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EXPERIMENTAL DETERMINATION OF THE ELECTRICAL CONDUCTIVITY OF NOBLE GAS-ALKALI METAL PLASMAS

by

Frank C. Halstead
Eugene L. Larson

S.M.,E.A.A.   Course XVI   August 1963

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by

FRANK C. HALSTEAD

S.B., United States Naval Academy (1951)

EUGENE L. LARSON.

S.B., United States Naval Academy (1957)

Submitted in Partial Fulfillment
of the Requirements for the
Degrees of Master of Science and
Engineer of Aeronautics and Astronautics.

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 1963

Signature of Authors _____

_____
Department of Aeronautics & Astronautics
August 1963

Certified by _____

_____
Thesis Supervisor

Accepted by _____
Chairman, Departmental Committee on Graduate Students

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CONDUCTIVITY OF NOBLE GAS-ALKALI METAL PLASMAS

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Frank C. Halstead
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Submitted to the Department of Aeronautics and
Astronautics on August 19, 1963 in partial fulfillment of the
requirements for the degrees of Master of Science and Engineer
of Aeronautics and Astronautics.

ABSTRACT

The electrical conductivity of an argon-potassium plasma
has been successfully measured. The experimental results
indicate that ~~the theory that~~ the temperature of the electrons
is elevated above the temperature of the plasma. It is
shown that the two temperature theory is correct as a first
estimate of the conductivity of the plasma. Joule heating,
conduction and radiation heat losses, varying collision cross
sections, thermionic emission, and non Maxwellian electron
energy distribution cause the theory to differ from the experi-
mental results. A successful method of measuring the electron
temperature in the plasma has been devised using simple
experimental apparatus, procedure and theory. This electron
temperature measurement definitely proves the two temperature
plasma theory.

Thesis Supervisor: Myron A. Hoffman

Title: Assistant Professor of Aeronautics and Astronautics

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The graduate work for which this thesis is a partial requirement was performed while the authors were assigned by the United States Air Force Institute of Technology, Air University, for graduate training at the Massachusetts Institute of Technology.

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LIST OF SYMBOLS

c	Speed of light
e	Electronic charge
h	Planck's constant
m	Mass
n or N	Particle density
j or J	Current density
k	Boltzman constant
S	Elastic collision cross section
T	Temperature

α	Defined on page 6
ℓ	Emissivity
ϵ_i	Ionization energy
ϵ_0	Permittivity of free space
ϵ	Mean thermal energy
λ	Wavelength
σ	Conductivity

Subscripts

A	Argon atom
a	Alkali metal atom
e or E	Electron
G	Plasma
K	Potassium atom
o	Inert gas atom

CHAPTER 1

INTRODUCTION

The future design of magnetogasdynamic generators and accelerators for space power and propulsion, as well as for many other applications, might make use of the high conductivity of a plasma consisting of a neutral noble gas seeded with an alkali metal. The plasma provides a high electrical conductivity when subjected to an external electric field, as the electrons in the plasma have a temperature which is above the mean plasma temperature.

To test the theory of the two temperature plasma assumed by Kerrebrock [4] and to extend the experimental work of Dethlefsen and Drouet [2], the following experiment has been conducted to determine the correlation between the theoretical and experimental values of conductivity of the seeded gas. Use was made of existing experimental equipment, with changes and improvements which hopefully have yielded more accurate results. Many problems with the existing experimental equipment have been solved, but there remain many more problems which must be resolved before highly refined data can be obtained.

CHAPTER 2

THEORY

Electrons will gain energy in excess of the mean molecular energy when diffusing through a gas in the region of an electric field if the thermal coupling of the electrons with the molecules is weak. The characteristic of weak coupling exists in monatomic gases if the electrons can exchange energy only with the translational degrees of freedom of the atoms. In a plasma consisting of a neutral gas seeded with an alkali metal at a temperature below $3,000^{\circ}K$ and one atmosphere pressure, the electron-atom collisions usually dominate the coulomb collisions. Thus the conductivity is sensitive to the degree of ionization. The energy transfer per collision between electrons is high compared to the energy transfer between electrons and atoms or ions since the electron mass is much less than the mass of the atoms and ions. If the electron collision frequency is of the same general magnitude as the frequency of electron-atom and electron-ion collisions, the electrons will demonstrate a Maxwellian energy distribution. The effective temperature of this distribution may be considerably higher than the plasma temperature since the electrons gain energy from the electric field. The electronic energy distribution is nearly Maxwellian for electron concentra-

tions greater than 10^6 cm^{-3} (Reference 4). If the ionization process is dominated by electron-atom collisions, the degree of ionization is governed by the electron temperature.

A brief outline of the theory in Reference 4 will be presented for later comparison with the experimental results.

The increase in electron temperature is given by

$$\frac{\epsilon_e}{\epsilon_a} = 1 + \frac{m_a}{\delta \epsilon_a} \left(\frac{j}{e n_e}\right)^2 \qquad (2.1)$$

which is derived from an energy balance for the diffusing electrons.

ϵ = $3/2$ kT = mean energy

k = Boltzmann constant

T_a = gas temperature

T_e = electron temperature

m_a = mass of atom

δ = collision constant

e = electron charge

j = current density

n_e = electron concentration

The electron concentration is assumed to be related to the electron temperature (as well as total concentration and the ionization energy) by the Saha equation in the form

$$n_e^2 = \left(\frac{4\pi m_e}{3 h^2}\right)^{3/2} \epsilon_e^{3/2} e^{-\frac{3 \epsilon_i}{2 \epsilon_e}} (n_a - n_e) \qquad (2.2)$$

where

h = Plank's constant

ϵ_i = ionization energy

n_a = concentration of ionizable species

and the electrons are assumed to have a Maxwellian distribution as previously stated.

These two equations can be solved for ϵ_e/ϵ_a and n_e/n_a as functions of ϵ_a, $p_a = n_a k T_a$, and j, which means the electron temperature and concentration depend on the state of the gas and the current density.

The conductivity for a mixture of an inert gas and an alkali metal is given approximately by

$$\frac{1}{\sigma} = \frac{m_e}{e^2 n_e}\left(\frac{8 k T_e}{\pi m_e}\right)^{\frac{1}{2}}\left[n_0 S_0 + (n_a - n_e) S_a\right]$$

$$+ 0.0176 \frac{e^2}{m_e \epsilon_0^2}\left(\frac{m_e}{2 k T_e}\right)^{3/2} \log \Lambda$$

(2.3)

with

n_0 = concentration of inert gas

n_a = concentration of alkali metal

σ = conductivity

m_e = electron mass

S_0 = electronic cross sections for inert gas

S_a = electronic cross sections for alkali metal

where the first term represents the resistivity due to electron-atom collisions, and the second term is due to electron-ion collisions. For electron temperatures below 2500°K the effect of electron-ion collisions is theoretically on the order of 10 percent of the electron-atom collisions. The dependence of Te and n_e on j is reflected in σ , which also reflects the trends in n_e/n_a . At the lower temperatures even a small current density has an enormous influence on σ . Ohm's law for a plasma is highly non-linear since the conductivity is a function of the current density.
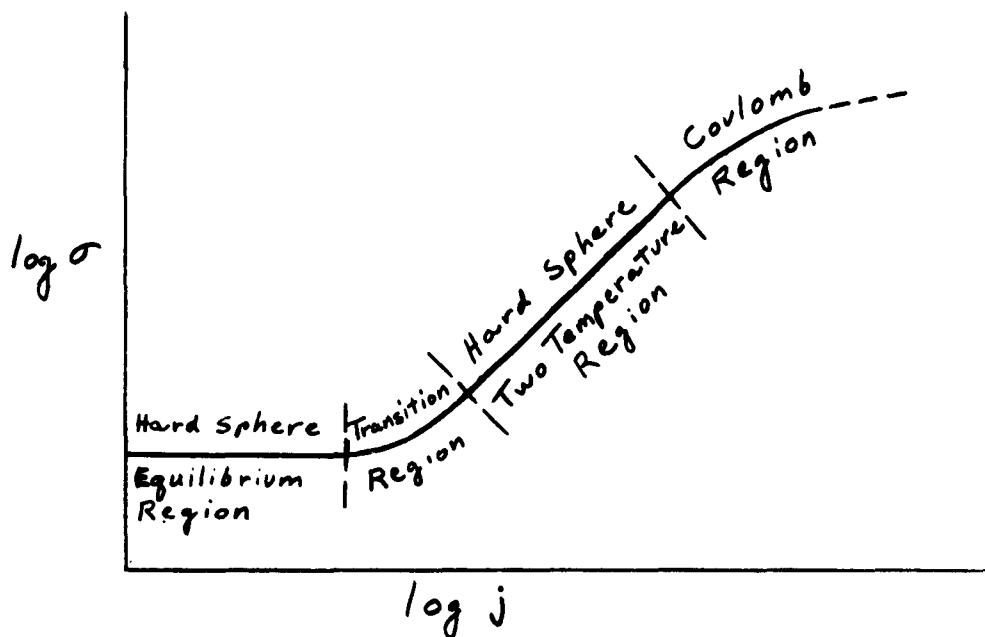
A graph of log σ vs. log j above shows that an approximation to the variation of σ with j in the hard sphere two temperature region is:

$$log\ \sigma\ =\ b + \alpha\ log\ j \qquad\qquad (2.4)$$

where b is a function of T_a and α is the slope of
the plot. Then $\sigma = j^{\alpha} e^{b(T_a)}$ and Ohm's law becomes

$$j = e^{\frac{b(T_a)}{1-\alpha}} E^{\frac{1}{1-\alpha}} \tag{2.5}$$

α depends only on ϵ_e/ϵ_a and ϵ_i/ϵ_a in the limit of the region
of interest. The figure above indicates the general relation
between conductivity and current density for a constant gas
temperature. In the hard sphere equilibrium region the current
remains essentially constant since there is negligible
ionization taking place. In the transition region ionizations
begin to occur in sufficient quantities to affect the curve.
The hard sphere two temperature region is of most interest
since it appears to be stable and obtainable. Above this
is the coulomb region which requires too much power input to
obtain a suitable output.

The theoretical curves of these equations are plotted on
Figures 8, 9 and 10. For these curves the following values
were used for an argon gas seeded with potassium:

$$S_A = 7 \times 10^{-17} \text{ cm}^2$$
$$S_K = 2.5 \times 10^{-14} \text{ cm}^2$$
$$\delta = 10$$
$$T_g = 1500^{\circ}K$$

δ must be regarded as a variable parameter when comparing
experimental results with theory. In the past δ has been
taken as 2, based on reasonable estimates as discussed in
Reference 4. However the value of 10 for δ seems to fit

the experimental data more accurately at $T_a = 1500^{\circ}K$. An increase in δ moves the j vs. σ plot to the right. With sufficient experimental data an accurate determination of δ can be made. The increase in δ can possibly be caused by radiation losses, and therefore it might be a function of temperature.

CHAPTER 3

EXPERIMENTAL APPARATUS

3.1 General

The experimental apparatus available to us was a heat exchanger, potassium boiler, power supplies and measuring equipment.

