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CHARACTERISTICS OF A RADIO-FREQUENCY A.C. ELECTRIC ARC

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CHARACTERISTICS OF A RADIO-FREQUENCY A.C. ELECTRIC ARC

THESIS

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Preface

The purpose of this study was to investigate the characteristics of radio-frequency, alternating currents arcs between electrodes. To the best of my knowledge, based on a comprehensive literature search, no previous work has been carried out on radio-frequency arcs at atmospheric pressure. It is hoped that this thesis will give some small knowledge of these arcs and will interest others to continue work in this field.

I an indebted to Mr. E. Soehngen of the Aeronautical Research Laboratory, WPAFB, for first interesting me in this topic and for his continued advice and support during the investigation. I also wish to thank Dr. Pfender, Mr. E. Moore, Capt. D. Dye, Capt. T. Andrada, Capt. H.R. Cannon, and the many other personnel in ARL without whose assistance the work could not have been completed. Thanks are due also to Lt. Meyfarth, my faculty advisor, and the other members of the faculty of the Department of Mechanical Engineering for their sponsorship of the thesis and their helpful criticism.

Lastly, I must thank my wife and family for their continued sacrifices and understanding during the past two years while I was undertaking this course and thesis. To my wife also goes thanks for proofreading and typing the first draft.

Alan J. Shade

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Abstract

The study of a-c arcs has become of interest in recent years during research into efficient means for producing high temperature plasmas. Little or no work has been done in the past with very high-frequency arcs. The purpose of the study was to determine if a stable arc could be produced at radio-frequency and, if so, to determine the arc's static and dynamic operating characteristics (voltage vs. current) using various parameters. The arc was operated in argon and nitrogen, using a Westinghouse 400 Kc., 200 Kw. power plant designed for industrial induction heating. Two 3/4-inch diameter, water-cooled, copper electrodes were used, inside a quartz tube. The arc was vortex stabilized. The r-f voltage and current, the d-c input power, and the temperature and flow of the cooling water were measured. High-speed photography (7000 and 28,000 frames/sec.) was used to obtain pictures of the arc in operation.

The flow rate of argon was varied from 0 to 350 standard cubic feet per hour. The gap between the electrodes was varied from 0 to 4-1/2 inches. The r-f voltage varied from 0 to 2000 volts while the current varied from 0 to 560 amperes.

A very stable arc was produced. It was found that the

characteristics varied very little with either gas flow or arc length. The static characteristic obtained was essentially the same as for a d-c arc; with a steeply negative characteristic for currents below 30 amperes, changing to a positive, constant slope of 0.5 ohms, above 50 amperes. It was found that the arc at these frequencies appeared to behave as a pure resistor, as had been predicted by arc theory.

This r-f arc was not found to be an efficient means of adding heat to a gas since the overall efficiency of the apparatus and power plant was only 8.8 percent. This was primarily due to the low efficiency of the power plant, high losses in the leads to the arc apparatus and the low efficiency of the arc. The efficiency of the arc itself was only 23.3 percent, due to very high losses by conduction to the walls and by radiation.

List of Symbols

a	distance between the intercepts on the ordinate axis of the dynamic characteristic
b	maximum total height of dynamic characteristic
c	specific heat of water
E	voltage across the arc apparatus
E_1	voltage across the arc apparatus at an arbitrary point(1) on the characteristic curve (Fig. 14)
E_2	voltage across the arc apparatus at a point (2) of lower voltage than point (1) on the characteristic curve
E_p	plate voltage to the oscillator tubes
I	radio-frequency current
I_1	radio-frequency current at a point (1) on the characteristic curve (Fig. 14)
I_2	radio-frequency current at a point (2) on the characteristic curve
I_{p1}	plate d-c current to one half of the oscillator
I_{p2}	plate d-c current to the other half of the oscillator
j	instantaneous current on dynamic characteristic
$\bar{j}$	root-mean-square value of current on dynamic characteristic
F_p	power factor (equal to the cosine of the angle θ)
$\dot{m}$	mass flow rate of the cooling water
P	d-c input (plate-dissipation) power to oscillator
P_1	d-c input power to oscillator with an arc in operation
P_2	d-c input power to oscillator with the electrodes short-circuited
P_3	d-c input power to the arc (equal to $P_1 - P_2$)

R	radius of arc column
R	resistive impedance (Fig. 20 only)
ΔT	rise in temperature of cooling water
v	instantaneous voltage on dynamic characteristic
$\bar{v}$	root-mean-square value of voltage on dynamic characteristic
υ	voltage gradient along the arc
V	radio-frequency voltage
V_1	total voltage across the arc apparatus with an arc in operation
V_2	total voltage across the arc apparatus with the electrodes short-circuited
V_3	voltage drop across the resistive portion of the arc impedance
X_c	capacitive impedance
X_L	inductive impedance
Z	total impedance

Greek Symbols

α	thermal diffusivity coefficient of the gas
ρ	density of the gas
ρ_a	density of argon
ρ_h	density of hydrogen
θ	angle between the instantaneous voltage vector and the instantaneous current vector
τ	characteristic time constant for an arc
ω	angular frequency of the power supply
ω_h	characteristic angular frequency for an arc ($\omega_h = 1/\tau$)

I. Introduction

The study of alternating current arcs has become of interest in recent years during research into efficient means for producing high temperature plasmas for such uses as hypersonic wind tunnels and space propulsion engines. Direct current arcs have been extensively investigated for many years and have been proposed for these tasks. However, since most power supplies are of an a-c nature it would appear that it might be more efficient and require less weight to match the heating device directly to the power plant rather than first converting the power to direct current.

One of the methods for producing high temperature plasmas, currently under study at the Aeronautical Research Laboratory, is the radio-frequency "electrodeless" discharge or induction heating method. In order to have a valid comparison of efficiency it was felt that a study should be made of an arc between electrodes at the same frequency as the electrodeless discharge.

Purpose of the Study

The purpose of the study was first to determine if a stable arc could be produced with radio-frequency alternating current. Second, if such an arc could be established, to determine the arc's static operating characteristics, that is, voltage vs. current. Third, to determine what effect, if any, the variation of such parameters as arc length, gas flow rate, and type of gas, produced on this characteristic.

Although it was not a part of the original study it was later decided to determine how much energy was lost to the cooling water and to attempt to obtain the arc's dynamic characteristic i.e. voltage vs. current during each cycle. In addition, by use of high-speed photography, the diameter, path, and nature of the arc column were determined.

II. Analytical Study

An extensive library research program was undertaken and over forty technical papers extensively studied. However, very little theoretical or experimental investigation work on high-frequency a-c arcs could be found.

References 3 and 4 showed the results of work carried out by Russian scientists with arcs at 2 Mc. However, all work was done at very low pressure and hence, was not directly applicable to an arc at atmospheric pressure.

In references 1 and 6 a theoretical treatment of a-c arcs is given. The equations derived by these authors are quite complicated and can be solved only for special cases by means of digital computers. The theory is therefore not repeated here as it is felt that the reader would be more enlightened by referring directly to the references.

Though the approach to the problem by the authors of the above references is somewhat different, the predicted dynamic characteristics of voltage vs. current for high-frequency arcs are almost identical. Both references give several dynamic characteristics, each for a different ω/ω_n ratio, where ω is the actual operating frequency and ω_n is the so-called "natural frequency" of the arc apparatus. The determination of ω_n for a particular apparatus is difficult.

For this arc a good approximation would probably be

$$\omega_n = \frac{10^9}{I^2}$$

where I is the current in amperes (Ref 1:15 and sample calculations Appendix B). Therefore, for a current of 225 amperes ω_n would be approximately 20,000 cycles per second (20 Kc.). Since the power plant operates at 400 Kc. this corresponds to an ω/ω_n ratio of 20.

Fig. 1 (b) shows the predicted dynamic characteristic for this ratio. The characteristic in Fig. 1 (b) has been normalized by dividing the instantaneous voltage (v) and current (j) by the root mean square values ($\bar{V}$ and $\bar{J}$). Fig. 2 shows the predicted characteristics for ω/ω_n ratios of 1 and 6.28, where V is instantaneous voltage and I is instantaneous current. From these curves it may be seen that as ω/ω_n increases the dynamic characteristic approaches a straight line. As may be seen from Fig. 1 (a) this means that the voltage-time and current-time curves are becoming closer to being coincident, as ω/ω_n increases. Since power factor (Fp) is defined as the cosine of the angle (θ) between the voltage and the current vectors, and this angle is approaching zero, then the power factor approaches one as the ω/ω_n ratio increases. For an ω/ω_n ratio of 10, the power factor is 0.999 (Ref 1:18). A straight line dynamic characteristic would correspond to the flow of alternating current in a pure resistor and the power factor would be one.

For an ω/ω_n ratio of 10 or higher the predicted dynamic characteristic is essentially a straight line and the arc behaves as a pure resistor.

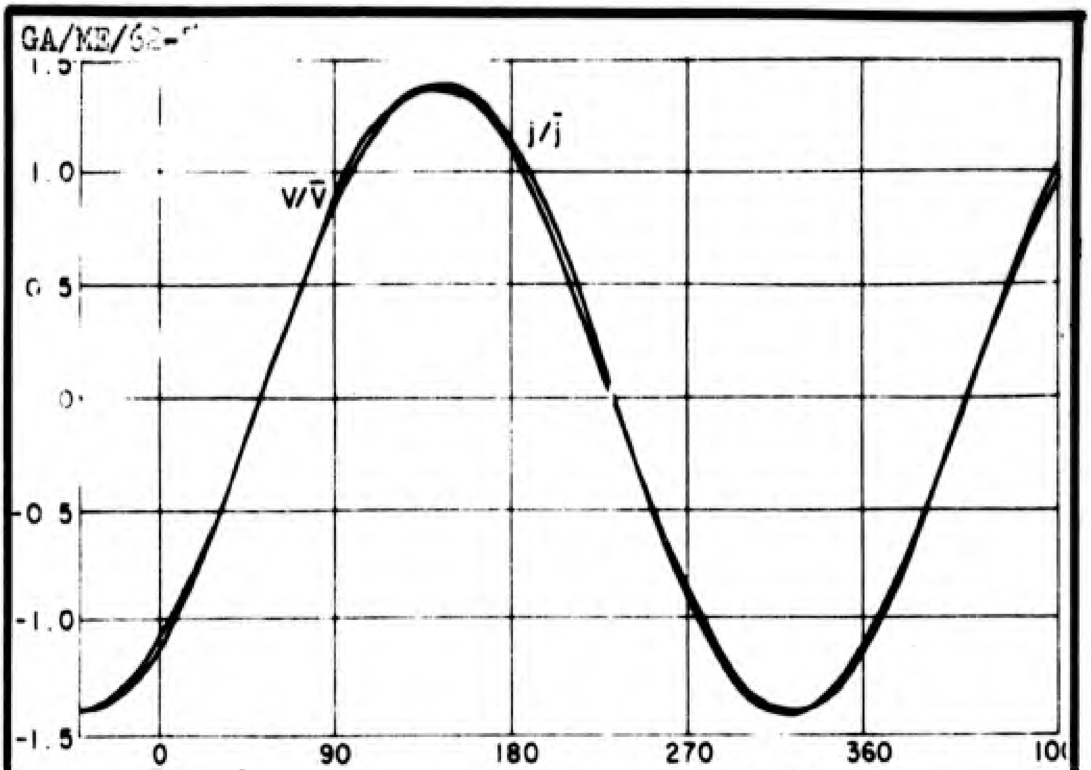
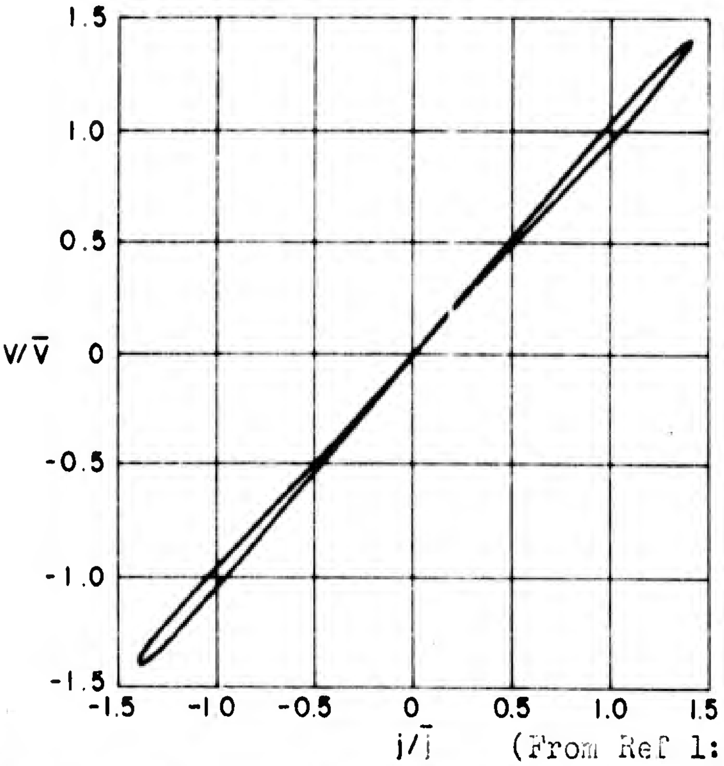


Fig. 1 (a) VOLTAGE-TIME AND CURRENT-TIME CURVES

for $\frac{\omega}{\omega_n} = 10$



(From Ref 1:37)

Fig. 1 (b) VOLTAGE VERSUS CURRENT CURVES for $\omega/\omega_n = 10$

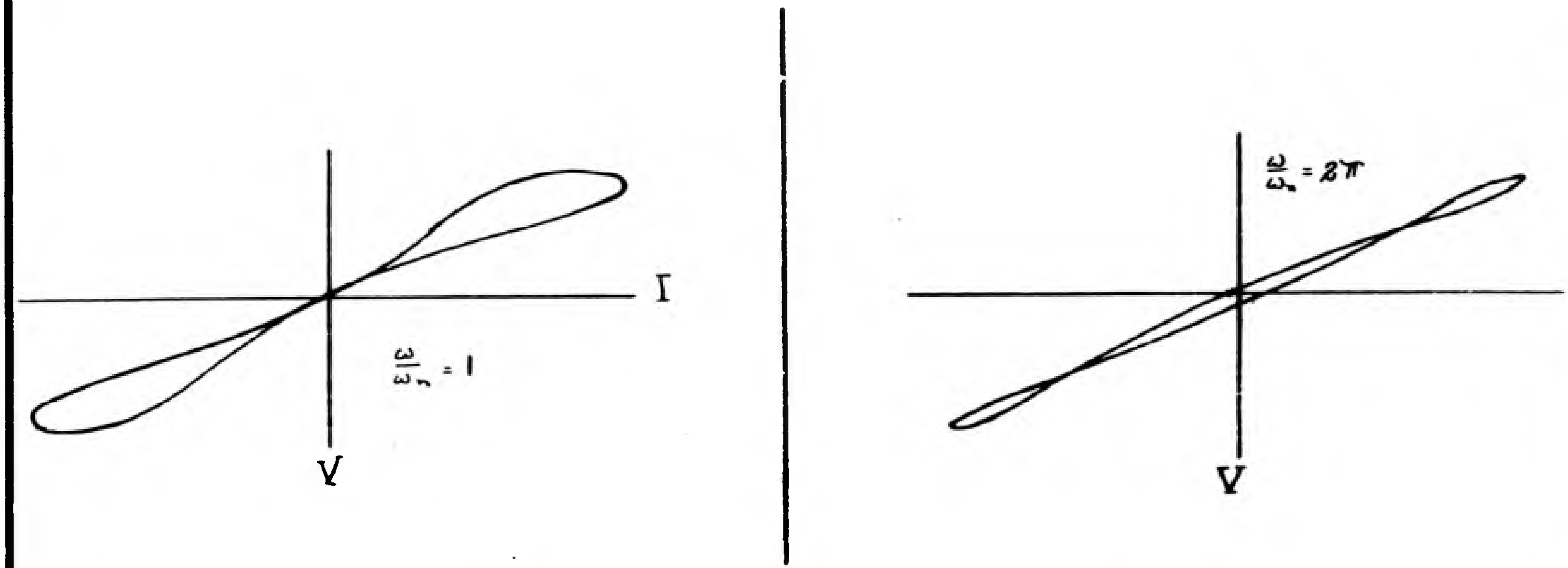


Figure 2 - Dynamic Characteristics of AC Arcs (from Ref 6:8)
Fig. 2

111. Experimental Apparatus

The experimental apparatus consisted of a radio-frequency (r-f) power supply, a power control panel and oscillator keyer, a bottled gas supply with a precision flowmeter, a cooling water supply with a precision flowmeter, the arc apparatus, an r-f ammeter, an r-f voltmeter, a high frequency oscilloscope, iron-constantan thermocouples, and a temperature recorder.

R.F. Power Supply

The power supply consisted of a Westinghouse radio frequency generator designed for industrial induction heating. It had a rectifier section which converted 3-phase 60 cycle A.C. into high voltage D.C. This voltage was then supplied to the plates of a tuned r-f oscillator. The frequency of the oscillator could be changed from 140 to 400 kilocycles, by varying the number of capacitors or the number of turns on the induction coil in the tuned plate circuit. However, to change this frequency the power plant had to be shut down, allowed to cool and then altered internally. The power plant was rated at 200 kilowatts of radio frequency energy. The power output could be varied by selecting one of nine transformer taps. These taps could be changed only when there was no load on the oscillator. The power output on a particular tap setting could be finely adjusted by the keyer unit.

