DESIGN AND OPERATION OF A PLASMA GENERATOR
USING ARGON AS THE STABILIZING GAS

By

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DESIGN AND OPERATION OF A PLASMA GENERATOR USING ARGON AS THE STABILIZING GAS

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF PLATES

Plate Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

CHAPTER I

INTRODUCTION

In the past five years there has been more and more interest directed toward the behavior and properties of high temperature gases which are dissociated and ionized. This interest has grown out of practical problems associated with the flight of aircraft and missiles at higher and higher velocities and altitudes. At very high Mach numbers, an extreme temperature rise is experienced by the air as it passes through the bow shock wave which causes thermal dissociation and ionization of the air. The missile or aircraft is then enveloped in a mixture of molecules, free atoms, ions, and electrons. This mixture is now commonly known as "plasma". At altitudes of 100,000 feet and above, the gases of the earth's atmosphere are dissociated and ionized by ultraviolet radiation from the sun. Flight at these altitudes has already become a reality and will be more common in the future.

There is a dearth of information concerning the properties and transport phenomena of dissociated and ionized gases. In an effort to supplement the available information many have turned to kinetic theory. For example, Gilmore (1) tabulated the thermodynamic properties of air to 24,000 degrees Kelvin, Hilsenrath and Beckett (2) published a similar table, and Hansen (3) developed approximations for the thermodynamic and transport properties of high temperature air.

Confirmation of this theoretical work has been hampered by lack of a suitable means of producing the necessary high temperature in a continual flow of gas. Recent work, using an electrical arc, by Lai, Gustavson, and Talbot (4), Giannini (5), and others indicate that a means of producing a stream of very high temperature gas, (above 5,000 degrees Kelvin), is technically possible. The investigators used a high-intensity electrical discharge to create high temperatures. However, the methods and composition of the gas jets varied widely between investigators.

Many plasma generators have been built by different investigators. The designs are numerous and rather varied. There is no clear understanding of the basic parameters that affect the efficient operation of a plasma generator. In an attempt to determine these parameters this investigation was initiated. This project simultaneously initiated a plasma research program at Oklahoma State University.

The purpose of the study contained in this thesis was twofold. The first aim was to build an operable gas-stabilized plasma generator which was flexible enough in design to permit adjustment, replacement, and redesign of the various components as easily as possible. The second aim was to test the plasma generator to determine the proper starting technique and the variation of the parameters for stable operation at different power levels.

To fulfill the above requirements, it was necessary to provide a source of direct current power, a gas supply, and a source of cooling water with appropriate controls and instrumentation for each. A direct current welding machine was used as a power source; bottled argon was used for the gas supply; and tap water was used for cooling. A control panel was designed to accommodate the attendant controls and instruments.

In view of the stated purpose, the results of this study were considered most satisfactory. A simple starting procedure was perfected. Stable, sustained operation was achieved with only negligible deterioration of the generator components.

CHAPTER II

PREVIOUS INVESTIGATIONS

The plasma generator is rapidly becoming recognized as a very valuable tool for delving into the secrets of outer space. Many different designs have been built which depend on the type of study being carried on. Some of the early development of the high intensity arc, followed by descriptions of more recent plasma generator designs, are presented in this chapter in order that some of the design considerations may be compared with the apparatus described in this thesis.

It is very likely the first plasmas ever formed were made while investigators were searching for means of producing nitric oxides and ozone. McEachron (7) states that in the year 1909 Hugo Spiel produced the nitric oxide (NO) by means of an electrical discharge in air. During the period 1918-1922 McEachron went on to do extensive study in this field. The arcs used by these investigators were of the low-intensity type (low current and high potential).

According to Koepnick (8), O. Beck, a German, was the first to use the high-intensity arc (high current and low potential). This was in the year 1913. Beck's arc operated with carbon electrodes with the anode cored out and filled with cerium fluoride and oxide. He reportedly achieved temperatures of 12,000 degrees Kelvin in the arc core. The arc was characterized by a very brilliant tail flame emitted by the anode in a direction not parallel to the arc.

In the 1930's Finkelnberg (9) conducted extensive studies of the high-intensity arc using many different kinds of materials in the anode. Before this time it was generally believed that the cerium-cored carbon anode was necessary to obtain a high-intensity arc. Finkelnberg proved this assumption to be in error and went on to produce high-intensity arcs utilizing many different kinds of anode material.