The counterflow heat exchanger is shown in Figure 1 and Illustration 1. It incorporates a plasma gun heating arc produced by AVCO (Type PG-040) capable of delivering 25 KW of power to the nitrogen. A separate motor-generator set delivers power to the arc. A tantalum tube carries the plasma flow through the heat exchanger. It is surrounded by a graphite tube and all hot parts are insulated with carbon batting and purged with nitrogen. The arc heats nitrogen gas which flows down the exchanger in the chamber between the tantalum tube and graphite tube and is exhausted. The heat is transferred to the plasma through the tantalum tube.

The plasma is formed by seeding argon with potassium. The argon is preheated in a molten lead both maintained at about $850^{\circ}C$ and then passes into the potassium boiler which is also heated to $850^{\circ}C$. The temperatures of the lead baths are determined by chromel-alumel thermocouples sealed in stainless steel, and read on Wheelco high precision potentio-

meters. The reference junction is kept at $0^{\circ}C$ in melting ice. The plasma temperature is measured by viewing the top end of the tantalum tube with a pyrometer, and applying previously determined corrections.

3.2 Boiler Assembly

The purpose of the boiler assembly was to inject the proper amount of potassium into the argon flow. For these experiments a potassium mole fraction range from 0.1 to 1.0 percent was desired.

The final boiler configuration is shown in Figure 4. It consists of a potassium chamber which is separated from the argon flow by a metering orifice. All parts of the boiler assembly, except the gasket are made of stainless steel.

The potassium flow was held constant by immersing the boiler in a lead bath and maintaining the lead temperature at $850^{\circ}C$ so that the potassium vapor pressure was sufficient to insure chocked flow through the orifice. For the lower mole fractions a .004 inch diameter orifice was used. A .006 inch diameter orifice was used for higher potassium flow rates. With a constant potassium flow the mole fraction was determined by the argon flow rate which was controlled by a flow meter.

Two boiler configurations were used during these experiments, but they differ only in the volume of the potassium chamber and in mechanical design. The original

boiler had a maximum capacity of 12 1/2 grams of potassium
(at 700°C). Twelve grams of potassium was insufficient when
running with a 6 mil orifice. Also there was
a large gasket area exposed to the potassium which could
lead to contamination uncertainties. A third disadvantage
was that several threaded joints were immersed in the lead
bath, and the resulting lead fouling made disassembly and
assembly difficult.

The final boiler design (Figure 4) has none of the
drawbacks of the original. Its potassium capacity is 47 1/2
grams (at 700°C) with a running time of about 3 hours when
using a 6 mil orifice. The small gasket area exposed to the
potassium is separated from the potassium by approximately
5/8 inch of threads, and the one threaded joint submerged in
the lead is protected by a gasket.

It was determined that the copper gasket used in the
original boiler was eroded by the high temperatures in the lead
bath. This erosion caused contamination of the potassium
which in turn plugged the orifice and restricted or completely
stopped the potassium flow.

Thin copper and nickel gaskets were tried in the redesigned
boiler, but they were both completely eroded after a few
hours in the lead bath. It was determined (Reference 6) that
both these materials are adversely affected by the molten
lead. It has been determined that a 1/16 inch pure soft iron
gasket will provide the required sealing.

This redesigned boiler assembly has functioned extremely

well, and the problems of orifice plugging have been eliminated.

3.3 Test Sections

The plasma flows through the tantalum tube to the top of the heat exchanger where a glass jar encloses the test sections and associated apparatus. The interior of the glass jar is purged with nitrogen and the pressure is maintained slightly above atmospheric pressure to prevent air from entering the jar. Oxygen has adverse effects on the operation of the unit. The test section fits directly on top of the tantalum tube.

The first test section was designed and constructed as shown in Figure 2. This configuration was chosen over previously used test sections as it provides symmetry and ease in replacing units. The test section and collar were constructed of Boron Nitride since they must withstand the high plasma temperatures, and also must provide electrical insulation for the probes and electrodes. The electrodes were 15 mil tungsten wire crossed as shown in Figure 2 to provide a good field in the plasma. The probes were single element 10 mil tungsten wire. Heating elements of 25 mil Nichrome on the test sections maintained a constant temperature to prevent excessive cooling of the plasma by the insulators and possible condensation of the potassium.

The heating elements were controlled by variacs which were isolated from the heaters by transformers. The transformers also provided the increased current required.

Chromel-Alumel thermocouples inserted in the body of the test section measured the section's body temperature through the use of a Wheelco potentiometer. The temperature was maintained at approximately $550^{\circ}C$. The electrodes and probes were placed at a distance of 1 cm apart and the gap between the top and bottom test section was 1 cm. This provided an easy calculation of the electric field. The test section assembly was held in place over the tantalum tube from the heat exchanger by means of an adjustable bracket (Illustration 1). The test section was made in two units with the gap between them to prevent the possibility of exterior shorting effects between the electrodes and also to allow measurements of electron temperature in the plasma by optical means.

This test section was used for two periods of approximately two hours each. The test section operated satisfactory and gave good experimental results. However, it was noted that after each experimental run was completed the top unit was slightly eroded and it was coated with oxidized potassium. Also the electrode A and probes B and C in the top unit were eroded to the extent that the wires extended only half way across the channel and the diameter was noticeably smaller. This condition was analyzed to be entrainment of oxygen by the plasma flow and some spillover of the plasma as it entered the top unit. The small amount of oxygen which managed to enter the glass jar was considered responsible for the adverse effects. Although the glass jar was purged by Nitrogen under pressure there were still impurities present. Due to these

problems only the voltage readings in the bottom unit were considered reliable.

A new test section was constructed in generally the same manner as the first, except that all the probes were placed in the bottom unit and the gap was reduced to 3 mm. The spacing of electrodes and probes remained at multiples of 1 cm. The test section was also slightly modified to provide a better fit over the tantalum tube. The test section is shown in Figure 3. The first experiment with this test section yielded limited results on conductivity measurements since the potassium boiler was over filled. When the boiler was heated the potassium expanded and flowed through the orifice in liquid form. This liquid potassium managed to flow up to the test section and cover it. Time was required for the potassium to evaporate. However, accurate electron temperatures were obtained.

The second experiment with test section two yielded excellent results. The redesigned boiler assembly was used on this experiment and it furnished a good flow of potassium to the test section. There was no erosion of the electrodes or probes as noted in the first test section. This can be credited to the small gap, the use of lubriseal to seal the bottom of the glass jar, and the use of a redesigned nitrogen purge system inside the jar. These all appeared to isolate oxygen from the test section. The current in the plasma reached 18 amps/cm^2. This current was limited by the available power supply. Higher currents are easily possible, but caution should be used to avoid burning out the test section. At

18 amps/cm^2 it was noted that the test section was extremely hot.

The test sections were wired as shown in Figure 5. A set of storage batteries provided a stable, isolated voltage source. The potential on the electrodes was controlled by a selector switch with variable resistors providing fine adjustments. The various voltages between test section electrodes and probes were selected by a rotary switch. This switch could be used to measure the voltage from any element to the bottom electrode as reference as shown in Figure 5, or it could be used to read voltages between adjacent elements with an electrode to electrode voltage taken as a check. The voltage and current readings were made using vacuum tube voltmeters. In the last two experiments an eight channel Offner Dynagraph Recorder was used. The recorder greatly increased the efficiency of data taking and also gave a continuous time history of the variations in current and voltages. This feature is very important when investigating the critical, unstable "hump" which occurs prior to theoretically expected operation.

The argon used for the experiment was welding grade with the following maximum impurities:

Nitrogen	15×10^{-6}
Oxygen	7×10^{-6}
Hydrocarbons	5×10^{-6}
Hydrogen	1×10^{-6}

CHAPTER 4

ELECTRON TEMPERATURE MEASUREMENT

The basis of the experimental determination of the conductivity of the plasma was the two temperature theory of non-equilibrium conditions in the plasma as postulated by Kerrebrock (Reference 4). This theory assumes that the effective temperature of the electrons in a plasma excited by an electric field is considerably higher than the gas temperature as described in Chapter 2.

An attempt was made to determine by direct experimental measurements the mean temperature of the electrons in the plasma. An optical system as shown in Figure 6 was established. The principal of the measurement is the Féry sodium-line reversal method (Reference 3 and 5). The presence of sodium in the potassium seeding material establishes the two yellow D lines at 5890 and 5896 Å when the sodium is heated to the working temperature of the plasma ($1500^{\circ}K$). When a light from a bright background source giving a continuous spectrum is passed through the plasma containing the sodium, the sodium lines will appear either in absorption, as dark lines against the continuum, or as bright lines against the continuum depending on the brightness temperature of the background. When the background temperature is exactly the same as the temperature

of the electrons forming the D lines, the lines will merge
into the background and disappear. A measure of the background
temperature at this condition will determine the electron
temperature. The apparatus in Figure 6 consists of a leaf
filament tungsten lamp which is focused by a lens to give an
image of the lamp at the center of the plasma flow. A second
lens forms an image of the lamp and plasma on the slit of
the Bunsen spectroscope. Stops were used in the system at
random points to insure no stray dispersion of light reaches the
spectroscope, and that the solid angle of light taken from the
plasma is the same as that from the image of the lamp.
The focal lengths of the lenses were approximately 3 inches.
Very careful alignment of the system along the optical axis
is required and the image of the background source must
completely fill the slit in the spectroscope.

The first two experiments which were conducted with the
first test section did not provide a line reversal. On the
second experiment a small amount of sodium was added to the
potassium to increase the sodium concentration above the
residual sodium impurity content present in the potassium,
but no results were obtained. On the third and fourth experi-
ments, when the second test section was used and a small amount
of additional sodium was introduced, line reversal was obtained,
and the smaller gap allowed less dispersed light to enter the
spectroscope, thus allowing reversal. A calibration of the
system was performed to determine the relation between the
input voltage to the tungsten lamp and the lamp temperature.
This was accomplished by using an optical pyrometer which

read directly the temperature of the filament. The calibration
was conducted on the lamp alone, the lamp as seen through
the first lens, and the lamp as seen through the first lens
and the first surface of the glass jar. There was a 10 percent
reduction in temperature when the lens was inserted, but
the glass jar had negligible effect.

Two corrections to the temperature determined by the
pyrometer are necessary to obtain the brightness temperature
at 5893Å. The first correction is to compensate for the
brightness temperature in the red for a mean wave length of
6550Å to a black body temperature. Then the black body tempera-
ture must be adjusted to the sodium line brightness temperature.
This correction can be computed from (Reference 5):

$$\frac{1}{T_{\lambda'}} = \frac{2.303}{C_{\lambda}}\left(\lambda \log \mathcal{E}_{\lambda} - \lambda' \log \mathcal{E}_{\lambda'}\right) + \frac{1}{T_{\lambda}} \qquad (4.1)$$

where:

λ = wavelength in red = (6650Å)

$\mathcal{E}_{\lambda}$ = emissivity of tungsten in the red

λ' = wavelength of region brightness temperature is desired = (5893Å)

$\mathcal{E}_{\lambda'}$ = emissivity of tungsten in desired region at 5893Å

T_{λ} = brightness temperature at 6650Å

$T_{\lambda'}$ = brightness temperature corrected to 5893A

C_{λ} = ch/k = 1.439 cm degree

The second correction is for reflection losses in the first
lens. Only the light from the lamp passes through the first
lens, therefore a correction is necessary. Both the light

from the lamp and plasma pass through the second lens, so
a correction is not necessary for the second lens. For the
case of sodium the reflection loss of approximately 10 percent
almost exactly cancels the brightness temperature correction.
The following table indicates this relation (Reference 3).

