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A STUDY OF AN INDUCTION-COUPLLED PLASMA OPERATING AT 400 KILOCYCLES

Howard R. Cannon

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A STUDY OF AN
INDUCTION-COUPLED PLASMA
OPERATING AT 400 KILOCYCLES

THESIS

Presented to the Faculty of the School of Engineering of
the Air Force Institute of Technology
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in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

By
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Graduate Astronautics
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Preface

This report concerns an elementary investigation of the problems of containing an induction-coupled plasma, measuring the plasma power and temperature, and determining the effects changing plasma operating conditions. I hope this report successfully establishes a starting point for future detailed investigations.

During the period of this study I was the guest of the Aeronautical Research Laboratories, and I wish to thank the members of ARL, who made my visit informative and enjoyable. Iy thanks particularly to the staff of the Thermomechanics Laboratory, ARl, for their support and encouragement.

I am especially indebted to E. Pfender for his guidance and support during his stay in this country, and to J. C. Brown and J. Birkeland, Plasma Physics Laboratory, ARl, for their explanation of Abel's Integral Transformation which appears in Appendix A. My thanks also to my lab partner, A. Shade, for the time and effort he devoted to assisting me, sometimes at the expense of his own study.

This report could not have been submitted in its present form without the patience and understanding of my Faculty Advisor, N. Wingerson. If time had permitted me to properly act upon his counsel, a far better report would have resulted.

And finally, my thanks to my wife, Carolyn, for her efforts to minimize distractions while I worked.
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List of Symbols

D_L = Diameter of Radio Frequency Induction Coil
D_p = Diameter of the Plasma
n = Power Coupling Effectiveness

n_0 = Diameter Power Coupling Effectiveness

I_P = Radiation Power Coupling Effectiveness

n_L = All Losses Power Coupling Effectiveness

n_T = Total Power Coupling Effectiveness

I_E = Plate Loss-excess
I_I = Plate Loss-illums
I_L = Plate Loss-total
I_R = Power ratio

n_R = Solar Power Power Ratio

I_R = Radiation Power Ratio

I_L = All Losses Power Ratio
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A rf, electrodeless plasma-generator was developed which operated at peak plasma powers of 50 kw. The plasma was vortex stabilized, and was contained within a water-cooled Vycor tube. Power was measured calorimetrically. Radiation power was measured by alternately using clear water and water made opaque with India ink to cool the Vycor tube.

A model temperature profile was deduced from electromagnetic measurements transverse to the plasma axis. Maximum plasma temperatures were shown to exist in a thin cylindrical sheath near the plasma surface, with relatively cooler temperatures existing at the center-line gas back-flow. Effects of changing gas flow rate, gas composition, rf power, and Vycor tube diameter on the effectiveness of the energy coupling mechanism are shown.
I. Introduction

An induction-coupled plasma is formed in a partially ionized gas by electric currents. It is indirectly coupled to a radio frequency (RF) excitation coil. This method of plasma production is capable of generating a more uniform excitation which is characteristic of direct-current and alternating-current arcs. These arc are contaminated by electronic erosion caused by the direct contact between the electrons and the arc.

Induction-coupled plasmas are "electrodeless arcs," and there is no direct contact between the plasma and the power supply.

Title of the Author

Dr. Peter of the Institute for Plasma Physics, Albert-Ludwiger-Strasse, Wernigerode, West Germany, initiated this study while he was engaged in research work at the "Hahn-Meitner" research laboratories (AM), Grünheidestrasse 41, D., at the suggestion of Dr. Becker, Chief of the Hahn-Meitner Institute, D. Dr. Peter is interested in this plasma because it provides a possible source of electrons, ions, and neutral atoms which are in local thermal equilibrium (Ref. 2: 524), while Dr. Becker was primarily interested in the energy transfer characteristics exhibited by this plasma coupling mechanism.
Statement of Problem

The objectives of this study were (1) to operate a stable plasma at atmospheric pressure at 200 kilocycles (kc) with a sustained, high-power operation capability, (2) to determine the temperature profile of the plasma as a function of the plasma radius, $T(r)$, (3) to measure the power transmitted to the plasma, and (4) to determine parameters important to the energy coupling mechanism.

Experimental Approach

The plasma was contained in a water-cooled Vycor tube (Fig. 1), and was stabilized in the vortex flow resulting from tangential gas injection in the manner prescribed by J. B. Reed (Ref. 2; 822).

The temperature profile, $T(r)$, was deduced from intensity profiles, $I(x)$, of the lambda 7435A and lambda 4863A spectral lines obtained by spectrographic scans transverse to the plasma axis.

The total power transferred to the plasma was determined by measuring the power the plasma transferred to cooling water. Radiation power was measured by circulating an opaque coolant instead of clear water about the Vycor tube which contained the plasma (Fig. 2).

The parameters varied in this study were rf power delivered by the power supply, gas flow, the diameter of the Vycor tube containing the plasma, and the gas composition. The rf power was varied by changing the plate voltage of the power supply, and the gas composition was changed by mixing helium and argon.
as stated by Reed, (Ref. 2; P22),

"It is still too early to say what the capabilities and limitations of inductive plasma generation are. We have used the plasma torch to grow single crystals of refractory oxides, and oxygen-containing plasmas will melt streamer oxide (mp = 2700°K). The temperatures achieved in the plasma will depend ultimately on the power available and the nondestructive containment of the plasma. Presumably, the induction plasma will find use wherever the dc plasmas are used, from measurement of spectral transition probabilities to preheating cases for use in hypersonic wind tunnels."

In addition to preheating the cases for use in hypersonic wind tunnels, stagnation temperatures attainable in hypersonic wind tunnels can be increased by heat addition in the supersonic flow section using an induction-coupled plasma.
II. Experiment

Description of Apparatus

Part of the experimental apparatus is shown in Figure 3. In the background is the rf power supply. Starting at the extreme left, the apparatus seen is a portion of the gas supply bottle, the vacuum pump and vent, the vacuum pump shut-off valve, the exhaust valve, and the vacuum system pressure gages. The pressure gages are mounted on the support stand. Above the support stand the calorimeter jacket, plasma-generator, and the support stand scaffold are seen. Behind the calorimeter jacket two meters are seen, which were not pertinent to this study. The image covers other equipment which was not pertinent.

Gas supply system. The argon and helium used in this study were supplied by the Burdett Oxygen Company, and contained no more than one percent impurities by volume. Gas flows were measured by Airco Dual Range Flowmeters for Argon, style number 865-1601. These meters were calibrated from 1 to 196 standard cubic feet per hour (scfh). Gas flows in excess of 196 scfh were measured by using the meters in parallel. Helium flowrates were obtained from the argon flowmeter readings by use of conversion graphs furnished by Airco.

Plasma-Generator. The water-cooled plasma-generator was made in four pieces, the top and bottom end-pieces, and the inner and outer tubes (Fig. 4). The end-pieces were made of brass, the outer tube was Pyrex, and the inner tube was Vycor. Standard rubber O-rings coated with high vacuum silicone grease provided the seals between the end-pieces
and tubes.

The top end-piece contains the gas inlet, the gas injection plate, and the coolant outlet. In the gas injection plate are eight 0.25-in.-diameter holes equally spaced on a two-inch-diameter circle. The holes are drilled fifteen degrees to the edge of the injection plate, as the gas enters the inner tube through these holes, the plasma-stabilizing vortex is formed. The coolant outlet is a piece of 3/8-in. copper tubing.

The bottom end-piece contains the hot-end exhaust port, the coolant inlet, and the coolant manifold. The hot-end exhaust exits axially through a 3/4-in.-diameter port, and a piece of 3/8-in. copper tubing provides the coolant inlet. The coolant enters and leaves the coolant manifold concentrically to prevent stagnation areas from forming in the coolant outlet. It circulates between the inner and outer tubes. The coolant manifold was formed by machining a groove in the bottom end-piece. The coolant leaves the coolant manifold through the annulus formed by the inner tube and the 3/4-in.-diameter port that forms the top of the manifold. This narrow exit annulus (1/16-in.) affects the coolant between the tubes, controlling hot-end effect at the coolant inlet. It permits an upward axially flow path, toe of stagnation area, to exit between the tubes.

