TWO-COMPONENT PLASMA CONDUCTION

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Memorandum No. UCB/ERL M00/62

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ELECTRONICS RESEARCH LABORATORY

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Introduction

This experiment will investigate how the limitations of electron conduction in a vacuum are improved when a two-component plasma is introduced. It will also confirm the ionisation potential of argon to be about 16V. In addition, attempts will be made to confirm the theoretical predictions for single-component conduction (Child-Langmuir regime), i.e. experimentally determining the constant K and charge-to-mass ratio of the electron. Temperature-limited conduction will be researched as well.

Theory

For the experiment, a cylindrical diode is constructed using an **884 gas triode** wired as shown in the schematic on the next page:

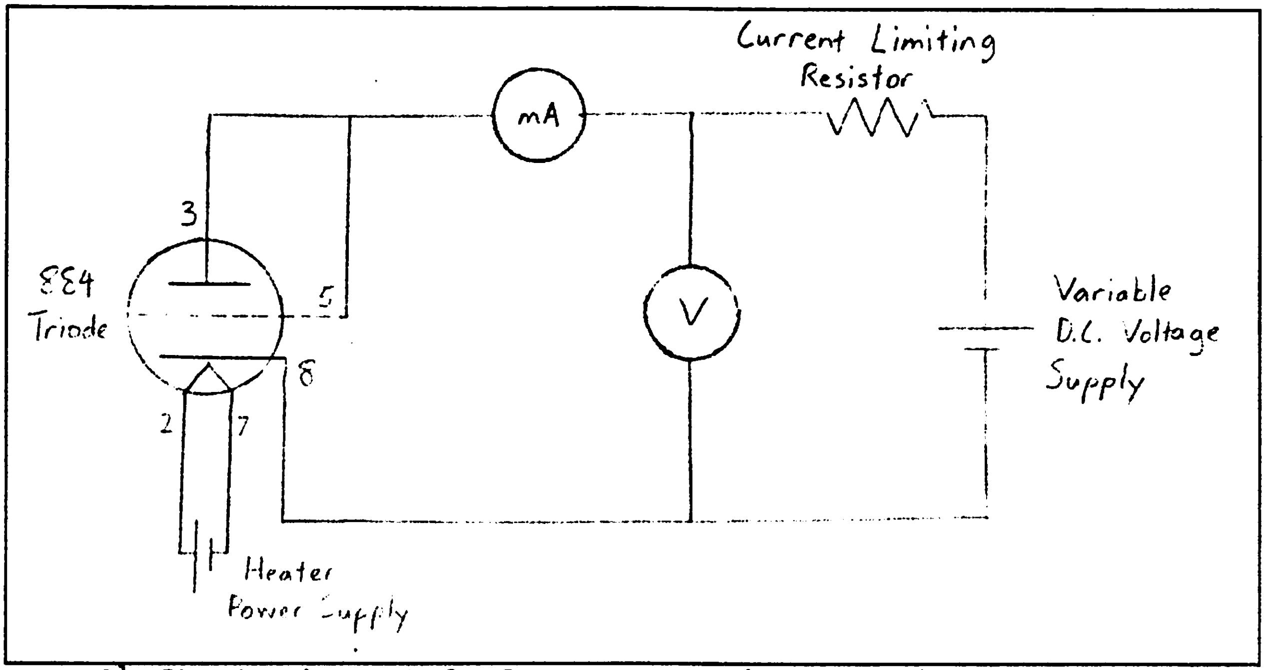

Figure 1[1]: Circuit schematic for 2-component plasma conduction

In a vacuum diode, electrons are 'boiled' off a hot **cathode** (**pin 8**), at potential zero, and accelerated across a gap to the **anode** (**pin 3**), which is held at a positive potential V. The cloud of moving electrons within the gap, called **space charge**, quickly builds up to the point where it reduces the field at the surface of the cathode to zero (**Fig. 3**). From then on a steady current I flows between the plates. The tube contains a small amount of argon gas which has no effect on the current at low applied voltage between the anode and the cathode. In this regime of operation, the **Child-Langmuir law** relates the current and voltage:

$$I = KV^{\frac{3}{2}}$$

where **K** is a constant of proportionality which depends on the geometry of the diode, and is given by

$$K = \frac{8\pi l \epsilon_0}{9 r_b \beta^2}\left(\frac{2e}{m_e}\right)^{\frac{1}{2}}$$

where ϵ_0 is the permittivity of free space, $\mathbf{r_b}$ is the anode radius (**Fig. 2**), and β^2 is the geometric factor for space-charge in cylindrical diodes (**Fig. 3**), for a given $\mathbf{r_b/r_a}$. The radius $\mathbf{r_a}$ is defined in **Fig. 2**, as well as $\mathbf{r_b}$ and ***l***.

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[1] Reproduced from laboratory write-up by Prof. Emeritus Igor Alexeff, EE Department, Ferris Hall at the University of Tennessee.

