the collector cylinder is 1.4 cm. The 1 mm O.D. nickel tubes are welded to the inside surface of the cylinder to serve as the support of the heater. The heater is needed for the decomposition and the activation of the collector. It is a 10 - mil insulated tungsten wire.

Gabor (14) found that it is necessary that the collector have a larger area than the emitter. After taking the surface areas of the attached tubes into consideration, the effective surface area of the collector is found to be 4.7 cm^2.

The auxiliary anode, which also serves as the activating anode for the collector, is a nickel cylinder of 2.4 cm diameter. All electrodes are supported at the top by the quartz plate which in turn is connected to the linear translation device of the vacuum system. The leads used to connect them to the side feedthrough are 20 - mil tantalum wires. The schematic of the upper assembly is also shown in Fig. 17.

Preparation of the oxide-coated electrodes

The coating compound consists of a mixture of barium, strontium, and calcium carbonates. Of the three materials calcium carbonate is the easiest to activate. Its usefulness as an emission provider is quite limited with time. An emitter made with any significant percentage of calcium will exhibit unacceptable emission decay within a matter of 10

hours or less. Barium activates more slowly and under stronger reducing conditions than calcium. Its life expectancy as an emission provider is much better than calcium. Barium oxide emitter has a life expectancy of 5 to 10,000 hours. Strontium is the most difficult to activate. Strong reducing action and considerable time is required. A strontium oxide emitter, once activated, has a life expectancy that is essentially undefinable.

The need for combination of the barium, strontium, and calcium oxides is apparent from the preceding comments. The object is to select a mixture which provides the optimum in initial emission and long life emission capability. Specifications of several commercial oxide coatings were studied, and after a series of tests an EA - 18 formulation cathode coating of Sylvania Electric Products, Inc. was used for both collector and emitter. The composition is as follows: 57.20% barium carbonate, 38.80% strontium carbonate, and 4.00% calcium carbonate.

Theoretically the device should work no matter how high the work function of the emitter is. The emitter temperature will have to be increased to compensate for high work function. As a result the heat loss will increase. Therefore, a compromise must be made in choosing the work function of the emitter. An emitter work function in the range of 2 eV is

acceptable while the work function of the collector should be as low as possible.

A spraying technique was used for coating both emitter and collector. Before this, the electrodes has been cleaned to prevent the formation of an interface layer between the coating and the core metal. The cleaning process is as follows:

1. Electrodes are rinsed in the following sequence:
   (a) In cleaning agent of 4.3 cc of Formic acid; 29.7 cc of Hydrogen peroxide; 70.0 cc of distilled water for one minute
   (b) In tap water
   (c) In distilled water
   (d) In methyle alcohol
2. Electrodes are dried with infrared lamps

The prepared electrodes and other components are then placed in their respective assemblies. Before putting these assemblies into the working chamber of the vacuum system, the exposed surfaces of the system are thoroughly cleaned with acetone. Extreme care must be taken in the alignment of the assemblies because the upper assembly must be able to move into the lower assembly freely and stay on top of it without any shorting between their components. As soon as all components are properly assembled, the vacuum system is closed and ready for evacuation.

Evacuation Procedure

The evacuation procedure is as follows:

1. With the roughing valves A, B opened (valves C, D, E are closed) the mechanical pump is turned on and leaks are checked at all connections.

2. The VacIon pump is started when the roughing pressure is 10 microns or less. The START - PROTECTION switch on the control unit is placed in the START position.

3. The roughing valve is closed when the pressure is 1 micron or less. If the voltage at the VacIon pump control unit falls when the roughing valve is closed, it should be re-opened for additional rough pumping.

4. When the pressure is about 10^{-5} mm Hg, the system is baked for 3-4 hours. Infrared lamps are used for this process.

5. The sublimation pump filaments are degassed at 30 amperes. (In case of new filament, it should be degassed while the roughing valve is open in early step.)

6. When the pressure decreases to 10^{-6} mm Hg, the system is ready for decomposition and activation.

Decomposition and Activation of the Electrodes

In order to produce the desire electrode work function the electrode coating must be decomposed and activated. When

the heater is heated to about 1150° K, a chemical reaction of the following form takes place.

$$XCO_3 \rightleftharpoons XO + CO_2$$

Carbon dioxide is formed gradually and the carbonates are reduced to their respective oxides. The above equation is determined by the dissociation pressure. The dissociation pressure of barium carbonate is lowest for a fixed temperature and this pressure is therefore the governing factor. If a temperature of 1150° K is selected for the decomposition process, then it is found that a pressure less than 100 microns should be maintained within the system. In this system the pressure during the decomposition was about 10^{-3} mm Hg.

The following procedure for decomposition is the same for emitter and collector:

1. The heater is connected to a dc power supply. When the heater is switched on, the pressure rises sharply due to the outgassing of the heater and electrode initially, and then due to the carbon dioxide during the chemical reaction.

2. The current is increased very slowly to protect the heater from thermal shock.

3. The decomposition starts at 1150° K and the temperature is increased gradually to 1200° K to ensure completion of the process. All temperature readings were made with an

Fig. 19. Collector and emitter assemblies

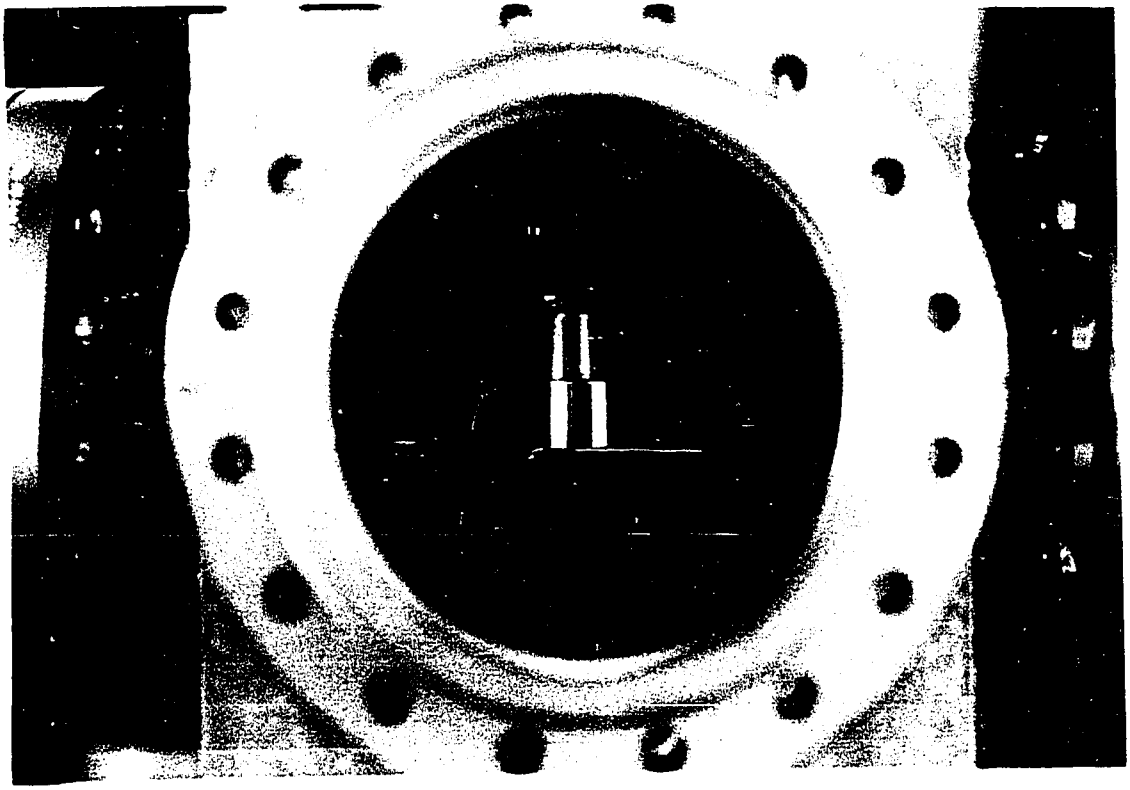
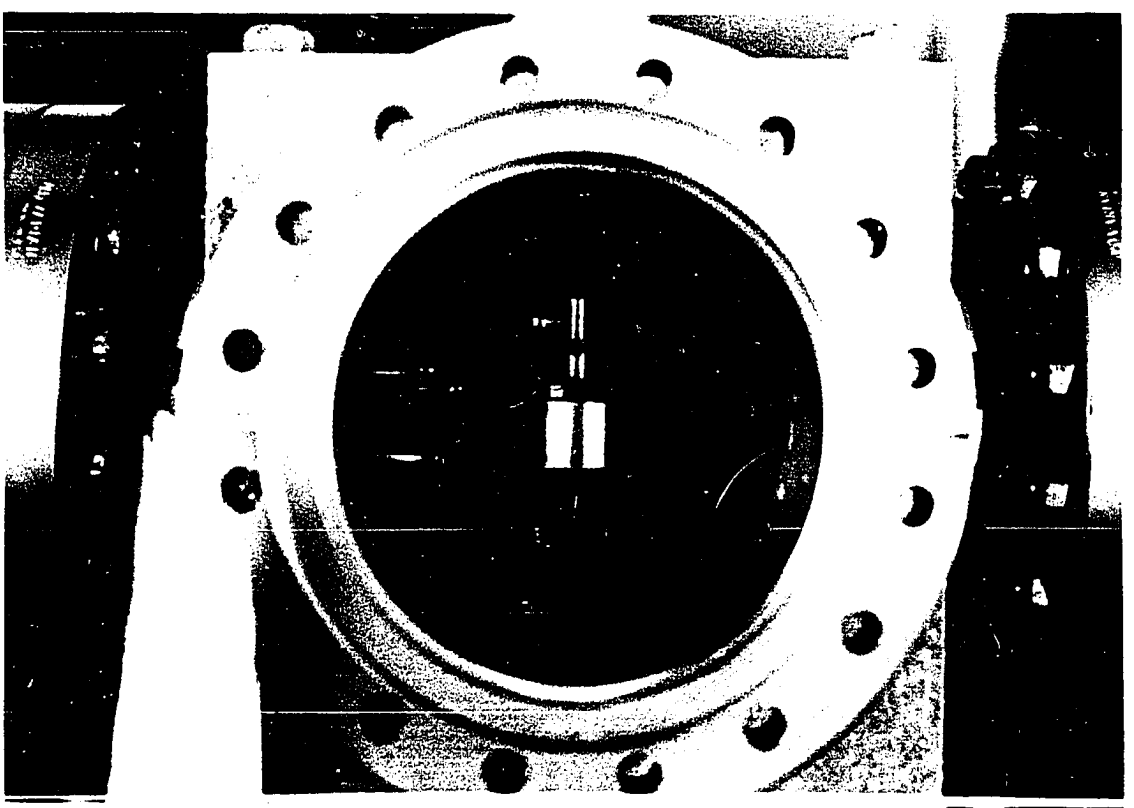