The tubes are mounted co-axially between the end-pieces. The inner tube is a Vycor tube 18-in. long with a nominal 75-mm outside diameter. Vycor was required because the inner tube must be capable of supporting a severe temperature gradient. On many occasions it was
observed that while the outer surface of the Vycoor tube remained at water temperatures, the inner surface was glowing red hot. The outside diameter is listed as a nominal 75 mm because variations in this diameter of plus or minus one or two millimeters are common, and the tubes are often out-of-round. Because of these irregularities, the ends of the Vycoor tubes must generally be sized before they were used.

The outer tube was a pyrex tube 18 mm. long with a nominal outside diameter of 57 mm. The outer tube carries the axial compressive loads which are applied to hold the lamina-water tube together. The end-plates are constructed in such a way that no axial or transverse loads can be applied to the inner tube. This was done to prevent possible breakage of the inner tube by the combined effect of axial compressive, thermal stresses, and hoop stresses caused by the pressure of the coolants.

Standard rubber rings were used to provide a seal between the end-plates and the inner and outer tubes. The rings were used at each seal to improve the reliability of the seal. Rubber saddles were used to prevent direct contact between the ends of the tubes and the end-plates to prevent chilling. The bottom end-plate is supported by the calorimeter and an O-ring provides the seal between these two parts.

Calorimeter. The calorimeter consists of an outer elliptical jacket and two inner coils of copper tubing (Fig. 1). The water enters the outer shell of the jacket, flows up the outer shell, down the inner shell and then leaves the jacket. The cooling water next flows through the ascending coil of copper tubing, which is wrapped around the descending coil of copper tubing, and then through the descending coil and
out of the calorimeter. The coils of copper tubing were modifications
made to existing equipment, and represent the simplest change that
could be made. An existing joint in the exhaust pipe was separated and
the cooling coils were inserted into the exhaust pipe. The cooling
arrangement that resulted was not ideal, but it was adequate. The
temperature of the exhaust gas was measured after the gas left the
cooler, and the exact cover remained in the exhaust gases at this
point was approximately 100°C (212°F). After the gas leaves the
cooler, it can be directed to the atmosphere or to a vacuum pump.

Vacuum system. The vacuum system used in this run was constructed
by Henry J. G. H. B. (1945), but is a single-stage, return-type, oil-sealed
oil-sealed. Oil was used as a seal for reducing the pressure in the vacuum chamber to 10^-4 torr, absolute
(0.0001 in.), under no-flow conditions.

Vacuum pressures were read on a vacuum pressure gage calibrated
from 0.0001 in. to 14 in. Hg. The area of interest was below
1 in. Hg. An oil diffusion system was also obtained, but installation
satisfactory results in the vacuum chamber, and a start could be made.
The beam was not operated in a vacuum other than under starting.
A second pressure gage in the system, which read pressures above and
below atmospheric. In lieu of mercury, we used to determine the
appropriate time for opening the exhaust valve. The exhaust valve was
opened when the pressure was indicated at some pressure.
Coolant water. The coolant system consisted of a coolant supply, the plasma-generator, the calorimeter, flowmeters, and connecting lines.

The primary coolant was tap water, but an alternate coolant supply was available for use in the plasma-generator. The alternate coolant was "black water" and was used to measure radiation power. The black water was a mixture of Carter's India ink, tap water, and aqueous ammonia. The approximate proportions used were 3.5 gallons of water, three pints of India ink, and one pint of ammonia. The ink was added to the water until the plasma was no longer visible through the plasma-generator, and the ammonia was added to prevent the ink from separating out of the water.

During operation, the black water was recirculated through a salvaged drum. The water with ink flowed through submerged cooling coils in the drum removed heat from the black water as it recirculated. The recirculating pump would deliver 250 pounds of water per hour at 31°F, which was 6.6 pounds per hour less water and six psi less pressure than the tap water supply provided. The higher flow rate for tap water was used to inhibit nucleate boiling in the plasma-generator, because nucleate boiling leaves mineral deposits in the inner tube which interferes with radiation measurements.

Selector valves in the plasma-generator coolant lines permitted a shift to black water without the necessity of stopping the plasma. A bypass line was put in the black water system to permit operation of the recirculating pump at any time.
Coolant inlet pressure was monitored during the runs. In general, the black water pressure remained constant, but occasional high frequency fluctuations were noted. The tap water pressure was often varying up and down as much as two psi several times a minute.

Coolant flow to the plasma-generator was measured by four Fisher and Water-stable flowmeters in parallel, and water flow to the water jacket was measured by a Fisher and Water-stable flowmeter. The flowmeters and flowmeter were accurate to the nearest five pounds per hour. The flowmeters could not be read when operating with black water, however, sufficient time was available between the time black water was selected and the time it reached the flowmeters to allow the new flow to stabilize and recirculate. Thereafter, the black water flow was recorded constant, which was assumed to be a valid assumption based upon the constant black water inlet pressure.

Temperature recording system. The temperature recording system consisted of three-General thermocouples, a cold junction, and a continuous recording voltmeter. The recording voltmeter used was a Honeywell voltmeter, Model 566-1500 mA. The system was calibrated at the bath temperature, black water temperature, and at 0°F and 180°F. The system was linear over this temperature range, with an average precision of 0.1°F per inch. The voltmeter traced a toroidal-volt-inch scale on the face, and the temperature traces were about 1/20-in. wide. The deflection of the center of the temperature trace was read to the nearest 1/4-in. Records were simultaneously made of the coolant inlet and outlet temperatures, and of the exhaust
and temperature after the gas left the calorimeter.

**Support stand and scaffold.** The calorimeter was mounted on the support stand (Fig. 3). The calorimeter supported the bottom of the plasma-generator, and the support stand scaffold restrained the top of the plasma-generator. The restraining force applied to the top of the plasma-generator was necessary to hold the plasma-generator together because of the pressure of the coolant in the plasma-generator. The force on the top end-piece caused by this pressure was strong enough to cause the original wooden cross-bar of the scaffold to bend and thus allow the top end-piece to move. For this reason, an aluminum channel was used to reinforce the cross-bar, and then the restraining force was adjusted so that the top end-piece did not visibly move when the coolant was turned on. The outer tube of the plasma-generator is required to carry this load, and also the load resulting from the vacuum in the inner tube, before the coolant is turned on.

**RF power supply.** The rf power supply was a Heathkit 25-watt oscillator rated at 250 kV at 2 Me. The power output of this oscillator could be controlled by selecting one of the nine discrete plate voltages available, and then selecting a duty cycle. The plate voltage could not be changed while the power supply was operating, however, the duty cycle could be varied at any time from 0-100%. At duty cycles less than 100%, the rf power was delivered in pulses of varying lengths depending upon the duty cycle selected. The pulse rate was 360 per second. A duty cycle of 50%, then, resulted in pulse lengths of 1/720 second. A 100% duty cycle was used for this study, except during starting.
Experimental Procedures

The experimental procedures had to be divided into three categories. These three categories are (1) pre-starting procedures, (2) starting procedures, and (3) late run procedures. The tasks covered under each category will be repeated in a typical case of experiment. In addition, it was vital to ensure that the same items were used under all conditions. To do this, a typical case of start-up procedure was presented.
when the course, which in this case usually a year and for all times
where the water enters the frame of control, small leaks of this nature can
often be stopped by turning the piston heads to thereby releasing the
water. If that effort fails, it is necessary to disassemble the
piston-pump and replace the piston of different sizes.

If no leaks are apparent, the intake inlet pressure is raised to
40 psi, in which case one should see a small flow. The flow
to be the flow-meter or it will be approximately 1.5 lbs. for 4 hr.,
and the flow to the valve must be about 1,000 liters. or
the collector of water must be in order to produce the time
required for the test of the pump.

We remove the side valves and check the black-water system,
the water of the black-water only to be filled by observing the sound of
the water interior to the channel and the water in the pump
channel. In this manner, water is released.

After the intake valve admits water, the water is
slowly released out the top until the desired amount is removed, and
any amount of the water has been examined for impurities and
contaminants.