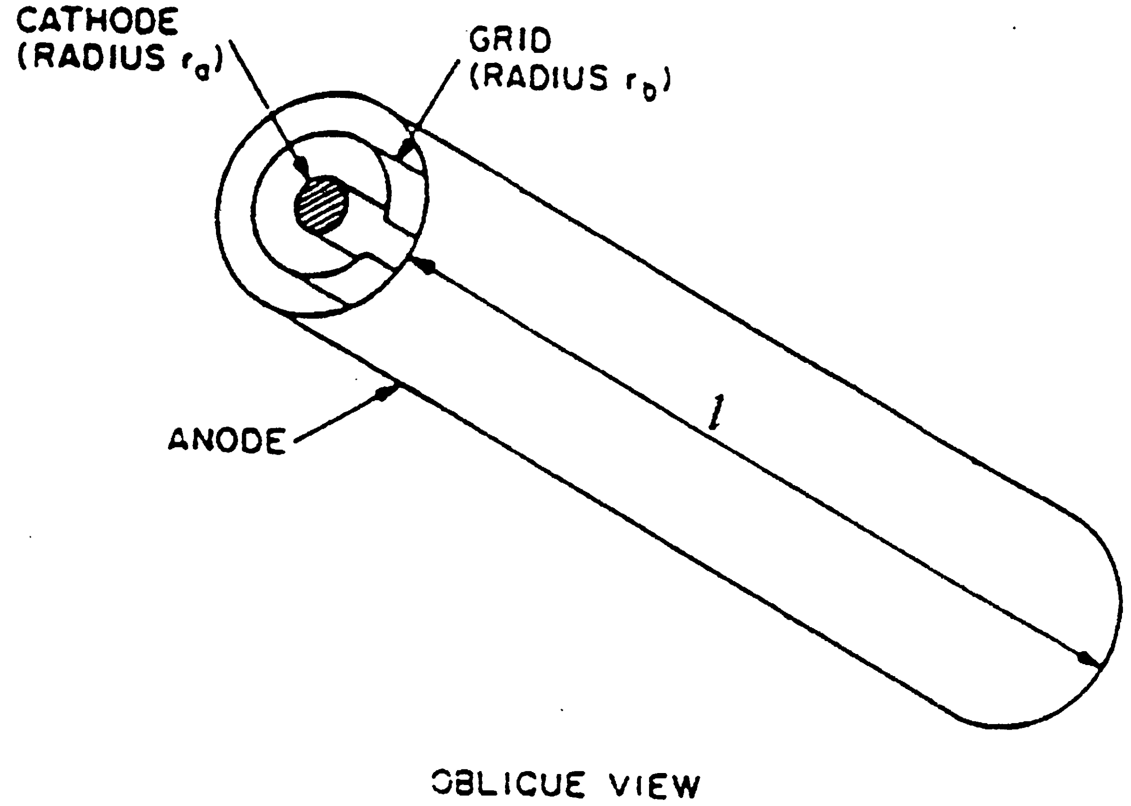

FIGURE 2

(See footnote[2])

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[2] Reproduced from laboratory write-up by Prof. Emeritus Igor Alexeff, EE Department, Ferris Hall at the University of Tennessee.