Fig. 20. Collector and emitter assemblies



optical pyrometer through the view port. The process takes about 60-80 minutes. When the heater power supply is turned off the pressure in the system is in the range of 10^{-7} mm Hg.

The emission current of the electrode can be increased by a further process, called activation. This is an oxide reduction process in which some barium oxide is dissociated electrolytically into barium and oxygen. Only barium is formed on the surface of the electrode while oxygen escapes. It was noted before that the monolayer of the free barium is necessary for good electron emission. The activation process also serves to remove residual gases from other electrodes. The following procedure is used:

1. The electrode is heated gradually to the temperature of 1250° K, the pressure in the system is maintained at 10^{-3} mm Hg.

2. A positive voltage of 150 volts is applied between the electrode and its activating electrode for 1 hour or longer. The emission current increases slowly at first and rapidly later on. A positive pulse voltage from a high power pulse generator is used later, and a pulse current is measured. This process takes about 60 minutes.

The decomposition and the activation of emitter and collector were done separately with both assemblies were in their original positions as shown in Fig. 19.

A common experimental method used to determine the work function of a solid is to measure the saturated electron emission at the solid temperature T, and apply the Richardson-Dushman equation (19). This equation is:

$$J = AT^2 \exp (- e\phi/kT) \qquad (2)$$

where J is the emission current density, T is the absolute temperature of the solid, e is the electronic charge, and k is the Boltzmann's constant. A statistical treatment of electron motion within solid predicts that A should be a universal constant (for homogeneous surface) having a value equal to 120 amp/cm^{2}K^2, and ϕ is the effective work function.

The system is allowed to cool for several hours. The pressure decreases to about 5×10^{-7} mm Hg. This ensures that the activation process has been completed. The upper assembly is then lowered down to rest on the quartz plate of the lower assembly as shown in Fig. 20. Continuity conditions between components are checked carefully. The compressed air tank is connected to the air cooling tube at the side feedthrough of the system. The sublimation pump valve B is closed to keep the converter assemblies under high vacuum. Proper amounts of neon and argon are admitted into the system to form the Penning mixture. The pressure of the gas can be read from the pressure gauge.

The gas must be purified, and the sublimation pump is used for this purpose. It is turned on and the filament current is set at 35 amperes. The amount of current determines the temperature of the filament and in turn the rate at which titanium is sublimed. The PERCENT ON dial is set at 50% which gives a cycle of 2 1/2 minutes on, and 2 1/2 minutes off. The sublimation pump will be pumping efficiently in the range of 10^{-6} to 10^{-7} torr. The pump is cooled during operation by running cold water through the water-cooled coils around the pump chamber. The pump is turned off after 2 hours. The pressure gauge will read a few mm Hg higher than before.

The sublimation pump valve is then opened to feed the purified gas into the working chamber. The final pressure of the gas in the system can then be read from the pressure gauge. The thermionic converter is then ready for operation.

CONVERTER CHARACTERISTICS

The electrical circuit for the operation of the converter is shown in Fig. 21. The 115 volt dc power supply was used for the emitter heater. Two 0-100 mA ammeters were used to measure the load current and the auxiliary anode current. The load resistance R_L was a 53 ohms rheostat. Two dc power supplies, V_B and V_A, were used as the bias voltage source and the auxiliary discharge voltage source. The oscilloscope was used to measure the load voltage.

Initially the characteristics of the planar electrode converter were investigated. Experiments were performed on different converters to study the effects of various system parameters on the performance of the converters. The results of the experiments on three different planar converters and a cylindrical converter are reported below.

The auxiliary discharge power required for producing the positive ions is equal to $V_A I_A$ watts. The cost of space charge neutralization per ampere of load current is then $\frac{V_A}{I_L/I_A}$ watts. The ratio I_L/I_A must be as high as possible for good efficiency of the system. The bias voltage V_B was used as the external accelerating field for electrons emitted from the emitter in order to compensate for the insufficiently large difference in work functions between emitter and

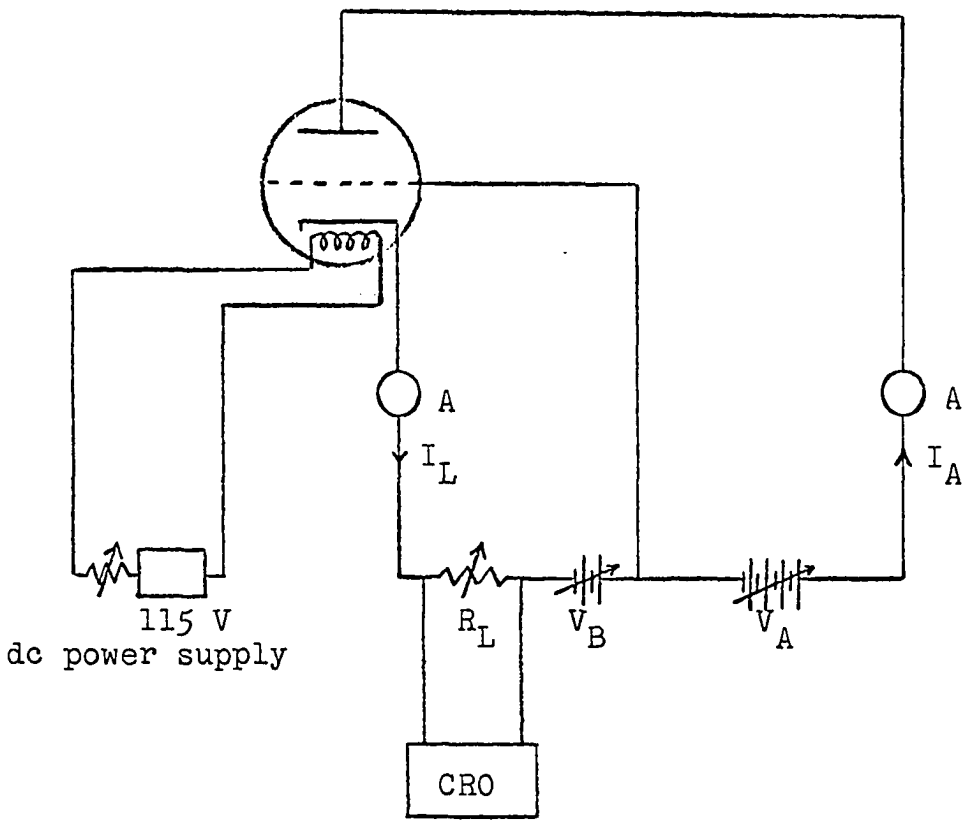


Fig. 21. Electrical circuit of the operation of the converter

collector. Therefore the system could be tested at different situations of electrode work functions.