With the complete of a 30-minute, 12-hour test, more than
50 percent operation are assured. However, the selection will be made on
the basis of experience, which must be constantly checked for a daily report of proximately 1 hour to hour sufficient
data to maintain for a long time.
**starting Procedure.** The starting procedure is not included in the data run section because special attention should be given to this critical portion of the plasma operation. The plasma is started in an argon atmosphere at an absolute pressure less than 0.005 Torr. Incandescent rose glow at the arc is desirable because starts may be obtained at lower rf output levels. This reduces the possibility of lower tube flashover. The flashover on occasions is not always the tube, but it may also occur due to metal residue, or due to over-boost.

After the starting pressure has been reached, the rf power is slowly increased. The rf power is slowly increased until a pale pink glow is seen in the torch-vacuum. At this time, the valve to the vacuum is turned off, and the valve to the torch is turned on, and the valve to the pressure is turned on. The pressure is built up in the plasma. The secondary valve is now turned off, and the valve to the flow is turned on. The flow is slowly increased to about 75 l/min, while the cover is gradually increased to about 15 torr, the pressure is increased with the gas flow. Should the cover be increased too rapidly, the plasma will extinguish if the cover is increased too rapidly, the plasma will extinguish. If the cover is increased too rapidly, the plasma will extinguish. If the cover is increased too rapidly, the plasma will extinguish.
The danger of discoloration rapidly decreases (due to plasma contraction) as the pressure and gas flow increase. As soon as the plasma contraction is noticed, the rf power may be increased fairly rapidly to a duty cycle setting of approximately 50%. Meanwhile, a close check on the helium pressure is maintained, and as the pressure case reaches zero volts, the exhaust valve is opened. Then this task has been accomplished, the starting procedure is complete.

**Note for**. The data run begins when the gas flow is increased to the maximum altitude of 25 sec. attainable, and the duty cycle is adjusted to 50%. The duty cycle remains on 50% for the remainder of the data run, while the gas flow is reduced in 25 sec. increments, until a flow of 0 sec. is reached. As soon as temperature equilibrium for each flow rate is indicated by the traces on the Wacholder tape, the tape is stopped after the gas rate is set, and all meters are read. The meters read are the rf power supply, rate multiplier and rate controller, and all the water flowmeters.

A lower limit of 10 sec. on the gas flow was established because at flows less than 10 sec., coolant boiling becomes substantial enough to cause mineral deposits to form on the inner tube, which interfere with radiation measurements.

After readings for a gas flow of 25 sec. are taken, the gas flow is increased to its maximum value as before, and the plasma-generator coolant supply is switched to black water. The coolant flowmeters must be read as soon as the coolant flow indications stabilize. There is
sufficient clear water in the coolant system ahead of the black water
to allow the stabilized flow-indications to be read, before the flow
indicators are obscured by the black water. The black water flow-rate
is assumed constant for the remainder of the data run. This assumption
is reasonable since the black water entry pressure remains constant
except for occasional indications of slow frequency fluctuations of plus
and minus 1/2 psi. The origin of these fluctuations is unknown, however,
the fluctuations did not appear to affect coolant flow-rate.

With the exception of the assumed constant values of black water
flow, water readings are obtained at 25 such flow increments as before.
After the final set of readings are taken, the gas flow is increased to
maximum value, and the duty cycle percentage is decreased, prior to
turning off the rf power supply. This was done to cool the inner surface
of the inner tube gradually enough to prevent post-operating tube cracks,
which result from residual stresses caused by rapid cooling.

After the rf power supply was turned off, the clear water coolant
supply was again selected, thereby flushing the black water from the
coolant lines.

Physical appearance of plasma

The plasma first appears as a brilliant blue-white discharge, in
the vicinity of the rf injection coil, the instant the argon gas flow
commences during the starting procedure. The plasma appears to extend
out to the Vycor tube when operating at this low pressure. As the
pressure and gas flow increase, the plasma contracts so that the
luminous cases no longer appear to contact the tube wall. The plasma is now shaped as a cylinder five to six inches in length and roughly centered in the rf coil area. This general shape is maintained until the gas flow approaches 75 sccm. At this gas flow, the top edge of the plasma intermittently extends up to the injection plate in the top end-piece. As the gas flow is increased to 7o sccm, the back-flow of cases up the center of the tube becomes strong enough to cause the top edge of the plasma to become permanently extended. The diameter of the extended portion of the plasma is largest at the top of the rf coil, and is smallest at a point about two inches below the injection plate (Fig. 4). At this point the plasma begins to diverge toward the inlet holes in the injection plate. Further increase in gas flow, the bottom edge of the plasma extends downward slightly below the bottom edge, the brilliance of the plasma fades very sharply into a ragged-edged tail-flame approximately one inch long.

This description is representative of typical plasma operation. The dimensions of the plasma were not measured, and all stated values are approximations. Further, the dimensions of the plasma, and the gas flows at which plasma extinction occurs are strongly dependent upon the rf power level. More important than the exact dimensions of the plasma are the changes in appearance of the plasma which result from changes in rf power and gas flow. Within the range of rf power and gas flow used in this study, increasing the rf power increases the diameter of the plasma and increases the length of the tail-flame, while increasing the gas flow decreases the diameter of the plasma, and increases
the length of the tail-flare. The changes due to changing rf power were observed by chasing the after cycle. After the rf power and res flow were set, for a data run any changes in the brilliance of the plasma were too subtle to be detected by eye. Due to the intense brilliancy of the plasma, it was normally observed for a few minutes only.

**Temperature profile**

A method for computing the temperature profile of an arc plasma is explained by [17]. In brief, this method is based on the temperature coefficient of the normalized relative intensity of the atomic lines with monochromatic light from the arc [19]. The observed intensities of three lines show a pattern, \( I(x) \), which is similar to intensity with the function of the radius, \( J(r) \), on the following integral (Appendix A). The temperature distribution will result in

\[
J(r) = \frac{I}{11} \left[ \frac{N'(x) \, dx}{\sqrt{x^2 + r^2}} \right]
\]

Figure 6 shows the results obtained by inverting observed \( I(x) \)'s to radial distribution, \( J(r) \)'s using this integral, and then normalizing each curve with respect to its maximum intensity. This figure clearly shows that \( J(r) \) has a more pronounced line at r equal zero, than does \( I(x) \) at x equal zero. The temperature profile, \( T(r) \), may now be plotted by taking the normalized relative intensity of one of the
spectral lines from Figure 6 for a particular radius, and obtaining the corresponding temperature from Figure 5. At this point, it is well to note that an ambiguity exists when using a single spectral line to determine temperature. With a normalized relative intensity of 0.85, it is possible to obtain values for temperature of either 12,000°K or 16,400°K. This ambiguity is solved by the presence of a measurable intensity of lambda 4921.14, which indicates temperatures above 14,000°K; or by the absence of this line, which indicates temperatures less than 14,000°K.

The investigation of the temperature profile of the plasma under study here is not complete; however, sufficient preliminary investigations were made to justify certain conclusions concerning the temperature distribution.

The intensity of lambda 4921.14, \( k(x) \), was recorded for off-center maxima successively after lower levels. The recorded \( k(x) \)'s showed maximum values of lambda center-line (\( k(x) \)). The recorded maxima intensity and the center-line intensity increased as a result of the first laser increase. The lower level was raised with consecutive increases in power produced an increase in the recorded maxima intensity. At this point the trend between the off-center intensity curve began to increase, and the center-line intensity began to stabilize. These off-center peak intensities were now interpreted to be the location of the 15,000°K isotherm. Since the center-line intensities as \( k(x) \), were always less than the off-center maximum, even when the off-center
maximun could not be identified with the 16,000F absorption. It was concluded that the center temperature was less than 15,000F. If, however, those low center-line intensities were indicative of temperatures above 16,000F, the temperature would have to be in excess of 17,000F. At this temperature, the calcium II line should show a weak intensity on the center-line, but the temperature did not exceed 16,000F. The presence of the calcium II line was detected in the plasma, but only very faintly, and the center intensity normal to the plasma. This feature was interpreted to indicate the existence of a lower temperature, and in a very thin sheath near the core of the plasma, with the center-line temperature less than 15,000F.