Control Panel and Keyer Unit

The power plant was controlled by a University of Florida Oscillator Control System consisting of a closed-loop servo, pulse-width trigger for the oscillator. This system could be controlled manually or by a preset program. The system provided smooth control from 0 to 100 percent power output by pulsing the oscillator on and off at 360 cycles per second (cps); the amount of on-time or "duty Cycle" determining the average power output of the unit. A view of the control panel is shown in Figure 3. In this thesis all control of the power plant was done manually.

Gas Supply

An inert gas supply was used to provide an inert atmosphere to prevent oxidation of the electrodes and a strong vortex to stabilize the arc. The gas supply consisted of one or more high pressure gas bottles connected in parallel through Airco precision argon flowmeters to the vortex generator. The flowmeters had two ranges, from 0 to 20 and from 0 to 200 standard cubic feet per hour (SCFH). To obtain higher flow rates two gauges were connected in parallel. The maximum flow rate that could be obtained with this system was 350 SCFH. The flowmeters could be read to within 0.2 SCFH on the low range, and to within 2.0 SCFH on the high range. The accuracy of the flowmeters was plus or minus 5 percent.

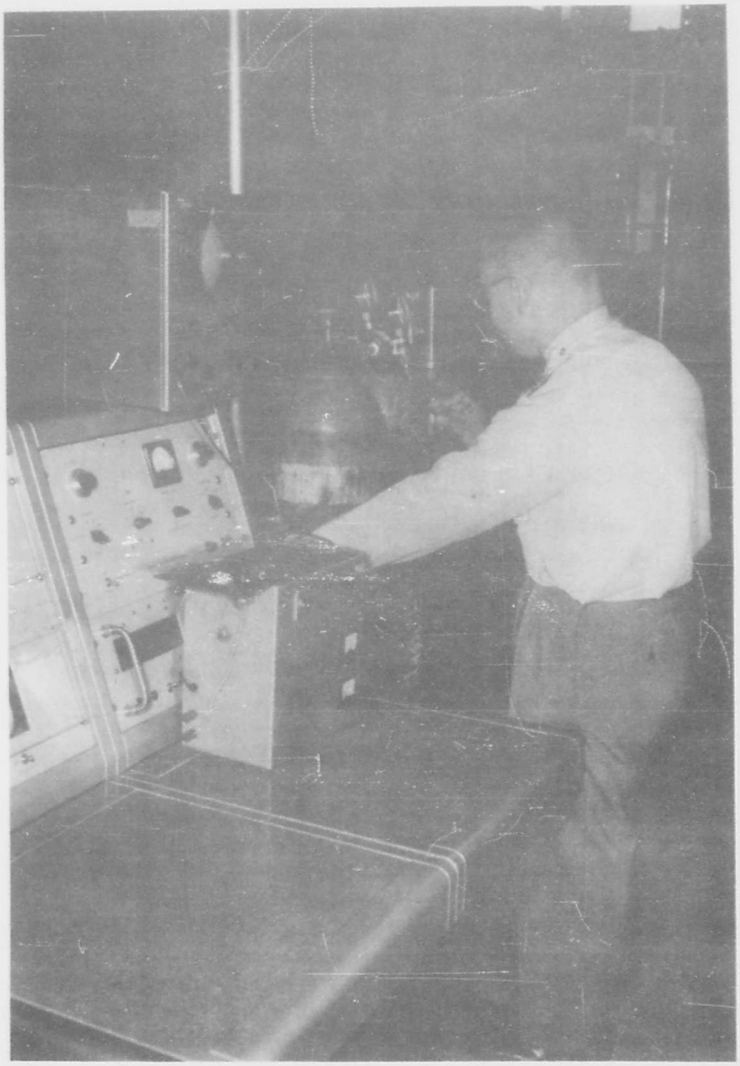


Fig. 3

R.F. Power Plant Control Panel, Electrode Actuator Controls, Gas Supply Bottles and Gas Flowmeter

Cooling Water Supply

Initially,water cooling was obtained by using the distilled water circulation system of the power plant. It was found that this supply did not provide sufficient cooling capacity. The majority of the runs were made using water from the laboratory supply mains. A Fisher and Porter precision flowmeter (serial number 59AA359373) which had a range from 0 to 2 gallons per minute (gpm) and that could be read to an accuracy of 0.04 gpm, was connected to the drain side of the apparatus. This flowmeter is shown in Fig. 4.

The Arc Apparatus

The general construction of the arc apparatus may be seen in Fig. 5, 6, and 7. The apparatus consisted of two 3/4-inch diameter, water-cooled, copper electrodes. One was fixed while the other was moveable by a 24 volt d-c electric actuator. This actuator had a range of about 5 inches, with the upper and lower limits being controlled by adjustable micro-switches. Since some variation in position and length of the lower electrode had to be allowed for, the actual gap between the electrodes could be varied between 0 and 4-1/2 inches.

The electrodes were surrounded by a 3-inch diameter quartz tube which was closed at one end by a vortex generator and at the other end by a water-cooled outlet chamber.

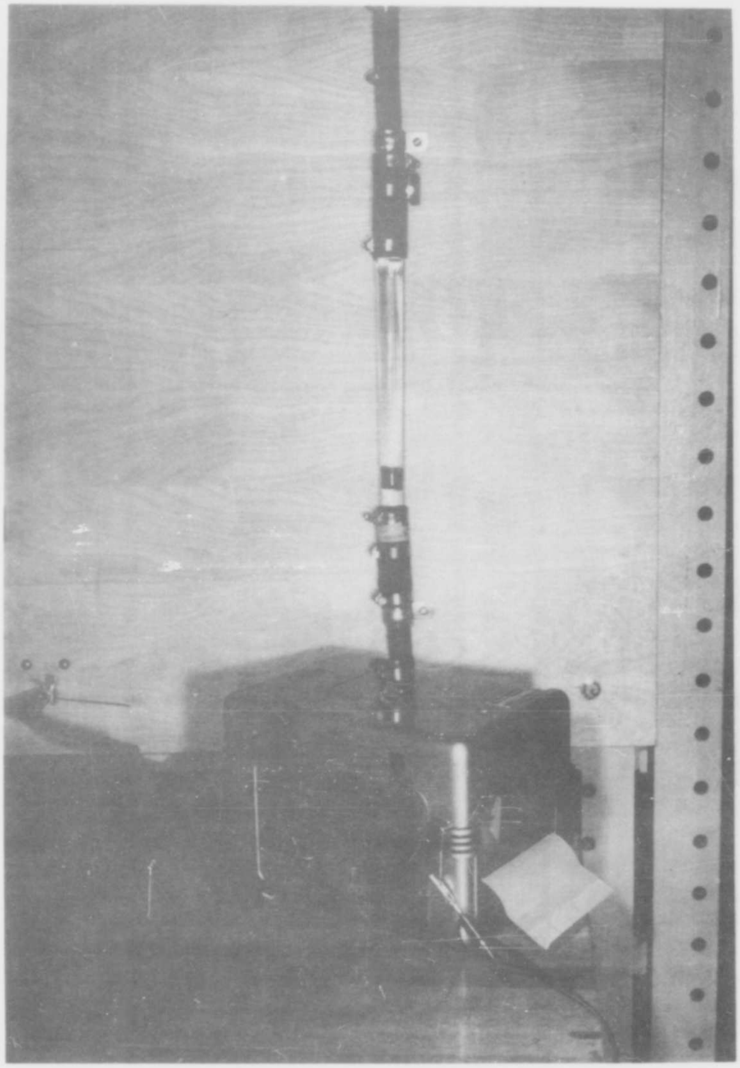


Fig. 4

Water Flowmeter and Visicorder

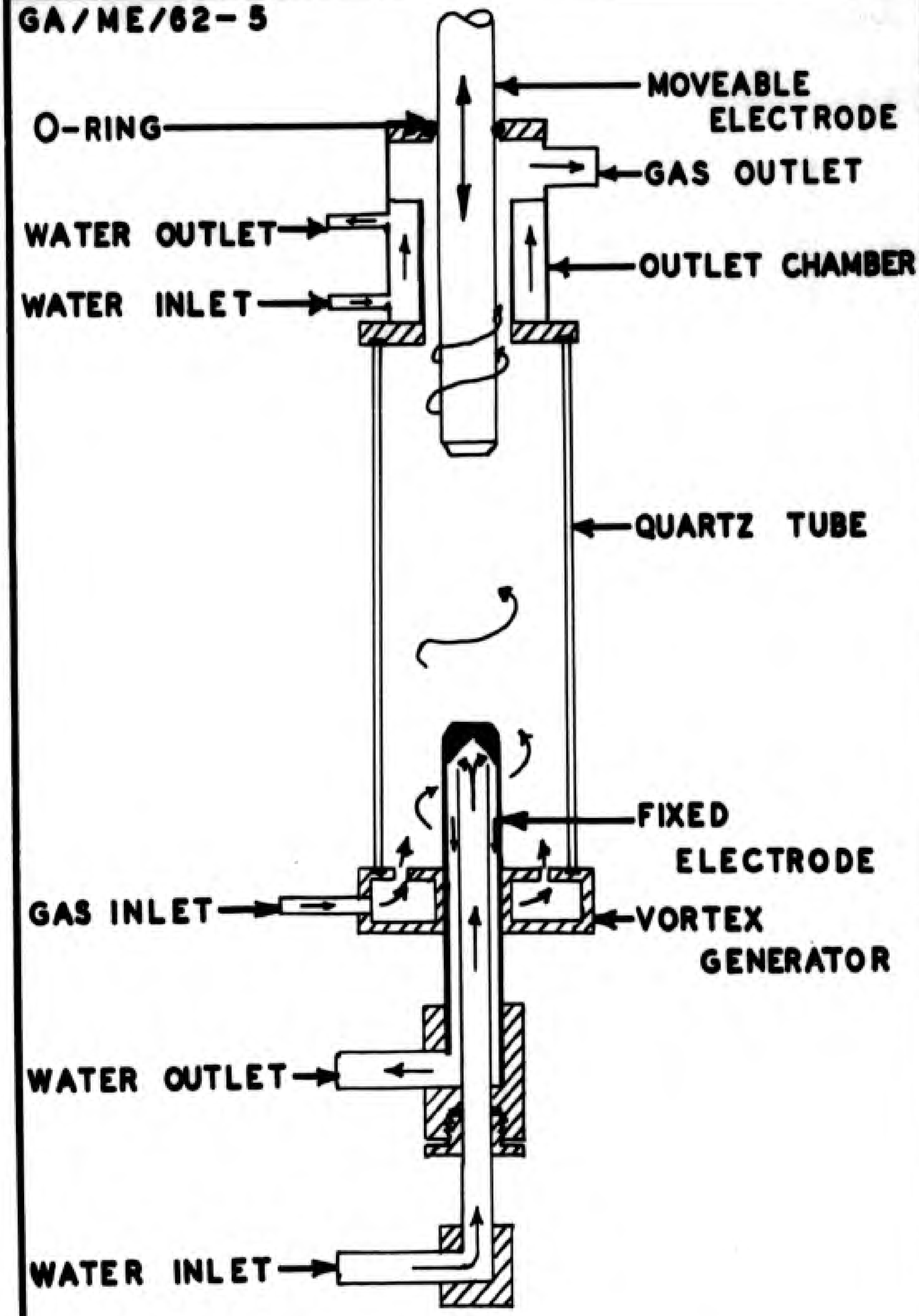


FIG. 5

SCHEMATIC OF ARC APPARATUS

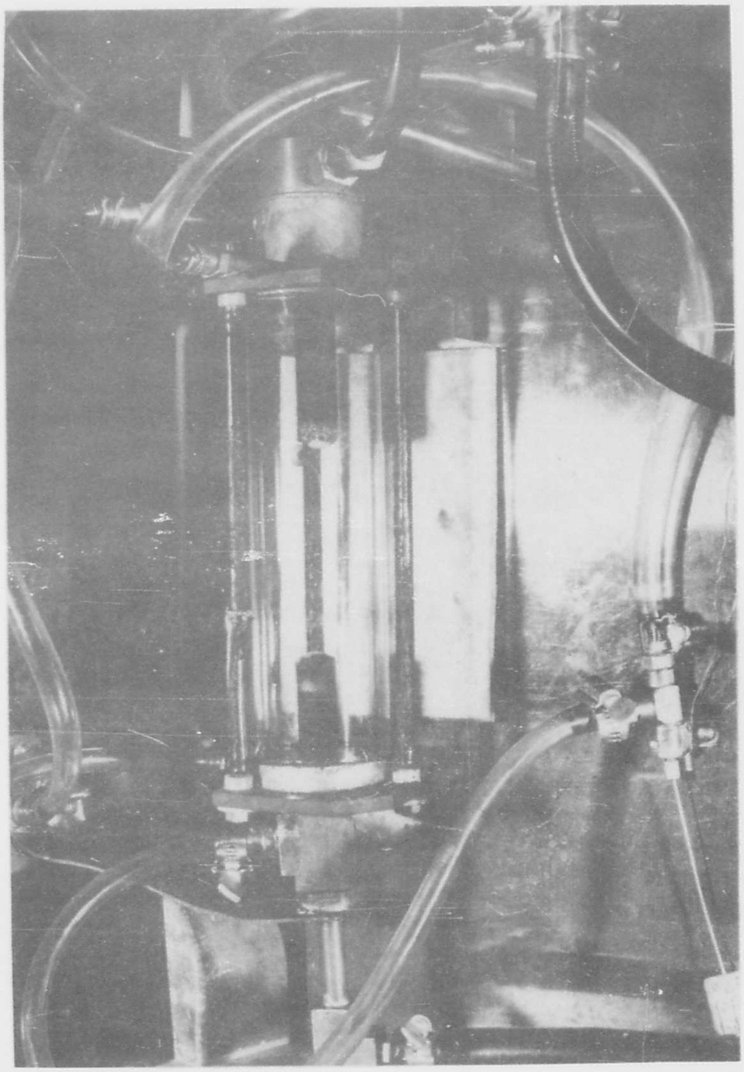


Fig. 6

Arc Chamber and Electrodes

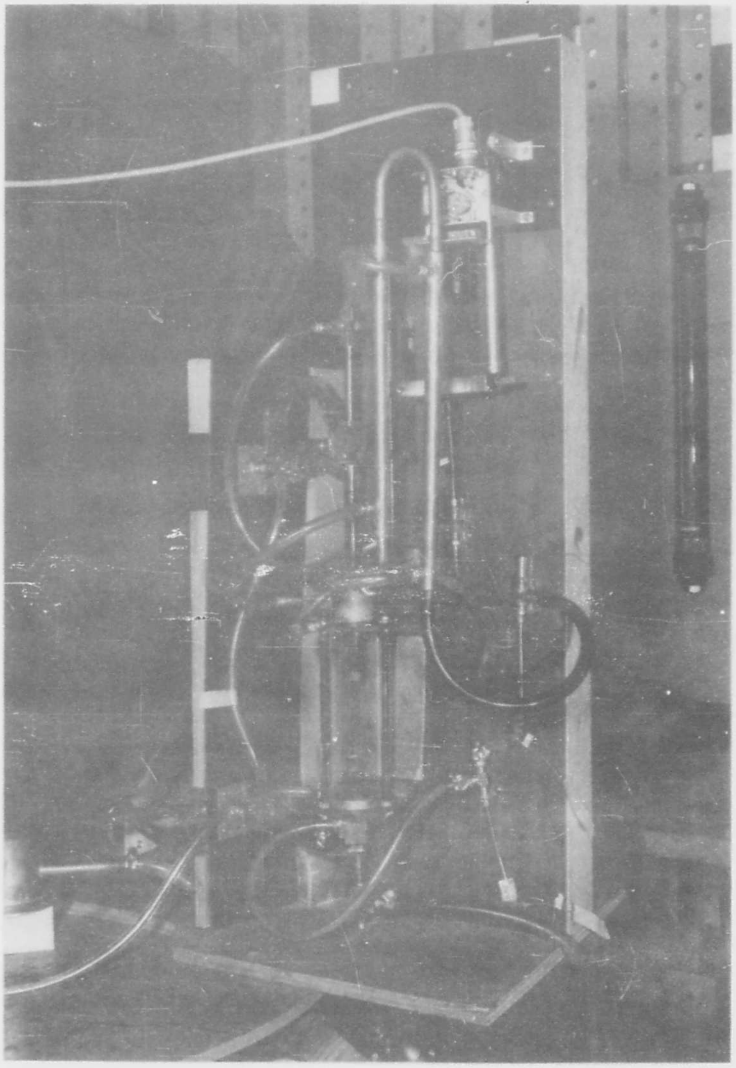


Fig. 7

Arc Apparatus and Calorimeter

A neoprene O-ring was used to seal the outlet chamber around the moveable electrode and at the same time to provide electrical insulation between them.

The gas entered the vortex chamber, circulated around the electrodes and passed out of the outlet chamber into a water-cooled calorimeter. This calorimeter consisted of a 1/2-inch diameter copper tube, with a concentric 3/4-inch diameter copper tube. The gas passed through the inner tube and the cooling water circulated between the two tubes. The calorimeter was bent into a U-shape to make it more compact and is the device similar to a 'trombone' visible in Fig. 7.