A planar converter having emitter work function of 1.79 eV and collector work function of 1.72 eV was investigated to study the effect of the difference in work functions between emitter and collector on the operation of the converter. The emitter temperature was 1200° K, the filling gas pressure, p, was 2.5 mm Hg, and the emitter-collector spacing was 3.1 mm. The onset of discharge in the auxiliary discharge region can be determined visually; the procedure consists of increasing V_A slowly until a pink glow is observed in the auxiliary discharge region. Because of the small difference in work functions between emitter and collector, this particular converter could not be operated in the power mode. In this case a minimum bias voltage of 1.2 volts was needed to achieve the Gabor mode operation. The auxiliary discharge voltage of 20 volts was required. This voltage is larger than expected. Fig. 22 shows the ratio of load current to auxiliary anode current for various values of V_B. The cost of space charge neutralization per ampere of load current, which is inversely proportional to the current ratio, was very high in this experiment. Therefore larger difference in the work functions of emitter and collector would be required in order to improve the cost of space charge neutralization.

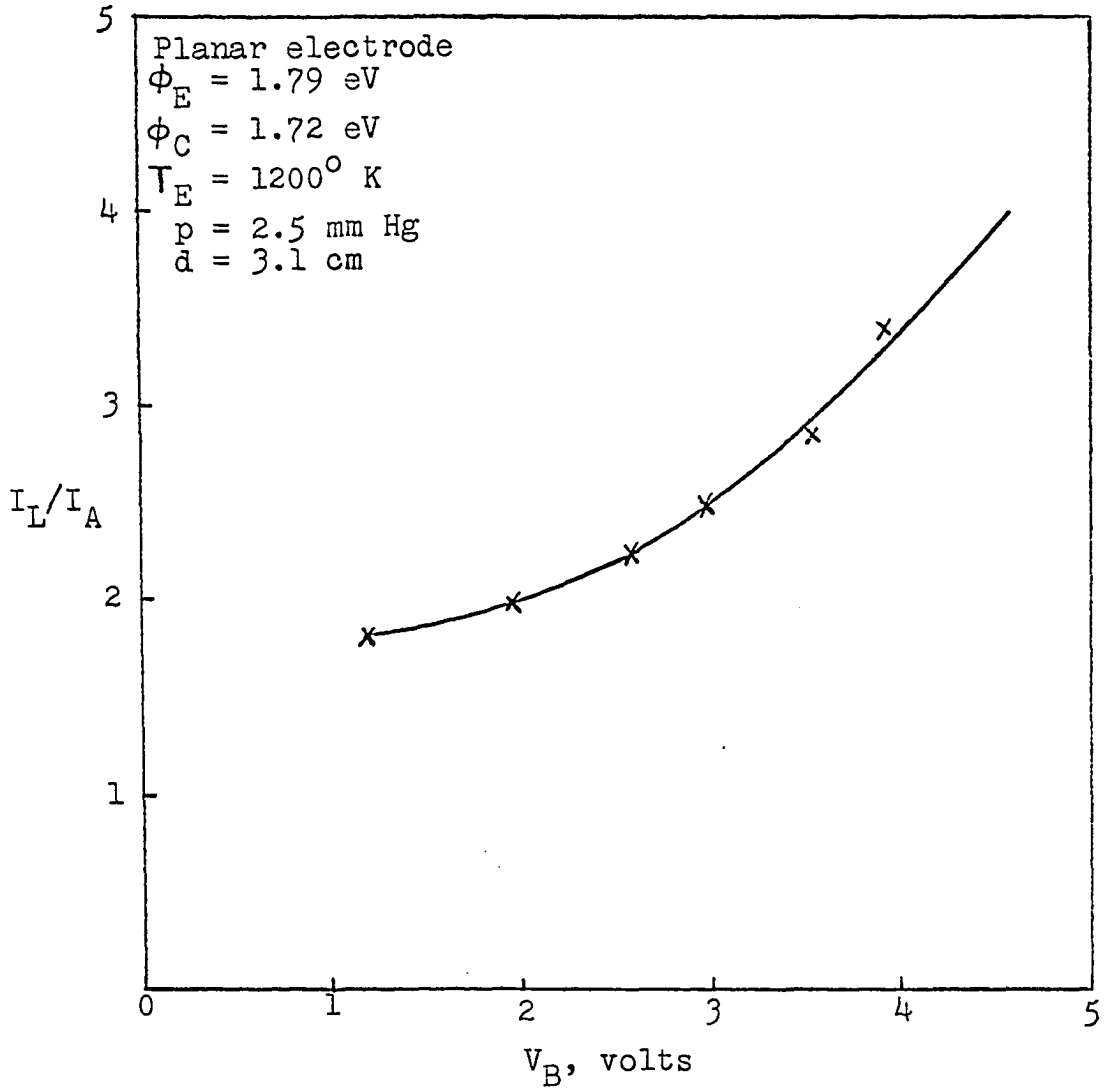


Fig. 22. Ratio of load current to auxiliary anode current versus bias voltage

Subsequently, another planar converter having emitter and collector work functions of 2.25 eV and 1.72 eV respectively was constructed. This converter was used for a number of different experimental studies that are described below:

To study the effect of the filling gas pressure on the cost of space charge neutralization, the ratio of load current to auxiliary anode current was measured at different values of filling gas pressures. The result is shown in Fig. 23. The maximum value of the current ratio was obtained at a filling gas pressure of 2.5 mm Hg.

The effect of the emitter-collector spacing on the cost of space charge neutralization was investigated. The ratio of load current to auxiliary anode current was measured at different values of V_B. In this experiment the system could be operated in the power mode because of the sufficiently large difference in the work functions of emitter and collector. Fig. 24 shows that the converter with spacing of 2.5 mm gives better results than the one with spacing of 3.1 mm. The short circuit between emitter and collector due to thermal expansion occurred at closer spacing.

Another experiment was performed to study the effect of the auxiliary anode voltage on the cost of space charge neutralization. The ratio of load current to auxiliary anode current was measured at various values of V_A. Fig. 25 shows that the current ratio decreased as the auxiliary anode

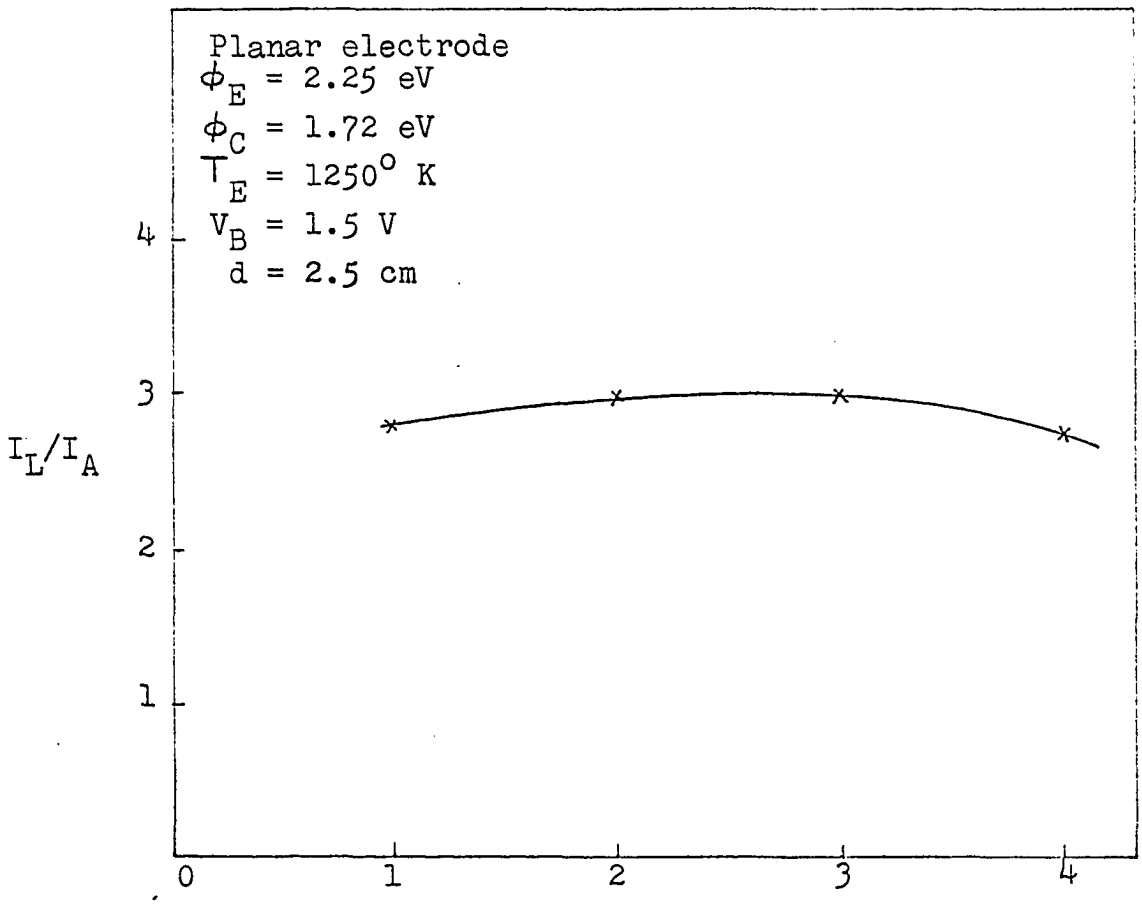


Fig. 23. Variation of ratio of load current to auxiliary anode current with gas pressure