These conclusions are consistent with the observed physical characteristics of the plasma. The first important characteristic is that the effect must be assumed to be transferred to the plasma in a manner that indicates an area of carbon electrical conductivity, which, in the case of maximum temperature, would indicate carbon deposition. The second characteristic observed was a reverse flow of plasma in the center of the tube, which, in a manner analogous to the motion of water in a river, is modified only slightly by the presence of the plasma. The existence of this indicated a change near the center of the tube where the existence of the cold temperature is the mere remnant of the rich plasma. This indicated a lower plasma temperature, above 16,000F, with the plasma in the center of the tube.

The plasma in the outer regions, below its maximum temperature, existing in a thin equilibrium sheet near the outer limit of the plasma, with a strong reverse flow of relatively cold plasma through the
center of the plasma. These findings are contrary to the findings of T. J. Reel who concluded that the highest temperatures exist at the plasma center (Ref. 1: 253). The plasma investigated by Reel was operated at a frequency of 4 megacycles at atmospheric pressure, using low arc elevators, in a partly closed and stable diameter of 30 cm.

**Table I**

The plasma was operated in four modes, as shown in Table I. As the study was originally conceived, Mode 1 was to be the standard mode for the laboratory, and the other modes were to be different from Mode 1 in only one parameter. However, the plasma would not start in the standard mode of operation, in Mode 4, and could not be started at a plate voltage of 7.6 kV, so the study was run in Mode 4. The plasma was chosen as the standard mode because operation in this mode was the simplest. Laboratory techniques used in this study resulted from the experience gained while operating in Mode 4.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Plate Voltage (kV)</th>
<th>Gas (l/hr)</th>
<th>Outer Shell Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.4</td>
<td>1.0</td>
<td>75 mm</td>
</tr>
<tr>
<td>2</td>
<td>8.2</td>
<td>1.0</td>
<td>75 mm</td>
</tr>
<tr>
<td>3</td>
<td>8.1</td>
<td>1.0</td>
<td>65 mm</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>0.3</td>
<td>75 mm</td>
</tr>
</tbody>
</table>
Note 3. Operation in Note 2 was to show the effect of increasing the power available at a duty cycle of 0.0. In particular difficulties were encountered with operation in this mode; however, power control, unit starting, and more critical since the power output increases more rapidly with increasing duty cycle, operation in Note 2 was not feasible.

Note 3. Operation in Note 3 was to show the effect of increasing the power available at a duty cycle of 0.0. In particular difficulties were encountered with operation in this mode; however, power control, unit starting, and more critical since the power output increases more rapidly with increasing duty cycle, operation in Note 2 was not feasible.

Note 4. Operation in Note 4 was to show the effect of increasing the power available at a duty cycle of 0.0. In particular difficulties were encountered with operation in this mode; however, power control, unit starting, and more critical since the power output increases more rapidly with increasing duty cycle, operation in Note 2 was not feasible.
the hole was approximately 4” smaller in volume. The phase was started in pure open and the culture was introduced after the duty cycle had been adjusted to 20%. The appearance of the phase which was 4” smaller was not very different from the appearance of a pure open phase. Indeed, if the substrate volume is greatly increased, the appearance of the ‘open’ phase will be different, and the phase will be extended.
III. Discussion of Data

The discussion of the data is presented here under three headings; data reduction, data presentation, and data accuracies. In this manner, it is hoped that the reader will gain a feel for the problems involved using the experimental techniques outlined in this study.

Data Reduction

The recorded data were in the form of volts, amperes, and flow rates. These data were first converted into power units, kilowatts, and then tabulated as shown in Table II.

Table II
Sample Power Measurements, Mode 3

<table>
<thead>
<tr>
<th>Row</th>
<th>Gas Flow (gph)</th>
<th>( q_w ) (kW)</th>
<th>( q_b ) (kW)</th>
<th>( q_c ) (kW)</th>
<th>( P_t ) (kW)</th>
<th>( P_{tl} ) (kW)</th>
<th>( P_{te} ) (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>175</td>
<td>0.14</td>
<td>3.93</td>
<td>147.0</td>
<td>121.0</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>175</td>
<td>12.08</td>
<td>4.00</td>
<td>152.0</td>
<td>121.0</td>
<td>31.0</td>
<td></td>
</tr>
</tbody>
</table>

The symbols used in the table are defined as follows:

- \( q_w \) - The power measured from the clear water used to cool the plasma-generator.
- \( q_b \) - The power measured from the black water used to cool the plasma-generator.
- \( q_c \) - The power measured from the cooling water in the calorimeter.
- \( P_t \) - The plate power measured in the rf power supply when the plasma is operating.
- \( P_{tl} \) - The plate power measured in the rf power supply when the plasma is not operating, or idle line plate power.
- \( P_{te} \) - The excess plate power, which is the difference between \( P_{tl} \) and \( P_t \).
The first row of data was recorded during the clear water run and the second row recorded during the black water run. The difference in plate power between these two runs of 5.8 kw is larger than most differences recorded, but it serves to show the necessity of normalizing the data before any computation of the radial radiation power, $Q_r$, can be made.

The quantity $Q_d$ is a measure of the power transferred to the walls by convection and that portion of the radiation absorbed by the clear water and the glass tubes. This portion of the radiation power was assumed negligible in comparison with either total radial radiation power, or convective power to the walls. The quantity $Q_b$ is a measure of the sum of the power transferred to the walls by convection, $Q_c$, and the radial radiation power, $Q_r$. $Q_r$ is radial radiation power that exists in the range of wavelengths for which Vycor, water, and Pyrex are transparent.

Note: The quantity $Q_r$ will hereafter be referred to simply as radiation power. It is in fact a measure of radial radiation only, as the axial radiation power is absorbed by the top end-piece of the plasma-generator and the calorimeter. No attempt was made to measure the axial radiation power, but it is included in the measurement of $Q_c$ and $Q_b$.

If we therefore subtract $Q_d$ from $Q_b$, the difference should be $Q_r$. From Table II, the value for $Q_r$ thus computed would be 3.84 kw. Implied in this computation is the assumption that all the additional power measured with the black water was radiation power, and no consideration was given to fact that the rf plate power was 5.8 kw higher during the black water run. This increase in plate power reflects an increase in rf power output of something less than 5.8 kw due to normal losses in
the rf power supply. In turn, there would be an increase in power transferred to the gas somewhat less than the increase in power output due to normal coupling efficiencies between the rf coil and the plasma.

The problem, therefore, is determining how much of the 3.4 kW is due to radiation, and how much is due to the increase in rf power output. As a first step toward this, Table II can be utilized by normalizing to a standard input of 1.6 kW before subtraction.

The values were normalized with respect to $\alpha_o$. Table III lists the values for $F_1$ for the different plate voltage settings. The $\alpha_P$, $\alpha_o$, and $\alpha_L$ were multiplied by a constant to maintain a constant efficiency which will be called $\alpha_{eq}$. The value for $\alpha_{eq}$ is $\alpha_P$, $\alpha_o$, and $\alpha_L$, respectively. Values for $F_1$ are plotted in Figure IV. Table IV lists the results of normalizing the data in Table II.

### Table III
Plating Plate Power

<table>
<thead>
<tr>
<th>Mode</th>
<th>Plate Voltage (kV)</th>
<th>$F_1$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>10.1</td>
<td>12.0</td>
</tr>
<tr>
<td>4</td>
<td>12.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Table IV
Sample Normalized Power, Mode 3

<table>
<thead>
<tr>
<th>Gas Flow (scfh)</th>
<th>$\alpha_{eq}$</th>
<th>$\beta_P$ ( )</th>
<th>$\beta_o$ ( )</th>
<th>$\beta_L$ ( )</th>
<th>$\alpha_T$ ( )</th>
<th>$\alpha_T$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>33.0</td>
<td>14.56</td>
<td>5.8</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>30.6</td>
<td>12.25</td>
<td>5.8</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

25
is taken as the difference between \( I_p \) and \( I_0 \), and is assumed to be unaffected by the different values of \( I_p \). The validity of this assumption is open to doubt, but it appears to be a better first approximation than assuming that \( I_p \) remains constant during the increase in \( I_p \).