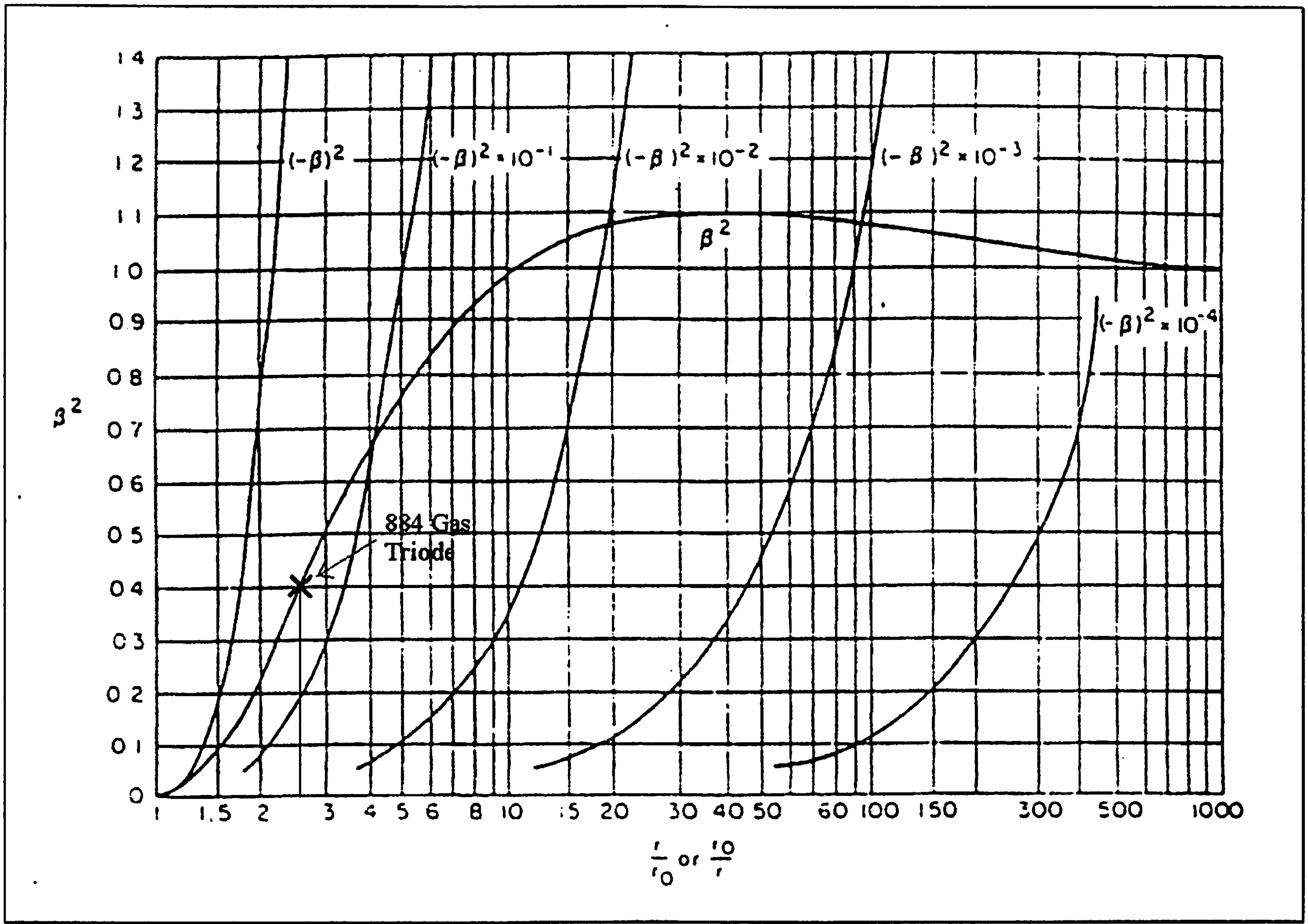

Figure 3[3]: Geometric factor for space-charge equation for cylinders (**r_0** = radius of cathode (r_a), **r** = radius of anode (r_b))

Note: The values for $-\beta$ refer to the case where the outer conductor is the emitter

Table 1: Dimensions of cylindrical diode and geometric factor	
r_b	1.5×10^{-3} m
r_a	6.0×10^{-4} m
l	2.0×10^{-2} m
β^2	0.4

As the applied voltage increases, the current will increase until at a certain voltage, defined as the **ionisation potential**, the argon gas begins to become ionised by energetic electrons. At this point, positive ions exist inside the tube and neutralises the space charge. This will then give a dramatic rise in current for a further increase in voltage (**Fig. 4**). Part of this experiment is to confirm that the ionisation potential for argon is about **16 volts**.

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[3] Reproduced from text "Gaseous Conductors" by J. D. Cobins, Pg 126, Dover Publications Inc., New York, 1958