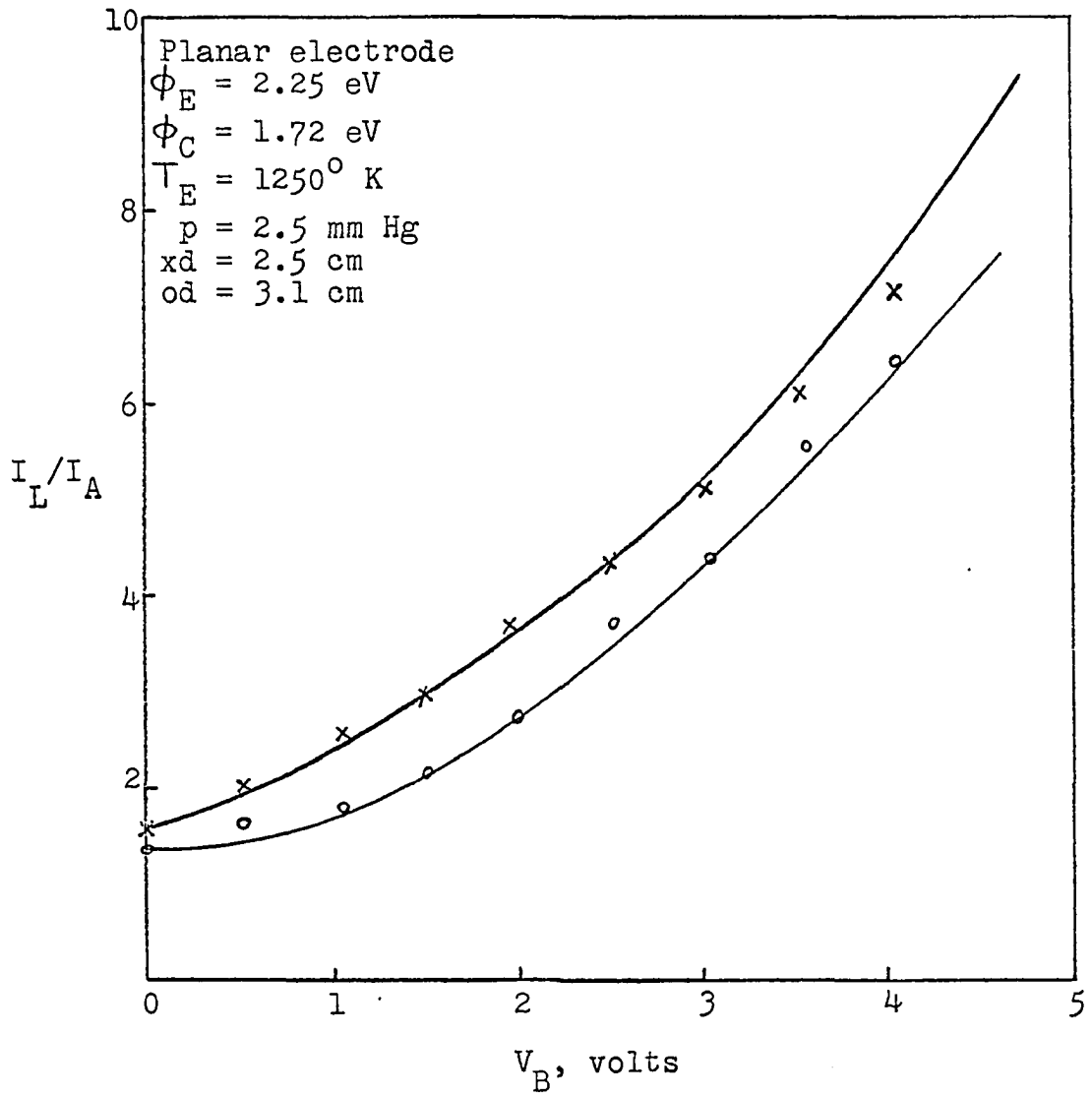


Fig. 24. Ratio of load current to auxiliary anode current versus bias voltage

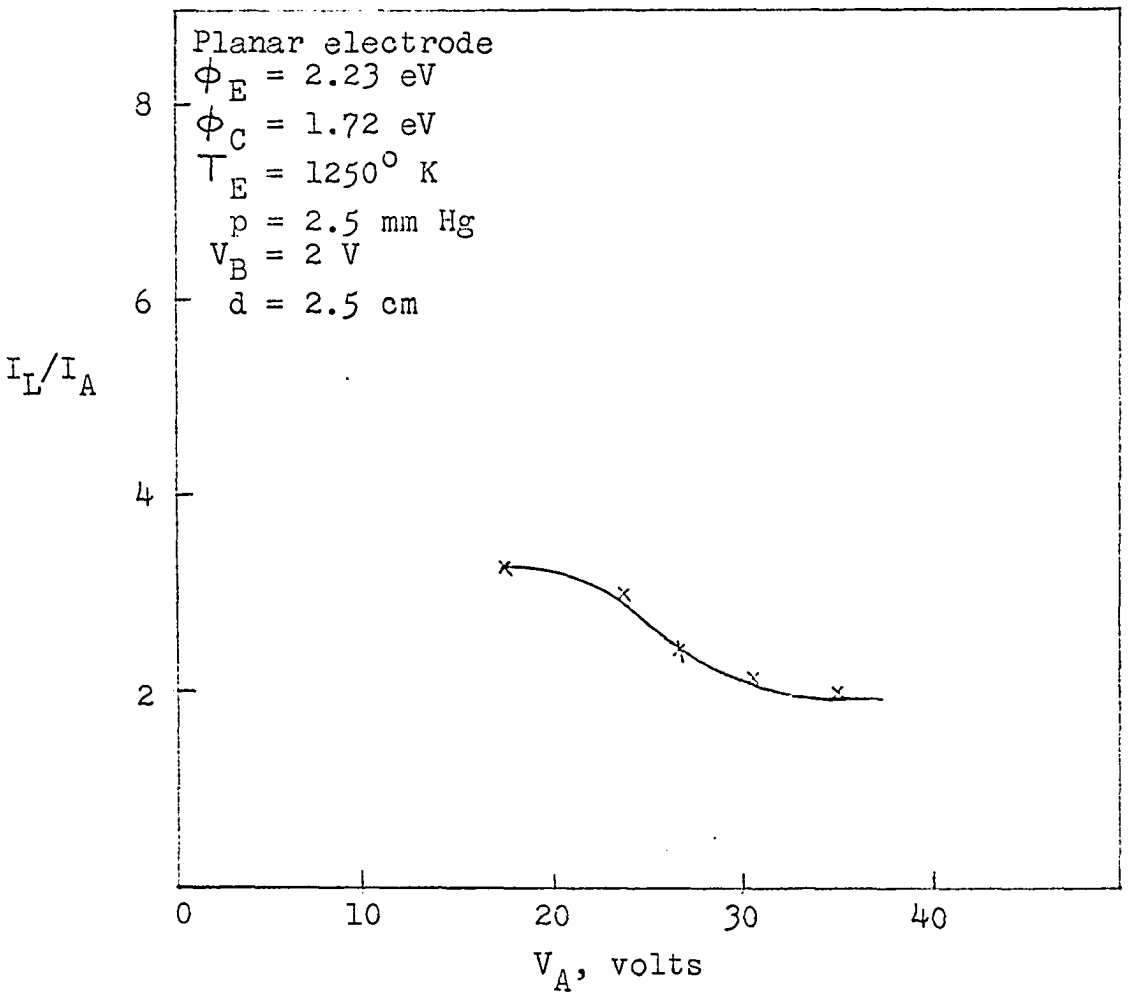


Fig. 25. Variation of ratio of load current to auxiliary anode current with auxiliary voltage

voltage increased. The minimum auxiliary voltage required to initiate the discharge was in the range of 17.5-20 volts.

The auxiliary voltage was measured at various values of bias voltages. The result is shown in Fig. 26. The cost of space charge neutralization which is directly proportional to V_A, decreased as the bias voltage increased.