A more detailed description of the arc apparatus is given in Appendix C.

Temperature Recording Equipment

The temperature of the outlet gas flow and of the cooling water at various points in the apparatus was measured using five iron-constantan thermocouples. These thermocouples were located as shown in Fig. 8. The cold junctions were placed in an ice bath. The output voltage of the thermocouples was supplied to the temperature recorder through low-pass filters to eliminate any induced r-f noise in the signal. The recorder used was a six channel Visicorder which consisted of six light-beam galvonometers which produced a permanent trace on photosensitive paper. This recorder is

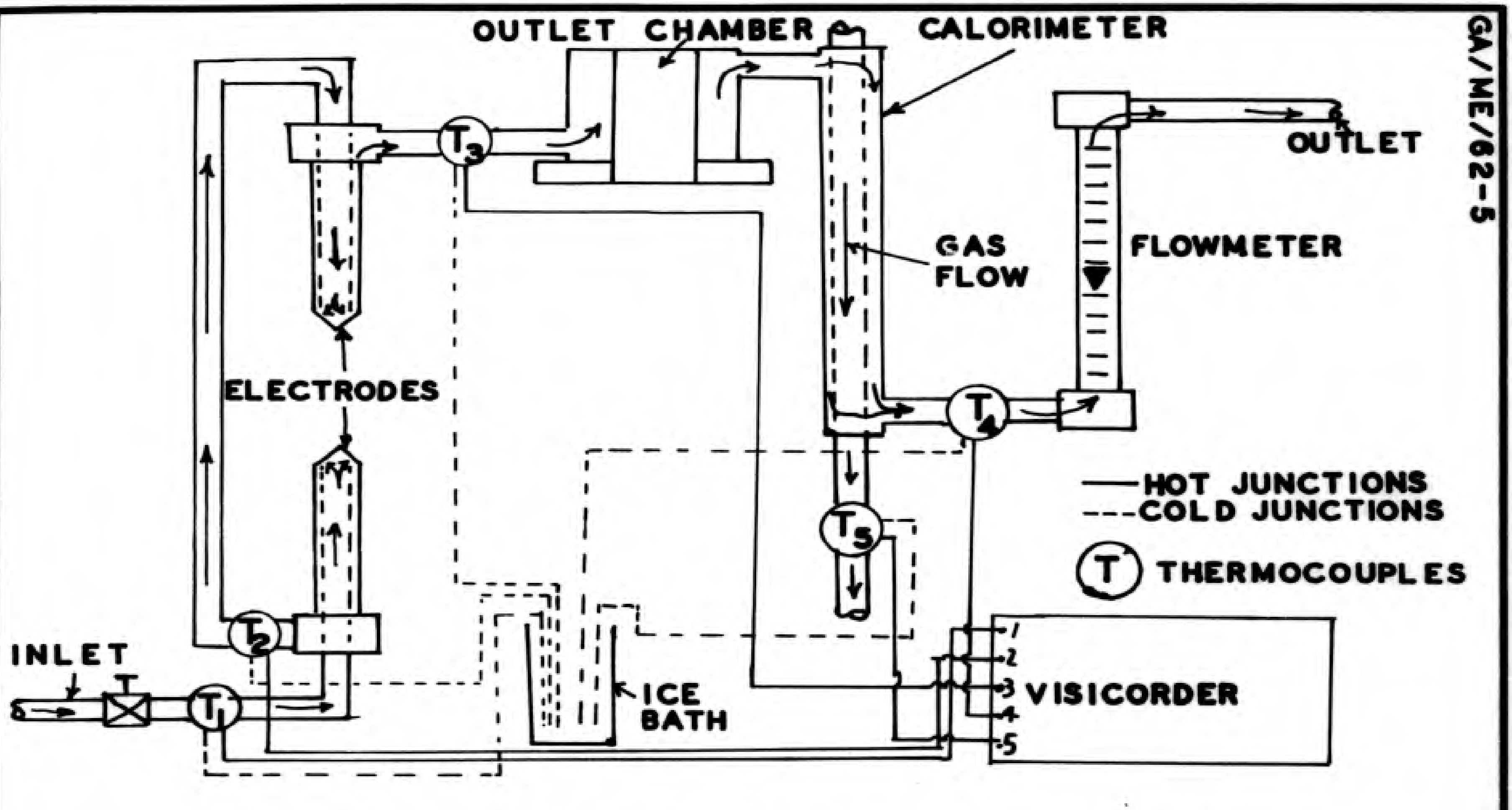


FIG. 8 SCHEMATIC OF COOLING SYSTEM

shown in Fig. 4.

Radio-Frequency Ammeter and Voltmeter

Commercial instruments for measuring voltage and current at this frequency were not available. Those used were specially constructed for use with this power plant by the University of Florida (Fig. 9). The voltmeter consisted of a half-wave rectifier, connected through series resistors to a milliammeter. The circuit diagram is shown in Fig. 10. The range of the voltmeter was from 0 to 5 Kilovolts and it could be read to an accuracy of 25 volts.

The ammeter consisted of a low inductance transformer with the primary directly in the power supply circuit. The secondary was connected to a milliammeter wtih a shunt resistor. The circuit diagram is shown in Fig. 11. The range of the ammeter was from 0 to 1000 amperes and it could be read to an accuracy of 5 amperes.

Both meters were calibrated so as to indicate root mean square values.

High-Frequency Oscilloscope

A Tetronix model 555 oscilloscope with dual beam trace was used to monitor current and voltage waveforms, percentage on-time, frequency and the dynamic characteristic (voltage vs. current) of the arc.

The voltage was detected by means of a capacitor-voltage-divider network. This consisted of twelve 5-micromicrofarad capacitors, with 600 volt ratings, connected in series. The whole network was connected across the power input leads and the oscilloscope was connected across one of the capacitors. This gave a twelve-to-one reduction from the actual arc input voltage to the voltage applied to the oscilloscope, with no change in phase angle.

The current was detected by means of a pickup loop suspended close to one of the input power leads. The magnitude of the voltage generated by the pickup loop could be varied by changing the distance between the loop and the input lead.

The oscilloscope was not available on all runs since it was used on several other apparatus in the laboratory.

Fig. 9

R.F. Voltmeter and Ammeter

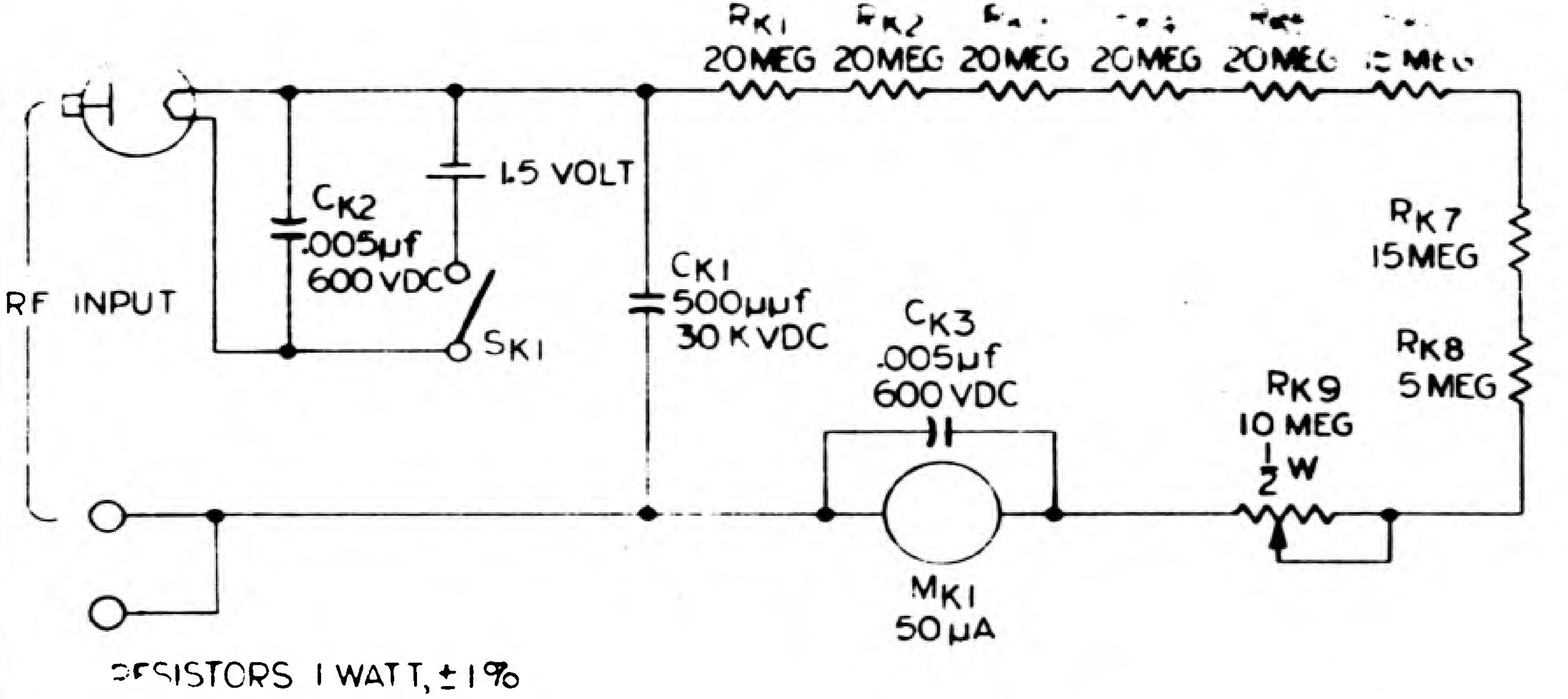
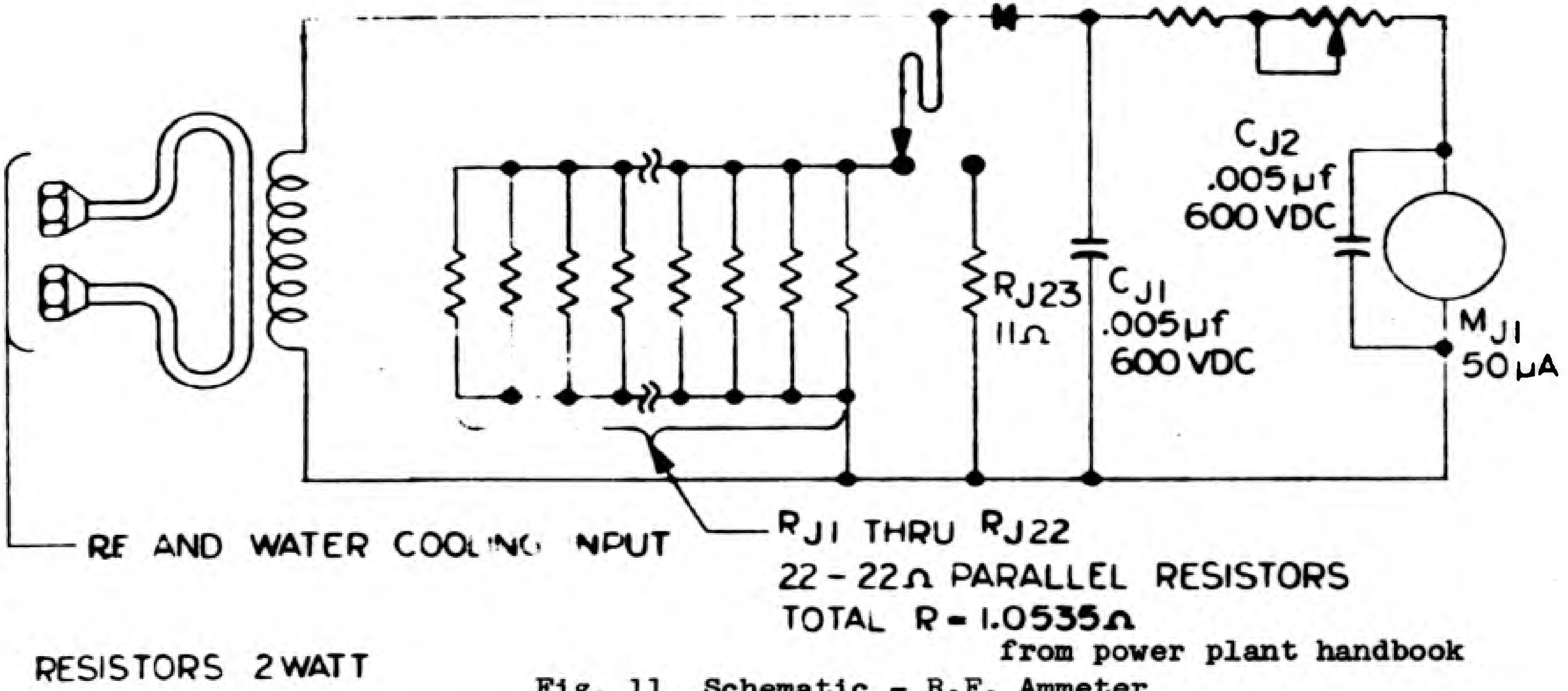


Fig. 5-2. Schematic - R.F. Volt Meter from power plant handbook
Fig. 10 Schematic - R.F. Voltmeter



from power plant handbook

Fig. 11 Schematic - R.F. Ammeter

IV. Experimental Procedure

The procedure outlined in this section is the general procedure utilized for all runs. Specific runs had minor differences depending on the purpose of the runs.

Preliminary Setup

Power Plant. In order to obtain consistent results and to prevent damage to the R.F. generator, it was necessary to ensure that the power plant had reached a correct operating temperature. Therefore, the power plant was started at least one hour prior to running and the run was not commenced until the thermometers mounted on the rectifier tubes read at least 20° C. One of the doors to the oscillator section of the power plant was kept open at all times, except during runs, as a safety precaution. This allowed the interlocks to operate thus preventing any possibility of power being accidentally applied to the apparatus.

Cooling Water. The cooling water was turned on at least one half hour prior to the start of the run to ensure that a steady flow rate and temperature were reached. The Visicorder was started at the same time and allowed to warm up. Just prior to igniting the arc the Visicorder was run for a short time to give a base-line temperature trace of the water supply.

Arc Apparatus. The arc apparatus was first checked for gas leaks by opening the argon flowmeter control valve very slightly, then plugging the outlet of the apparatus. This pressurized the apparatus. If there were no leaks the flowmeter indication then dropped to zero. The moveable electrode was positioned by adjustment of the lower microswitch so that there was approximately a 1/16-inch gap between the two electrodes.

Instrumentation. The r-f voltmeter and the high-frequency oscilloscope were turned on to allow at least a half-hour warm-up prior to ignition of the arc.

Control Panel. The manual keyer circuit of the control panel is transistorized, which tends to make the keyer control somewhat unstable and subject to long-term drift. To avoid possible errors it was therefore necessary to calibrate the percent on-time control prior to each run. The power to the control panel was turned on a half-hour prior to calibration to ensure complete warm-up. An oscilloscope was mounted above the control panel and connected to the keyer output. The square wave output of the keyer could now be monitored on this scope. The percent on-time control was calibrated by means of an adjustment screw so that when set to 0 percent on-time there was no output signal from the keyer, and when set to 100 percent on-time there was a continuous d-c output from the keyer.

Start-up Procedure

When the power plant was at the operating temperature as signaled by the "plate-ready" light, the power plant was ready to operate. The desired transformer tap was now selected. The gas supply was adjusted to the desired flow rate. The safety door was then closed. With the percent duty cycle control set to zero, the selector switch set to off, the "plate-on" button was pressed. The Visicorder paper drive was now started. The selector switch was turned to manual and the percent on-time gradually increased until an arc was obtained. The percent on-time was increased to approximately ten percent. At this point power was applied to the d-c electrode actuator and the arc length increased to the desired operating point. Readings were now taken of plate dissipation current, plate voltage, r-f voltage, r-f current, water flow rate and temperatures at ten percent on-time intervals until 100 percent on-time was reached. The percent on-time was then reduced to 10 percent. The same readings were again taken while the percentage on-time was decreased by approximately one percent intervals, until the arc was extinguished.

The "plate-off" button was then pushed, cutting off power, and the safety door was opened. The gas was allowed to flow for a few minutes to cool the apparatus. The Visicorder was left running until water and gas temperatures had stabilized.

Oscilloscope Readings

During several of the runs the dynamic characteristic of the arc was obtained by connecting the r-f voltage to the vertical deflection plates and the r-f current to the horizontal deflection plates. Photographs were taken of the oscilloscope display. The oscilloscope was also used to observe the shape of the current-time curve and the voltage-time curve.

High-Speed Photography

On approximately ten runs high-speed movies were taken of the arc, either by the Fastex camera at 7,000 frames/sec or the Dynafax camera at 28,000 frames/sec. These movies were used to obtain information such as extinction time, the shape of the arc, and the diameter of the arc column.

V. Range of Experimental Parameters

A total of 57 runs was made to obtain data on the variation of the arc characteristics due to changes in the following parameters: (1) the rate of gas flow, (2) the length of arc path, (3) the power output of the power supply, and (4) the type of gas used within the arc cylinder. A total of 10 runs was made in order to determine the dynamic characteristics of the arc and to determine the heat transfer to the cooling water. The above total does not take into account the many runs that were made during the development and testing of the apparatus or the runs that were terminated due to failure.