		Tungsten Temperatures °K	
Brightness Temp. at 6550 A	True Temp.	Brightness Temp. at 5893 A	Effective Brightness Temp. Allowing 10% loss
1500	1586	1514	1499
1800	1929	1816	1802
2100	2276	2119	2098
2400	2641	2426	2402
2700	3014	2735	2703

↑————————————— Comparison —————————————↑

Therefore, the temperature as read with the pyrometer
on the lamp alone was used to calibrate the input voltage to
the electron temperature, since it was felt this was well
within experimental limits. The temperatures measured by this
method using the Tungsten lamp ranged from $1800°K$ to $2700°K$
with the only restriction being the current limit of the lamp.
Higher temperatures could be read perhaps with a carbon or
zirconium lamp as the D lines were very evident at the higher
currents. Lower temperatures could also be read using a
suitable lamp.

CHAPTER 5

EXPERIMENTAL RESULTS

The four experiments conducted for this thesis yielded
a large amount of useable data. There was sufficient
stability to the plasma flow and seeding fraction to obtain
curves for eight different concentrations of potassium to argon.
Many other experimental points were obtained, but were not use-
able since it was not possible to estimate the concentration
of potassium in the plasma due to unexplainable transient
effects. All the experimental results are on file with the
thesis supervisor.

The concentration of potassium in the plasma was estimated
by two methods. The orifice used for the experiment was
calibrated by passing argon through it to determine the
volumetric flow rate. This value was then converted to
the mass flow rate of potassium. The flow rate of the
working argon was controllable and measurable. From the
mass flow rate of potassium and the flow rate of argon the
seeding concentration could be calculated. For the second
method, the exact amount of potassium loaded in the boiler
was known. A fairly good estimate of the total potassium
flow time was obtained, and thus the average potassium flow
rate was determined. Both methods assume a constant flow of

potassium through the orifice in the boiler, which should be
correct since the orifice flows chocked under the experimental
conditions imposed. However, leaks or partial blocking of
the orifice could cause deviations from these estimates.
Comparison of the concentrations estimated by the above
methods varied up to factors of 5. From the experimental
results it could be inferred that the flow rate changed
throughout the experiment. This could be caused by orifice
erosion or clogging. A time history record of the potassium
concentration in the plasma is required in order to obtain
an accurate plot to compare with the theoretical curves.

The experimental voltage versus distance along the test
section results are shown in Figure 7 for the two test sections
and various concentrations. The results for test section one
show a variation on the voltage gradient between probe B and
probe D. It is felt this is due to entrainment of oxygen
and other impurities into the plasma caused by the large gap
between the two units. For these results it was felt that
the only suitable gradient that could be used for the gradient
versus current plots, Figures 7 and 8, was between probe D
and probe E. For test section two the gradient is constant
within experimental measurements between probe B and probe E,
except for the low applied voltages where an increasing
gradient going up the test section is present.

Figures 8, 9 and 10 contain the satisfactory and useable
experimental results obtained over the period of one month.
Figure 8 shows the relation between the theoretical values
and the experimental values of the electric field versus the

current density. Figure 9 compares the theoretical conduc-
tivity versus current density with four experimental runs at
various potassium concentrations. Two of these plots show
the measured electron temperatures. These can be compared
with the theoretical electron temperatures plotted on the
figure in dotted lines. Figure 10 indicates all the satisfac-
experimental data for conductivity.

Figure 12 is a plot of the electron temperature versus
the current density for the experimental and theoretical values.

Figure 13 is a plot of the theoretical conductivity
corrected for varying cross sections as discussed in the next
chapter and the Appendix. Also shown are the experimental
results normalized to a concentration of .0028. This concentra-
tion was chosen as it is the optimum concentration which
yields the maximum conductivity for a given electron temperature.
The normalizing process should cause all of the experimental
results to plot on a single line. For the concentrations
indicated by $\diamond$, $\triangledown$ and x the upper portion of the results
are a single line. The variations in the other curves are
caused by uncertainties such as concentration estimates and
gas temperature estimates.

The results were all obtained for the bottom electrode
(electrode F) as the emitter. A couple of points were deter-
mined for the top electrode as the emitter. Under this condition
the current was reversed but the conductivity was considerably
smaller. In one case the conductivity changed from .04 mho/cm
to .004 mho/cm, and in another case it changed from .06 mho/cm
to .014 mho/cm. However, the electron temperatures remained

essentially the same when the anode and cathode were reversed.

An attempt was made to exactly duplicate a set of results at a given concentration. The first set was obtained by increasing the voltage in steps across the test section. When the maximum voltage was reached, the voltage was decreased in steps to obtain the second set. The results are shown in Figures 8 and 10. The ∇ is for increasing voltages and the $\diamondsuit$ is for decreasing voltages. These plots indicate a definite but consistent variation. This could be caused by a hysteresis effect due to transient electrode heating. However, at the point of maximum current it was noted that the current and voltage gradient changed with no changes being made in the controls, and then a stabilized condition again existed. It is believed that the variation was caused by a system change such as a change in concentration due to the orifice clearing of a constriction rather than a hysteresis effect. Therefore it is felt that duplication is possible. This was verified for individual points by randomly returning to a specified current and obtaining the same conductivity.

The results shown on Figure 8 indicate a distinct voltage "hump" at the low currents. This phenomenom was difficult to measure as this was a very unstable region. The exact shape of this "hump" had to be estimated from the location of the experimental points. This area was better defined when the eight channel recorder was used. The recorder should be used if it is deemed necessary to more accurately study this region.

For the experimental points in the figures the following flow rates of potassium were used:

⊙	.005 g/sec
⊡	.005 g/sec
△	.0054 g/sec
▽	.0004 g/sec
◇	.0005 g/sec
+	.002 g/sec
×	.002 g/sec

These flow rates were very rough estimates.

An attempt was made to measure the mole fraction of potassium in the plasma using the apparatus designed by Masek[7]. No successful results were obtained as many design problems were encountered. This equipment should be further developed as it has the potential of greatly refining the experimental data.

CHAPTER 6

DISCUSSION OF RESULTS

Figure 9 shows the experimental results and their
relation to the theoretical curves for a δ = 10. This value
of δ had been used in the past instead of the value of 2
since it showed fairly good agreement with the experimental
results. The effect of changing δ from 2 to 10 is to move
the theoretical j vs. σ plot to the right. On Figure 8
the effect is to move a theoretical point to the right and
up by the square root of the ratio of the new to the
original δ. Therefore the difference in the experimental
and theoretical curves was assumed to be losses in the system
which was compensated by changing δ.

This movement of the theoretical plots by increasing δ
might not be sufficient when the measured electron temperatures
are considered. These temperatures indicate that the tempera-
tures are much higher than the theory predicts, which means
that a reduction in δ from 10 is required. To bring the
theory back to the results with a smaller δ a greater
collision cross section would be required. A smaller δ
and a larger cross section would have the effect of moving
the theoretical plots in Figure 9 to the left proportional
to the square root of δ and down by the factor $\dfrac{S_A + n_K/n_A S_K}{S_A' + n_K/n_A S_K'}$

as covered in the Appendix. The value of the collision cross section used for the theoretical plots was assumed to be constant as outlined in Chapter 2, but in Reference 1 it is shown that this value is constantly changing according to the energy of the electrons. Therefore it was felt that the deviations from theory were caused more by varying cross sections than by losses reflected in a varying δ . The effects caused by the changing cross sections might explain the entire shape of the experimental results curves, with Joule heating and heat losses causing perturbations. Accurate data is not available on the collision cross section at the low temperatures (below about $4000^{\circ}K$), but the indication is that the cross section will continue to increase as the temperature decreases at least for a temperature decrease of 1500° to 2000°. This would explain the observation that the experimental results have a larger slope than the theory predicts for a constant cross section as previously used.

Figure 13 shows the results of this investigation. This figure shows:

(1) The theoretical conductivity versus current curve at optimum concentration, i.e., n_K/n_A = .0028, and T_g = $1500^{\circ}K$, δ = 2, and the constant cross section as given in Chapter 2.

(2) The theoretical curve using the same values as above but corrected for varying cross sections as outlined in the Appendix.

(3) The experimental results normalized to n_K/n_A = .0028.

The results of the plot show that there is an extremely close agreement with theory (corrected for varying cross sections) above 1 amp/cm^2 for all but one run. For this run ($\odot$) it is felt that the estimated potassium concentration is incorrect since the curve has the correct shape but is displaced. The fact that all of the other experimental plots do not converge exactly to a single plot is probably also due to errors in potassium concentration approximations (see Chapter 5). Temperature differences in the plasma will also change the conductivity as shown theoretically in Figure 11. The three concentrations which do plot as a single line (x, $\triangledown$, $\diamondsuit$) show a tendency to decrease in slope as current increases above 2 amps/cm^2. This could be caused by radiation and conduction cooling effects. Also to be considered in this region are the ohmic heating effects which have a tendency to increase the slope. Further study of this region was limited by the available power and temperature limitations in the test sections.

The effect on conductivity of varying the cross sections as given in Reference 1 with δ = 2 is almost the same as using a δ = 10 with the constant cross sections, except the corrected theory has a slightly steeper slope. Therefore, we believe that the theory should be based on a δ = 2 and varying collision cross sections.

To explain the experimental j vs. σ results by variation of the cross sections at electron temperatures less than about 2000°K would require the cross sections to change rapidly and radically. It is possible that they do, but there is no

evidence one way or the other on the cross-section behavior in this region.

The radical deviation from theory in this "hump" region shown in Figures 8, 9 and 10 may also be caused by a non-Maxwellian distribution. Although calculations, based on Maxwellian distribution, indicate that the minimum number of electrons is of the order of 10^{+12} cm^{-2} at the lowest measured electron temperatures there may be loss mechanisms which deplete the high energy electrons until an "ignition" point is reached. Further study of this region is required if an explanation is desired. For MHD plasma jets and generators this region is not of particular interest since the high current regions are desired. The "hump" shown in Figure 8 could be overcome in practical equipment by using a pulsed E or B field to start the process.

Another major result of this work has been the measurement of the electron temperatures. It is believed that this is the first time that accurate, useable data on electron temperatures in this type of plasma has been determined to test the theoretical assumptions. The results are felt to be within the limits of experimental accuracy. The electron temperature appears to be directly related to the current in the plasma as shown in Figure 12. For a given current the electron temperature is very stable, and the temperature reading is repeatable when randomly returning to a given current for a constant plasma concentration. This confirms Kerrebrock's approach in using j rather than E for characterizing the difference between the electron and gas temperatures.

When visually watching the plasma flow in the gap of
the test section, a definite increase in brightness of the
plasma occurred as the current increased. This is probably due
to the electron-atom, electron-ion collisions in the plasma.

Now that it has been shown that the electron temperature
can be measured, a more sophisticated and stable optical
bench can be designed to eliminate minor alignment errors which
cause negative results. The amount of sodium added to the
potassium must be closely controlled to yield temperature
readings, but not adversely effect the properties of the
plasma.