The load characteristic was determined when the converter was in operation and the result is shown in Fig. 27. The maximum power output of 5.14 mW occurred at point P in the figure when V_L was 0.25 volt and R_L was 12.2 ohms.

An analysis of the result from the load characteristic was made. The potential profile of an idealized model of a thermionic converter had been shown in Fig 2 (b). It was assumed that the collisions and space charge were completely eliminated. The emitter current density J_E increases exponentially as V_L decreases according to the equation:

$$J_E = J_{ES} \exp \left[(\phi_E - \phi_C - V_L)/kT_E \right] \qquad (3)$$

where J_{ES} is the saturated emitter current density and k is the Boltzmann constant (20). The natural logarithm of Eqn. 3 is

$$\ln J_E = \ln J_{ES} + (\phi_E - \phi_C - V_L)/kT_E \qquad (4)$$

The plot of $\ln J_E$ against $(\phi_E - \phi_C - V_L)$ would give a straight line with a slope of $\frac{1}{kT_E}$. For the emitter temperature of 1250° K the slope would be 9.30.

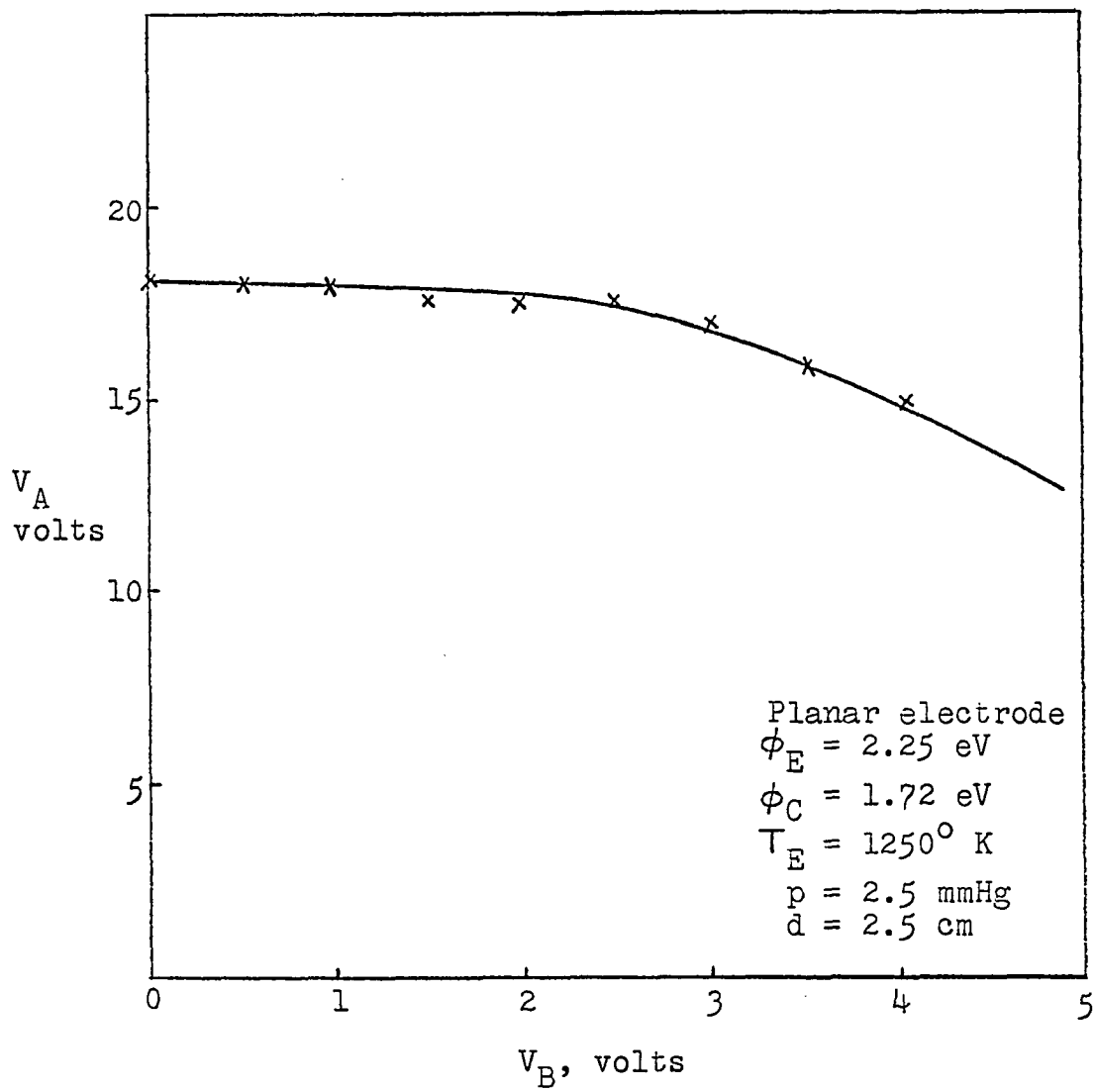


Fig. 26. Variation of auxiliary anode voltage with bias voltage

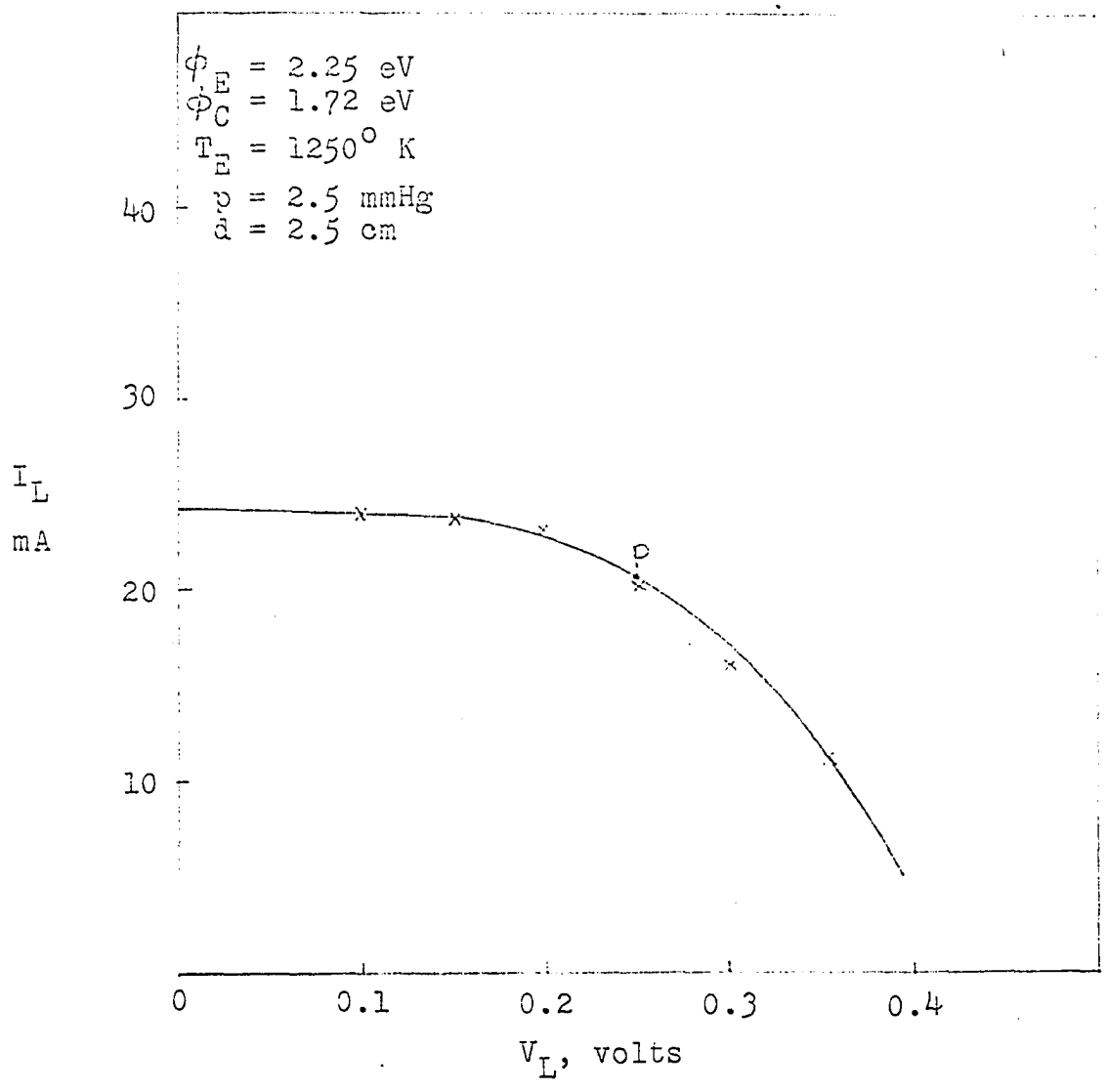


Fig. 27. Planar electrode converter load characteristics

To compare the experimental result with the preceding discussion, the output current density J, obtained from the experiment, is assumed to be equal to the emitter emission J_E. Fig. 28 shows the plot of log J against $(\phi_E - \phi_C - V_L)$. The slope of the lower part of the curve was computed to be 13.10. The deviation from the theoretical value is due to the space charge and the collector back emission which were neglected in the ideal converter. The saturated current part of the curve resulted from the effect of space charge which occurred in the actual converter.