On most of the runs between 10 and 20 experimental points were obtained by varying the percent on-time of the oscillator keyer.

Individual Parameters

Gas Flow. The flow rate of the argon was varied in steps of 50 standard cubic feet per hour from 0 to 350 SCFH. Only three runs were made with nitrogen, all of which were at 200 SCFH.

Length of Arc. The arc length was varied from 0 to 4-1/2 inches.

Power Supply. The power supply was varied from 0 to 100 percent on-time on eight of the nine available transformer taps. The r-f voltage varied from 0 to 2000 volts. The r-f current varied from 0 to 560 amperes. The d-c plate dissipation power varied from 0 to 250 kilowatts.

Frequency. All runs were made at 400 Kc. nominal frequency. The actual frequency varied from approximately 380 Kc. to 408 Kc., but this was not considered significant since the variation of 28 Kc. would not change the ω/ω_n ratio by a sufficient amount to significantly change the arc characteristics.

VI. Results

The most important result of this study was the attainment of a long, stable, radio-frequency arc at atmospheric pressure. As far as is known, this is the only arc of its kind which has been operated at this high frequency. The apparatus, in its present configuration, is most reliable and may be run for prolonged periods at low power levels. It was run for 15 to 20 minute periods at 30 percent on-time on tap one. With some modifications, as discussed in the recommendations, the apparatus should be capable of much longer operating periods at higher power levels.

Data obtained from the apparatus is very reproducible. By this it is meant that two different runs made perhaps a month apart, but using the same settings for the power plant and gas supply, will yield almost identical data. This is not a usual characteristic of arc apparatus and is a good indication of the stability of the arc and power plant.

The arc column obtained was quite diffuse with the visible portion of the arc, as determined from high-speed photographs, varying from 1/2 inch to 7/8 inch in diameter. At high power settings there was also a glow discharge around each of the electrodes in addition to the arc itself.

The effect of the variation of various parameters on the characteristics of the arc apparatus will now be discussed in detail. It should be pointed out that the characteristic curves obtained in this thesis and shown in Fig. 14, 15, 16, 17, and 18 are for the arc apparatus and power plant combination. The characteristics, then, include the effect of long copper lead-in tubing and electrodes as well as the operating characteristics of the power plant. More will be said on this subject under the various sub-sections.

Arc-Power Plant Characteristics

Fig. 14 illustrates the characteristics obtained for the arc apparatus as a whole. As previously pointed out and as will be discussed later in this section, these characteristics are not, therefore, those of the arc itself. It is felt that the characteristic for the arc itself will have the same general shape as the envelope of these curves, however, the magnitude of the voltages will be considerably less.

The individual curves in Fig. 14 represent pseudocharacteristic volt ampere curves for the apparatus-power plant combination. They were each obtained, on a particular transformer tap setting, by varying the percentage on-time from 0 to 100 percent. The five lower curves were obtained by putting resistors in series with the arc apparatus. These individual curves are not too significant and they have been termed pseudocharacteristic curves since the current values shown are somewhat misleading. Due to the frequency response of the r-f ammeter it tended to indicate an average current value and hence, give a false reading at other percentages on-time than 100 percent. For example, on tap 6 at 100 percent on-time the ammeter indicated 395 amperes; on the same tap setting at 50 percent on-time it read 200 amperes, since there was approximately a 400 ampere current flowing 50 percent of the time.

The lines joining the 100 percent points are valid characteristic curves since at this setting the ammeter reads correctly. It will be seen that there are two of these lines. The one is for the original apparatus. The second is for the apparatus after a modified outlet chamber was installed. The modified outlet chamber improved the flow of gas in the vortex. This made the arc more stable and lowered the voltage required to maintain a particular arc current.

Both of these characteristic curves are straight lines which indicates that the impedance of the apparatus and arc is a constant value. This value is 2.7 ohms for the original apparatus and 2.3 ohms for the modified apparatus.

The left side of the envelope of curves in Fig. 14 shows the high reignition potentials required when the arc was extinguished for a large percentage of the time. As the percent on-time was decreased below 10 percent the voltage across the arc apparatus increased rapidly. It is interesting to note that regardless of the tap setting, all of these readings fell on this same curve, which is almost a vertical line. Voltages as high as 2500 volts were measured just prior to extinction.

High-speed movies taken of the arc showed that if the power plant was set, for example, to 50 percent on-time, then the arc would appear in slightly more than half of the frames comprising a complete cycle (1/360 second). There would be no arc visible in the other frames. Whether an arc was or was not recorded on the film was, of course, a function of the lens opening of the camera, the type of film used and the speed of the shutter; nevertheless, it would appear that the visible portion of the arc was extinguished and then reignited. The plasma, during extinction, must remain hot enough to contain sufficient conducting ions and electrons to enable the arc to reignite over this long gap setting. However, as the percent on-time was decreased to very low values the extinction time was sufficiently long for the gas to cool considerably. This led to a reduction in the number of conducting ions and electrons, requiring a much higher potential for reignition of the arc as mentioned above. The voltage required increased drastically as the percentage on-time was decreased below the critical point, and at the same time the arc became very unstable and did not follow the same path each time it ignited.

The critical point for this phenomena appeared to be a function of temperature in the plasma since it varied not only with the percent on-time, but with the current flow, amount of water cooling and the amount of gas flow.

Gas Flow Rate

Readings of r-f voltage and current were taken, with a 4 inch arc and with the power plant set to 100 percent on-time on tap one, while the argon flow was varied from 350 SCFH down to 0 SCFH.

It was found that the gas flow rate was not a significant parameter over the range of 100 to 350 SCFH. Variation of the flow over this range produced no measurable change in the voltage and current readings. The major portion of the voltage drop across the apparatus was in the leads and electrodes, as will be shown later. Therefore, it is possible that small undetected changes occurred with changing gas flow in the voltage drop across the arc itself.

When the flow of argon was reduced below 100 SCFH the arc became unstable. At 50 SCFH there was an increase in voltage of about 50 volts and a slight decrease in current. Below a flow of 50 SCFH the arc became so unstable that the meters fluctuated wildly and readings could not be taken. In general, however, as the gas flow was reduced the r-f voltage continued to increase.

At high rates of gas flow a glow discharge was visible along the sides of the electrodes, but this disappeared at the lower gas flow rates. It is believed that this was due to the low-pressure area created in the center of the vortex at high flow rates.

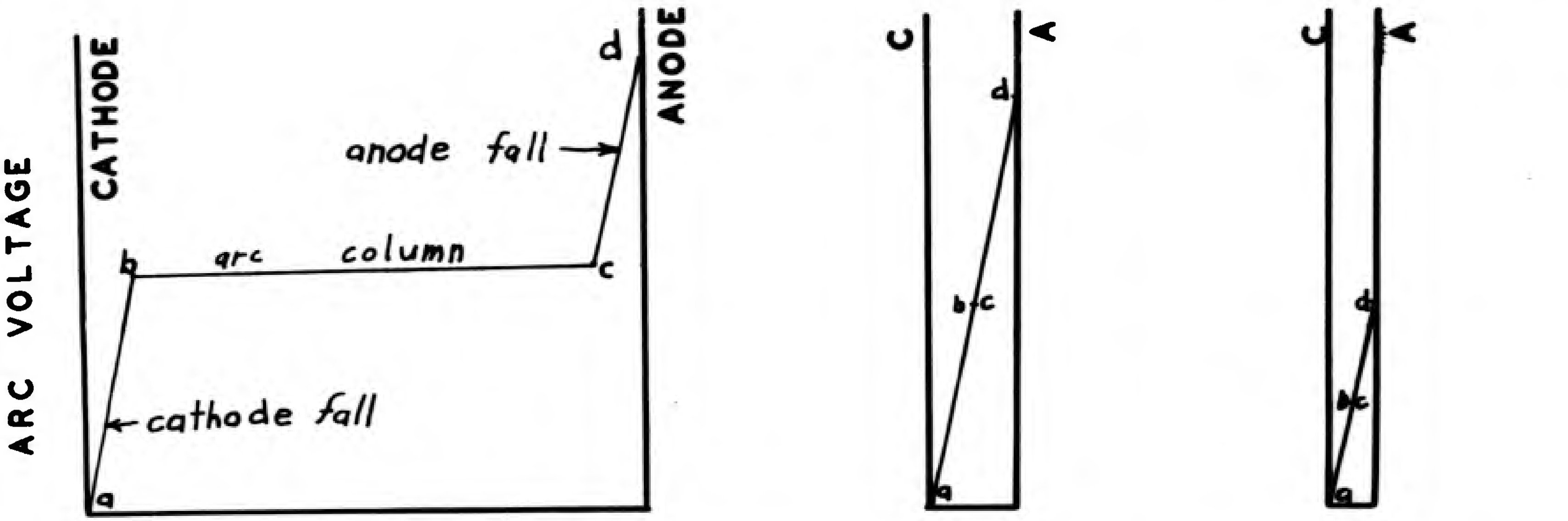
Heating of both the quartz tube and the electrodes increased as the gas flow decreased. On two occasions the arc was maintained in an argon atmosphere, but with no gas flow, by turning off the argon after the arc had been established. The arc was extremely unstable and the heating effect very severe.

Type of Gas

Fig. 15 shows a comparison of the characteristics of the arc apparatus when run on nitrogen as compared to a similar run on argon. Gas mass flow rates were approximately the same. As may be seen, a much higher voltage was required, for the same current flow, for nitrogen as compared to argon.

Arc Length

As may be seen from Fig. 16 arc length did not turn out to be an important parameter. This had been expected since most arcs have a steep voltage gradient, close to each electrode, called the cathode fall and the anode fall (ab and cd in Fig. 12) and then a very shallow gradient across the remainder of the arc gap, (bc in Fig. 12 A). The differences in potential and current for long or short arcs was so



ALL ABSCISSAS REPRESENT DISTANCE ALONG ARC

(A) NORMAL ARC (B) SHORT ARC (C) VERY SHORT ARC

FIG. 12 VOLTAGE GRADIENT IN A TYPICAL ARC slight that it could not be detected by the instruments. As mentioned on page 33, any change in voltage across the arc probably was masked by the large voltage drop in the leads and electrodes.

In order to explain the steep increase in the measured r-f voltage and current at very low gap settings, as shown in Fig. 16, it is necessary to consider the overall circuit and power plant characteristics. Fig. 20 is a schematic of the circuit diagram of the apparatus. It may be seen from Fig. 14 that the power plant has a slightly rising characteristic; that is the voltage output (V_1) increases slightly with increasing current.

As the arc gap was decreased it is felt that the voltage drop across the arc itself (V_3 in Fig. 20) decreased. As may be seen from Fig. 12, when the arc gap is reduced to the point that c coincides with b (Fig. 12 B), the anode fall and the cathode fall lie almost in a straight line. Any further reduction in the gap will produce a significant decrease in the arc voltage. Indeed, it must be zero when the electrodes are short circuited.

However, when the voltage drop (V_3) across the arc decreases the total voltage drop across the leads (V_2) and across the arc (V_3) is less than the output voltage (V_1), hence, a higher current flows. As the current increases the output voltage (V_1) also increases as pointed out above. Thus a decrease in arc voltage leads to an increase in voltage and current readings on the meters. Eventually the power plant and arc apparatus reach a new operating point where the voltage drop across the arc apparatus equals the voltage output of the power plant.

True Arc Characteristic

As has been pointed out previously the envelope of curves in Fig. 14 is not characteristic of just the arc itself. One of the major difficulties in obtaining a true characteristic for the arc alone is that voltage readings could not be taken at the tips of the electrodes. Due to the surrounding quartz chamber and the large copper-sheet leads needed for the voltmeter at this frequency, it was found necessary to couple the voltmeter to the input lines. As may be seen from Fig. 16 the voltage drop across the electrodes and leads was very high even with the electrodes short circuited (zero gap). If the leads, electrodes, and arc were pure resistive loads, this voltage drop would not be a severe problem since one could subtract the voltage drop with no arc gap from the voltage drop with an arc, at the same current, and obtain the actual voltage drop across the arc. That these loads were not all resistive will now be shown.

The Kilovolt-amperes into the arc apparatus were calculated by multiplying the measured r-f voltage by the measured r-f current at 100 percent on-time. The d-c plate dissipation power of the oscillator was also measured. Fig. 15 shows a plot of these two quantities versus transformer tap setting. Fig. 16 shows the ratio of these two quantities versus tap setting. It may be seen that the measured Kilovolt-amperes run as high as twice the d-c input power to the oscillator. This could be true only if the arc apparatus had a low power factor.

Attempts were made to measure this power factor by photographing the oscilloscope presentation of the dynamic characteristic as shown in Fig. 13. Measurements obtained from similar photographs indicated the power factor to be between 0.41 and 0.45 at 100 percent on-time and tap one.

Since the measurements taken by the above means could not be too precise, another approach to the problem was tried. The d-c plate input power versus r-f output current was measured first with an arc (P_1) and then with the electrodes short circuited (P_2), at 100 percent on-time on each of the eight tap settings. At the same time, the total voltage across the apparatus with an arc (V_1) and then with the electrodes short circuited (V_2) was recorded. The power curves are plotted in Fig. 19 and the voltage curves in Fig. 21.

If it is assumed that power losses in the power plant and the apparatus are functions of output current only, then

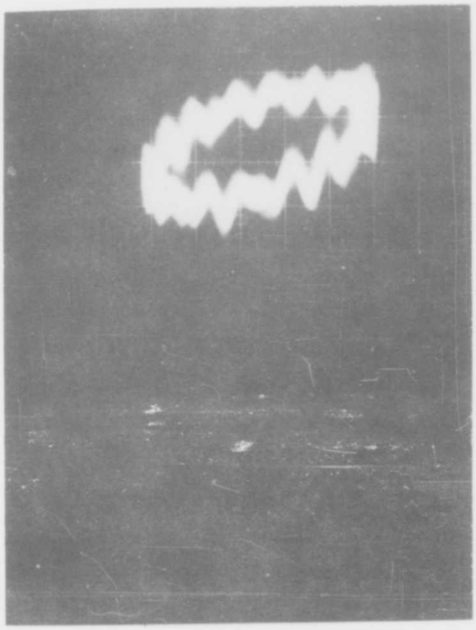


Fig. 13

Photograph of Oscilloscope Showing the Dynamic Characteristic of the Arc Apparatus (voltage is displayed on the vertical axis, and current on the horizontal axis) the difference between these two curves ($P_1 - P_2$) should represent the actual power into the arc (Fig. 19). If it is further assumed that the arc is a pure resistive load at this frequency, as predicted in reference 6, then one may obtain the true arc voltage (V_3) by dividing the arc power by the arc current (Fig. 21).

Using the three voltages shown in Fig. 21, it is now possible to draw a vector diagram. A vector diagram for the arc apparatus at 100 percent on tap one, is shown in Fig. 22. From this diagram the power factor, which is the cosine of the angle (θ) between the total arc voltage (V_1) and the arc current. As shown in Fig. 22 this power factor is 0.44 which is in excellent agreement with the experimentally determined values given on page 38.

This result suggests that the second assumption stated above was probably correct since, if the arc was not purely resistive then there would have been an additional inductive or capacitive voltage drop at right angles to the resistive drop (V_3) calculated from the real power. The power factors would then not be in agreement since this additional voltage drop would change the angle θ in Fig. 22.

The voltage across the arc (V_3) as calculated from the arc power represents a portion of the probable real arc characteristic. The method was applied only down to an r-f current of 230 amperes. The plot of arc voltage (V_3 in

Fig. 21) is a straight line with a positive slope, as was the arc-power plant characteristic shown in Fig. 14, above 50 amperes. It should be possible therefore to extrapolate the plot of V_3 down to a current of 50 amperes. This is shown in Fig. 23.

At very low currents, below 20 amperes, the voltage drop in the leads and electrodes (V_2) becomes negligible as can be seen if the plot of V_2 in Fig. 21 is extrapolated to low currents. Therefore, the voltages measured across the arc apparatus and plotted on the left side of Fig. 14 are, very closely, the actual arc voltages. This curve was also plotted on Fig. 23 to give a probable true characteristic for the arc itself. This characteristic was very similar to that obtained for a d-c arc.

From Fig. 21 a value of 0.5 ohms was calculated as the resistive impedance of the arc itself. This impedance appeared to be a constant for all values of current, for this particular 4-inch-long arc column. A value for voltage gradient varying from 10 to 26 volts/cm. was obtained which was in very good agreement with values obtained experimentally for d-c arcs (Personal communication from Lt. P. D. Tannen, ARL).

Power

All readings of cooling water flow and temperatures were made with the power plant set to tap one, since the high temperatures reached by the apparatus at higher tap settings precluded runs of long duration. Power losses and efficiencies were therefore only calculated for this one tap setting.

Fig. 19 indicates that for a current of 230 amperes (Tap 1 at 100 percent with a 4 inch arc) approximately 30 Kilowatts of power was delivered to the arc itself. Measurements of temperature and flow of the cooling water to the electrodes indicated that of this power 10 Kw. was lost in cooling the electrodes.