The measured electron temperatures shown on Figures 9
and 12 show a consistent variation from the theory. On Figure 12
the slopes above about 200 ma/cm^2 agrees closely with theory
but the actual temperatures vary about 400°. The sharp rise
in electron temperature at the very low current densities
is as yet unexplained. Using the varying cross section
"corrected theory" as on Figure 13 the theoretical electron
temperature in the region where experimental data was taken
is closer to the readings, but still off by about 200°.
A reasonable explanation for this difference has not been
found. However, the measurement of the electron temperatures
verifies the theory that there are two distinct temperatures
present in the plasma, i.e., (1) the temperature of the gas,
and (2) the temperature of the free electrons.

The voltage gradient plots in Figure 7 indicate a high
electrode drop especially at the cathode or emitter. This
voltage drop is thought to be caused by the energy input to

the electrons to raise the electron temperature to the equilibrium condition. This energy input occurs over a short distance for the high voltage-current conditions. At the lower voltages an increasing gradient along the test section would indicate a decreasing conductivity since the current density is considered constant throughout the test section. This would mean a decrease in electron temperature. This is possible if the effects of conduction and radiation cooling are considered. The energy input to the electrons for this case is not sufficient to counteract the cooling effects. At the higher currents the Joule heating of the plasma would offset the cooling and might even dominate.

In summary, above approximately 1 amp/cm^2 the experimental results agree closely with the two temperature theory, (even though the measurement of potassium concentration was uncertain to within a factor of two or three). These results indicate that the conductivity of the plasma can be predicted by the two-temperature model with good accuracy provided the proper collision cross-sections are used in the calculations.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The conclusions are:

(1) The conductivity of a noble gas-alkali metal plasma agrees very closely with Kerrebrock's two temperature theory[4] above a well defined unstable threshold region.

(2) Results to date indicate that the theoretical prediction of the plasma's behavior, using the two temperature model, should be based on a changing collision cross section with the loss parameter, δ , on the order of 2.

(3) The voltage versus distance plots in Figure 7 indicate that the electrons heat in a short distance, and thereafter a nearly adiabatic condition exists as assumed by the two temperature theory. For a more refined estimate the Joule heating and heat losses from the flow must be considered. The heat losses will be a function of the type of test section and experimental apparatus used.

(4) The sodium line reversal method of measuring the electron temperature seems to be effective and it provides much needed information required to fully study the behavior of the plasma subjected to an electric field.

Recommendations for future work are:

(1) A more positive and accurate method of measuring the potassium concentration in the plasma is a necessity before further study is attempted. If the concentration changes throughout an experimental run the results can be normalized to obtain a true picture of what is happening.

(2) The electron temperatures at the higher currents should be studied to determine the true relation between the temperature and the current.

(3) The effects of ohmic heating and conduction and radiation losses should be investigated to determine the degree of variation they contribute to the experimental results.

(4) A set of runs with reverse polarity might help in the study of the low end of the conductivity curves and give information on the thermionic emission of the cathode.

(5) The next step should be subjecting the plasma to an external magnetic field to determine the gas properties for MHD power and propulsion systems.

EXHAUST

GLASS JAR

TEST SECTION

PYROMETER
VIEWPORT

ARC

N_2

CARBON BATTING
INSULATION

N_2

TANTALUM
TUBE
GRAPHITE

N_2 EXHAUST

FLEXIBLE HOSE

VENT

NOBLE
GAS

MOLTEN
LEAD

ALKALI
METAL
MOLTEN
LEAD
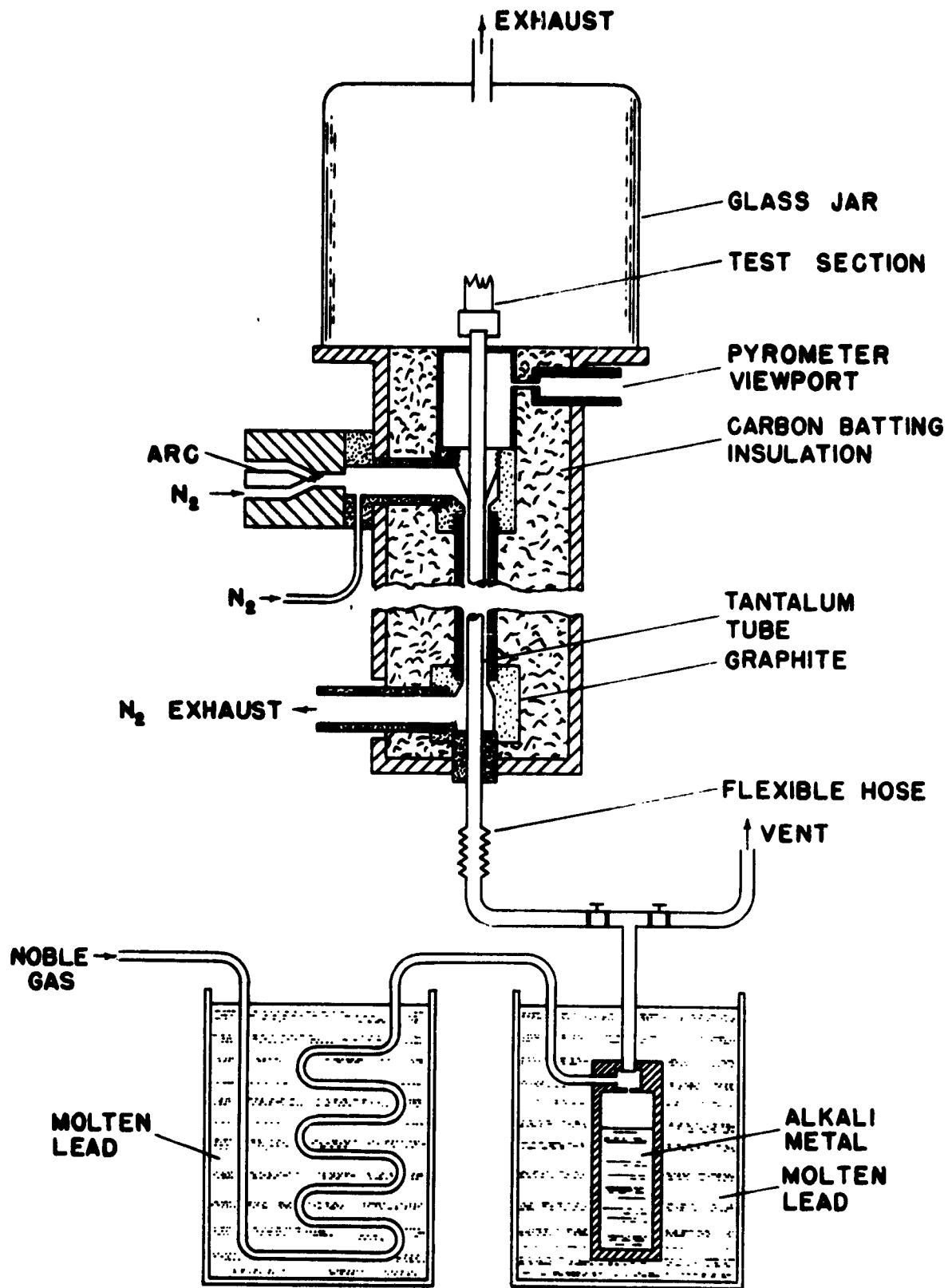
EXPERIMENTAL APPARATUS

FIGURE I

HEATING ELEMENT
COLLAR
ELECTRODE A

PROBE B

PROBE C

PROBE D

PROBE E

ELECTRODE F

TANTALUM TUBE
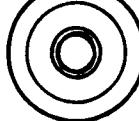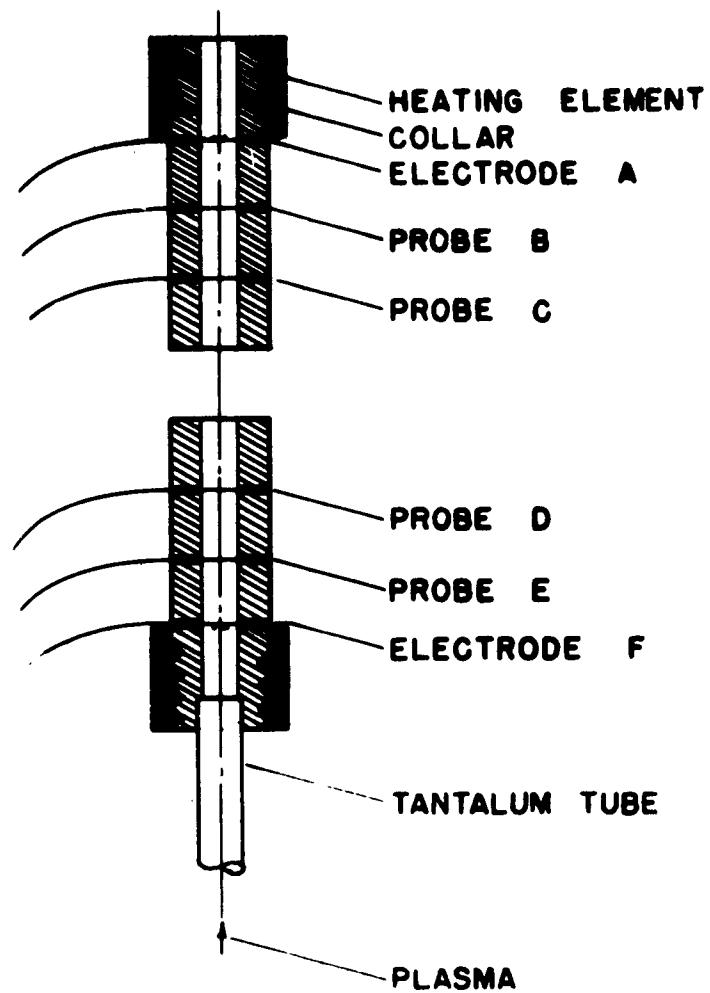
PLASMA