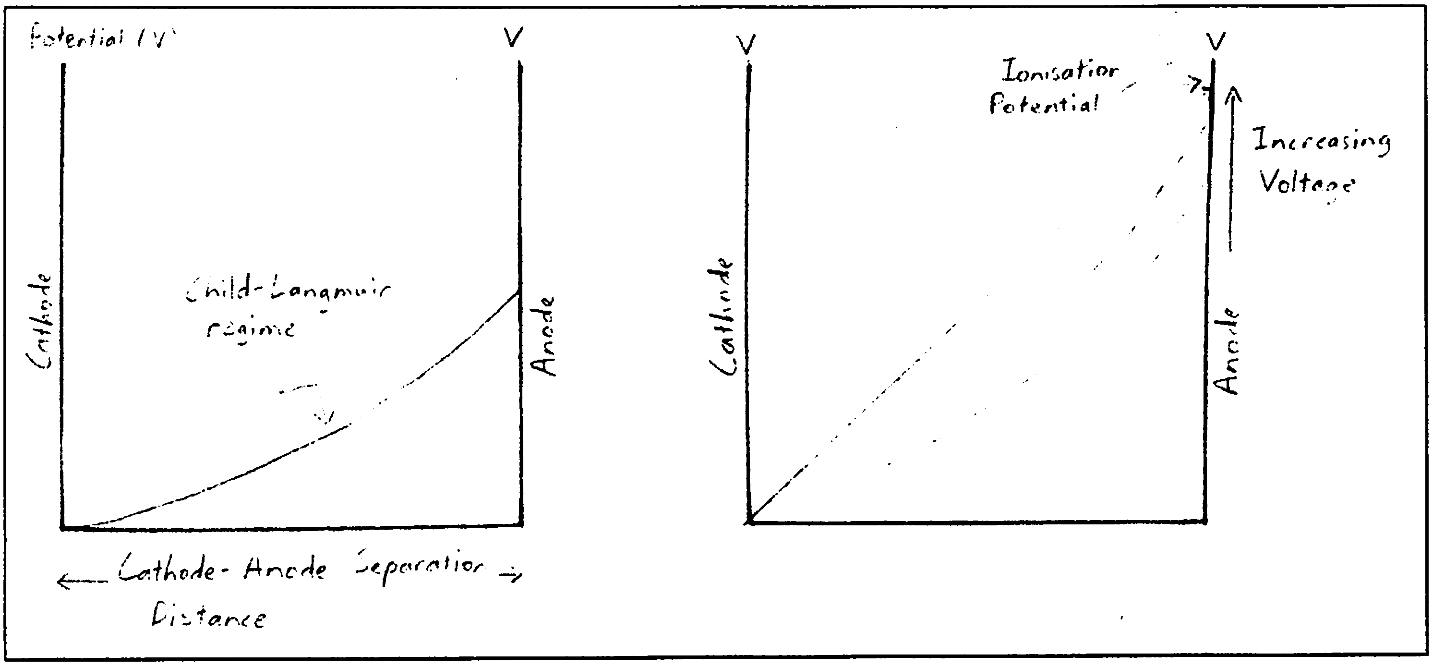


Figure 4: Potential Profile between Cathode and Anode

Experimental Procedure and Data Collection

Using the circuit as shown in Fig. 1, the heater filament of the gas triode and the entire circuit were connected to separate power supplies. The power through the heater was first set at its operating voltage and current of 7.0V and 0.6A respectively.

After this initial setup, the voltage of the power supply to the circuit was varied from 0 to approximately 20V, where the current through the milliammeter approached 100mA. Precaution was taken to not exceed 100mA, as it would burn the tube out. The current and voltage were then recorded at 1-volt intervals, along with the voltage at which the current rose rapidly. This procedure was also repeated by varying the voltage supplied to the heater, to a lower value of 5.0V. (See **Table 2**)

Power into Heater: 4.2W (7.0V, 0.6A)	
Voltage (V)	**Current (A)**
1	0.002
2	0.0035
3	0.0045
4	0.006
5	0.0075
6	0.009
7	0.011
8	0.013
9	0.0155
10	0.017
11	0.019
12	0.0205
13	0.023
14	0.025
15	0.027
16	0.0325
17	0.044
18	0.059
19	0.097

Power into Heater: 2.3W (5.0V, 0.45A)	
Voltage (V)	**Current (A)**
1	0.002
2	0.003
3	0.004
4	0.005
5	0.0065
6	0.0085
7	0.01
8	0.012
9	0.014
10	0.016
11	0.018
12	0.02
13	0.0215
14	0.0235
15	0.0255
16	0.028
17	0.036
18	0.046
19	0.063

Table 2: Voltage and corresponding current in 1V intervals

Data Analysis

The data collected was plotted on a logarithmic graph with current as a function of voltage. As you can see below, there are data points for each graph that correspond to abrupt increases in current when the ionisation potential was surpassed.

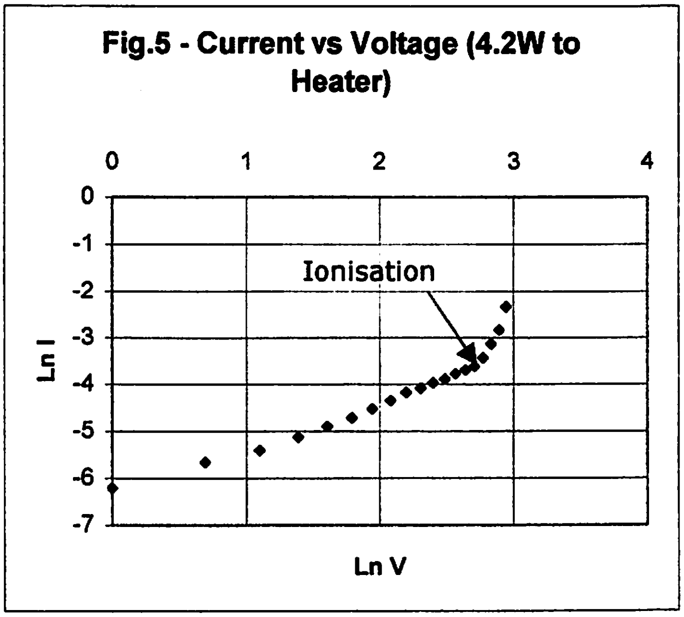


Fig.5 - Current vs Voltage (4.2W to Heater)