Temperature readings of the calorimeter cooling water and of the exhaust gas indicated that 7 Kw. was transferred to the gas. Therefore, 13 Kw. were lost by conduction and radiation to the walls of the chamber. An indication of these high losses is that the quartz tube glows cherry-red after about 10 seconds of operation at this power setting. These power losses, which amounted to 43 percent of the input power, appeared to be extremely high. Capt. H. R. Cannon carried out experimental work at ARL, on a similar argon plasma and found that losses to the walls by conduction and radiation were from 50 to 65 percent. Since the wall of his apparatus had a larger surface area and the temperature of the plasma used was somewhat higher, the values are in good agreement.

Efficiency

The results shown on the previous page indicate that this r-f arc does not appear to be an efficient means of transferring energy to a gas. The overall efficiency may be defined as the power transferred to the gas divided by the power input to the power plant.

For this apparatus at 100 percent on-time on tap one

Power input to the oscillator	80Kw.
Power input to the arc apparatus	30Kw.
Power transferred to the gas	7Kw.

The overall efficiency of the arc apparatus and power plant was calculated to be 8.8 percent. The efficiency of the arc apparatus itself was found to be 23.3 percent.

The efficiency of the energy transfer to the gas, in an actual engine would probably be much higher since most of the losses due to radiation could be eliminated. However, due to the low efficiency of any r-f power plant, the overall efficiency would still be low.

VII. Conclusions

1. A radio-frequency arc may be operated in argon or nitrogen at atmospheric pressure.
2. Such an arc may be effectively stabilized by a vortex.
3. The voltage-current characteristic of such an arc consists of a steep negative slope from 0 to approximately 40 amperes, where it then changes to a positive slope.
4. The arc itself is probably a pure resistive impedance, and the dynamic characteristic is therefore almost a straight line.
5. The current and voltage in the arc are probably in phase and the power factor is very close to one.
6. This arc apparatus is not an efficient means of transferring energy to a gas when operated at radio-frequency.
7. It is doubtful that an r-f arc has any advantage over a d-c arc as a means of transferring energy to a gas.

VIII. Recommendations

Modification of Instrumentation

Both the ammeter and voltmeter were operating only on a very small portion of the scale. The wiring for both of these instruments is quite simple (see Fig. 10 and Fig. 11). By inserting a rotary switch, coupled to precision resistors, the meters could be provided with several scales to give much more accurate readings.

Some means of accurately detecting voltage and current for display on an oscilloscope is necessary. The capacitor-voltage-divider network, used in this study, operated satisfactorily. By inserting resistors in parallel with each capacitor to increase the time constant, this network could also be used to give magnitude values on the scope. However, some means of isolation is required to protect both the oscilloscope and the operator from high radio-frequency voltages.

The loop method for picking up current flow is not satisfactory. Using a resistive length of copper lead-in tube appears to be more satisfactory and should be further investigated.

Apparatus Modifications

Voltage Pickup. An attempt to measure the voltage directly across the arc should be made. This might be done by probes through the glass tube or by sliding contacts on the electrodes.

Cooling System. One of the biggest disadvantages of the present apparatus is the high temperature attained by the quartz tube and other parts of the apparatus after only a short period of operation. By installing a double-wall, water-cooled, Vycor tube, continuous operation at fairly high power levels should be possible.

A better calorimeter should be built so that the gas could be cooled down to inlet conditions. This, together with the water-cooled wall, should enable one to achieve steady state conditions.

Length of Arc. In view of the very small gradient of the voltage versus arc length curve and the high voltage available from the power plant, it should be possible to draw a much longer arc, perhaps as long as three feet. If this were done it should be possible to operate at much higher power levels.

It would be necessary to couple the apparatus much closer to the power plant and to use larger lead-in pipes so as to decrease power and voltage losses in the leads.

Concentration of the Arc. The arc in its present configuration is quite diffuse. It should be possible to produce a much more concentrated arc by increasing the operating gas pressures. It might be possible to produce a highly concentrated arc by using cavity-type electrodes in a vortex-chamber, such as the one developed by Dr. Pfender and Capt. T. Reinhardt at the Aeronautical Research Laboratories.

Copper-Oxide Prevention. The formation of a coating of black, copper-oxide on the inside of the tube made observation of the arc, over long periods, very difficult. The apparatus was sealed so that outside air could not enter the chamber. It is believed that the oxygen needed to form the copper-oxide must then come from water vapour that permeated the Tygon tubing used to connect the gas bottles to the apparatus or that remained in the argon from the water pumping process used to refill the high pressure bottles. A drier such as is used in aircraft oxygen charging systems could be installed close to the apparatus to eliminate water from both of these sources.

Energy Balance

With the existing apparatus it was not possible to make an exact energy balance since first, the apparatus could not be operated for a long enough period to reach steady state conditions and second, the heat lost by radiation and conduction to the walls could not be measured. If the water-cooled double wall modification is carried out it would eliminate both of these difficulties.

By using thermocouples on the inlet and outlet of the water cooling to the wall, it would be possible to measure the heat added to this cooling water. This heat would equal the amount of heat conducted to the walls by the gas plus the small amount of radiation absorbed by the transparent glass and water.

Black India ink could now be added to the water and the heat added to the cooling water again measured. Since this black water would have an absorptivity close to one, the heat added to the water would be equal to the heat conducted and all the heat radiated to the walls. By subtracting the conducted heat measured previously, it would be possible to determine the amount of heat transferred by radiation.

The above method was used by Capt. H. R. Cannon at ARL with good success to obtain the values indicated on page 42.

By varying gas flow and arc length while measuring the power input to the arc and the various heat losses, it would be possible to determine if optimum conditions exist where the percentage of the input power transferred to the gas would be a maximum.

Types of Gases

The time available did not permit a study of the characteristics of the arc with other gases such as nitrogen, helium, and hydrogen. The few runs that were made on nitrogen indicated that more heat could be added to it than to argon. It is felt that a study should be made to find out if some gases give higher efficiencies than others. This would probably give different results from those obtained with d-c arcs since at this frequency it is possible to excite the atoms by the r-f field produced by the arc as in an electrodeless discharge.

Comparison at other Frequencies

It would be most interesting to take an apparatus, similar to the present one, but with a water-cooled tube, and operate it at radio-frequency, then at perhaps 400 cycles (a common aircraft supply frequency), then at 60 cycles, and finally on direct current. By using the same apparatus, gas flow, etc. on each, and doing an energy balance each time, a very good investigation of how efficiency varied with frequency could be made. It is felt that the results of such an investigation would be far more conclusive than the present isolated studies.

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Appendix A

Graphs of Results

Figures 14 to 23

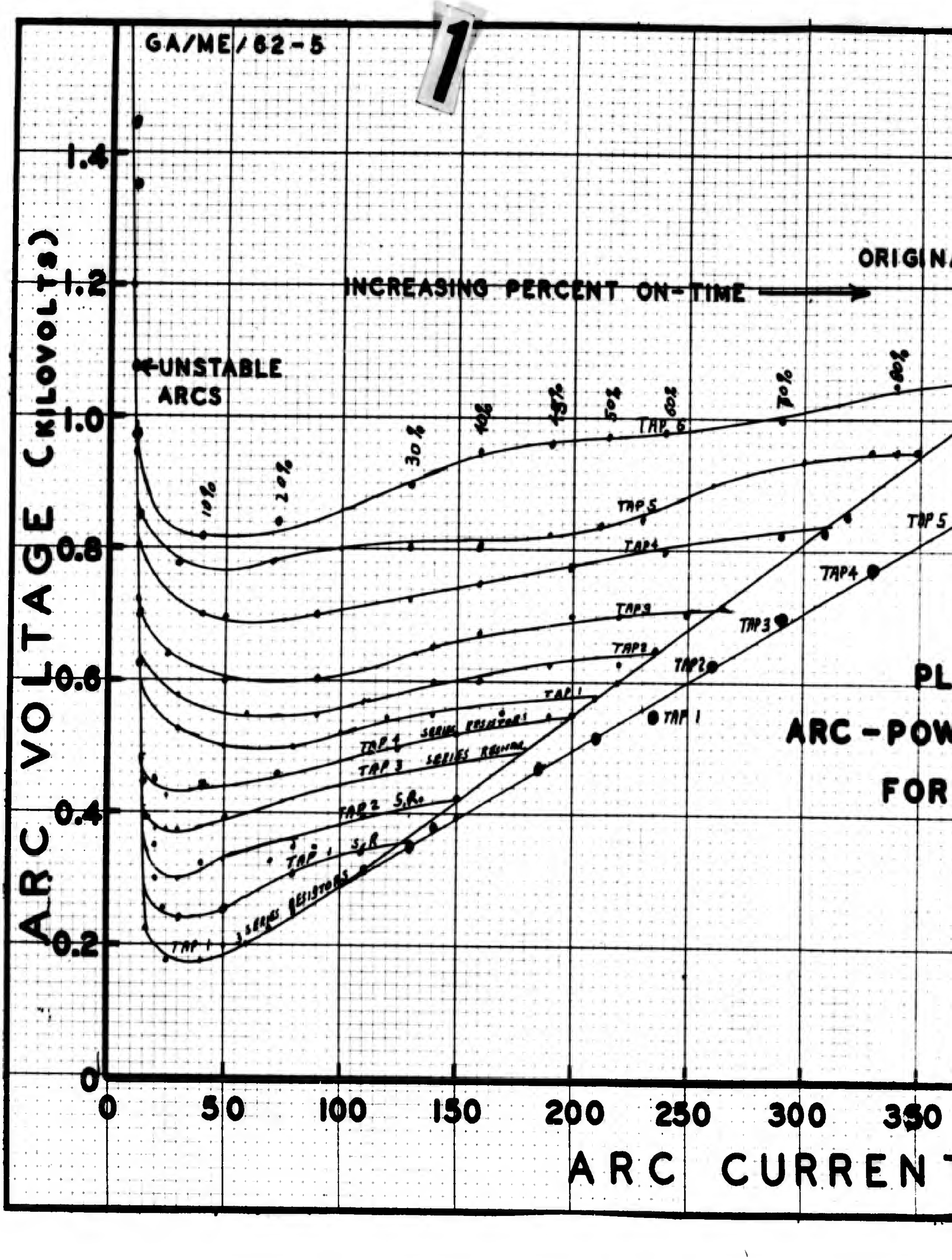
The parameters for these Figures were as follows:

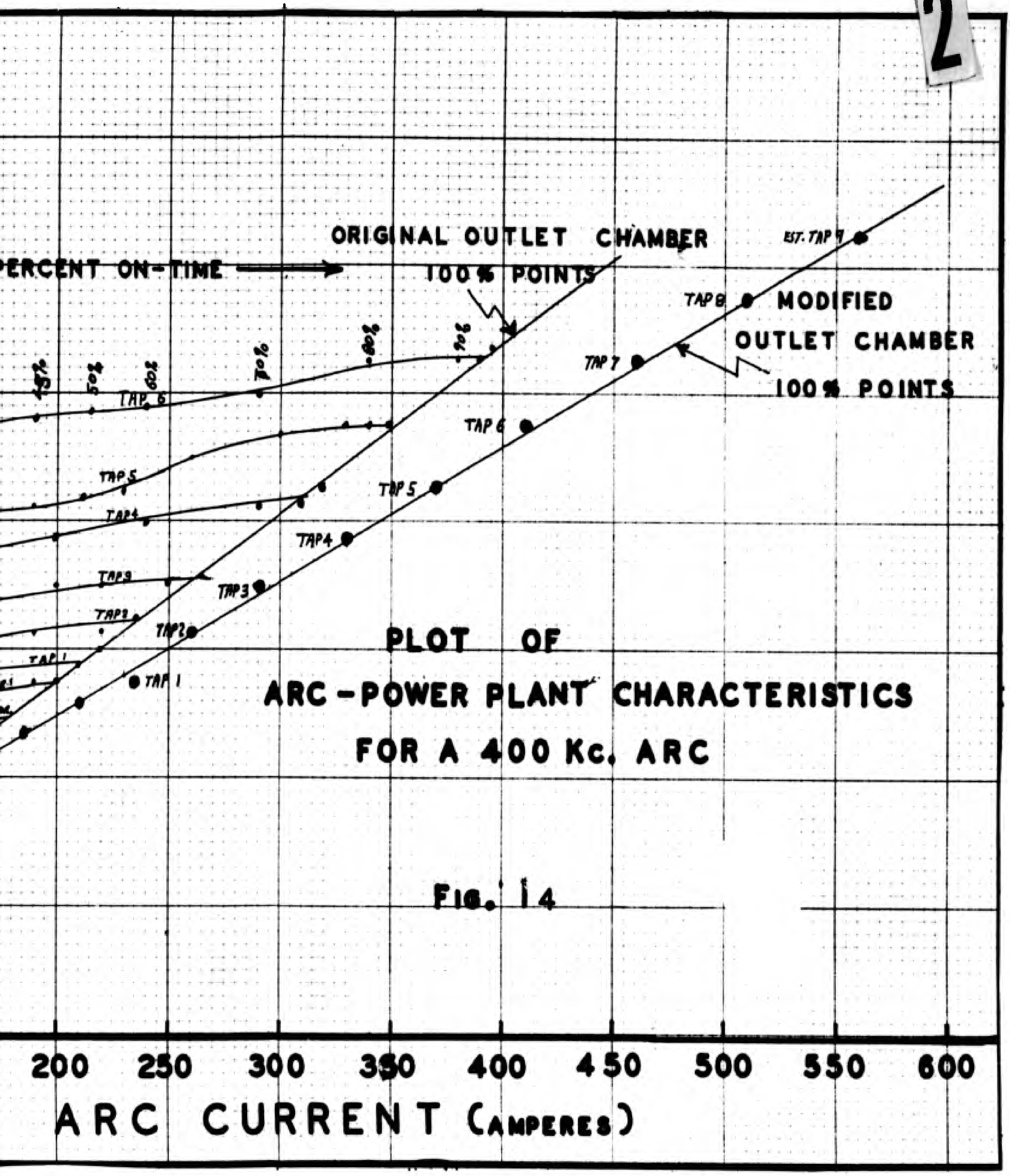
1. Flow Rate. All curves shown with the exception of nitrogen curve in Fig. 15 were for an argon flow rate of 200 SCFH. The nitrogen curve was for a nitrogen flow rate of 220 SCFH.
2. Arc Length. An arc length of 4 inches was used to produce the results shown in all the Figures except Fig. 16, where the arc length was varied as shown.
3. Percent On-time. The data in all Figures except Fig. 14 and Fig. 15 were taken at 100 percent on-time.
4. Transformer Tap Settings. Fig. 15, 16, and 22 are for tap one only. In all other Figures the tap setting was varied.

FIG. 14

PLOT OF

ARC-POWER PLANT CHARACTERISTICS FOR A 400 Kc. ARC


GA/ME/62-5
1
ARC VOLTAGE (KILOVOLTS)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
ARC CURRENT
INCREASING PERCENT ON-TIME
ORIGINA
UNSTABLE ARCS
10%
20%
30%
40%
45%
50%
60%
70%
80%
TAP 6
TAP 5
TAP 4
TAP 3
TAP 2
TAP 1
TAP 4 SERIES RESISTORS
TAP 3 SERIES RESISTORS
TAP 2 S.R.
TAP 1 S.R.
TAP 1 SERIES RESISTORS
TAP 5
TAP 4
TAP 3
TAP 2
TAP 1
PL
ARC-POW
FOR