ELECTRODE
CONFIGURATION

TEST SECTION I

FIGURE 2

HEATING ELEMENT

COLLAR

ELECTRODE A

PROBE B

PROBE C

PROBE D

PROBE E

ELECTRODE F

TANTALUM TUBE

PLASMA

TEST SECTION 2

FIGURE 3

NOBLE GAS

SEEDED GAS

TUBE FITTING

WELD

ORIFICE

COPPER GASKET

ALKALI METAL VAPOR

BOILER ASSEMBLY
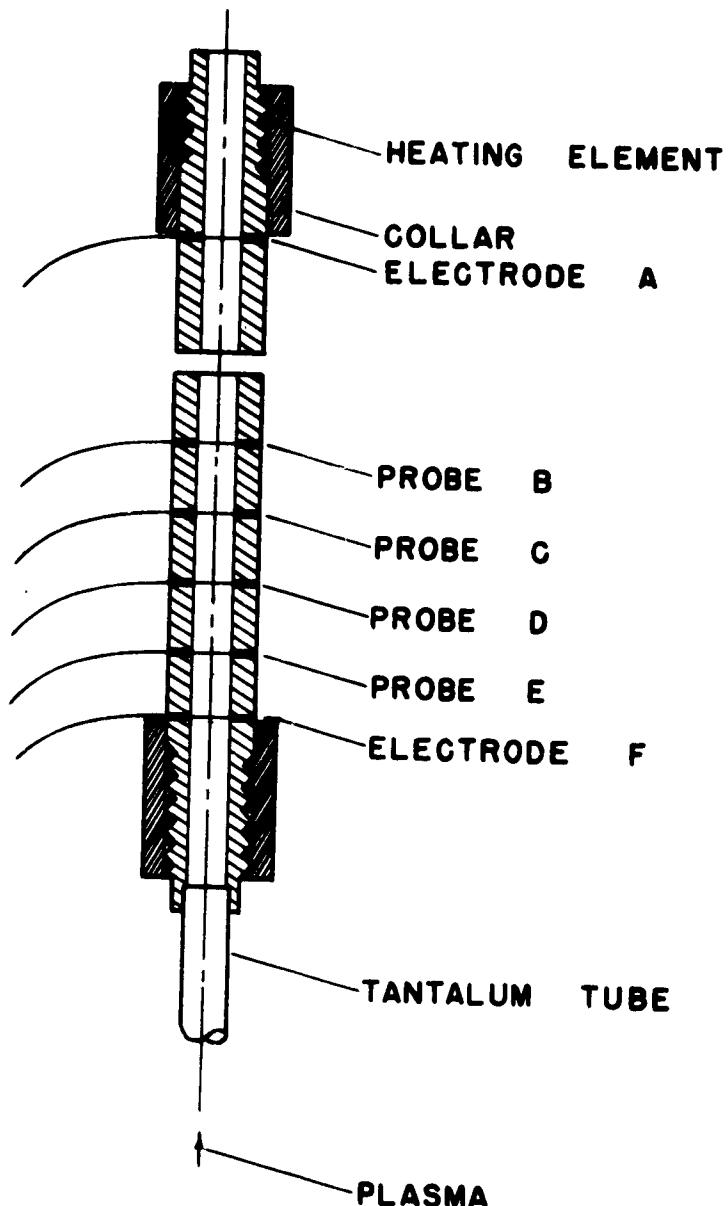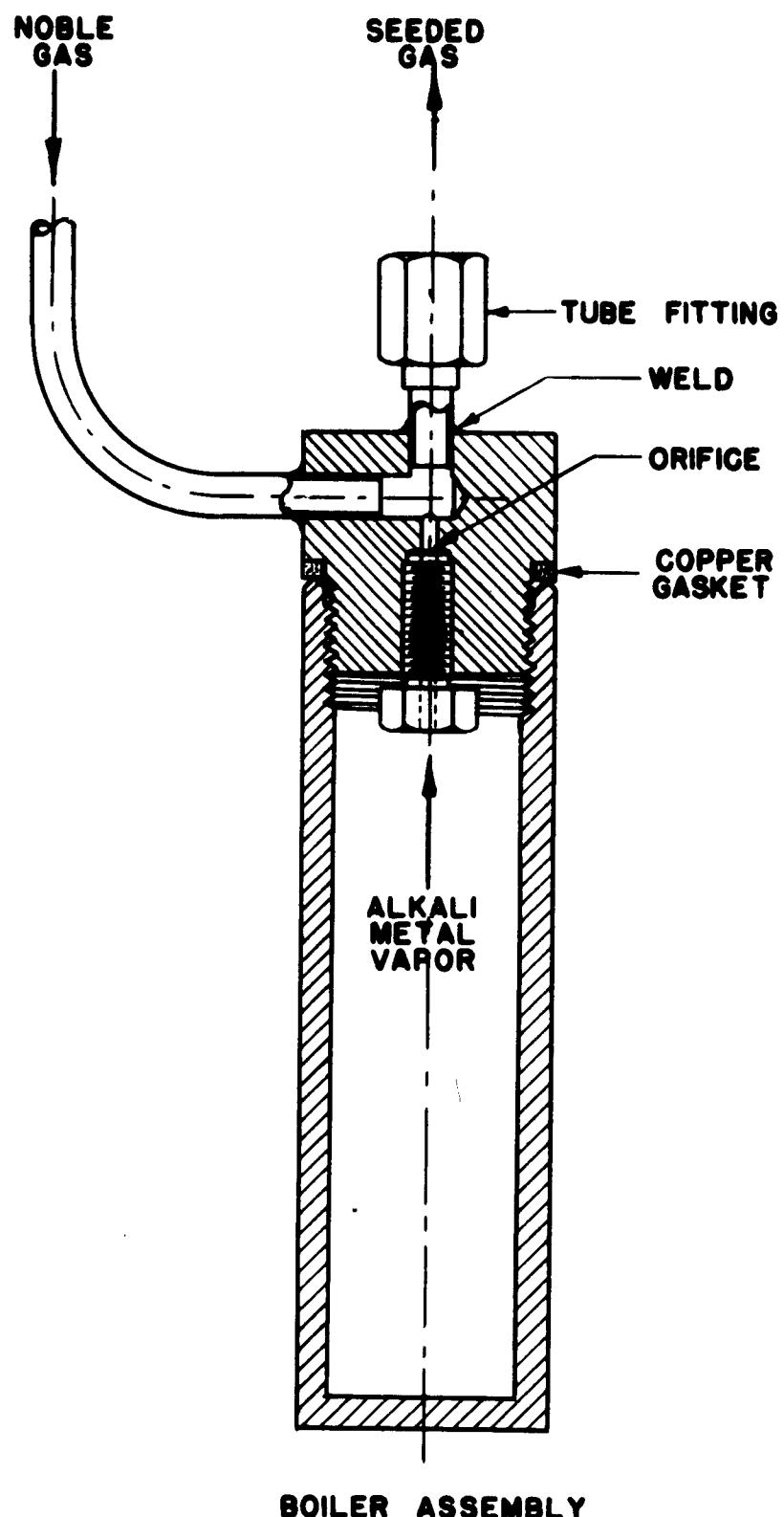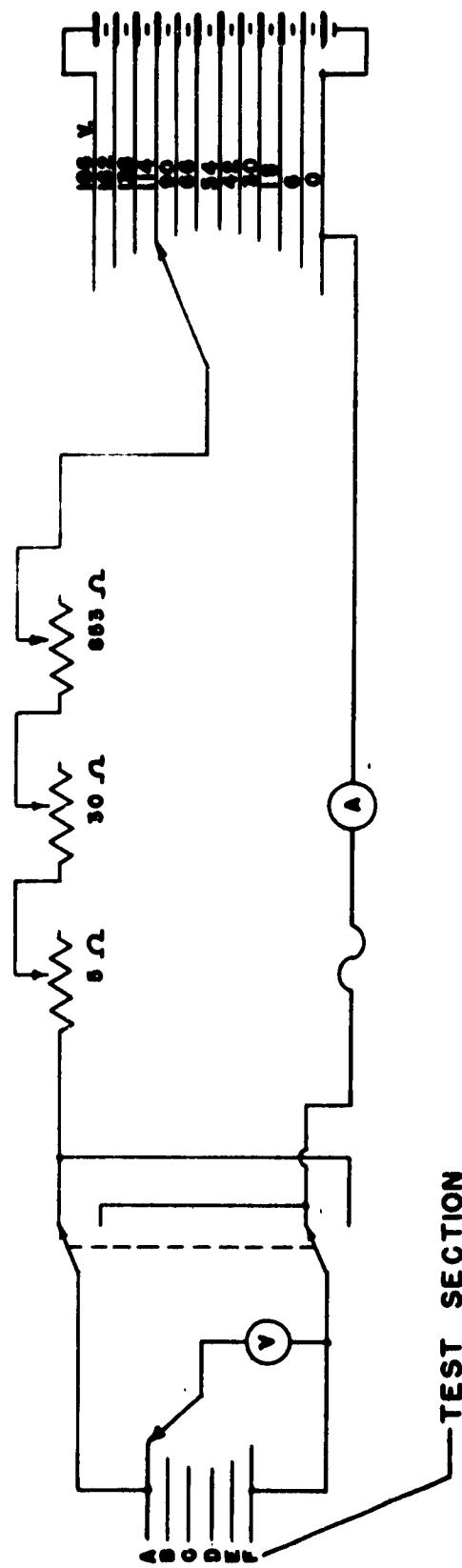
FIGURE 4