Similar experiments were performed on the cylindrical electrode converter. A converter having an emitter work function of 1.85 eV and a collector work function of 1.21eV and emitter-collector spacing of 2.5 mm was constructed. The device could be operated in the power mode due to the sufficiently large difference in the work functions of emitter and collector. Experiments were performed to determine the effect of emitter temperature on the cost of space charge neutralization and the results are shown in Figs. 29 and 30. The operation at 1250° K gave better results than at 1200° K. Further increasing the emitter temperature gives larger radiation loss and probable short circuit between the electrodes. It was also found from this experiment that the cost of space charge neutralization does not improve much in the present method of collector cooling.

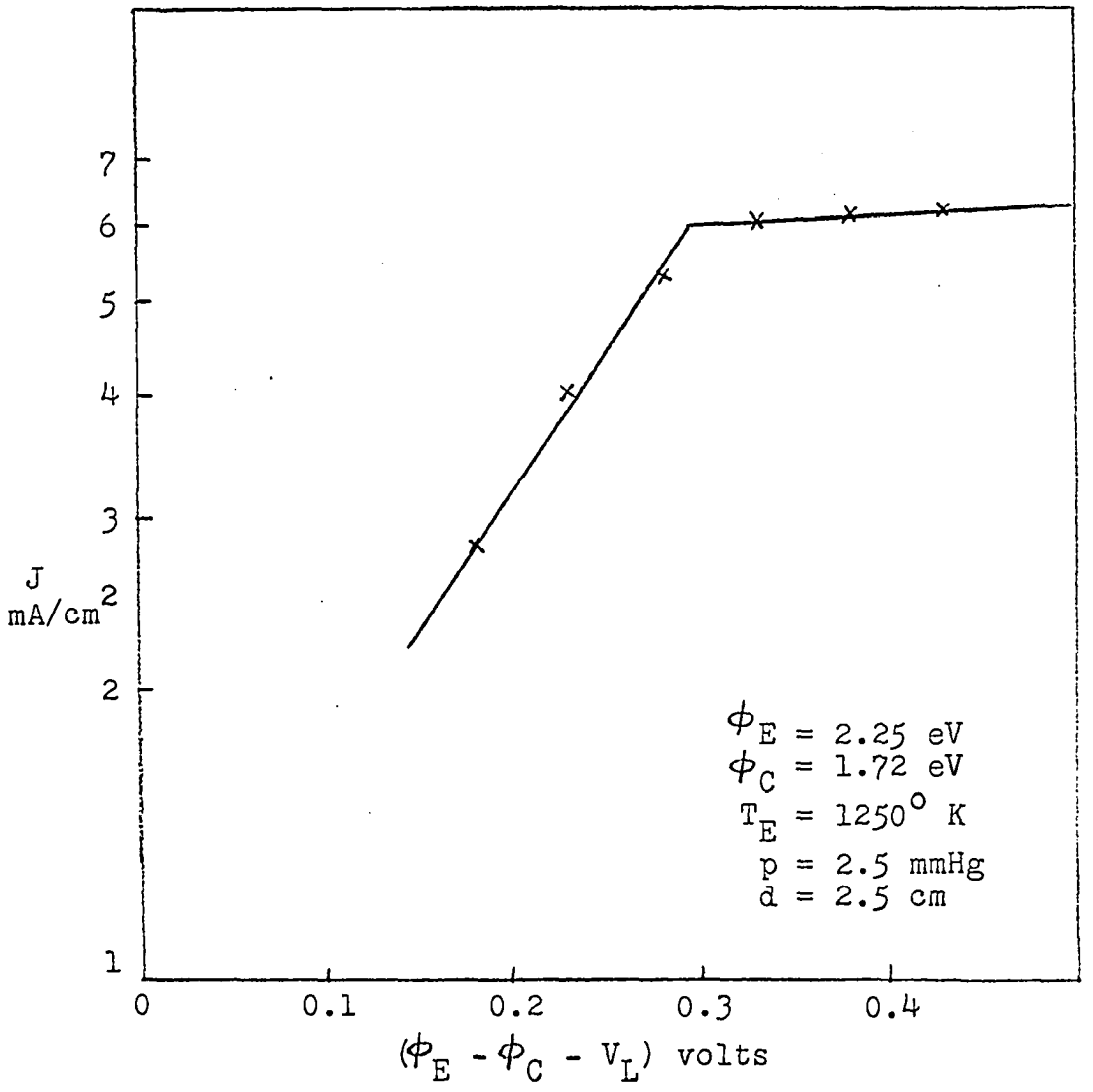


Fig. 28. Planar converter output current density vs. $(\phi_E - \phi_C - V_L)$

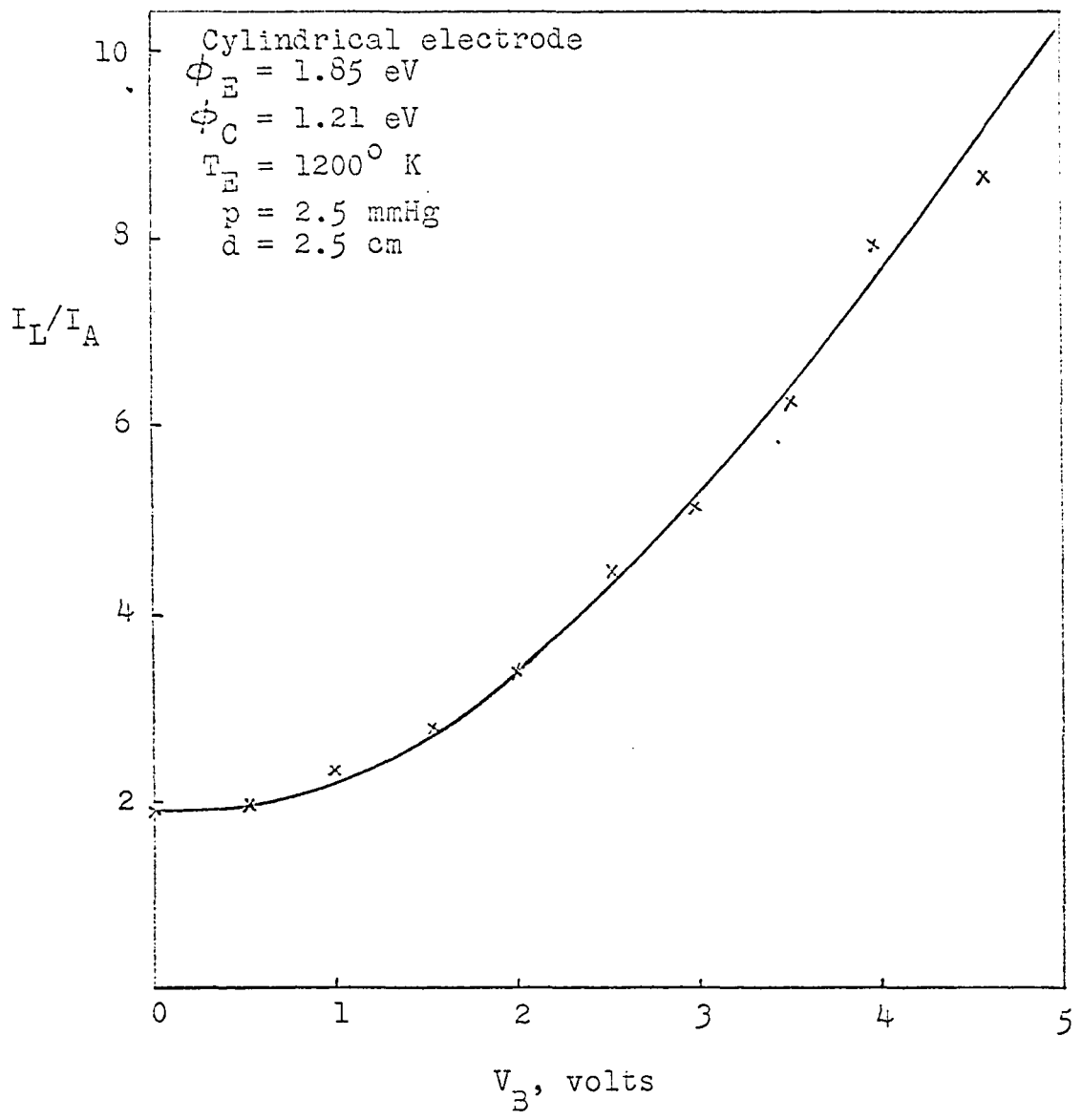


Fig. 29. Ratio of load current to auxiliary anode current vs. bias voltage at 1200° K