PLOT OF
ARC-POWER PLANT CHARACTERISTICS
FOR A 400 Kc. ARC

FIG. 14

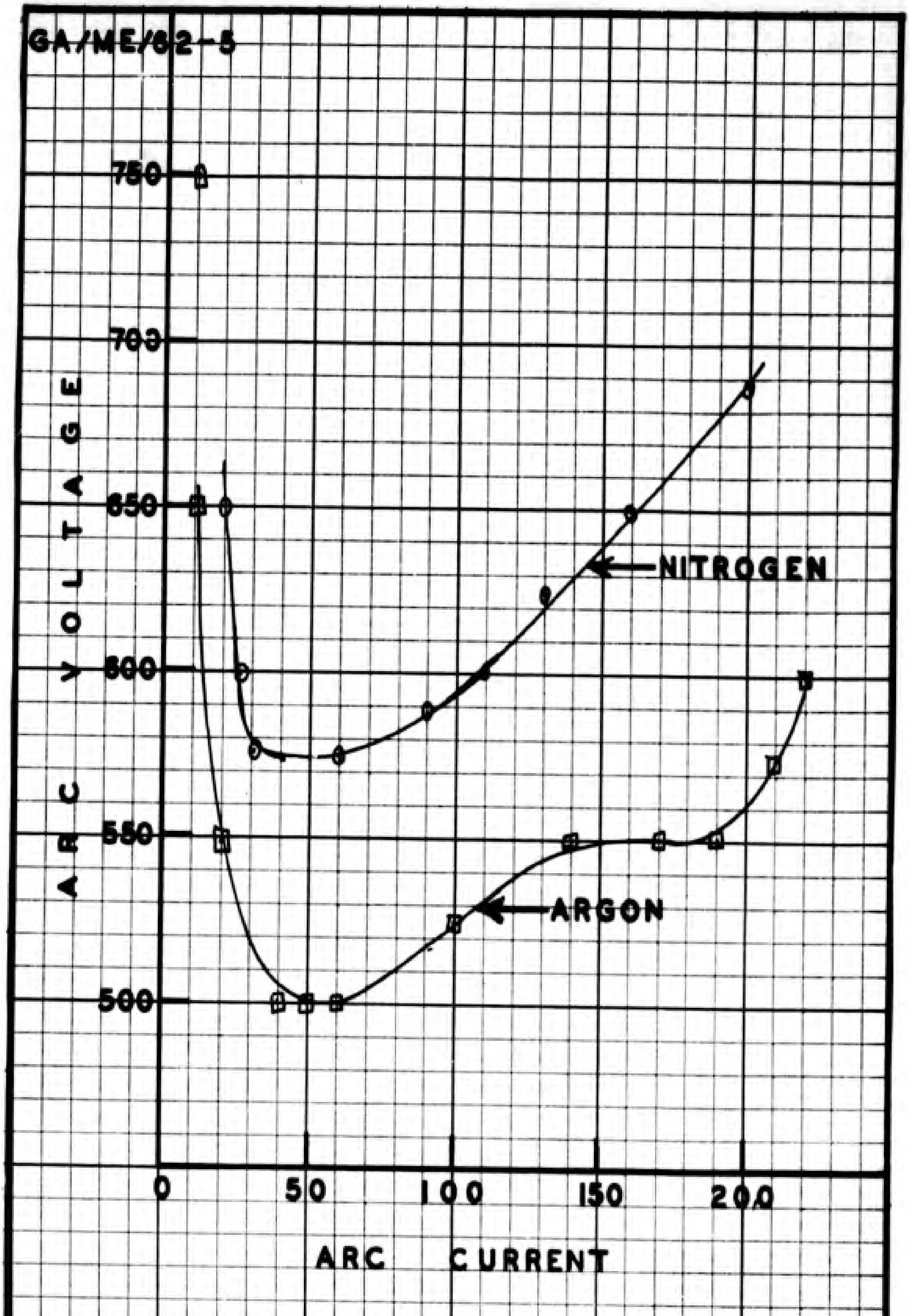


FIG. 15 VARIATION OF CHARACTERISTICS WITH TYPE OF GAS

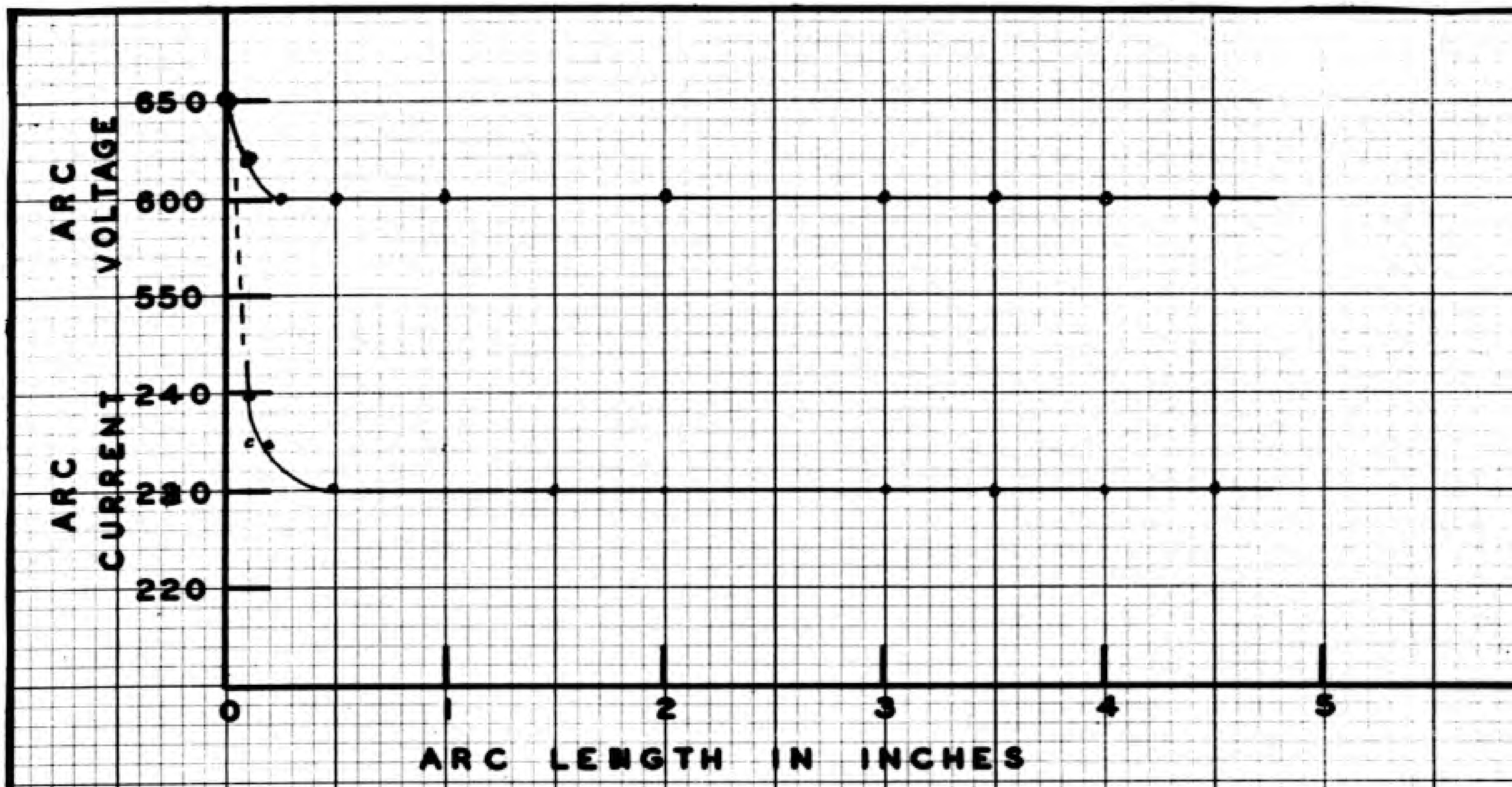


FIG.16 VARIATION OF ARC CHARACTERISTICS WITH LENGTH OF ARC

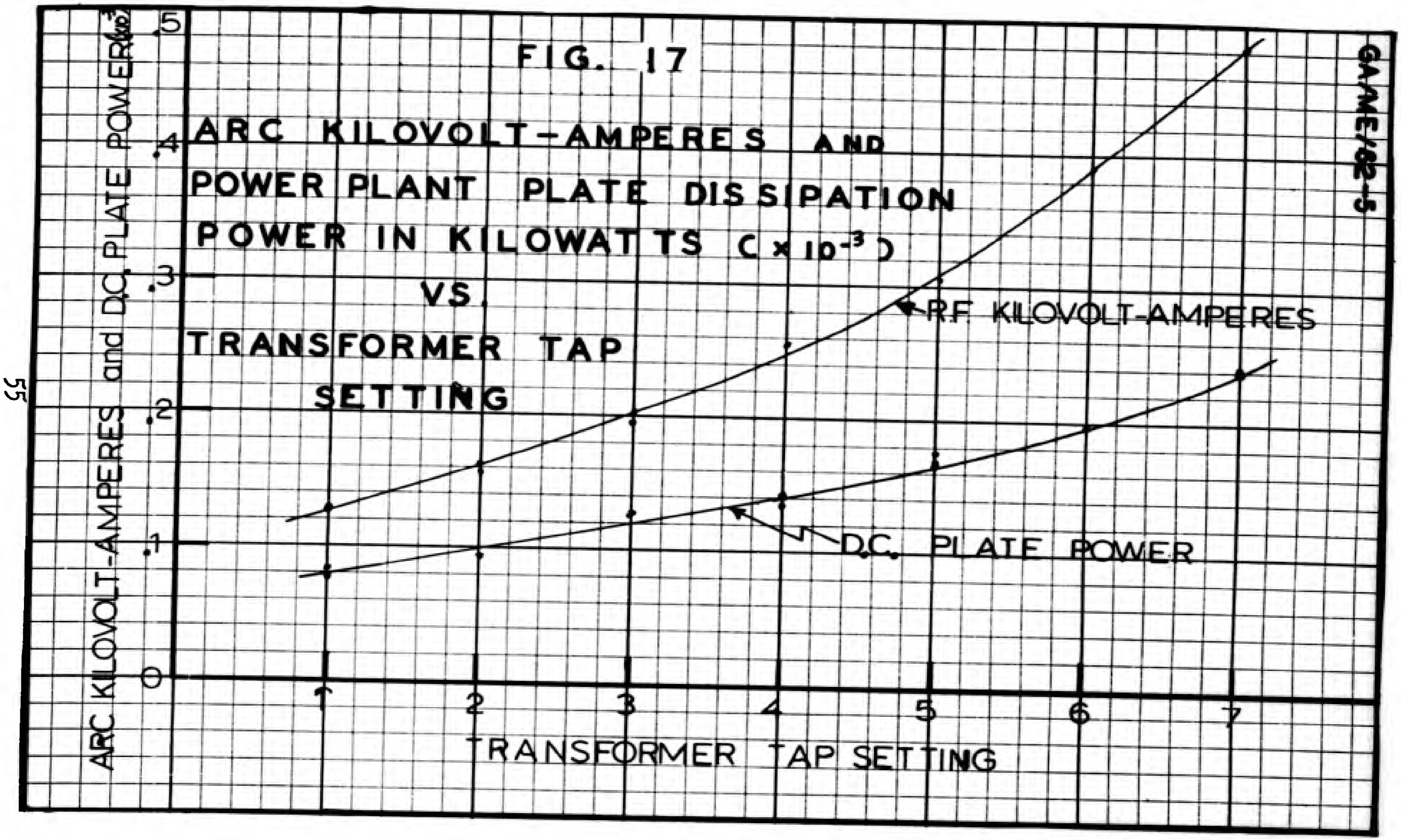


FIG. 17

ARC KILOVOLT-AMPERES AND POWER PLANT PLATE DISSIPATION POWER IN KILOWATTS (× 10⁻³) VS. TRANSFORMER TAP SETTING

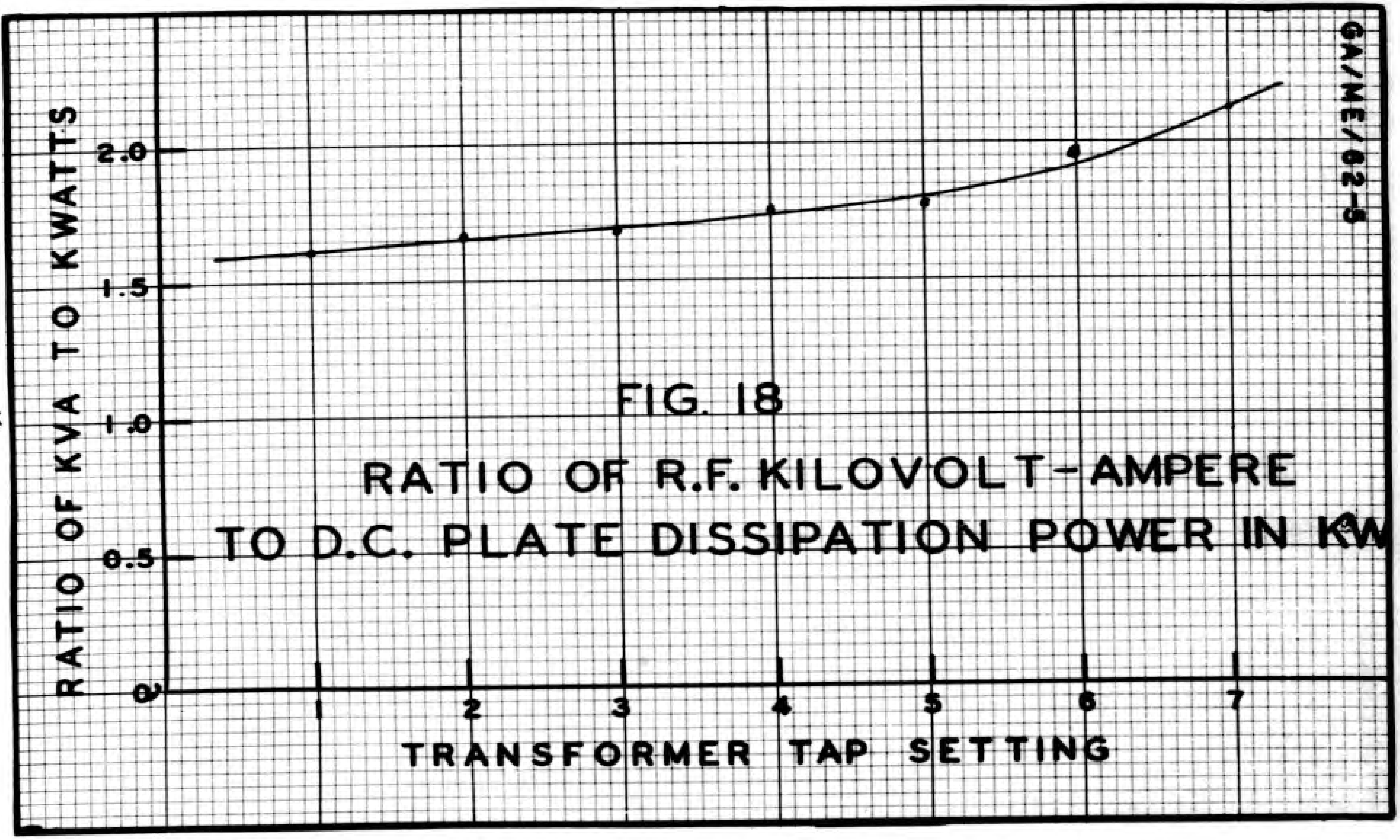


FIG. 18

RATIO OF R.F. KILOVOLT-AMPERE TO D.C. PLATE DISSIPATION POWER IN KW

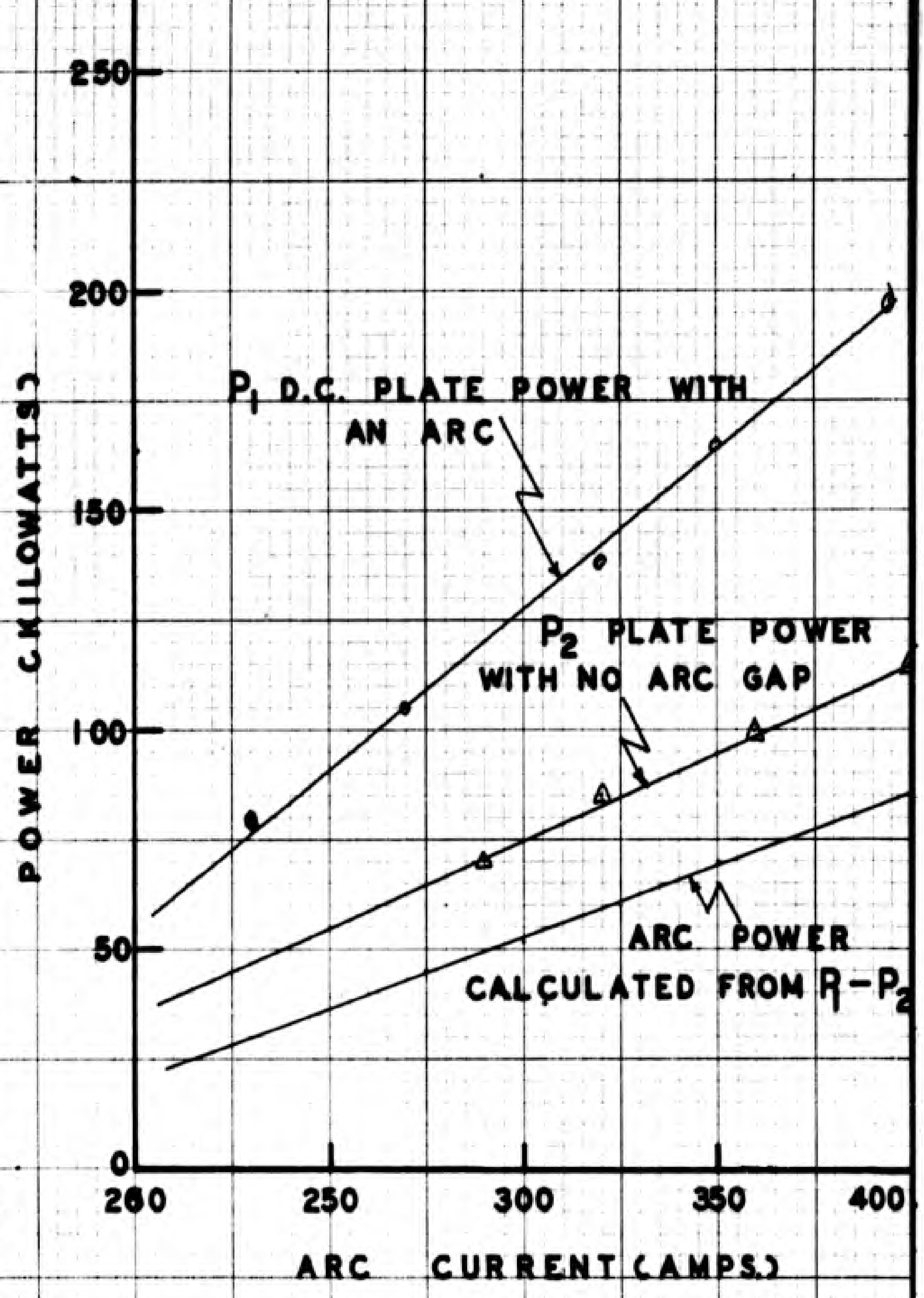
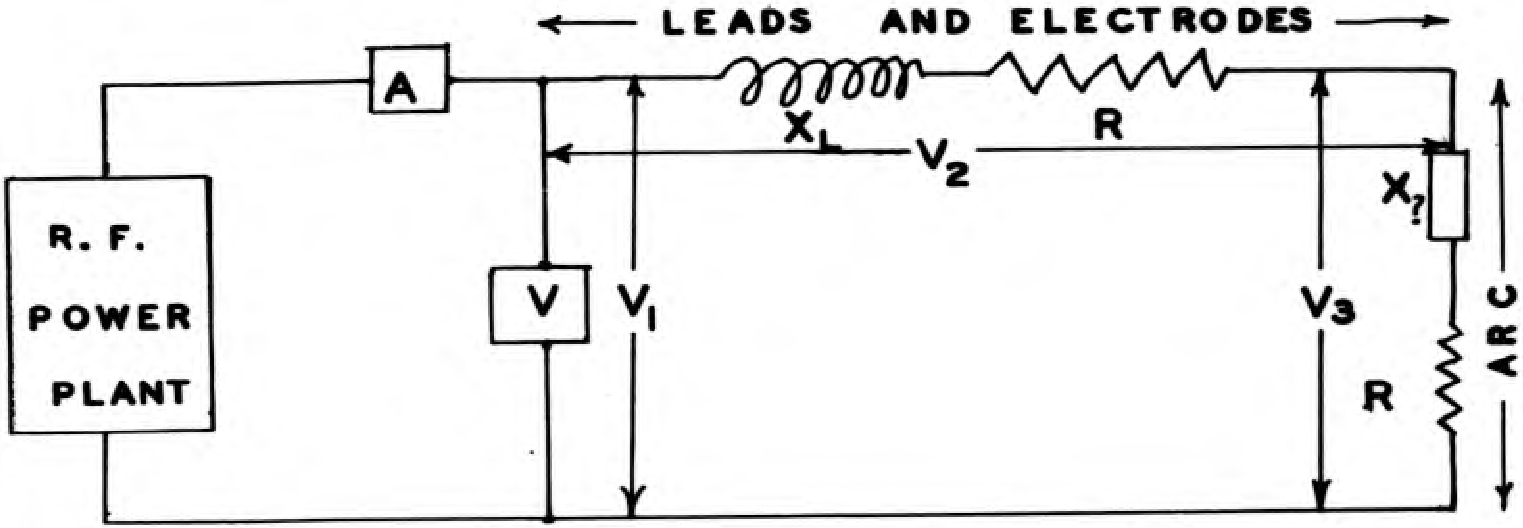