CIRCUIT DIAGRAM

FIGURE 5

OPTICAL SYSTEM
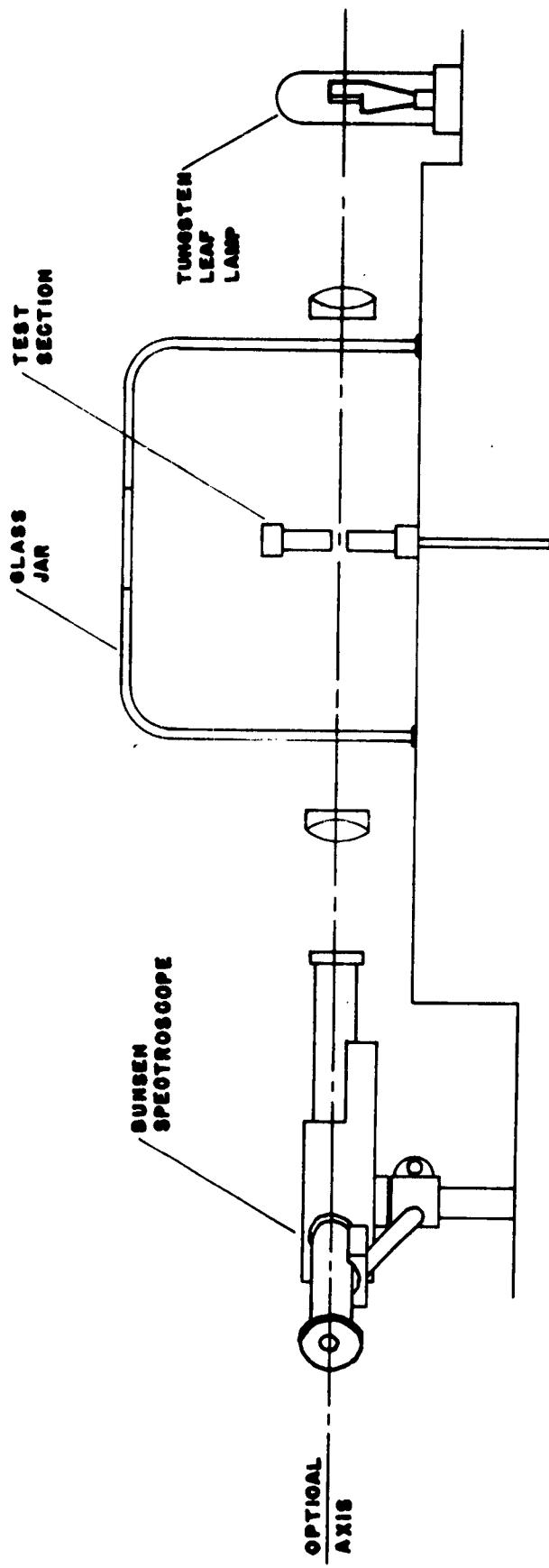
FIGURE 6
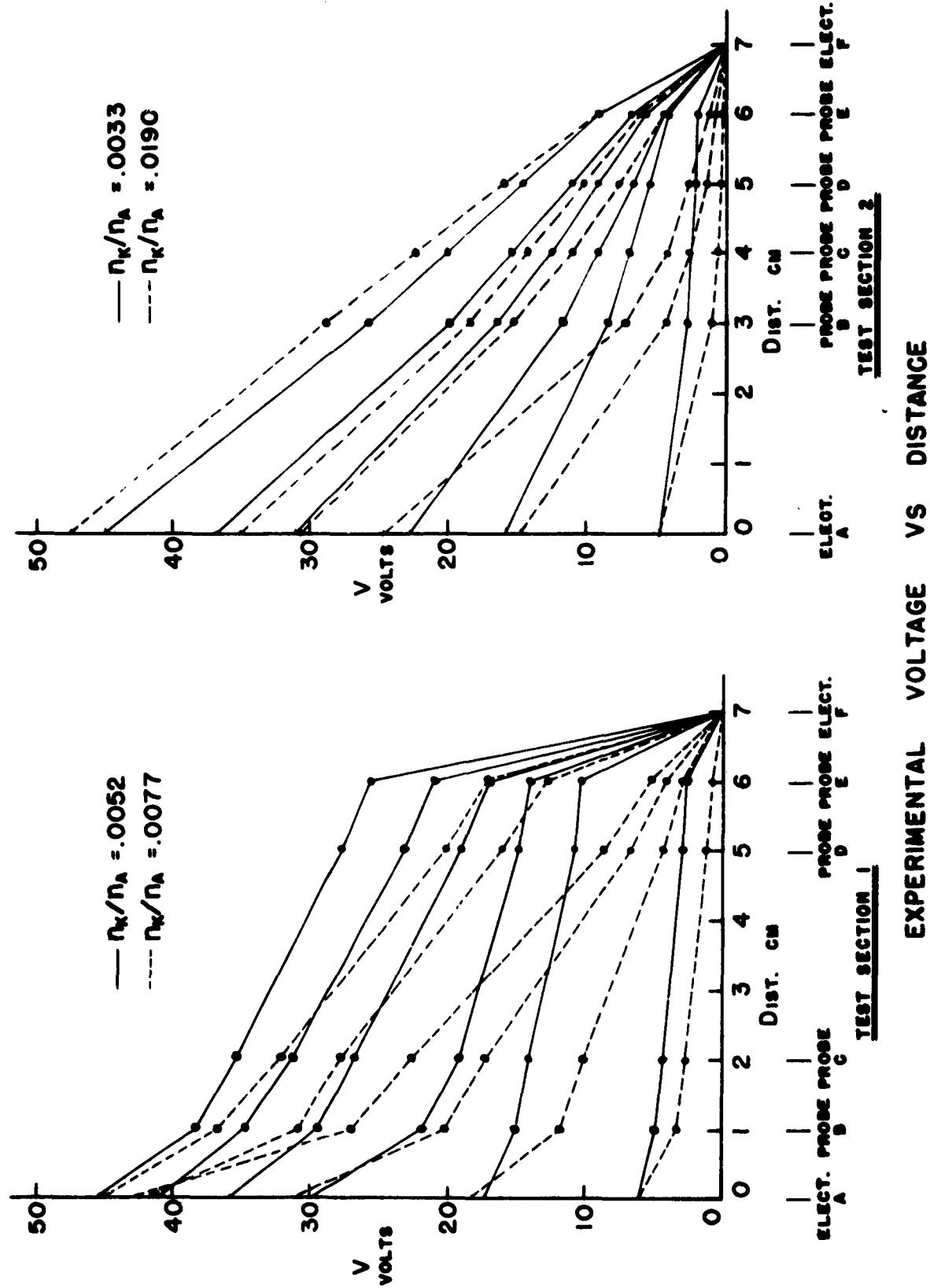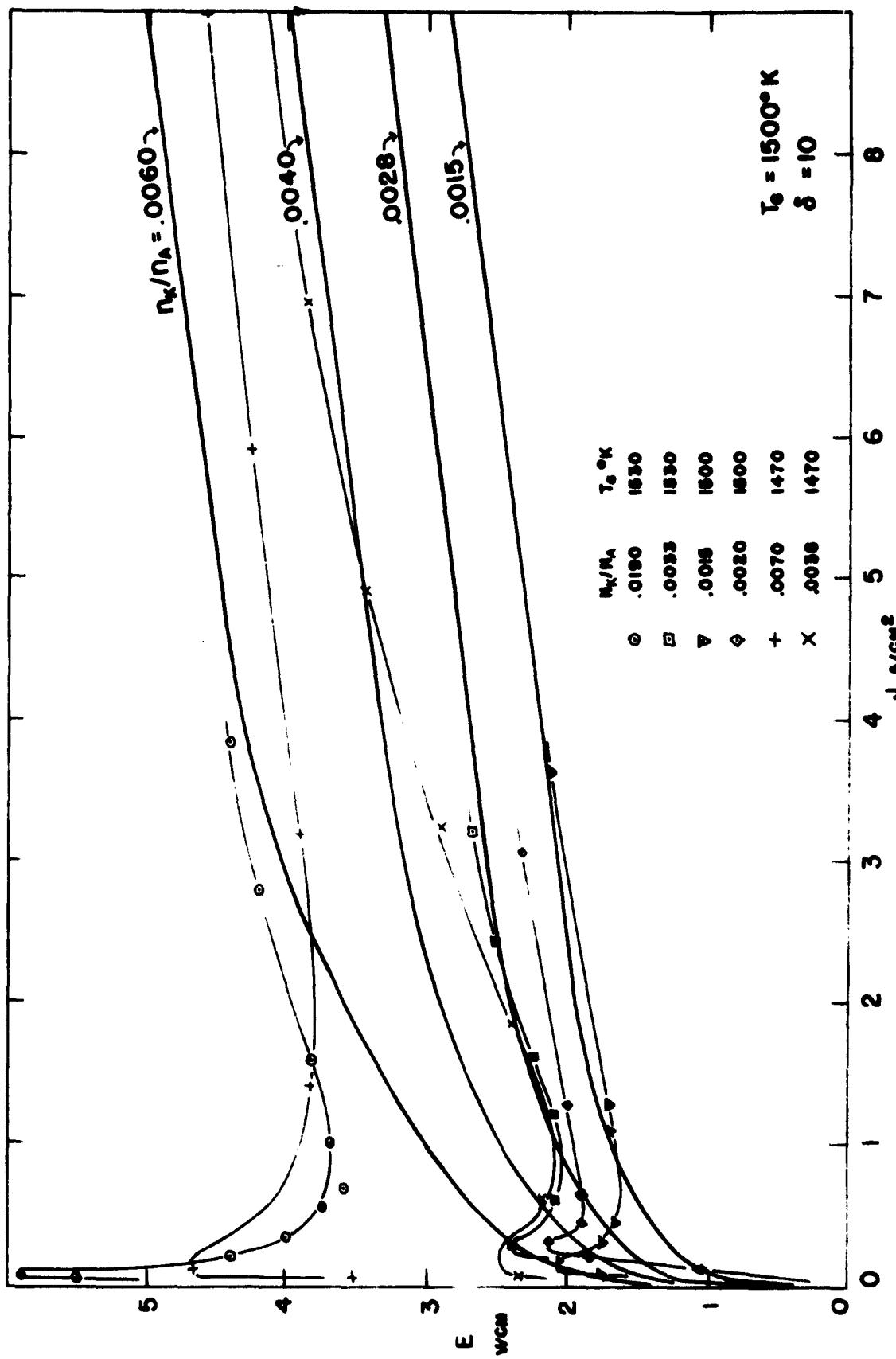
FIGURE 7