The values for \( I_p \) listed in Table IV are found by multiplying \( I_p \) by the appropriate \( I_0 \). This was done for the sake of comparison with the normalized values for \( I_p \) of 0.25 \( I_0 \). It is also apparent from Table IV that two values for \( I_p \) can be obtained at each gas flow. Hereafter, when a value is given \( I_p \), whether it be in text, table, or graph, the value given will be the average of the two values of \( I_p \) for that gas flow. From Table IV, the value of \( I_p \) is 0.41 for a gas flow of 175 SCFH.

The quasi-efficiency notation of the quantity \( u \) was mentioned, without discussion, before. \( u \) as defined, is the percentage of excess plate power which goes to the plasma. The percentage of additional RF power which goes to the plasma would be of more interest to this study, but no means of measuring RF power was at hand. It is possible to say, however, that the amount of RF power available from this power source to operate the plasma is less than \( I_0 \), as it is not likely that all of this excess plate power is converted to RF power. Therefore, the values found for \( u \) will be conservative estimates of the overall efficiency between the RF coil and the plasma. An item of interest, in addition to power conversion efficiencies, is the manner in which the power that goes to the plasma is distributed between the wall, radiation,
and the calorimeter. After \( B_d \), \( B_p \), and \( B_c \) are found, they can be summed to form a total effectiveness, \( E_t \). Let the ratio of \( E_d \), divided by \( E_t \), be defined as \( R_d \). Similarly, define \( R_p \) and \( R_c \). These ratios show the distribution of power within the gas, as illustrated in Table V.

<table>
<thead>
<tr>
<th>Table V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Power Ratios, Mode 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gas Flow (sqf)</th>
<th>( R_d (% ) )</th>
<th>( R_p (% ) )</th>
<th>( R_c (% ) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>69.8</td>
<td>10.9</td>
<td>25.3</td>
</tr>
</tbody>
</table>

**Data Presentation**

The data are presented in terms of the power coupling effectiveness, \( E_t \), and the power distribution ratio, \( R \), vs. gas flow in Figures 10 through 16. The points on the \( B_d \), \( B_p \), and \( B_c \) vs. gas flow graphs (Figs. 14 and 15) were obtained by normalizing \( B_d \), \( B_p \), and \( B_c \) with respect to \( B_p \). The curves on these graphs represent the best fit to the data points by a second order (parabolic) curve. However, there is good argument for use of a third order (S-shaped) curves for \( B_p \), Mode 2, and for \( B_d \), Modes 2 and 3, based on the number of data points and their distribution. The type curve chosen to represent a series of data points should be based upon the exactness to which each data point can be located, as well as to the number and distribution of the points. If high confidence in the location of each data point is justified, a curve which closely fits all the data points can be drawn. If, however,
the possible variation in the exact location of a data point is large,
then a lower order curve which tends to average out the point location
uncertainties is more reasonable. The exact locations of the data
points for $E_y$ and $E_b$ are not known with sufficient accuracy to justify
more than a second order curve.

The feet attached to each end of these curves show the possible
vertical displacements of the data points based upon the probable
error in reading the coolant temperatures of plus or minus one degree
Fahrenheit. These vertical displacements are essentially constant for
all data points along that curve, and this display method was chosen
over attaching the feet to each data point to prevent excessive clutter-
ing of the graphs.

After the curves for $E_b$, $E_y$, and $E_c$ were plotted, the difference
between the $E_b$ and $E_y$ curves was drawn as the $E_r$ curve (Fig. 11), and
the sum of the $E_b$ and $E_c$ curves was drawn as the $E_t$ curve (Fig. 13).
The data dispersion which is inherent in the process of subtracting at
each data point, and then plotting, is shown quite well in the plots
of the data for $E_r$. The data points shown result from the subtraction
of $E_y$ data points from $E_b$ data points. The subtraction technique will
always produce this type of dispersion whenever the data are not per-
factly smooth. The probable vertical displacement of points on the $E_r$
curve was taken as $(2)^{1/2}$ times the average displacements for the $E_b$
and $E_y$ curves since these displacements are close to being equal.

The curves for $R_y$, $R_r$, and $R_c$ result from dividing the $E_y$, $E_r$, 
and $E_c$ curves by the $E_t$ curve. In this manner, the normalizing quantity
If not fully understood, and the resulting quotients, $Q_v/Q_t$, $Q_r/Q_t$, and $Q_c/Q_t$, are the power distribution ratios, $R_v$, $R_r$, and $R_c$ (Fig. 14, 15, and 16).

**Data Accuracies**

The only significant source of error in the data results from the low accuracy to which the coolant temperature rises can be determined. By reading the deflection of the center of the temperature trace to the nearest 1/40-in., the probable error in temperature measurement is approximately plus or minus one degree Fahrenheit. The following example illustrates the consequence of such an error.

For a typical coolant flow of 2500 pounds per hour, an error of plus or minus 0.732 kW may be expected in the value for $Q_v$. The resultant errors in $E_v$, from errors in power of this size, range from plus or minus 2.5% to plus or minus 0.9%. That is to say $E_v$ equals 40% plus or minus 2.5%. For $E_r$, the errors due to inaccurate temperature measurement, range from plus or minus 2.2% to plus or minus 0.8%, which are slightly less than errors for $E_v$ due to the lower black-water flowrate. The errors in $E_r$ will contain the errors in $E_v$ and $E_b$. Since the errors in $E_v$ and $E_b$ for a particular operating mode and gas flow are approximately equal, the error in $E_r$ was taken as the $(2)^{1/2}$ times the numerical average of the errors for $E_v$ and $E_b$. The range of errors thus computed for $E_r$ are from plus or minus 3.3% to plus or minus 1.2%. Except for some variations in coolant flowrates, the errors in $E_v$, $E_b$, and $E_r$ due to an error of plus or minus one degree Fahrenheit, are inversely proportional to the normalizing quantity, $P_c$. Other errors...
result from the accuracy to which the coolant flowmeters, plate
voltmeter, plate ammeters, and gas flowmeters can read, and from the
failure to remove all of the power from the gas in the calorimeter.

The two plate ammeters can be read to the nearest 0.1 ampere,
and the plate voltmeter can be read to the nearest 0.1 kv. The in-
herent error here is plus or minus 0.0035 kw which is insignificant
when compared with the lowest value of Pe, which is 27 kw.

The Airco flowmeters are stated to be accurate within five
percent, and they can be read to the nearest one scfh. It is assumed
that any inaccuracies in the flowmeter are distributed over the whole
range of the flowmeter. This type error will be shown as a scale
derror on the graphs, without appreciably changing the general appear-
ance of the curves. The inaccuracy in reading the flowmeter would
show as a horizontal displacement of a data point on the graph,
however, a horizontal shift of one scfh would be hard to detect on the
scale of 50 scfh per inch.

The largest amount of power remaining in the gas as it left the
calorimeter was on the order of 0.03 kw. Had the calorimeter been
totally effective, this power would add to \( Q_c \). Since the smallest
value for \( Q_c \) was 2.62 kw, the error in neglecting the power remaining
in the gas is acceptable.

The water flowmeters could be read to the nearest five pounds
per hour, or to within two and one-half pounds per hour. This error
in coolant flow can lead to an error in power measurement up to 0.06 kw
depending upon the coolant temperature rise. The largest coolant
temperature rises were in conjunction with power measurements on the
order of 30 kW, so that this error is also negligible.
IV. Results and Conclusions

Before presenting the results and conclusions, it is necessary to fix in the mind of the reader exactly what was measured during this study, and what the purposes of the study were.

The quantities $q_w$ and $q_b$ represent the power transferred to the coolant as it passes through the plasma-generator. The quantity $q_e$ represents the power transferred to the coolant in the calorimeter.

$q_w$ is composed of three terms; a wall loss term, a radiation term, and a heat loss term. The wall loss is the power transferred by convection to the wall in the area of heat addition to the plasma. Since the plasma extends up to the injection plate, some wall loss is experienced there also. The radiation term is composed of the radiation absorbed by the coolant, the outer iyrex tube, the inner iyrex tube, and the top and bottom end-plates. The heat loss term represents power transferred to the wall which was available in the gas flow as enthalpy after the gas left the area of heat addition.