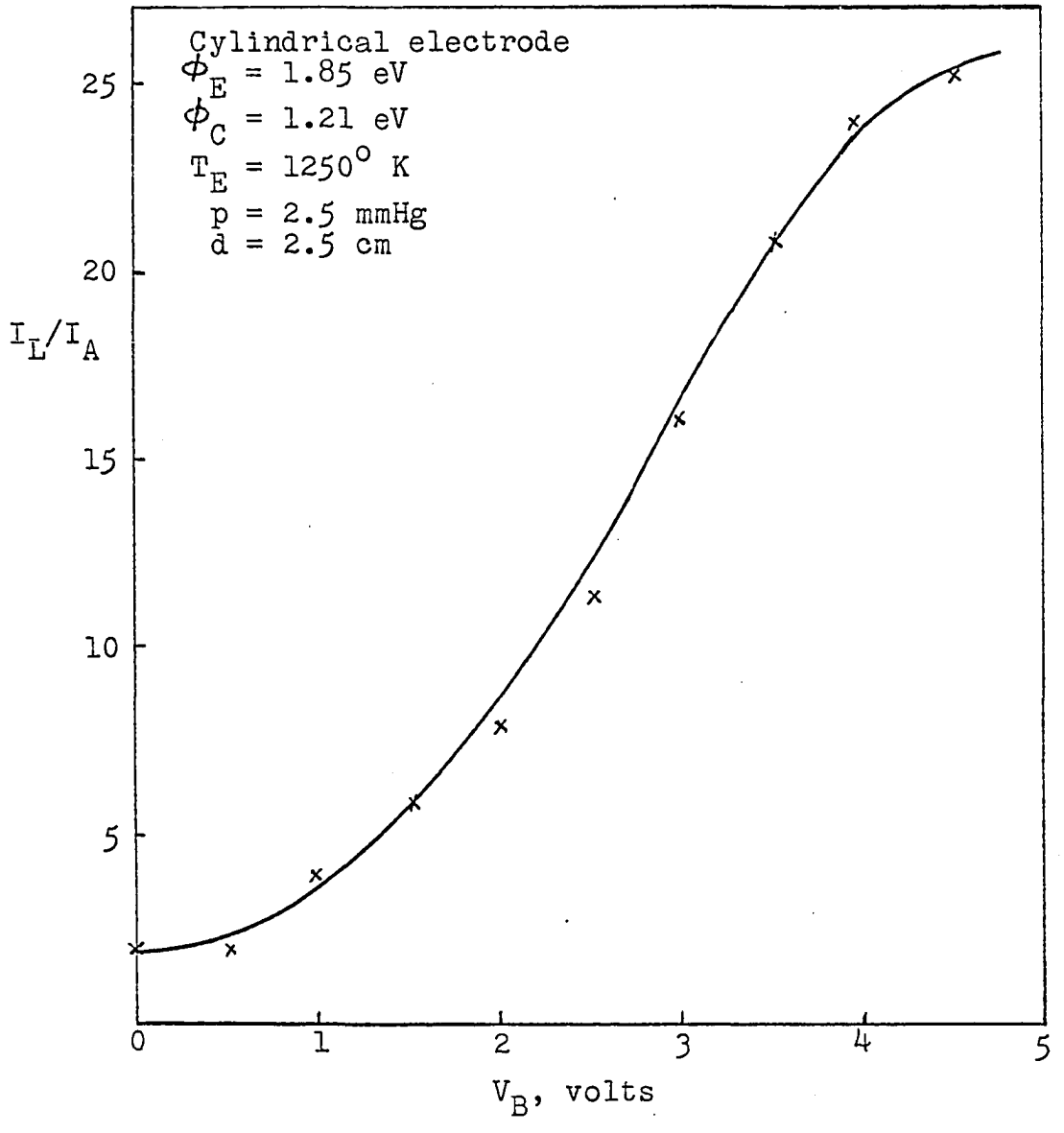


Fig. 30. Ratio of load current to auxiliary anode current versus bias voltage at 1250° K

The relation between the auxiliary voltage and the bias voltage is shown in Fig. 31. The same conclusion as in the planar converter can be drawn; the cost of space charge neutralization decreases as the bias voltage increases.

Another set of data was taken to study the load characteristics and the result was plotted in Fig. 32. A higher load current was obtained when the collector was cooled. The maximum power output occurred at point P on Fig. 32 when V_L was 0.4 volts and R_L was 18.1 ohms. The power output was then plotted against output voltage as shown in Fig. 33. The maximum power output of 8.6 mW was obtained.