THEORETICAL & EXPERIMENTAL CURRENT CHARACTERISTICS OF PLASMA

FIGURE 8
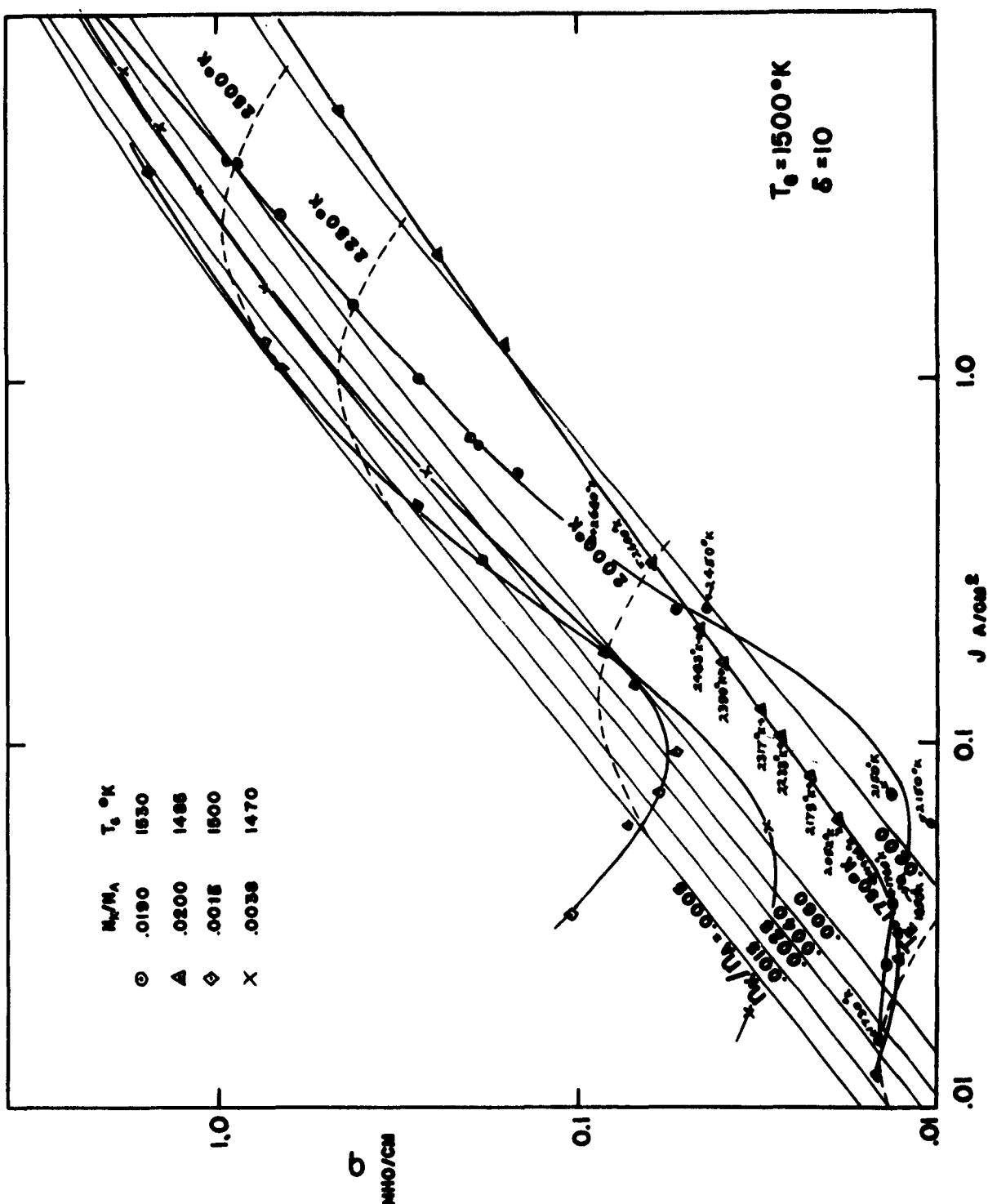
THEORETICAL & EXPERIMENTAL CONDUCTIVITY OF PLASMA

FIGURE 9
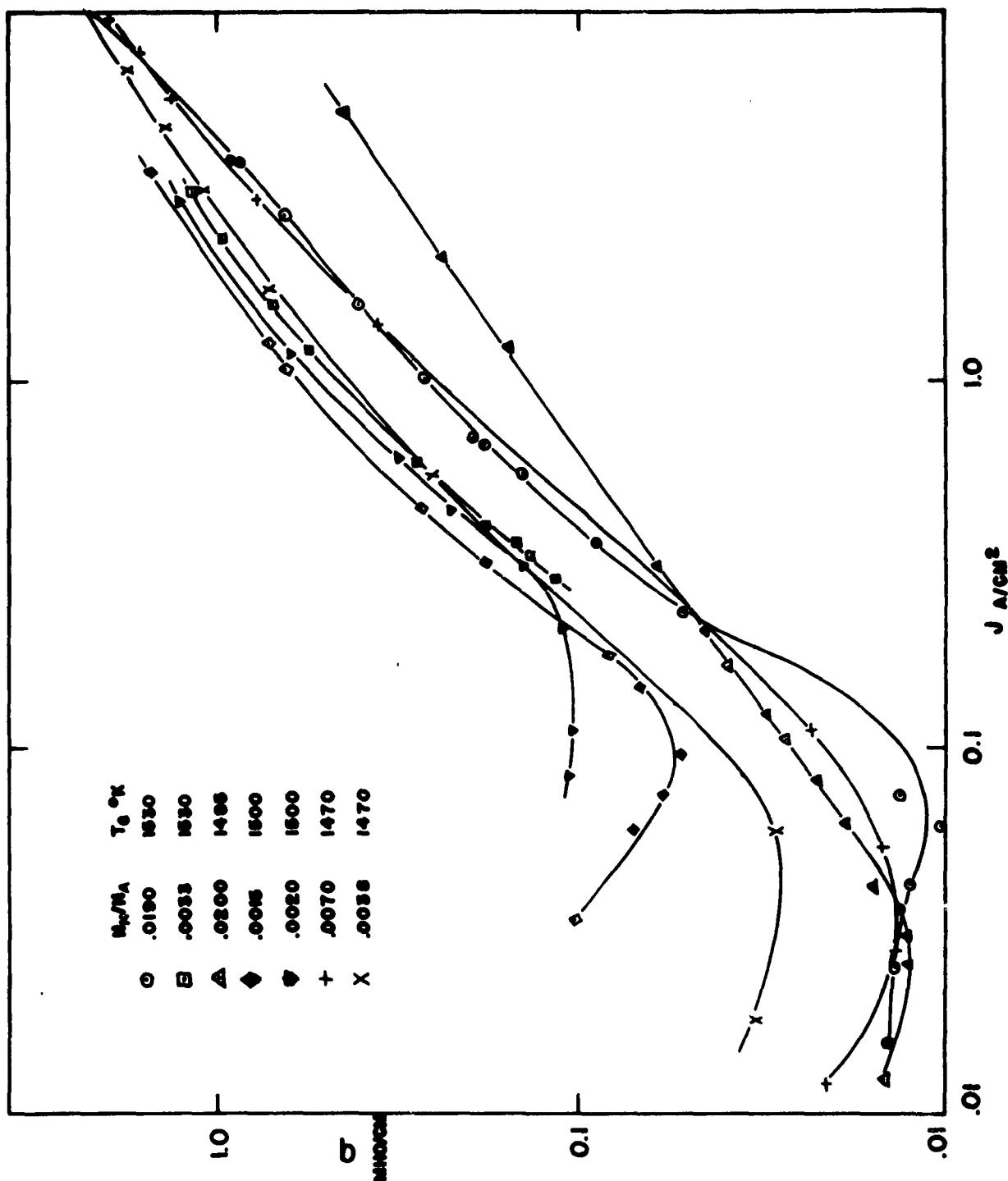
EXPERIMENTAL CONDUCTIVITY OF PLASMA