Finkelnberg and Hoecker (10) investigated the high-intensity arc after World War II placing special emphasis on learning more about the factors affecting the direction of the anode tail flame and the shape of the positive column. These investigators found that the general shape of the arc, and especially the direction of the anodic tail flame, is independent of the orientation in space and does not result from the convection of hot vapors or gases. Their theory was that the specific shape of high current arcs is greatly influenced by the arc's own magnetic field caused by the ionized particles within the arc column. The magnetic field squeezed the arc into a smaller than natural cross section which increased the current density giving rise to very high gas temperatures.

In the early 1950's, exhaustive efforts were made by various German investigators to produce a unidirectional stream of plasma with the high-intensity arc. Weiss (11) achieved the most notable results by stabilizing his arc with water. Figure 1 is a schematic diagram of Weiss' water stabilized arc.

The Weiss arc was struck between a solid carbon anode, which was extensible, and a hollow disc shaped cathode. Water introduced into the chamber in a swirling motion surrounded the arc. The stabilizing vortex of the water was heated by contact with the arc forming a cy-

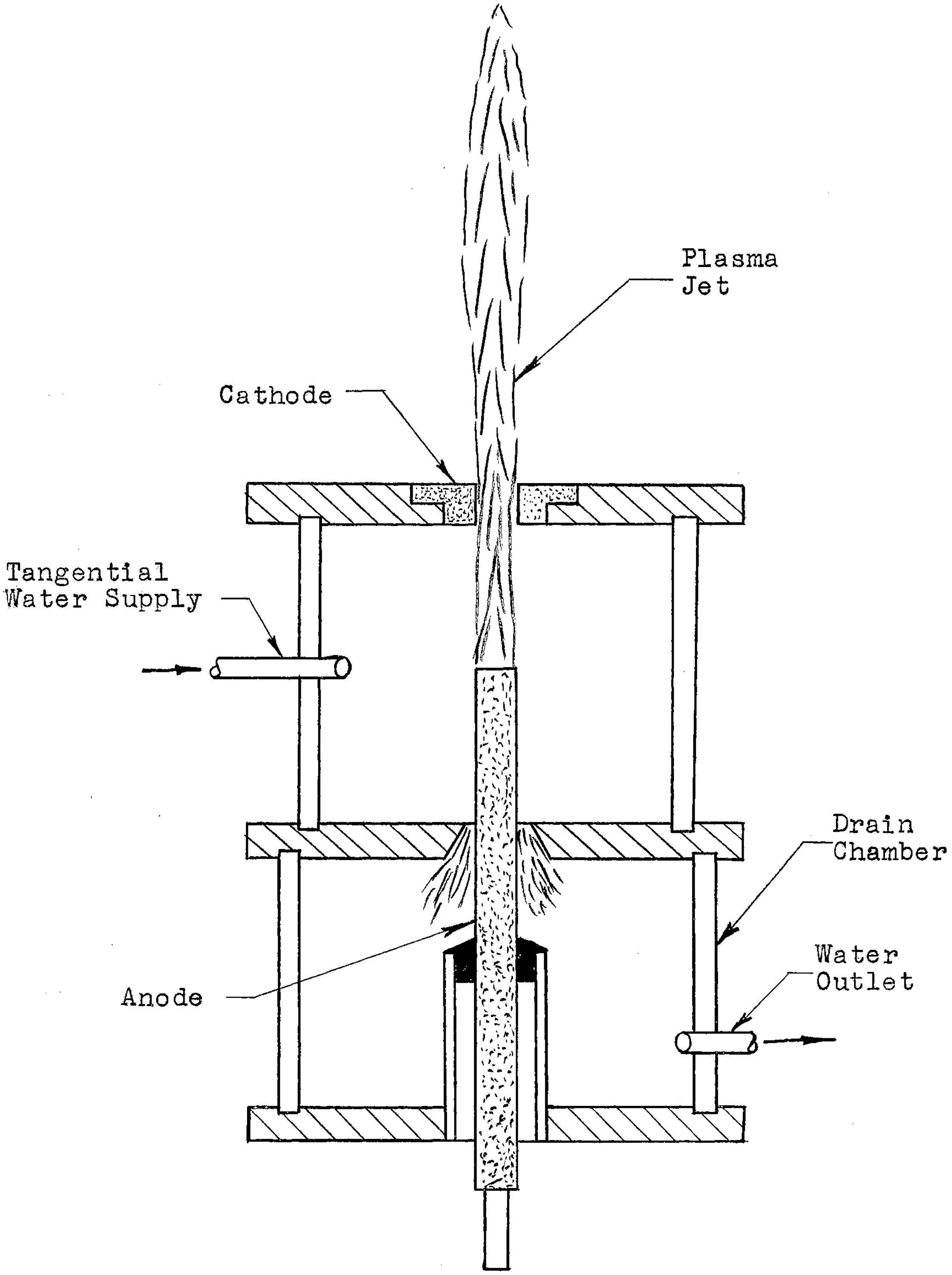


Figure 1. Weiss Water Stabilized Generator

lindrical tube of water vapor. Upon passing into the arc the vapor was dissociated and ionized and emitted through the hollow cathode as plasma. Excess water drained out around the anode into the lower chamber and to a limited degree helped cool the anode rod. The erosion rate was very high for both the anode rod and the cathode ring. As a result, the cathode was continuously fed into the arc chamber. Deterioration of the cathode ring allowed water to stream out and after 1 or 2 minutes the arc would be extinguished. Weiss' arc was approximately 5 centimeters long, 7 millimeters in diameter, with a current of 150 to 200 amperes. The jet was approximately 4 centimeters in length. Arc core temperatures of 13,000 degrees Kelvin were reported with a steep gradient in the radial direction and a rather low gradient in the axial direction. A high degree of ionization was reportedly achieved with velocities in the jet as high as 10 kilometers per second.