FIG. 19

POWER CHARACTERISTICS VS. R.F. CURRENT



F I G. 20

SCHEMATIC CIRCUIT DIAGRAM FOR ARC APPARATUS

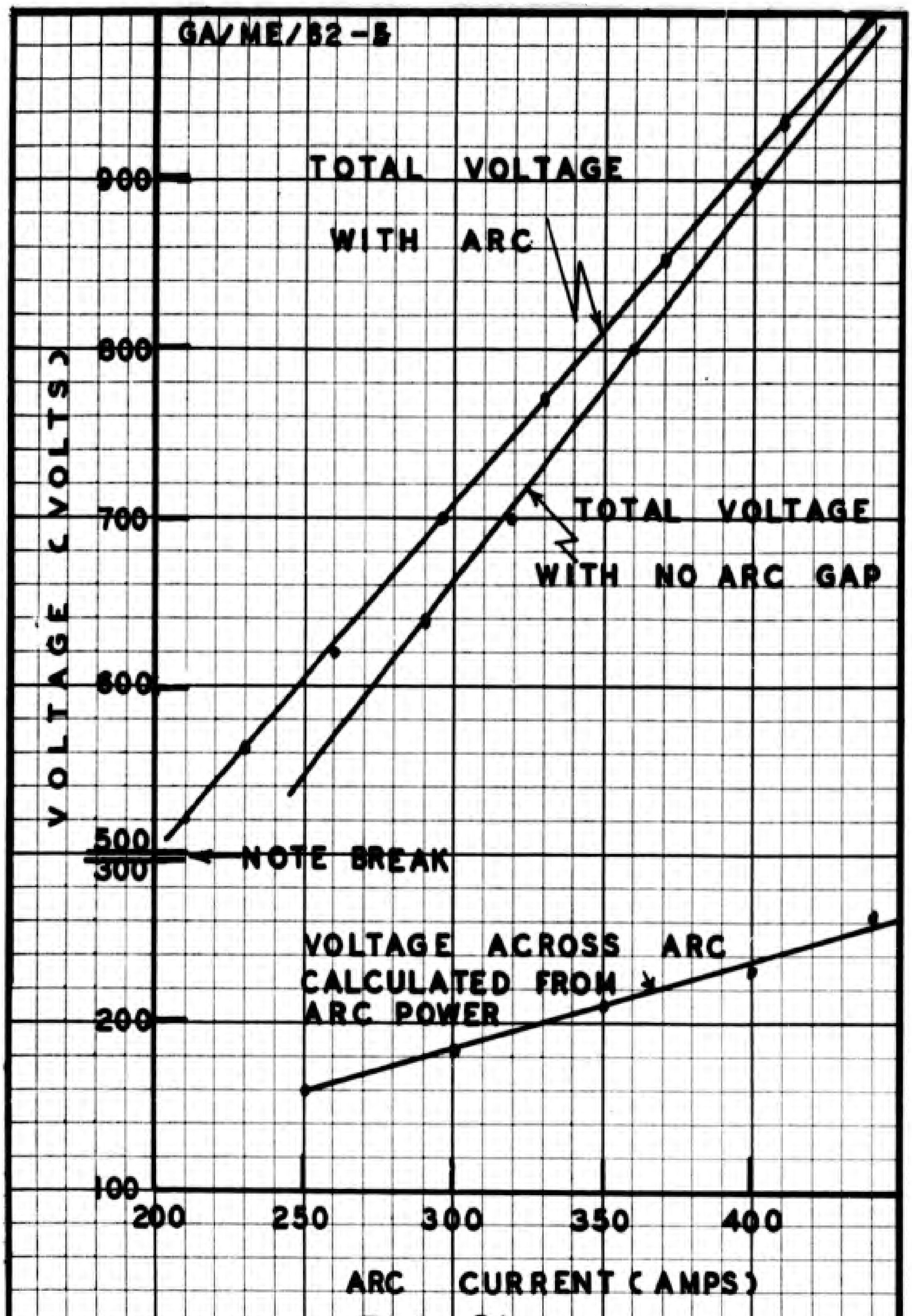
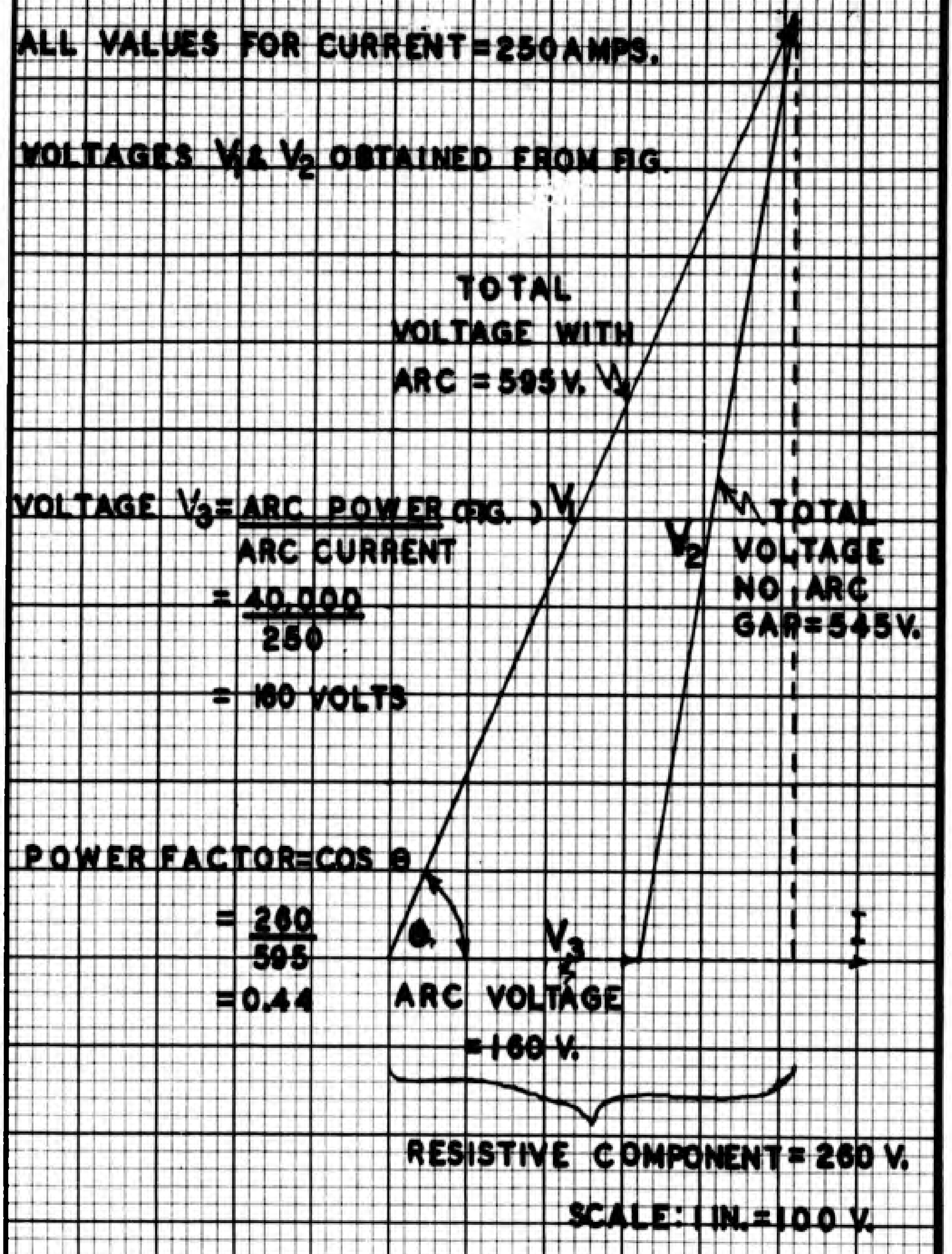


FIG. 21

VOLTAGE VS. CURRENT WITH & WITHOUT AN ARC GAP



ALL VALUES FOR CURRENT = 250 AMPS.

VOLTAGES V_1 & V_2 OBTAINED FROM FIG.

VOLTAGE $V_3 = \frac{\text{ARC POWER (FIG.)}}{\text{ARC CURRENT}}$

$= \frac{40,000}{250}$

$= 160$ VOLTS

POWER FACTOR = COS θ

$= \frac{260}{595}$

$= 0.44$

SCALE: 1 IN. = 100 V.

FIG. 22

VECTOR DIAGRAM OF VOLTAGE

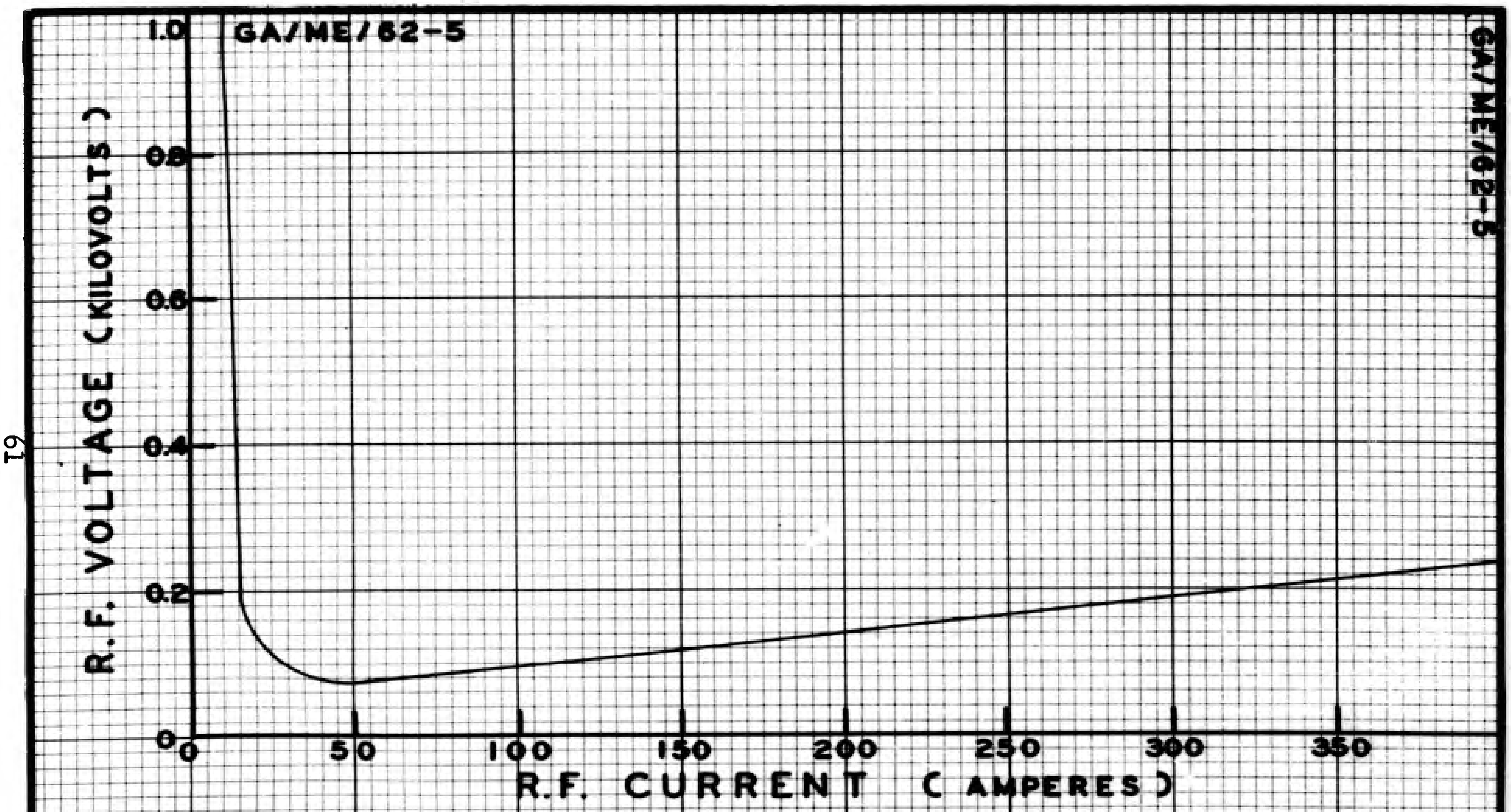


FIG. 23 PROBABLE TRUE ARC CHARACTERISTIC

Appendix B

Sample Calculations

(1) Natural Frequency of an Argon Arc (ω_n)

$$\tau = 0.18 \frac{R^2}{\alpha} = 2 \times 10^{-10} I^2$$

(Ref 1:15)

for a hydrogen arc, where:

R - radius of arc column

α - thermal diffusivity coefficient

τ - arc time constant

I - arc current

$$\frac{\alpha_h}{\alpha_a} = \sqrt{\frac{\rho_a}{\rho_h}}$$

where ρ - density

and the subscripts a and h refer to argon and hydrogen respectively.

$$\therefore \frac{\tau_h}{\tau_a} = \frac{\alpha_a}{\alpha_h} = \sqrt{\frac{\rho_h}{\rho_a}} \doteq \sqrt{\frac{2}{40}} \approx \frac{1}{5}$$

$$\tau_a = 5\tau_h = 10^{-9} I^2$$

$$\text{Now } \omega_n = \frac{1}{\tau_a} = \frac{10^9}{I^2}$$

$$\text{at 225 amperes } = \frac{10^9}{(225)^2} = 2 \times 10^4 = 20 \text{ Kc.}$$ for argon

(2) Dimensionless Ratio (ω/ω_n)

$$\frac{\omega}{\omega_n} = \frac{400 \text{ Kc.}}{20 \text{ Kc.}} = 20$$

ω - angular frequency of the power supply

(3) Impedance of the Arc Apparatus (Z)

$$E = IZ$$

where E - voltage across the arc apparatus

$$Z = \frac{E_2 - E_1}{I_2 - I_1}$$

where the subscripts 1 and 2 refer to different points on the characteristic curve (Fig. 14)

$$Z = \frac{1080 - 810}{400 - 300} = \frac{270}{100} = 2.7 \text{ ohms}$$

for the original apparatus

(4) Arc Kilovolt-Amperes (KVA)

$$KVA = \frac{E\,I}{1000}$$

where for Tap 1 at 100 percent on-time I = 230 amps, E = 550 volts (Fig. 14)

$$KVA = \frac{(230)(550)}{1000} = 126.5 = 0.13\text{x}10^3$$

(Fig. 17)

(5) D.C. Input Power in Kilowatts (P)

$$P = \frac{(I_{p1} + I_{p2})(E_p)}{1000}$$

where I_{p1} and I_{p2} -plate currents to the two oscillator tubes

E_p -plate voltage to the oscillator tubes

for Tap 1 at 100% $$P_1 = \frac{(4.5 + 6.5)(7,500)}{1000} = 82.5\text{Kw.}$$

where P_1 -input power with an arc

for Tap 1 at 100% $$P_2 = \frac{(3.5 + 5.3)(8000)}{1000} = 70.4 \text{ Kw.}$$

at an R.F. current of 290 amperes

where P_2-input power with the electrodes short circuited

(6) Arc Power (P_3)

$P_3 = P_1 - P_2$ taken at the same r-f current from Fig. 19

at 230 amperes current

$$P_3 = 77 - 47 = 30 \text{ Kw.}$$

(7) Power Factor from Oscilloscope Photograph ($F_p = \cos\theta$)

$$\sin\theta = \frac{a}{b}$$

where a-distance between intercepts on the ordinate axis

b-maximum height of the ellipse

$$\sin\theta = \frac{18}{20} = 0.9 \qquad \text{(Fig. 13)}$$

$$\cos\theta = \sqrt{1 - \sin^2\theta} = \sqrt{1 - (0.9)^2}$$

$$F_p = .44$$

(8) Power Factor from Vector Diagram

$$\cos\theta = \frac{260}{595} = 0.44 \qquad \text{(Fig. 22)}$$

(9) Voltage Gradient (σ)

$$= \frac{E \text{ (volts)}}{\text{length of arc}}$$

$$= \frac{190}{10} = 19 \text{ volts/cm.}$$

at 300 amperes r-f current (Fig. 23)

(10) Power in Coolant Water

$$\text{Power (Kw)} = (\Delta T)(\dot{m})(c)$$

where ΔT -temperature rise of the water

$\dot{m}$ -mass flow rate of the water

c -specific heat of the water

$$\text{Power} = (34\,^{0}\text{F})(1000\#/\text{hr.})(1\ \text{BTU}/\#\ ^{0}\text{F})$$
$$= 34{,}000\ \text{BTU/hr.}$$
$$= \frac{34{,}000}{3412.76} = 10\ \text{Kw.}$$

(11) Energy Extracted from Gas by Calorimeter Cooling Water

$$\text{Power} = (24\ ^{0}\text{F})(1000\ \#/\text{hr.})(1\ \text{BTU}/\#\ ^{0}\text{F})$$
$$= 24{,}000\ \text{BTU/hr.}$$
$$= 7\ \text{Kw.}$$

(12) Energy Balance

Input Power with Arc (P_1) = 80 Kw.