$q_b$ is composed of the same terms as $q_w$ with an additional radiation term. This additional term represents the radial radiation power absorbed by the black water.

$q_e$ is composed of two terms. The first term represents the power available in the gas flow as enthalpy after the gas leaves the plasma-generator. The second term represents the radiation from the plasma which is absorbed in the calorimeter. For the most part, this radiation
is axial radiation, but at high gas flow in small diameter tubes, the visible plasma could extend down into the calorimeter, in which case some radial radiation would also be measured.

The definitions for $Q_r$ and $Q_t$ need not be further expanded. $Q_r$ remains the difference between $Q_b$ and $Q_d$, and represents the difference between the total radial radiation and that portion of radial radiation which is absorbed by the plasma-generator, clear water, and the calorimeter should the plasma extend that far down. The total power transferred to the wall, $Q_t$, remains the sum of $Q_b$ and $Q_c$.

The normalized quantity, $F_0$, is the difference between a varying total rf power above plate over $P_t$, and the constant value of tilling plate power, $P_t$. When a constant duty cycle is chosen, no control can be exerted on $P_t$, as the rf power supply automatically adjusts $P_t$ in response to the load placed upon it. Since $F_0$ differs from $P_t$ by a constant, the variation of $F_0$ with gas flowrate can be deduced from the plot of $F_0$ vs. gas flow ($F^r$, 17). Refer to Table III for values of $F_t$.

The normalized quantities, $E_w$, $E_r$, and $E_c$ represent a percentage of $F_0$, and therefore show how much of $F_0$ was effectively transferred to the wall, to radiation, and to the calorimeter. When each of these characteristics is divided by their sum, $E_t$, the ratios $E_w$, $E_r$ and $E_c$ are obtained. These ratios show the percentage of the total power transferred to the plasma that goes to the wall, to radiation, and to the calorimeter.
In general, $E_t$ did not vary greatly with gas flow (Fig. 13). Therefore, if either $E_v$, $E_r$, or $E_t$ shows a strong variation, one or both of the other parameters must make compensating variations. Further, the relative constancy of $E_t$ ensures that increases or decreases in $E_v$, $E_r$, or $E_t$ are reflected by corresponding increases or decreases in $E_v$, $E_r$, or $E_c$. For this reason, the results and conclusions will be discussed in terms of $E_v$, $E_r$, $E_c$, and $E_t$ only.

The objectives of this study were (1) to operate a stable plasma at atmospheric pressure at 3.0 mw with a sustained high-power operation capability, (2) to determine the temperature profile of the plasma as a function of the plasma radius, $T(r)$, (3) to measure the power transmitted to the plasma, and (4) to determine parameters important to the energy coupling mechanism.

**Plasma Operation**

Using the techniques described in this study, a stable plasma was operated at 2.00 kw at atmospheric pressure. No endurance runs were made, however, the plasma has been continuously operated for forty minutes during some data runs which included peak plasma powers up to 52 kw. With a modified injection plate to prevent injection plate damage, and heat resistant seals to prevent seal deterioration, the plasma is believed capable of continuous operation at the 50 kw power level at gas flows above 100 scfh, in a 75-mm Vycor tube. Stable operation of the plasma was concluded on the basis of apparent constant plasma geometry, and stationary values of coolant temperature indications during operation at constant gas flow.
Temperature Profile

Although temperature profile measurements were not complete, the existence of a temperature of \(1,600^\circ\text{K}\) near the outer surface of the plasma was verified, and a model temperature profile was deduced. The deduced temperature profile shows the highest temperatures occurring in a thin cylindrical shell near the outer surface of the plasma, and relatively cooler center-line temperatures existing in a reverse gas flow.

Power Measurements

The techniques used to measure power were only partially successful. The margin for error in determining the coolant temperature rise was unacceptable for so critical a measurement. This fault coupled with the shift in \(P_0\) between the clear water and black water runs, led to excessive data dispersion which in turn prevented obtaining point-by-point radiation power values by subtraction of the point values for \(Q_y\) and \(Q_x\). \(Q_y\) and \(Q_x\) were normalized with respect to \(P_0\) and the results plotted as \(E_y\) and \(E_x\) vs. gas flow in each. A smooth curve for \(E_y\) was then drawn and subtracted from the smooth curve drawn for \(E_x\). This yielded smooth curves for normalized radial radiation power, \(E_r\). The usefulness of radiation values obtained in this manner rests on the validity of the averaging processes inherent in normalizing data and plotting smooth curves. In consideration of the limitations imposed by possible data accuracies and experimental techniques used in this study, the information displayed on all graphs should be viewed as
first approximations of actual values and trends.

The black water technique as applied in this study is very useful as a means of determining total plasma power. Better measurements of radiation power would be possible with the use of an improved black water which did not leave deposits on the inner tube. This innovation is discussed under "Recommendations". With the use of an improved black water, this technique of measuring radiation power should yield usable radiation power data without the necessity of first normalizing the data.

**Coupling Parameters**

The controlled parameters were rf power supply plate voltage, inner Vyceor tube diameter, gas composition, and gas flow, however, other implicit parameters were present. The implicit parameters appearing in this study are plasma pressure, vertex strength, rf power supply plate power, and plasma length and diameter. No control can be exerted over these parameters, as they are the natural consequences of varying the controlled parameters.

Conclusions concerning a coupling parameter must be supported by a reasonable quantity of data pertinent to the effects of that parameter. The predominance of information gathered in this study directly concerned gas flow. For this reason, the effects of varying gas flow are well described. The effects of varying gas composition, inner tube diameter, and plate voltage cannot be described nearly as well due to the meager investigations made of each of these parameters.
Direct comparisons of the operating modes which contain these parameters as variables can establish a trend which would have some short range validity, but any long range projections made on the basis of these limited comparisons are of doubtful validity.

Gas Flow. The effect of increased gas flow on all operating modes is similar, but somewhat varying in degree. For instance, a sharp decrease in \( E_y \) is noticed with an increase in gas flow for Modes 1, 2, and 3, but Mode 4 exhibits only a slight decrease in \( E_y \). In general, the decrease in wall loss and radiation characteristics and the increase in the calorimeter characteristics with increasing gas flow can be attributed to the decrease in plasma diameter which occurs with increasing gas flow. Some lengthening of the plasma tail-flame is also noted with increased gas flow, but no significant increase in length of the highly ionized portion of the plasma was observed. As the plasma contracts at high gas flows, wall losses are exhibited by the increased separation between the plasma and the walls, and the effective volume of radiating plasma is decreased, thereby reducing radiation losses. The reduction in radiating volume apparently offsets any tendency to increase radiation power through possible increased plasma temperatures. In the absence of temperature measurements to the contrary, it is believed that plasma temperature very likely decreases with the increasing gas flow due to the decrease in energy coupling to the restricted plasma volume.

The reduction of wall losses and radiation losses at higher gas
flow is reflected by an increase in power carried to the calorimeter by the flowing gases.

Gas Composition. The only gas used other than argon was a mixture of argon and helium. The mixture used was approximately 47% helium by volume, or about 8.9% helium by weight. This dilution of pure argon led to marked differences between the results of Mode 1 and Mode 2. The increase in wall loss characteristics and the decrease in radiation loss characteristics are respectively believed to be the result of the higher thermal conductivity and lower emissivity of helium. The calorimeter characteristics for these two modes are nearly equal, which suggests that the increased radiation losses were offset by equivalent increases in wall losses.

Plate Voltage. The effects of increasing plate voltage appear in the comparison of Modes 1 and 2. The changes experienced by raising the plate voltage were the least predictable of all changes resulting from varying the other parameters. It was earlier observed that an increase in rf power output increased the diameter of the plasma. During any data run it was also observed that as the diameter of the plasma increased $E_L$ increased. These two bits of information seemed to point the way toward an increased coupling effectiveness at higher plate voltage settings. It was predicted that the higher rf power output, which would accompany the higher plate voltage setting, would increase the plasma diameter which would in turn increase $E_L$. The effect on $E_L$ was just the opposite; $E_L$ decreased. $Q_w$, $Q_t$, and $Q_t$, however, increased in Mode 2, but these increases were obtained at relatively higher increases.
In Mode 2, so that \( b_2, b_3, \) and \( b_4 \) decreased in Mode 2. The most unexpected result was that \( q_0 \) for Mode 2 was less than \( q_0 \) for Mode 1, for an increase in all power measurements was expected because of the increased RF power output.