Jacobs (12) and other American investigators conducted investigations of water stabilized arcs which were similar to that of Weiss previously mentioned. The electrical power employed was the most significant aspect of his work. His first unit, built in July 1956, had a d-c power input of 20 kw, and in a few months was increased to 80 kw. In January 1957 he built and tested a 2400 kw unit. In view of the most powerful arc previously produced by Finkelnberg (20) of approximately 100 kw, the significance of his work is more meaningful. Like Weiss, this investigator was seriously handicapped by the short time of permissible operation.

Giannini and others (5), (6) chose to use a noble gas as the stabilizing media for the high-intensity arcs which they investigated. These investigators were of the opinion that the composition of the steam-carbon plasma was unsuitable for basic research of any kind, because of the large and unpredictable quantity of carbon present. To eliminate the carbon in the plasmas, water cooled, temperature stable, tungsten electrodes were used. Figure 2 is a schematic diagram of Giannini's gas stabilized plasma generator. It was reported that only insignificant electrode erosion was evident even after prolonged operation (10 to 20 minutes). This was most significant in that continuous, sustained operation was at last feasible. Plasmas of argon, helium, nitrogen, and air were obtained, although operation with air was much more difficult than with simple monoatomic or diatomic gases. Temperatures of 10,000 to 15,000 degrees Kelvin were obtained with power inputs of the order of 40 kw.

Koepnick (8) constructed a plasma producing arrangement early in 1958. His purpose was to study the arc characteristics as influenced by geometry of the gas flow field, and polarity of electrodes with respect to the above field. A schematic diagram of his design may be seen in Figure 3.

Two basic arrangements were used by Koepnick with nitrogen and air as the stabilizing media. First, an arc was struck between two carbon electrodes in still air (Figure 3a). A tail flame was emitted by the anode that appeared to be redirected back along the anode rod. This behavior was attributed to the strong magnetic field present around the arc. When the polarity was reversed the above condition was also reversed.