FIGURE 10
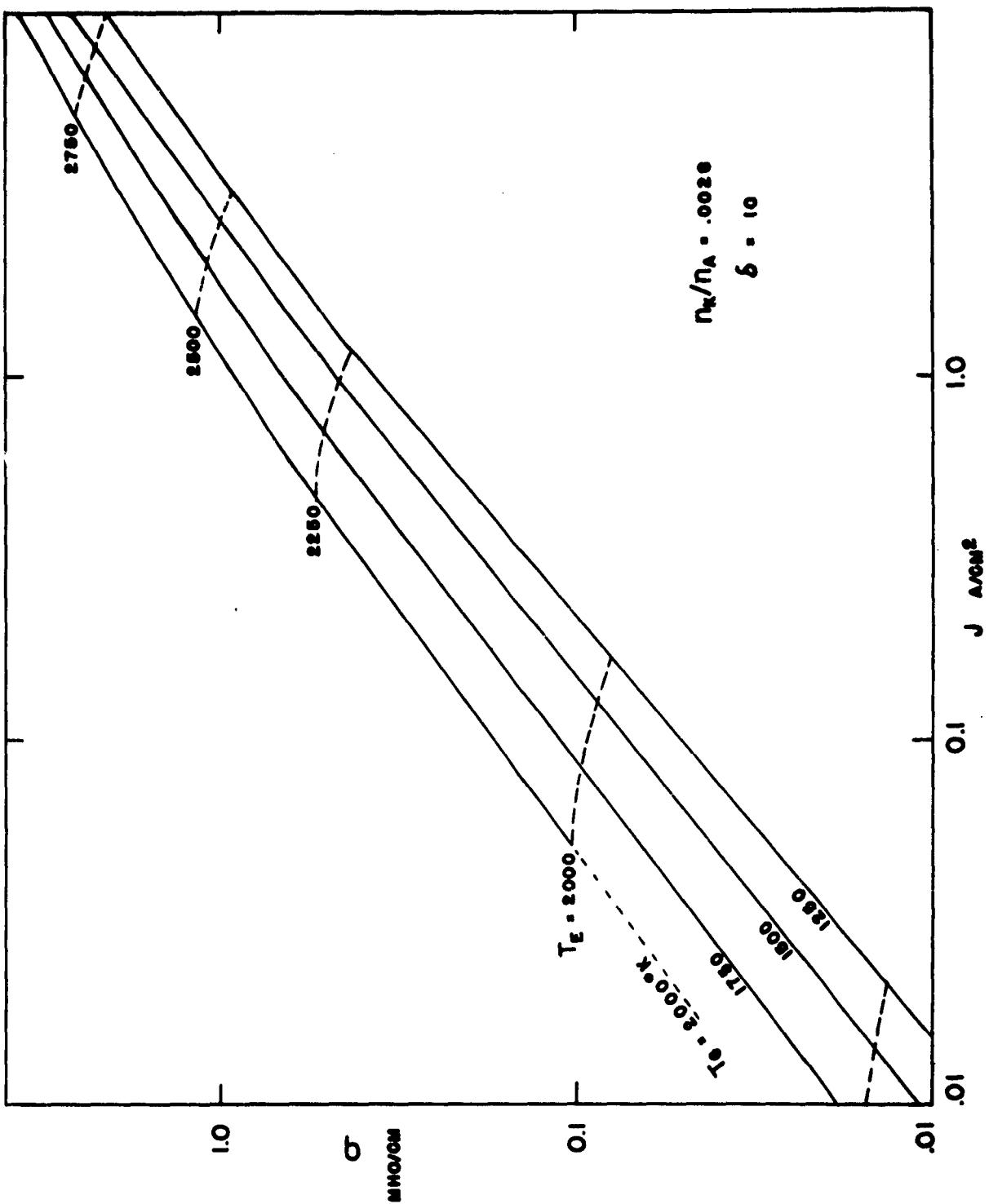
THEORETICAL   CONDUCTIVITY   FOR   CHANGING   T₀

FIGURE 11

ELECTRON TEMPERATURE
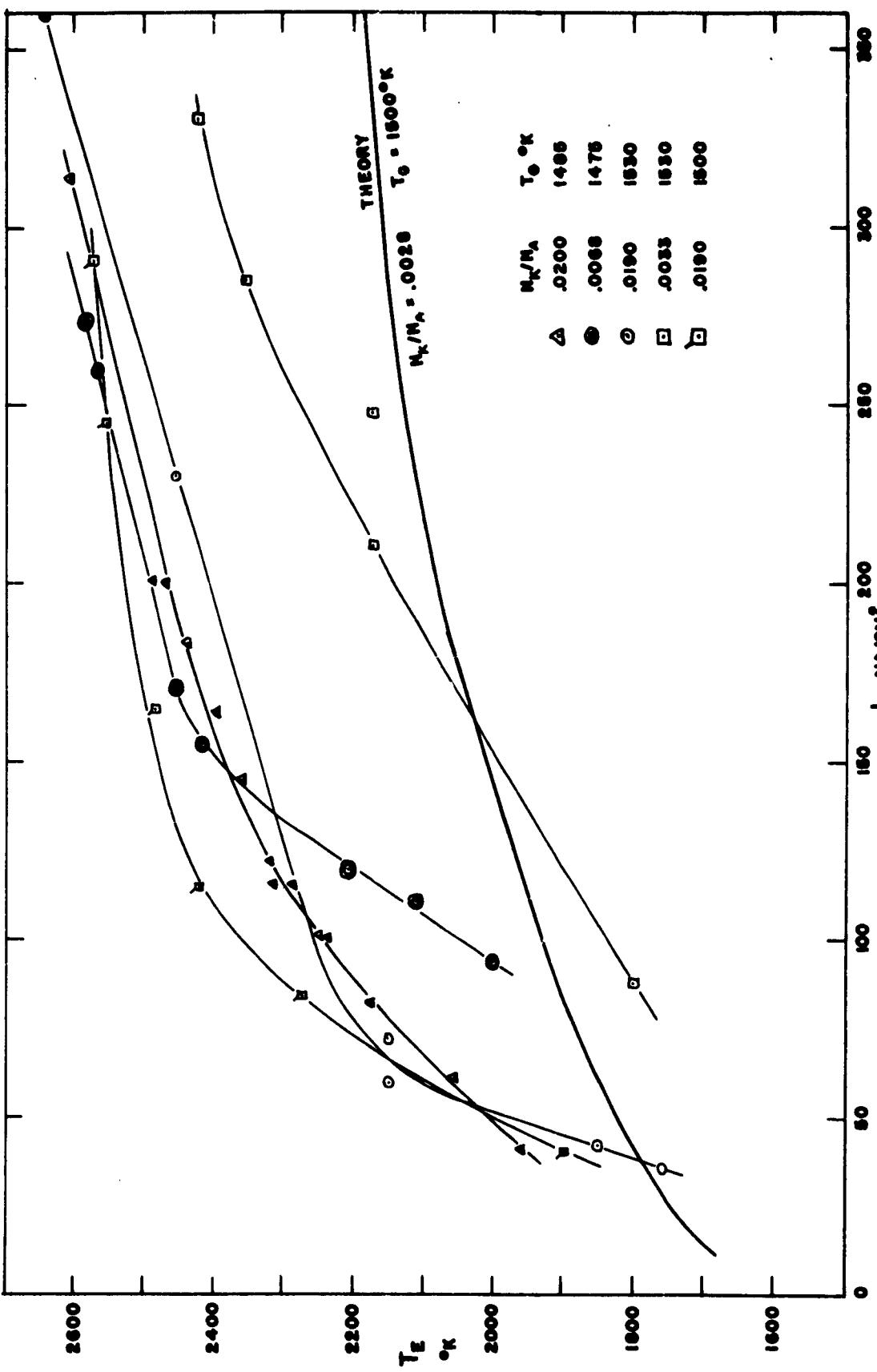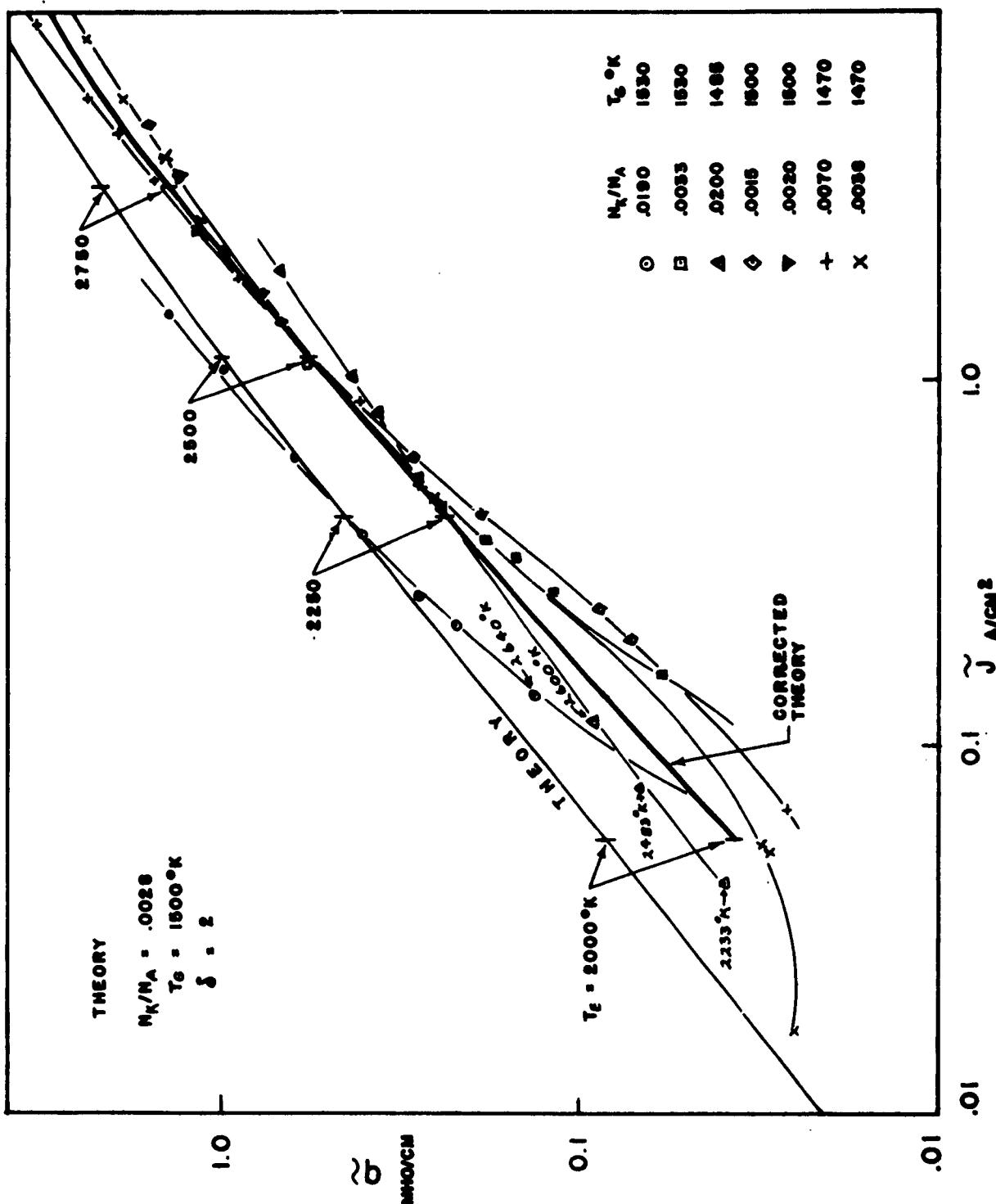
FIGURE 12

CORRECTED THEORY AND NORMALIZED RESULTS

FIGURE 13
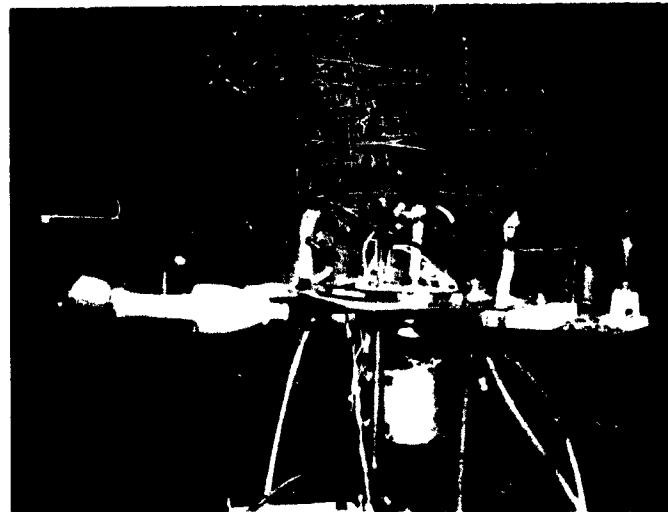
GENERAL EXPERIMENTAL APPARATUS
SHOWING TOP OF HEAT EXCHANGER,
OPTICAL SYSTEM, PYROMETER,
AND TEST SECTION TWO

ILLUSTRATION I

REFERENCES

1. Brown, S.C., *Basic Data of Plasma Physics*, Technology Press and John Wiley and Sons, Inc. (1959).

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APPENDIX

MODIFICATION OF σ BY VARYING S_A AND S_K

The conductivity of the argon-potassium plasma has been approximated by:

$$\frac{1}{\sigma} = \frac{m_e}{e^2 n_e} \left(\frac{8kT_e}{\pi m_e}\right)^{1/2} \left[n_A S_A + (n_k - n_e) S_k \right]$$

$$+ 0.0176 \frac{e^2}{m_e \epsilon_0} \left(\frac{m_e}{2kT_e}\right)^{3/2} \log_e \left[12\pi \frac{(\epsilon_0 kT_e)^{3/2}}{e^3 n_e^{1/2}} \right]$$

where the first term represents the electron-atom (hard-sphere) collisions and the second term represents the electron-ion (coulomb) collisons. For electron temperatures below 2500°K the second term contributes 10% or less, however it becomes increasingly important at higher temperatures.

Initially it was believed that S_A and S_K could be assigned average values which would be valid over the temperature region of interest, and the theoretical log σ vs. log j curves were computed on that basis. The average values used were:

$$S_A = .7 \times 10^{-16} \text{ cm}^2$$

$$S_K = .25 \times 10^{-13} \text{ cm}^2$$

However Brown[1] and others have shown that both S_A and S_K are functions of electron energy, and that their values vary considerably over the temperature range with which we are concerned. Although there is little agreement in exact values the trend for argon is obvious. Data on S_K is not as complete as on S_A but Reference 1 contains one curve of S_K vs. electron energy.

For the modification of our theoretical log σ vs. log j curves the electron-atom cross section vs electron energy curves presented in Reference 1 were averaged and extrapolated to obtain the following:
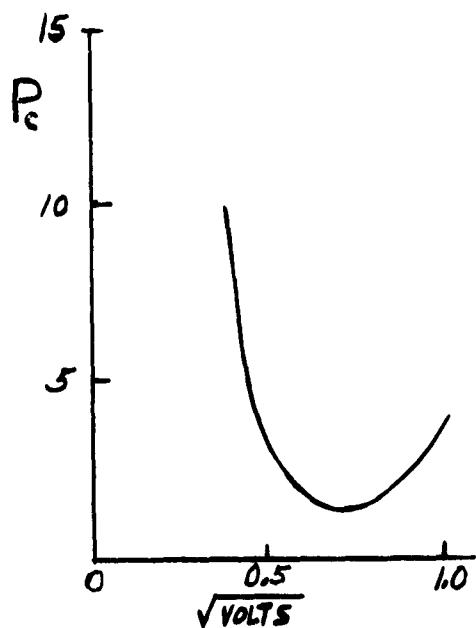
ARGON
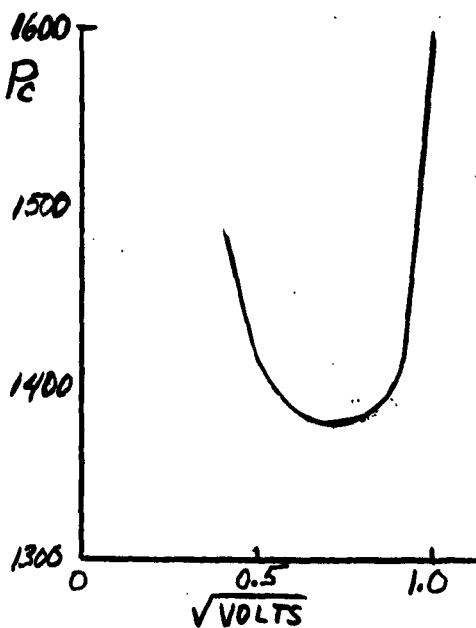
POTASSIUM

There was no attempt to extrapolate for electron temperatures less than 2000°K (.1725 volts) for reasons discussed in Chapter 6.

Because the cross section data was very rough it was decided to neglect the electron-ion collision term and to assume $n_e \ll n_K$ in the modification of σ . The expression for $1/\sigma$ then becomes:

$$\frac{1}{\sigma} = \frac{m_e}{e^2 n_e} \left(\frac{8 k T_e}{\pi m_e}\right)^{1/2} n_A \left(S_A + \frac{n_K}{n_A} S_K\right)$$

Since, for constant j, the cross sections are the only variables in the above expression:

$$\frac{1}{\sigma} = K \left(S_A + \frac{n_K}{n_A} S_K\right)$$

if σ' is used to denote the corrected σ :

$$\frac{1}{\sigma'} = K \left(S_A' + \frac{n_K}{n_A} S_K'\right)$$

or:

$$\sigma' = \sigma \frac{S_A + \frac{n_K}{n_A} S_K}{S_A' + \frac{n_K}{n_A} S_K'} \qquad \text{(at constant j)}$$

where S'_A and S'_K are values obtained from P_c vs $\sqrt{v}$ curves. To use the cross section curves the following conversion factors were necessary:

$$S = .283 \times 10^{-16} P_c \, cm^2 \qquad \text{(Reference 1)}$$

$$1 \text{ volt} = 11,600°K$$