No explanation of the decrease in \( b_2 \) is offered. An examination of Figure 8 shows a decrease in electrical conductivity of an argon plasma at temperatures from 22,000K to 25,000K. A decrease in conductivity of the plasma could account for the decrease in \( b_2 \), but the existence of temperatures of the order of 22,000K is ruled unlikely, although at a temperature of 25,000K at this power level was not attempted.

The decrease in \( q_0 \) is possibly due to increased energy losses to the wall. Due to present temperatures occurred closer to the walls.

Further studies needed to clarify the apparent contradictions that occurred with Mode 2 operation.

Inner tube plasma. The variations in plasma characteristics resulting from using a smaller diameter inner tube in Mode 3, show the effects of constraining the plasma, and thereby reducing the energy coupling and the effective radiation volume of the plasma, and the effect of the close approach to the wall by the plasma. The total effective coupling is low due to reduced energy coupling. The radiation characteristics are low due to the small radiation volume and probable lower plasma temperature, and the wall loss characteristics are high due to the close proximity of the plasma to the wall. The calorimeter characteristics are also noted to be high, but these values
are questionable. The possibility that the plasma extended down into
the calorimeter during Mode 3 operation was previously mentioned. This
event would result in measuring a certain amount of radial radiation in
the calorimeter, and suggests that the values shown for the calorimeter
characteristics are too high, and that the values shown for radiation
characteristics accordingly are too low.
V. Recommendations

General

The conclusions presented here were based on a study which just
brought to the surface of the research needed for the proper under-
standing of the behavior of the induction-coupled plasma. These
conclusions represent the best that the present investigation has to
offer.

The main areas for improvement and continued study brought out by
this study are (1) the plasma-generator, (2) the coolant temperature
measurement, (3) base temperature measurement, and (4) radiation
power measurement.

An additional operator is available through the use of the
high-cycle control on the plasma supply which should be studied. Duty
cycle is less than 0.5 and has an important bearing on the efficiency
of a limiteds-plasma glow lamp as a gas heater.

Plasma-Generator

The Injection Plate. The present gas injection plate with eight
injection holes as a two-inch diameter circle offers no flexibility to
gas injection, and the center of the plate is subjected to severe
heating at high power operation. To add flexibility to gas injection,
it is recommended that the injection system use the sets of injection
holes drilled on different diameters. Each set of holes should be of
different size and be supplied gas through independent gas manifolds.
This arrangement would allow the selection of different vortex strengths at the same total gas flow. In this manner, the effects of vortex strength could be shown. The results of this experiment could be presented as illustrated in Figure 1F. The curves would be lines of constant gas flow. The left-most point would represent 100% of the gas passing from the manifold with the larger holes, and the right-most point would represent 100% of the gas passing from the manifold with the smaller holes.

A method for eliminating the heat loss on the injection plate was suggested by R. Johnson. He suggested that a small amount of gas injected axially from the center of the injection plate would prevent the plasma from contacting the plate. As an extension of this idea, it might very well be possible to accurately position the tips of the plasma by varying the axial gas injection which would control the reverse gas flow. Preventing the plasma from contacting the injection plate will allow operation at either powers without contamination of the plasma by material from the injection plate.

**Tube Diameters.** The manner in which the power capacity increases at the plasma extends suggests that the ratio of plasma diameter over rf coil diameter (Dp/Dc) is a parameter which should be studied. Studies should be made using larger diameter tubes, but keeping the same waterjacket thickness, or possibly reducing the waterjacket thickness, in order to increase Dp/Dc.
**Starter Mechanism.** A large percentage of tube damage and breakage that occurred in previous test runs could be directly attributed to "hot starts" with the vacuum start technique. T. D. Merde used an inductively heated gun of a similar refractory design to start the plasma at a very high pressure ({}^10{}^6 T), thus lowering the breakdown potential of the tube. He found that the tube was sufficiently protected from the hot cathode if the plasma was started at atmospheric pressure. If an "off switch" is included in the gun design, it can be used for starting purposes.

In order to form the water seal, the water tubes were provided by standard contact. The ends of the water tube and the bottom of the inner tube are subjected to severe loading, and cannot be reused. The water tubes are coated by the inside of the water chamber to prevent the inner tube. Should the plasma extend into the water-cooled gun, at the lower, these water seals almost certainly will have to be replaced if a sufficient vacuum can be maintained. If another potential problem is the cooling of the water-cooled tube. It was shown that the water-cooled tube can be cooled to a temperature of 70°F in at least one test chamber.

**Water Inlet.** The space between the inner and outer tubes for a large part determines the water flow necessary to prevent local boiling. The water inlet, or the water tubes, leads to an extremely reduced water flow requirements for the purpose of reducing local boiling. Reducing the water flow in turn reduces
the error in power measurements due to water temperature determination accuracy. If the water jacket is made too thin, however, the black water technique for total power measurement may not be effective. In general, though, smaller water flow rates, and higher temperature rises lead to better accuracies for power measurements, and therefore, a thin water jacket should be considered.

Coolant Temperature Measurements

Coolant temperature measurements are very critical to power measurements, especially at high coolant flows. Temperature measurements accurate to the nearest one-half degree Fahrenheit would make nearly equal the magnitude of error in power measurements resulting from temperature inaccuracies to the magnitude of error resulting from water flow inaccuracies. Reducing temperature inaccuracies beyond this point will yield little improvement in overall accuracy, and therefore become luxurious. At the least, temperature measurements should be accurate to the nearest degree Fahrenheit.

Plasma Temperature Measurements

An accurate knowledge of the temperature profile of an induction-coupled plasma is essential to the understanding of the basic phenomenon of induction-coupled plasmas, and to the development of theories to explain this phenomenon.

At present, M. T. Braun of the Physics branch, Aeronautical Research Laboratory, and C. Grabner, Chief of Analysis Branch, Digital Computation Division, Aeronautical Systems Division, are developing a
computer program which will yield a spectral line intensity profile, \( J(r) \), from an observed \( N(x) \). The computer program will be applicable to any measurements for which axial symmetry can be assumed. When the program is established, the computer will fit an even ordered polynomial \( (a_0 + a_2x^2 + a_4x^4 + \ldots + a_{2n}x^{2n}) \) to the observed data to obtain an analytical expression for \( N(x) \). It will then differentiate \( N(x) \) with respect to \( x \), substitute \( N'(x) \) into the integral equation, Eq (1), and perform the integration to obtain \( J(r) \).

When this valuable tool is available to make multiple temperature profile determinations practical, a series of test runs in the pattern of this study should be made to determine the parameters which effect the maximum temperatures attainable, and the radius at which these maximum temperatures occur.

Radiation Laser Measurements

Radiation laser measurements in this study were hindered by two basic faults, other than inaccurate temperature measurements. The time difference between the clear water and black water readings is one fault, and the other fault is the inability to reproduce the plasma, as evidenced by the different values of \( f_0 \) which occur at the core gas flow during the same data run. Ideally, all measurements are made simultaneously so that there is no time difference and no non-reproducibility problem.
Since plasma power is not time dependent while operating at a constant gas flow, measurements can be made at different times and still be valid if they do not depend upon reproducibility. This condition is satisfied by leaving the gas flow constant and switching the coolant supply between clear and black water to get measurements of both \( w_a \) and \( w_b \). However, the black water used in this study deposited on the inner tube, and no clear water measurements could be taken after black water was once used. Therefore, an opaque coolant which does not deposit on the inner tube should be found for use in this radiation measurement technique.