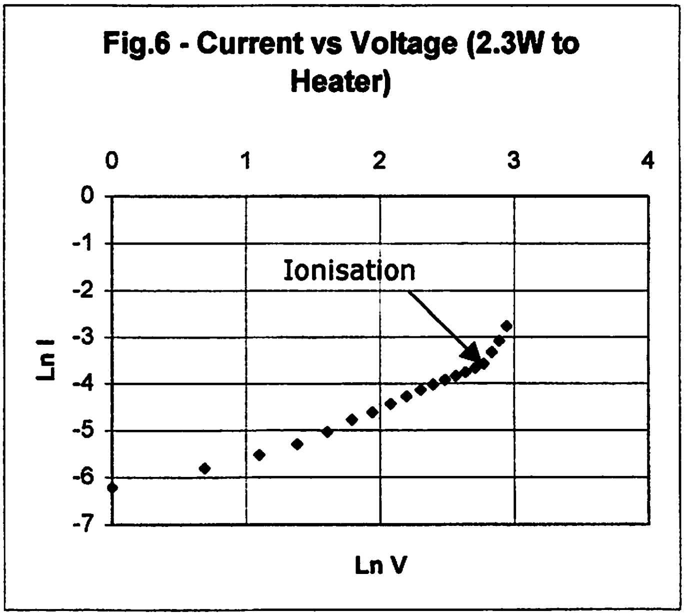


Fig.6 - Current vs Voltage (2.3W to Heater)

The ionisation potential was determined from both cases to be in the range:
$15V < V_i < 16V$
This is in good agreement with the known value of **15.76 volts** as the ionisation potential for argon gas.
A linear regression was then fitted to the data in the Child-Langmuir regime (ignoring the end data points where the ionisation potential was surpassed). The first few data values were also ignored because their errors were substantial, coming about from 'eye-balling' the scales on the meters. On the logarithmic plot, the Child-Langmuir equation, $\mathbf{I} = \mathbf{K}\mathbf{V}^{\alpha}$ appears as:
(taking the natural logarithm of both sides),

$$ln\mathbf{I} = \alpha ln\mathbf{V} + ln\mathbf{K}$$

By inspection, this equation is analogous to the slope-intercept equation of a line:

$$y = mx + c$$

where $y = ln\,\mathbf{I}$, $m = \alpha$, $x = ln\,\mathbf{V}$ and $c = ln\,\mathbf{K}$

Hence the axis-intercepts and gradients of the regression lines on the logarithmic plot provide information about the power relationship between current and voltage in the Child-Langmuir regime:

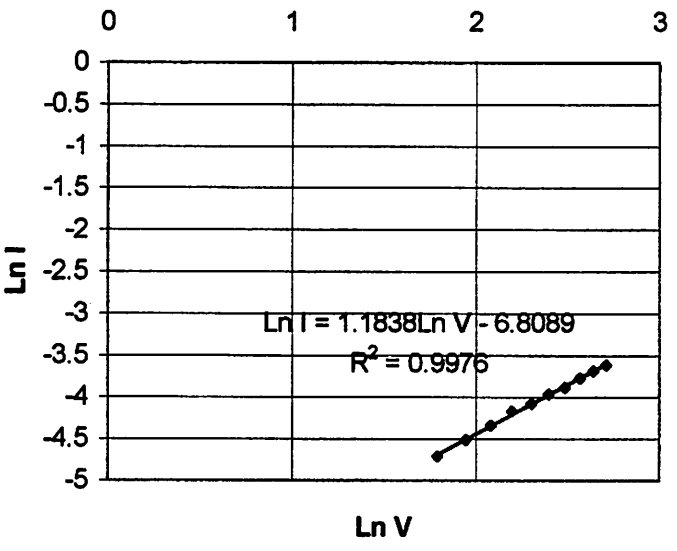


Fig. 7: I vs V in Child-Langmuir Regime (4.2W to Heater)