Koepnick's second arrangement had one electrode just flush with the swirl chamber with the other electrode on the same line but in still air (Figure 3b). With no swirl the general behavior of the arc

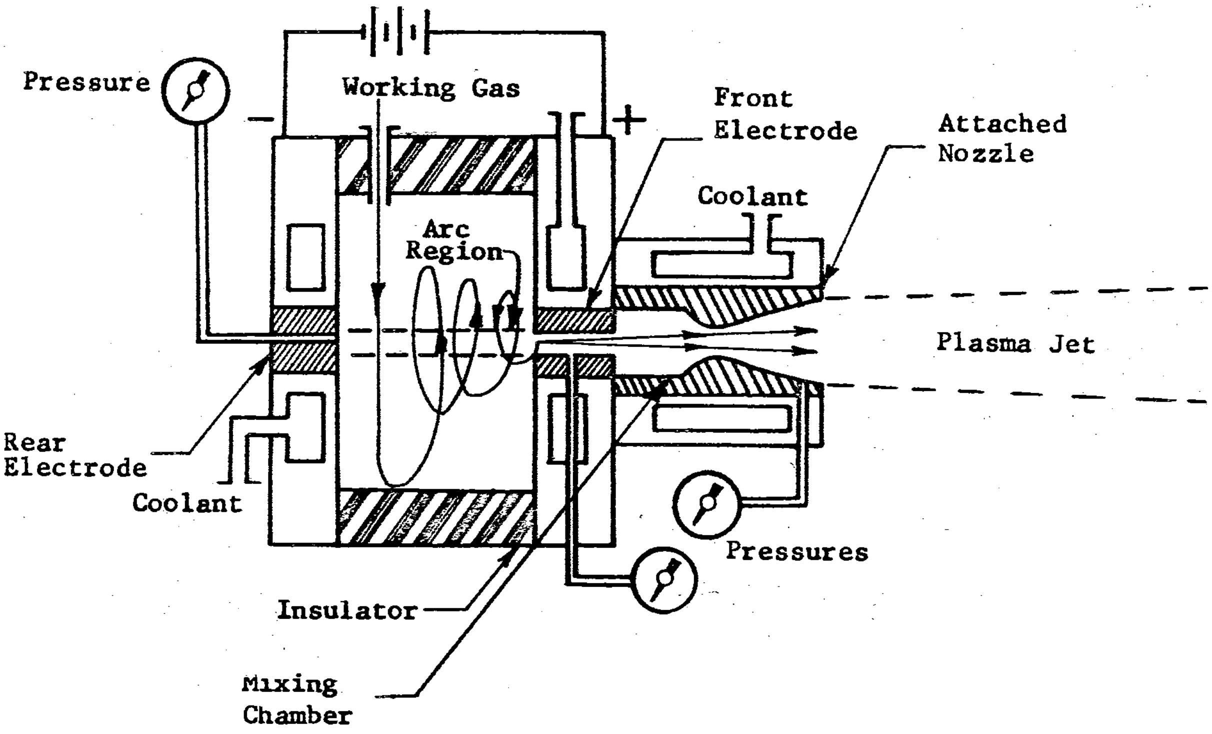
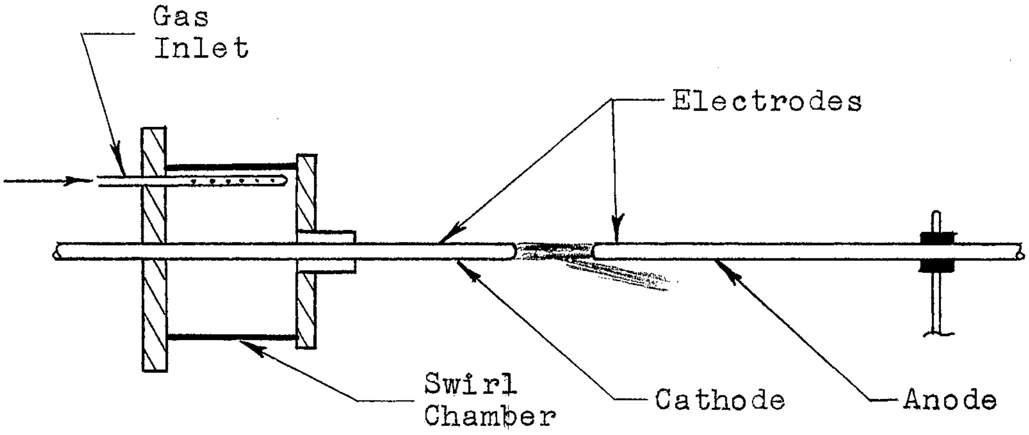
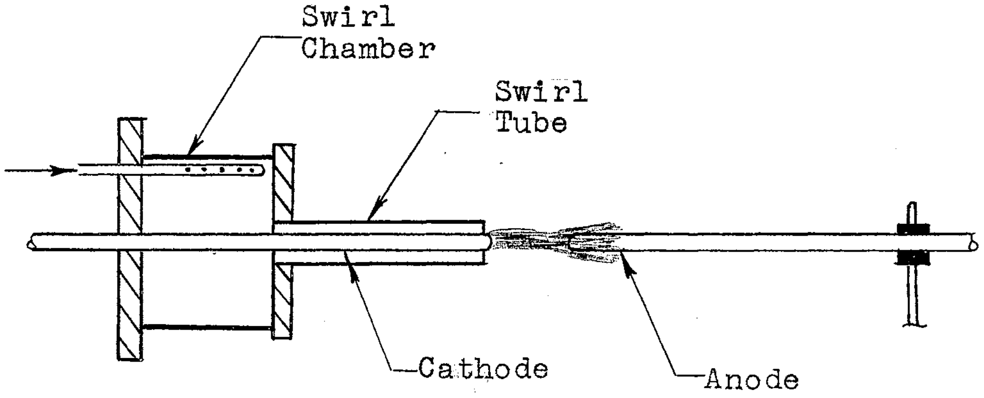