A possible method for obtaining simultaneous power measurements was suggested by H. Winder, Physics Department, Air Force Institute of Technology. He proposed that the amount of radiation falling on a radiometer at some fixed distance from the plasma should be compared with the radiation measurements made by switching to black water without changing gas flow, to determine if the two radiation measurements are in some manner proportional. Using the present black water supply, this method entails cleaning the plasma-generator, between test runs. If a proportionality exists, then the radiometer should be carefully calibrated by a series of runs, so that subsequent radiation measurements can be made using the radiometer. The ability to obtain simultaneous power data is well worth the effort to calibrate the radiometer, therefore, tests for proportionality should be made.
Energy Balance

An energy balance on the plasma was not performed because no measurements of total electrical power transferred to the plasma could be made. There is a relatively simple method available to measure the electrical power absorbed by the plasma, but it requires additional instrumentation on the rf power supply. This method was suggested by Taylor and Hastings (Ref. 3: 1371). The additional instrumentation required is an rf ammeter in the circuit with the rf induction coil, and water flowmeters and thermostats in the cooling system for the triodes in the rf power supply.

The total electrical energy supplied to the triodes can be measured with direct-current meters. The energy lost in the triodes is given off as heat and can be measured by reference to cooling water temperature rise and water flow. The energy not lost in the triodes is converted to rf energy output.

To obtain a measure of rf energy transferred to the plasma, the power supply is first operated in the absence of a plasma at some set value of rf current on the rf ammeter in the induction coil circuit. Total electrical energy to the triodes and total triode losses are then measured as previously explained. The difference between these values is the rf energy losses which occur at that rf current. The power supply is next operated in the presence of a plasma, at the same rf current. The total triode energy input and losses are measured as before. The rf energy losses at this rf current were previously determined. The rf energy losses are added to the triode losses which
occurred on the second run, and this sum is then subtracted from the total energy supplied to the triodes on the second run. This difference is the energy which is transferred to the plasma.

By knowing the rf energy supplied to the plasma, a proper energy balance can be made. An energy balance is deemed necessary to validate the measurements made on the plasma by the techniques used in this study.

**Supersonic Heating**

The possibility of adding heat to the air in the supersonic region of a hypersonic wind tunnel by a rf induction-coupled plasma, was mentioned in the introduction. However, plasma operation in gases with high linear velocities is unstable because the plasma cannot propagate fast enough upstream. In the vortex-stabilized plasma, ionized gas is blown upstream by the back-flow. This feedback system continuously supplies the ions necessary to maintain coupling between the rf induction coil and the plasma.

Stabilization by vortex flow in hypersonic wind tunnels cannot be considered, because it disrupts the gas flow. A schematic presentation of a stabilization scheme is shown in Figure 19. This scheme involves a constant supply of electrons being injected into the gas flow near the throat of the wind tunnel. These electrons are carried downstream, by the fast moving gases, into the plasma coupling area where they couple with the rf induction coil, and thereby stabilize the plasma. As the electrons move downstream past the plasma area they are returned to ground, leaving a neutral gas behind.
The electrons can be generated in a typical electron-dynamic ion-production method. For negative ion production, the corona discharge needle is given a high negative charge, just short of breakdown potential. The positive ions created near the needle point are attracted to the needle, whereas the negative ions are attracted to the nearby ground. Before the electrons can reach ground, however, they are carried downstream through the plasma discharge area by the ion stream.

This stabilization seems feasible. There is no doubt that the negative-ion stream can be generated; but only experimentation will show if this ion stream will couple with the induction coil, and if the plasma thereby generated can be confined to a volume small enough to prevent destruction of the tunnel walls. If coupling occurs without damage to the tunnel walls, the usefulness of this heat addition method is limited only by the extent to which the plasma experiences a breaking effect caused by interaction between induction currents in the plasma and the field of the rf coil.

This heat addition system in the supersonic flow section of a hypersonic wind tunnel appears feasible, and should be checked by experimental means.

Duty cycle as a parameter

A duty cycle control on the rf power supply allows selection of any duty cycle desired between 0 and 100%. For any particular plate voltage setting, this allows selection of any plate power from zero to the maximum attainable on that plate voltage setting. Consequently,
with a prior knowledge of all plasma plate cover, P, for that plate voltage setting, a particular value of \( f \) can be selected exactly by use of the duty cycle control.

Then the rf cover simply is operated at a duty cycle less than 100%, the rf power is emitted in, plus of the rate of 25 per second, the duty cycle percentage corresponds to the length of these pulses. a duty cycle of 25%, for example, yields power pulses whose duration are about second, and pulses appear at a rate of 25 per second. During any second then, the rf cover is emitted for 25% second.

The duty cycles of this cover simply will conceivable have important implications in the use of an electron-arc-lamp plasma as a gas heater, such as beetle-arc. Such models. One of the characteristics of plasmas, and of all in a direct-current arc, is that they are so wide as they defy efforts to blow them through the arc channel. This allows the effectiveness of cooling and by electric arc. An intense part of area can be overlooked in a closed electron-arc-lamp, because instead of relaying on putting the cold areas by cooling the through the plasma, the plasma generates through the cold areas. High-speed photomicrographs taken of a plasma operating at a duty cycle of 50% clearly show the pulsating nature of the plasma. Then the cover first emits the plasma in very pulse radically, and the pulsating plasma radially shrinks toward the center of the tube. Then the next pulse, the same, it couples with the remaining conducting gas, and the plasma gradually swells to normal size. The pulsing of the plasma is not visible to the eye, and normal size refers
to the size of the plasma seen by the eye. It is proposed that this
galvanic action of the plasma more effectively heats the gas than
operation of the plasma at a duty cycle of 1.0, because wall losses
and radiation should decrease due to pulsing the power. A series of
tests would be run at the same gas flow and $P_0$ on the nine possible
plate-voltage settings to confirm or deny this proposal.

January

Very little information is available on induction-coupled plasmas
to date. This study is the only work known to the author which is
available on induction-coupled plasma operation below the recirculation
rate. The recombination of hydrogen is versatile enough
to test the feasibility of the investigator to use it. It is probable
that sufficient energy is available to investigate plasmas in rare cases
other than those at room temperature. If a plasma-generator is
developed to match it, an initial volume could be conducted on
induction-coupled plasma in an attempt to determine if it could be desirable
to utilize a somewhat, less-tight pattern of investigation. This
study has established the general characteristics of a high-power
induction-coupled plasma-generator, and has revealed a number of experi-
mental difficulties which must be considered. Thus a comprehensive
program of investigation may now be confidently undertaken.
Bibliography


Appendix A

Abel's Integral Transformation

The transversely observed radian'se of the plasma image, N(x), is inverted to the radiant intensity, J(r), in the following manner.

\[
N(x) = 2 \int_0^y J(r) \, dy
\]

But,
\[
y = \sqrt{r^2 - x^2}
\]

And,
\[
dy = \frac{r \, dr}{\sqrt{r^2 - x^2}}
\]

Therefore:
\[
N(x) = 2 \int_0^\infty \frac{J(r) \, r \, dr}{x \sqrt{x^2 - r^2}}
\]

This is Abel's integral, which inverts analytically to form

\[
J(r) = -\frac{1}{\pi} \int_0^R \frac{N(x) \, dx}{\sqrt{x^2 - r^2}}
\]

The prime indicates differentiation with respect to x.
Fig. 1

Plasma-generator with clear water coolant
Fig. 2
Plasma-generator with black water coolant
Fig 4
Schematic of plasma-generator and calorimeter
Typical observed intensity of $\lambda 7635\AA$.
Fig. 9
Modified outer tube
for Mode 3
Fig. 16

Re (Calorimeter Ratio) %

Mode 1
Mode 2
Mode 3
Mode 4

Gas Flow - Scfh

100
200
300
400
Fig. 18

Power coupling as a function of changing vortex strength, with excess plate power and total gas flow constant
Fig. 19
Supersonic heating by induction-coupled plasma
Vita

Edward H. Cannon was born in [redacted] on [redacted]. He graduated from [redacted] School in [redacted] City, [redacted] in 1947. In 1947, he enlisted in the United States Air Force, and was appointed to the United States Military Academy from the Senior Air Force in June 1947. In [redacted], he was commissioned a second lieutenant in the Senior Air Force, and graduated from the United States Military Academy on [redacted] with a Bachelor of Science degree in [redacted]. He then attended the Air Force Institute of Technology and served as a systems operations officer in [redacted], [redacted].

[Redacted]

[Redacted]