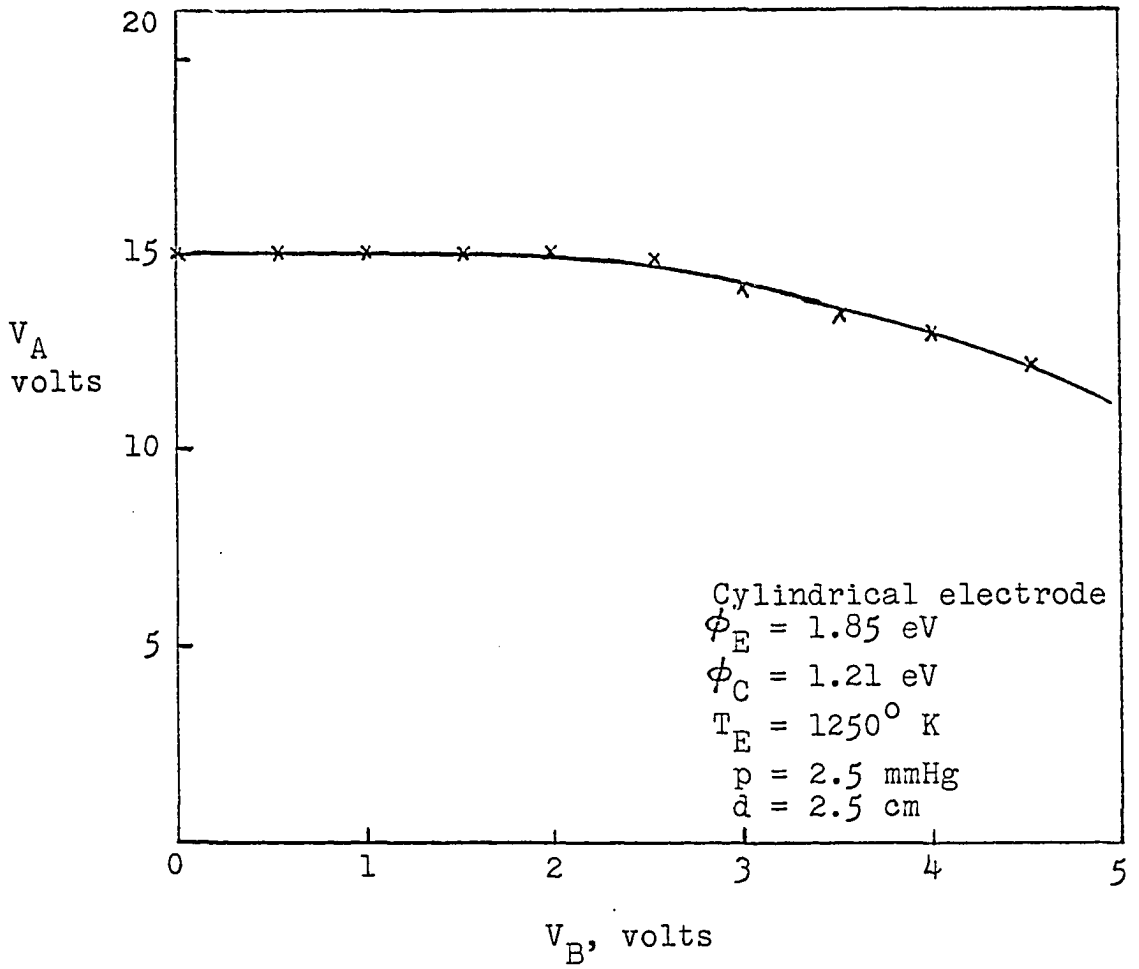


Fig. 31. Variation of auxiliary anode voltage with bias voltage

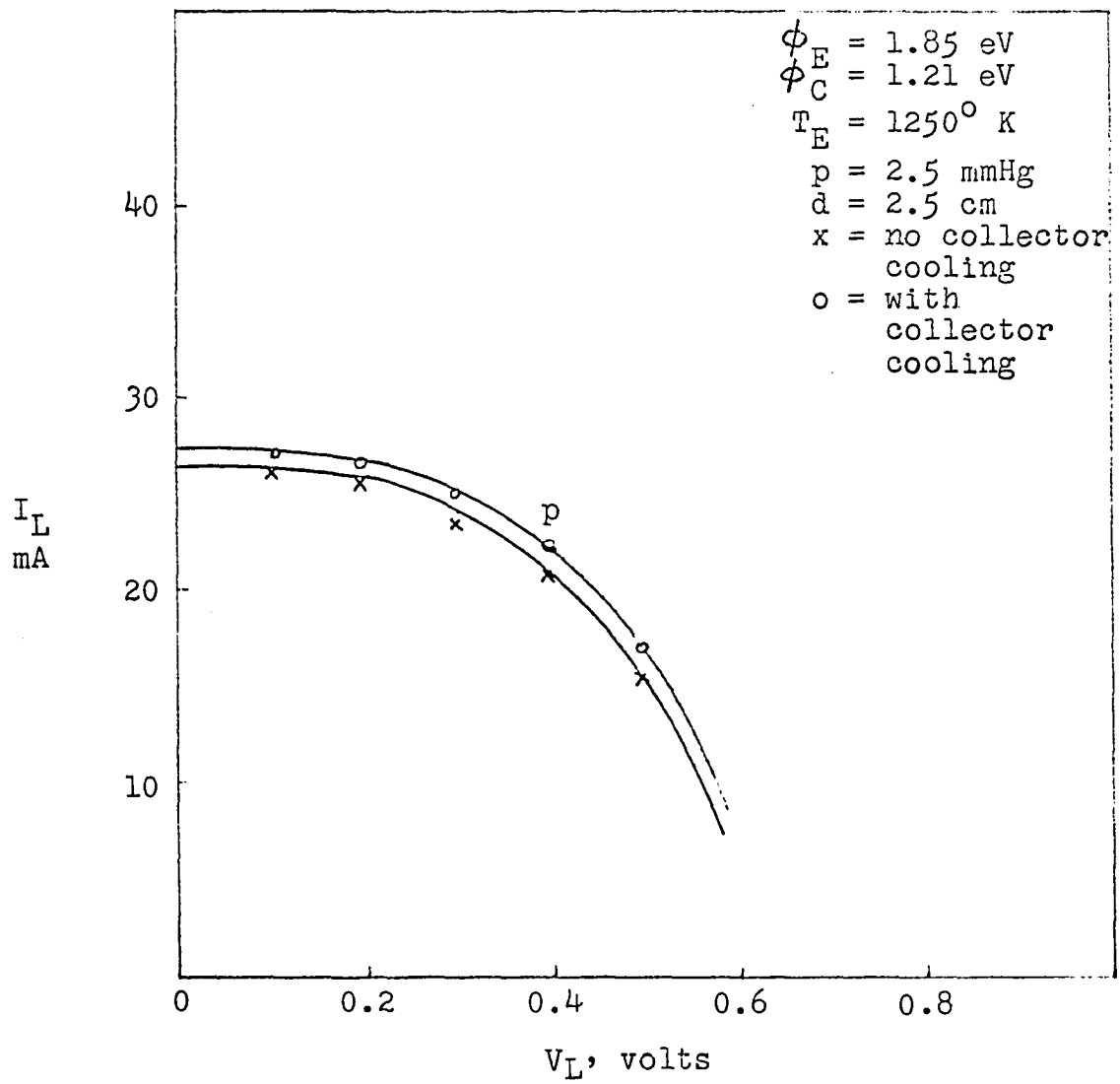


Fig. 32. Cylindrical electrode converter load characteristics

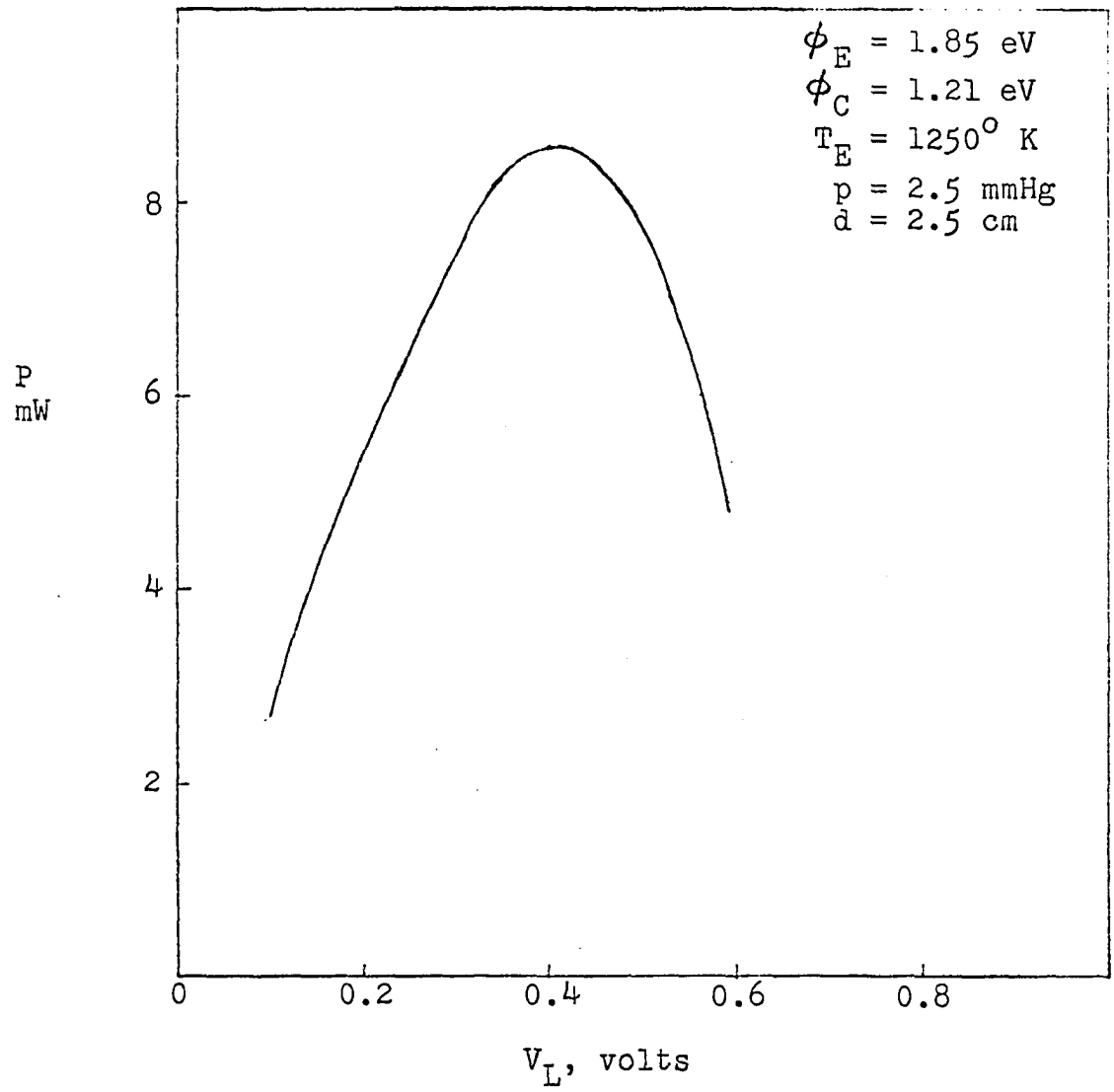


Fig. 33. Output power as a function of output voltage of cylindrical electrode converter

SUMMARY

The design, fabrication and testing of the Gabor type auxiliary discharge thermionic converter are described. The cost of space charge neutralization was found to be improved in the cylindrical electrode converter. By making the collector surface area larger than the emitter surface area the probability of an emitted electron returning to the emitter was reduced. There is probably an optimum ratio of collector surface area to emitter surface area. The system can be operated in the power mode as soon as the collector work function is sufficiently lower than the emitter work function.

It is observed that after long periods of operation a deposition of emitter coating material occurs on the quartz plate surface. These deposits, which can build up on the surface, eventually result in emitter to collector short circuits. This must be eliminated in order to have a longer life of the device.

The efficiency of the system is very low. This is partly due to the high auxiliary power required to produce the positive ions. Therefore the selection of suitable filling gas is very important in an actual converter where the efficiency of the system is essential. It was found that the introduction of proper amounts of neon and argon into the

system to form a Penning mixture is not simple. It might be possible to select a single gas with low ionization potential.

A certain number of electrons are also emitted from the collector due to ineffective collector cooling. These electrons partially cancel the load current. Further studies of methods of collector cooling would be worthwhile.

Although the progress in this research has been encouraging, much work remains to make thermionic conversion devices useful as real system components.

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