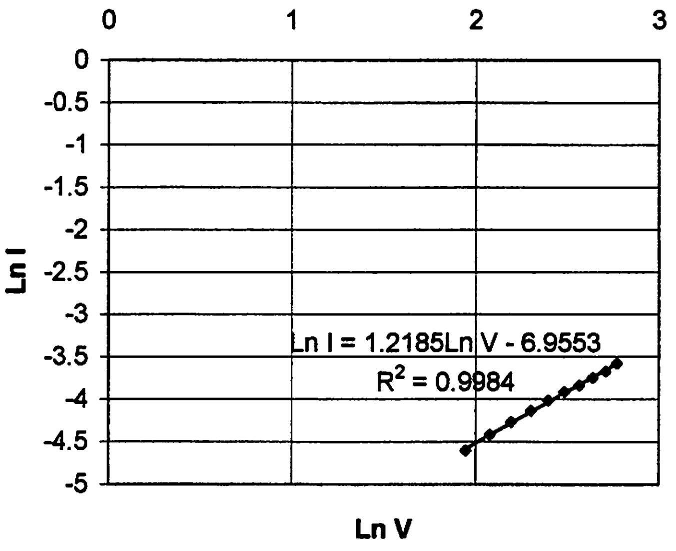
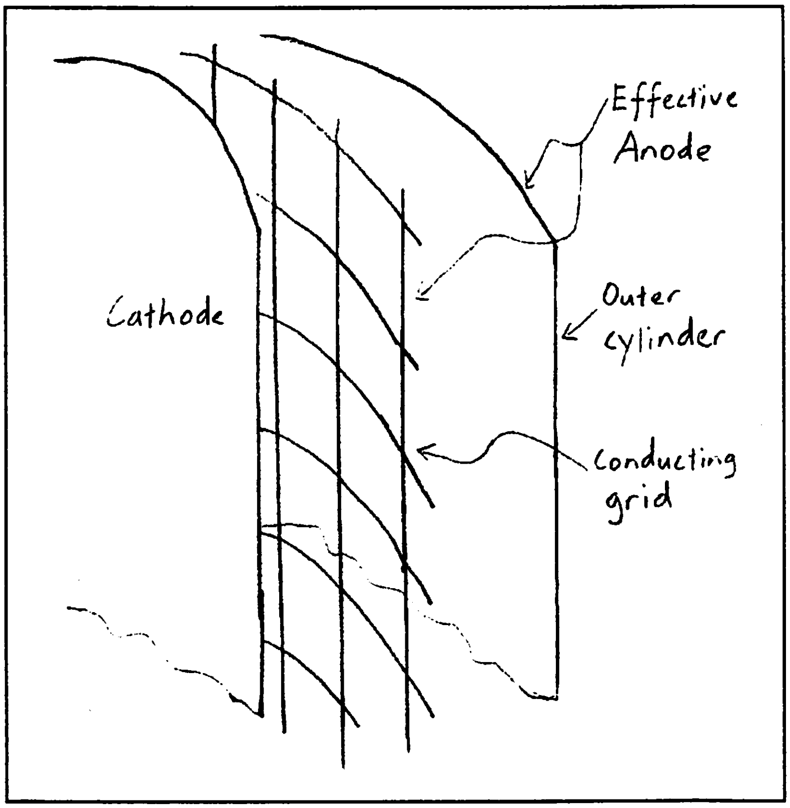


Fig. 8: I vs V in Child-Langmuir Regime (2.3W to Heater)

Reading off the regression equations:

Table 3	**Experimental**	***Theoretical***
α	1.20 ± 0.025	*1.5*
K	$1.03 \times 10^{-3} \pm 1.06 \times 10^{-4}$ AV$^{-3/2}$	*4.89×10^{-4} AV$^{-3/2}$*
e/m	$7.79 \times 10^{11} \pm 8.05 \times 10^{10}$ C kg^{-1}	*1.76×10^{11} C kg^{-1}*

The experimentally determined value of α does not agree with theory. This could be attributed to the fact that the vacuum tube is a gas triode, and the anode used was actually made up of 2 components: a **grid** (**pin 5**) and a concentric outer cylindrical conductor (**pin 3**).



⊂ **Figure 9**: Cutaway view of construction of cylindrical diode from 884 gas triode

The Child-Langmuir Law, $I = KV^{\frac{3}{2}}$ seems to only hold for both cathodes and anodes being plated, not composed of metallic grids. This inconsistency between experiment and theory invited further investigation into the experimentation. Instead of both **pins 3** and **5** being connected to the circuit at the same time, the experiment was repeated with **only one** of each connected.

Further Investigation

The power input to the heater was maintained at 4.2W (7.0V, 0.6A) and only the conducting **grid** (**pin 5**) was connected. The data obtained were as follows:

Grid Connected Only (Pin 5)

4.2W to Heater (7.0V, 0.6A)

Voltage (V)	**Current (A)**
1	0.002
2	0.003
3	0.0045
4	0.006
5	0.0075
6	0.009
7	0.011
8	0.013
9	0.0155
10	0.0175
11	0.019
12	0.021
13	0.023
14	0.0245
15	0.027
16	0.032
17	0.038
18	0.047
19	0.056
20	0.069