Figure 2. Giannini Gas Stabilized Generator



(a) Arc In Still Air



(b) Arc With Full Swirl

Figure 3. Koepnick Gas Stabilized Arc

was the same as in the first arrangement above. When the gas was given a swirling motion the arc was squeezed to a much smaller diameter and the tail flame was directed along the anode in a steady unidirectional stream.

Post (13) explains the squeeze or pinch effect in the following simplified manner. Ions attempting to escape from the boundaries of the positive column are reflected upon entering the region of strong magnetic field. The motion of a reflected charged particle constitutes an infinitesimal current which has its own magnetic field. Interaction of the main field and the infinitesimal fields result in a radial force directed inward, and a longitudinal force whose direction depends on the axial component of velocity. This component would most likely be in the direction of the cathode, and the resultant force would be toward the anode.

Koepnick's study indicated that the flow field should have a strong radial component with respect to the arc for stability. Also, the position of the anode dictates the direction in which the jet will be emitted. These two points were believed most significant in the design of a plasma generator.

Lai, Gustavson, and Talbot (4) designed and tested a high-intensity arc plasma generator in the latter part of 1958. A schematic diagram of their Model "B" generator is shown in Figure 4. The most important requirements of their design were:

1) The generator was to be capable of continuous operation at high power levels without damage to any of its components.
2) Contamination of the gas stream by materials evaporated from the electrodes had to be small.