Input Power without Arc(P_2)= 50 Kw.

Arc Power (P_3) = 30 Kw.

Electrode Cooling Losses = 10 Kw.

Power in the Gas (heat) = 7 Kw.

Total Losses = 17 Kw.

$\therefore$ Power Losses due to Radiation & Conduction = 30 - 17

= 13 Kw.

(13) Efficiency of Arc Apparatus

Power in the Gas = 7 Kw.

Input Power (P_1) =80 Kw.

Overall Efficiency $= \frac{7}{80} \times 100 = 8.8\ \%$

(14) Efficiency of the Arc

Power in the Gas = 7Kw.

Input Power to the Arc= 30Kw.

Efficiency of the Arc = $\frac{7}{30} \times 100 = 23.3\ \%$

para. 13 and 14 calculated at an r-f current of 250 amperes

Appendix C

Details of the Design, Construction, and Modification of the Arc Apparatus

In order to test the feasibility of obtaining an arc, using the Westinghouse r-f generator as a power supply, it was decided to use as simple an apparatus as possible. Accordingly, a Beck-type, carbon-electrode arc (see Fig.24) was modified by replacing all steel parts with copper or brass, to minimize induction heating. Power was supplied to the apparatus by 1/4-inch diameter copper tubing, using the distilled water system of the power plant for cooling. Three runs were made with this apparatus and it was determined that an r-f arc could be drawn, however, there were three major difficulties. First, the electrodes became white-hot after only a few seconds of operation. This also led to severe erosion of the electrodes due to oxidation. Second, the longest arc that was successfully drawn was 1/8 inch in length. Third, on extinction of the arc severe damage occurred to the bias control of the oscillator due to large surge currents.

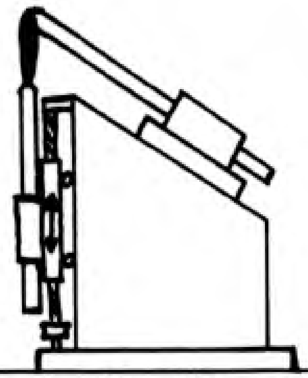


Fig. 24

Beck Type Arc Apparatus

It was apparent that these difficulties could not be overcome by modification of the apparatus. Accordingly, a complete, new apparatus was designed by the author, with the aid and advice of ARL staff personnel. A schematic of this design is shown in Fig. 5, with the exception that there was no cap or O-ring seal on the original outlet chamber; the exhaust gas escaped between the top electrode and the outlet chamber. The complete blueprints of this apparatus are contained in drawings for assembly RN-62-D-1061 at the Aeronautical Research Laboratories.

The electrodes consisted of a 1/2-inch-diameter copper tube with a solid copper tip silver-soldered into place. A 3/8-inch copper tube inside this supplied the cooling water to the tip. The water then flowed between the tubes to the outlet, thus providing additional cooling. Power was again supplied to the apparatus by 1/4-inch copper tubing, directly coupled to the distilled water, power plant cooling system. Tygon tubing was used to allow the water to flow from one electrode to the other, while still being electrically insulated. The water flow was essentially the same as shown in Fig. 8.

The glass chamber consisted of a six inch length of 45 mm. Vycor tubing, ground flat at each end. This was sealed by high-temperature washers to the outlet chamber and the vortex chamber. An insulating plate was fastened to both the outlet chamber and the vortex chamber. The whole assembly was then clamped together with three nylon rods. This type of assembly may be seen in Fig. 6.

The arc was successfully ignited on the first attempt and a long, stable arc was produced. However, it was found that the arc attached itself to the silver-solder which held the tip in place, rather than to the tip itself. On the third run, the arc melted the silver-solder and cut the tip completely out of the electrode. This may be seen in Fig. 25.

The apparatus was redesigned, with the tips of the electrodes being turned and bored out of 3-inch long, 1/2-inch-diameter, copper rods. The silver-solder was thus kept well away from the arc.

A good stable arc was obtained, however, after five runs the tip of one electrode melted (see Fig. 26). During the course of the last run vapourized copper had deposited and completely plated the inside of the Vycor tube. It was decided that: (1) the cooling water flow available from the distilled water power plant system was insufficient for cooling. (2) the area of the electrodes was insufficient for the high values of r-f current obtained.

The apparatus was rebuilt, using the same general layout. The electrodes were now made from 3/4-inch-diameter, thin-walled, copper tubing; with 1/2-inch-diameter concentric

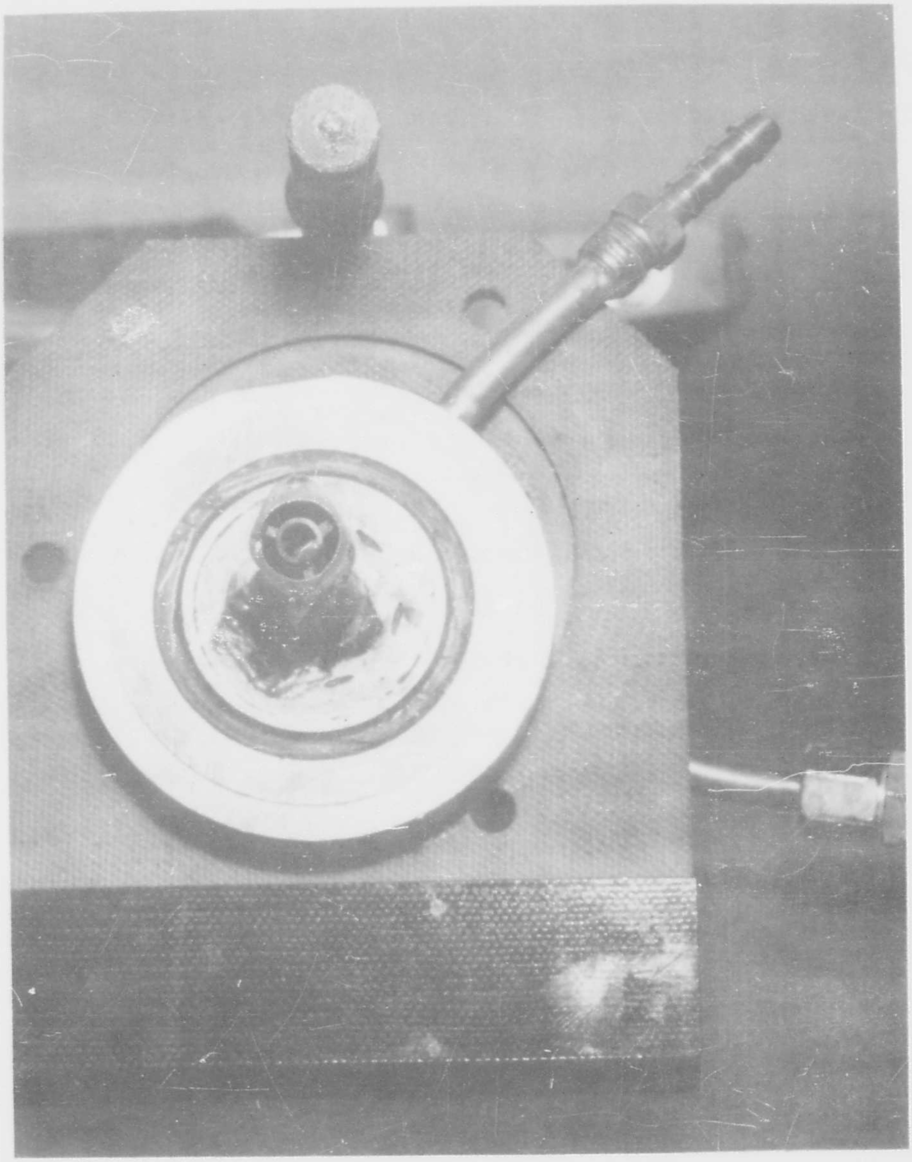


Fig. 25

Failure of Original 1/2-Inch Electrodes

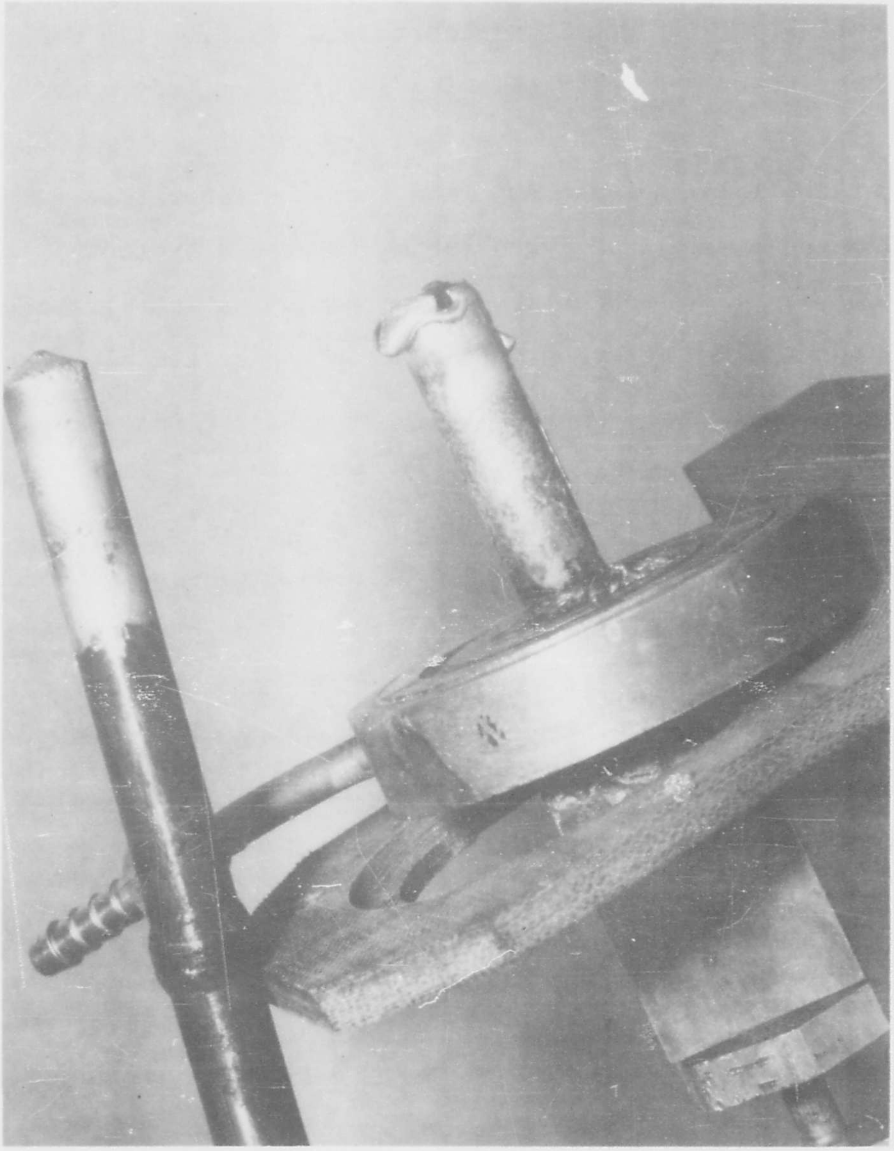


Fig. 26

Failure of Modified 1/2-Inch Electrodes

tubing supplying cooling water to the tip. The tip was again turned and bored out of a 3-inch-long section of copper rod.

Cooling water was supplied from the laboratory supply mains using 3/8-inch Tygon tubing between all electrically 'hot' parts. A flow meter and thermocouples were installed so that the effectiveness of the cooling system could be evaluated. Electrical connection to the lead-in tubing coming from the power plant was made by laminated copper shimstock sheets to provide a large surface area and thus avoid excessive heating. The two lead-in tubes were connected together by Tygon tubing to provide a complete return path for the distilled water system of the power plant.

The nylon rods which held the assembly together had shown signs of melting. These were therefore replaced by copper rods passing through nylon insulating sleeves at top and bottom.

A 1/8-inch-thick sheet of asbestos, painted with gold paint for high reflectivity, was placed behind the Vycor tube, to prevent overheating of the phenolic mounting board.

This apparatus was very successful at low levels of power. Electrode erosion was extremely low and no copper plating on the Vycor tube was observed. However, when higher power was applied to the apparatus, arc-overs to the Vycor tubing occurred several times. It is believed that a slight film of copper deposited on the inside of the tube which made it conductive. The gap between the electrodes and the Vycor walls was now only about 7/16-inch. Once the arc was ignited the gas was partially ionized and thus this small gap offered little resistance to an arc.

By using a larger tube several advantages could be obtained: the gap between the electrodes and the wall would be increased, the surface area of the tube would almost be doubled, and a much larger vortex chamber could be installed. The result would be higher gas flow, a stronger vortex, more stable arc, better cooling, less copper deposit on the glass, and less possibility of arc-over.

It was decided to use 70 mm. quartz tubing since it was readily available and it would tolerate much higher temperatures than the Vycor and hence, higher input levels. The length of tube was increased to 8 inches to provide a longer arc travel and a more stable vortex flow around the arc.

The apparatus thus built proved to be excellent. This is the configuration that is shown in Fig. 6 and 7. The only major difficulty that was still present was a heavy deposit of black copper-oxide that was formed on the inside of the tube making observation of the arc very difficult. Since the arc was run in a protective atmosphere of argon at all times, it was obvious that oxygen was somehow leaking into the systems. It was felt that air was probably being drawn into the low pressure area at the center of the vortex.

A further modification was installed to prevent this possibility. A cap for the outlet chamber was machined which provided an O-ring seal to the top electrode. The O-ring also provided electrical insulation. The exhaust gas was allowed to escape through an outlet on the periphery of the chamber where the pressure was the highest.

This modification did decrease the copper-oxide formation but also had an important side effect. It decreased the voltage required for a given current flow in the arc. This is believed due to the much improved pattern of flow obtained in the vortex resulting in a more stable arc.

The chamber did not completely eliminate the formation of copper-oxide. Since air could not now be drawn into the completely sealed chamber it was felt that the oxygen must be obtained from water vapour that was contained in the argon (which is water-pumped) or which permeated the Tygon tubing. It is felt that a dryer installed in the gas supply line would eliminate this.

The last modification which was installed was a small water-cooled calorimeter to measure the energy contained in the exhaust gases. This is the trombone-shaped device visible in Fig. 7.

Vita

Alan John Shade was born on [redacted] [redacted] [redacted] [redacted], [redacted], the son of John Shade and Mary [redacted] Shade. The family emigrated to Canada in May, 1940. After graduating from Montreal High School in 1950, he attended the Canadian Military Colleges at Victoria, British Columbia, and Kingston, Ontario, graduating with honours in Mechanical Engineering from the Royal Military College in 1954. He received his permanent commission as a Flying Officer in August, 1954. He attended Queens University, Kingston, Ontario, receiving the degree of Bachelor of Applied Science, Mechanical Engineering in June, 1955. His military assignments prior to his coming to the Air Force Institute of Technology were as a Maintenance Officer in Air Defence Command and as a Special Projects Engineer with the Institute of Aviation Medicine, Toronto, Ontario.

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