Table 4: Voltage and corresponding current in 1V intervals

Fig. 10: Grid Connected Only (Pin 5) - I vs V

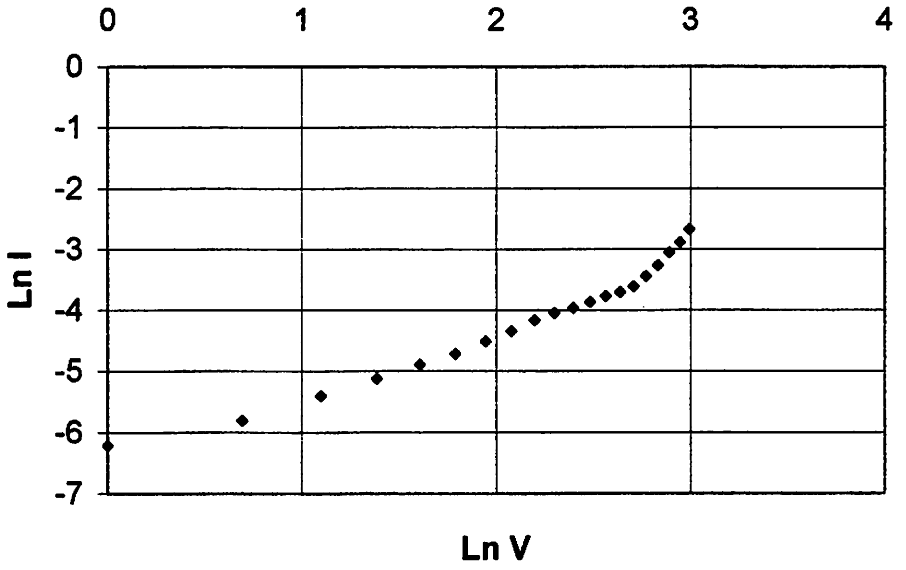


Fig. 11: Grid Connected Only (Pin 5) - I vs V in single-component electron conduction region

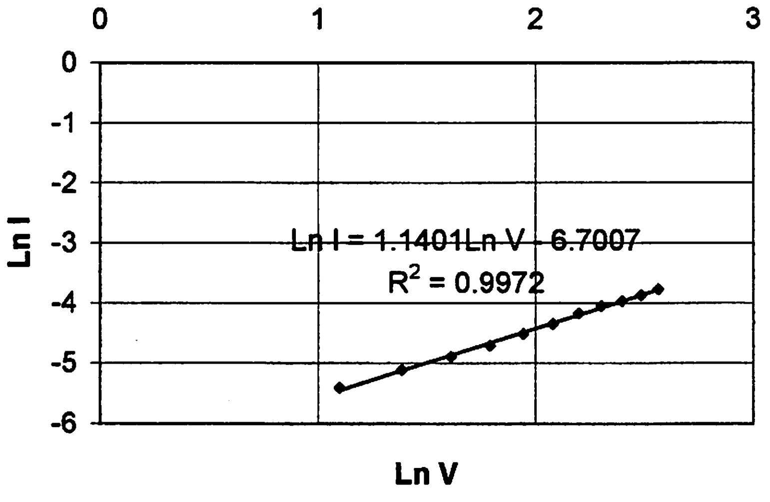


Table 5: Results

15V < V_i < 16V	
α	1.14
K	1.23×10^{-3} AV$^{-1.14}$

Hence, a relationship can be obtained between current and voltage for single-component electron conduction between a plated inner cylindrical cathode and an outer grid:

$$I = KV^{1.14}$$

where K = 1.23×10^{-3} AV$^{-1.14}$

Next, only the outer concentric plated cylinder (**pin 3**) was connected and the experimental procedure repeated.

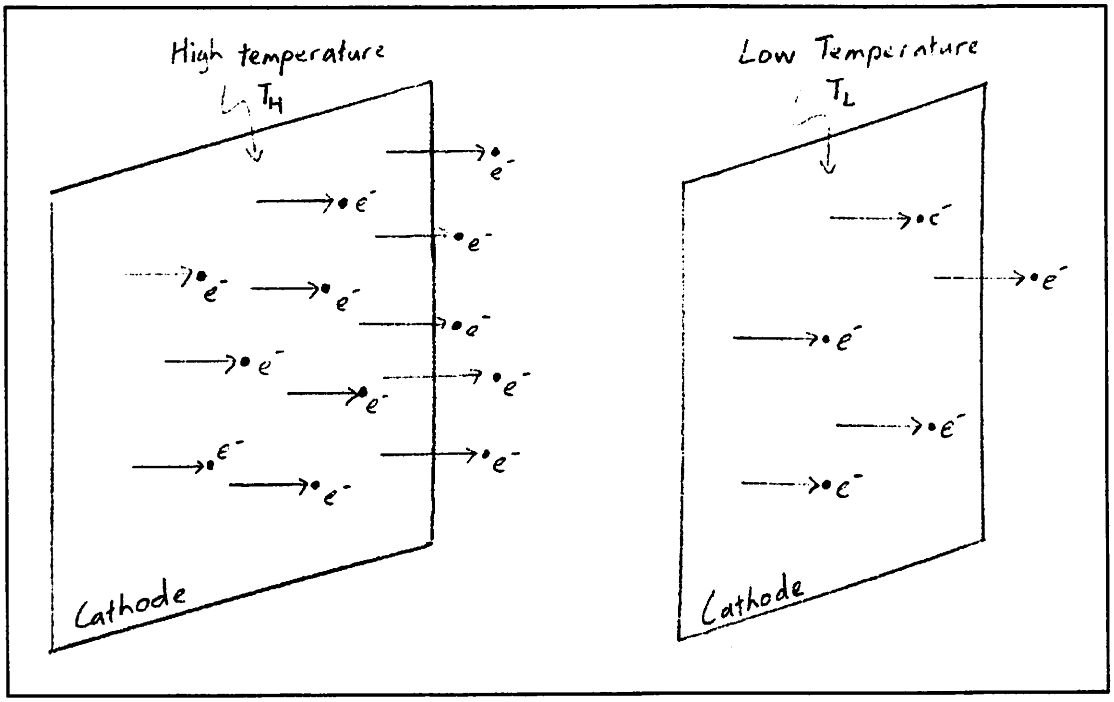
In this case, there was no simple relationship between current and voltage. As the voltage was increased from 0 to ~22V, no current flowed through the tube. At around 22.5V, there was an abrupt and sudden increase in current to 31.5 mA. As more power was supplied to the circuit, the voltage across the tube *decreased* and dropped towards ~15V, while the current continued to rise past 100mA!

Volts (V)	0 → 22	➲	22.5	➲	→ 15
Current (mA)	0		31.5		→ 100

As yet, this phenomenon is not clearly understood and more research is needed in order to explain such an observation.

Temperature-Limited Conduction

In the previous sections, there was much analysis on space-charge limited conduction. There is also a different phenomenon where the conduction is not limited to space-charge between the cathode and the anode, but to the temperature of the heated cathode. When the power supplied to the heater and thus its temperature, is diminished a sufficient amount, the conduction process will strongly become dependent on the temperature. In this regime of operation the electrons "boiled" off are all now being drawn off towards the anode, and so the current and thus the amount of electrons flowing from the cathode depends on how the hot cathode can 'boil' off electrons.



➲ Figure 12: The high temperature dependence on electron current.

To test the temperature-limited conduction regime, the voltage to the heater was set down to 3.0V and the experimental procedure repeated:

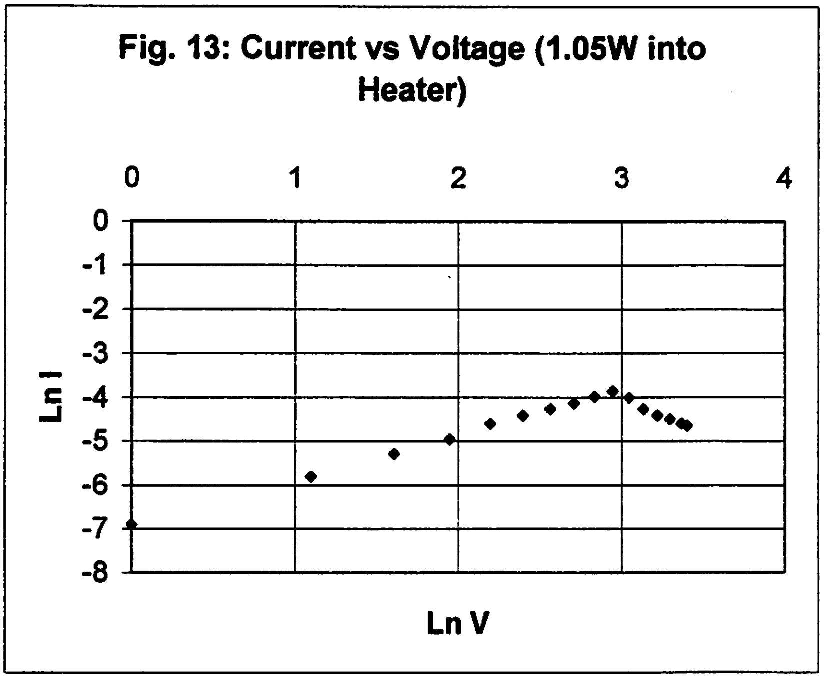


Fig. 13: Current vs Voltage (1.05W into Heater)

Power into Heater: 1.05W (3.0V, 0.35A)	
Voltage (V)	**Current (A)**
1	0.001
3	0.003
5	0.005
7	0.007
9	0.01
11	0.012
13	0.014
15	0.016
17	0.0185
19	0.021
21	0.018
23	0.014
25	0.012
27	0.011
29	0.01
30	0.0095

Table 6: Voltage and corresponding current in 1V intervals

As can be seen from the plot above, there is no well-behaved relation between current and voltage. Past what seems to be a 'critical' potential of ~19V, the current begins to *decrease*! In this region, the differential rate of change of current with respect to voltage is *negative*: $\frac{dI}{dV} < 0$

Yet again, there has been no conclusive explanation found for this occurrence.

Conclusion

Based on the experiment write-up by Prof. Emeritus Alexeff of the University of Tennessee, this research endeavour investigated how space-charge limited conduction in a vacuum are improved when a two-component plasma is introduced. Although it confirmed the ionisation potential of argon to approximately 16V, there were discrepancies with the theoretical predictions for single-component conduction, in the Child-Langmuir regime. It was hypothesised that this could be attributed to the structure of the gas triode containing a metal grid as part of the anode instead of just a plated surface. Modifications to the experimentation led to unusual observations that are currently not understood. Temperature-limited conduction was also explored, but this led again to peculiar observations that inferred a critical potential that if exceeded, caused a *decrease* in current flow.

Acknowledgement

This research was based on the laboratory write-up written by Prof. Emeritus of the Electrical Engineering Department, Ferris Hall, of the University of Tennessee.
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