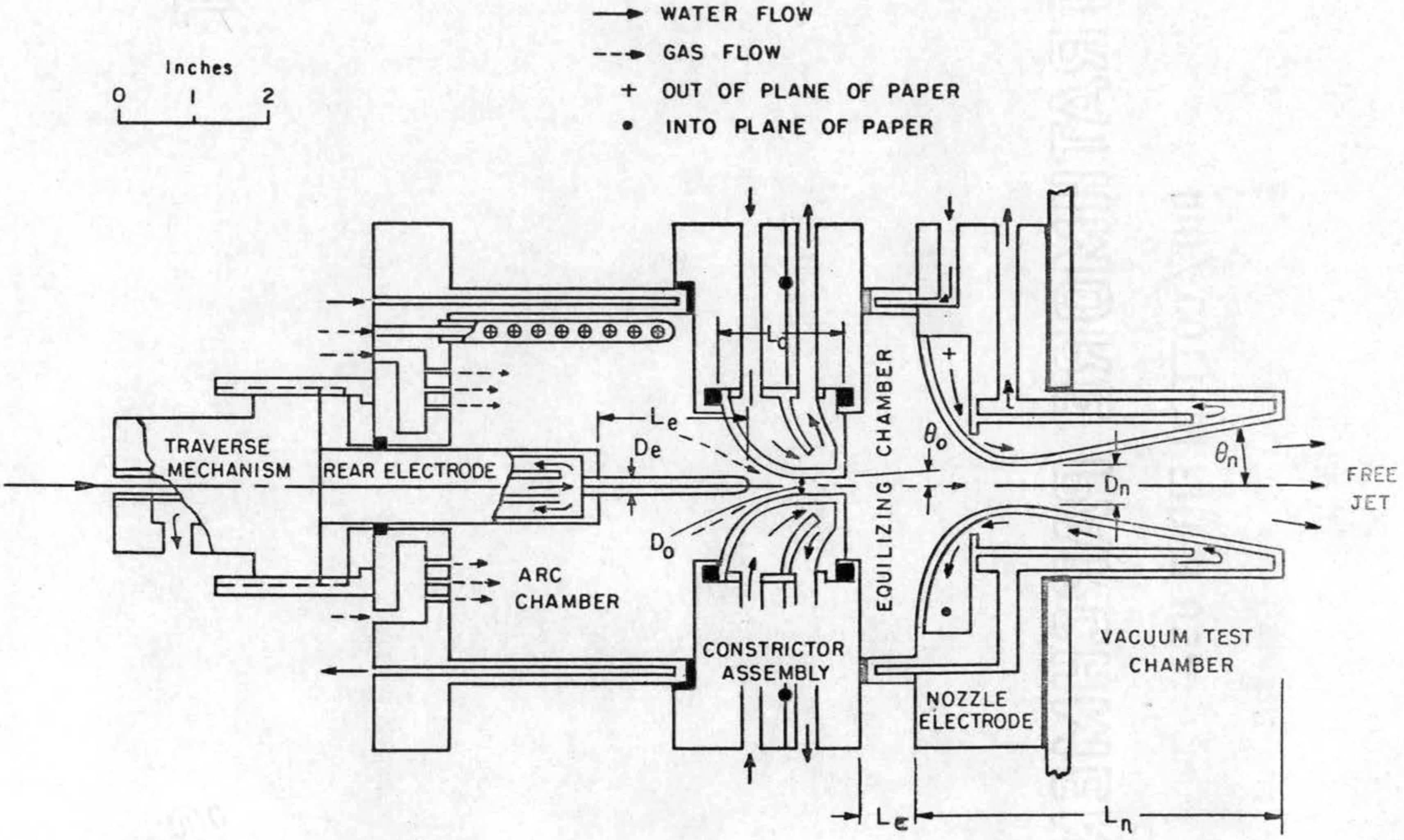


Figure 4. Model "B" Generator

3) The arc and jet flow had to be sufficiently stable so that fluctuations in the test region would be within limits acceptable for aerodynamic testing.

The general operation of the generator was typical of other designs discussed previously in that the arc was established between the rear electrode and either the constricting orifice (actually a short nozzle), or the expansion nozzle. Gas was introduced in a tangential fashion to the arc chamber, passed through the arc, and expanded through the constrictor-nozzle assembly into the test chamber, which was maintained continuously at a low pressure by vacuum pumps. The resultant flow was a supersonic, low density, free jet, of high total enthalpy.

The Model "B" generator was composed of four major components which will be described briefly.

Rear Electrode

The rear electrode was solid thoriated tungsten silver-soldered to the end of a water cooled copper tube. The tungsten tip was 1/4 inch in diameter by 1 1/4 inches long. The electrode assembly was attached to a traversing mechanism which provided for accurate positioning with respect to the constrictor. Tungsten had the advantage of being less subject to erosion and evaporation than carbon.

Arc Chamber

The arc chamber was a cylinder about 4 inches in diameter by 5 inches long with a thin annular space for water cooling. Provisions were made for admitting gas to the chamber in either an axial or tangential motion. The Chamber was also equipped with a pyrex window.

Constrictor (nozzle)

The constrictor was arbitrarily designed to give a smooth converging section with a throat diameter of 5/16 inch. There was a short diverging section (approximately 10 degrees divergence). Water cooling was provided with the passage so designed to give maximum velocity around the throat section where the highest heat rates were expected.

Equalizing Chamber and Expansion Nozzle

The equalizing chamber was the same diameter as the arc chamber but was of variable length to allow changing of the chamber volume. The expansion nozzle was of copper with a nickel-plated surface. Both of these components were water cooled.

Electric welders were used as a source of power. With the welders wired parallel about 60 kw was available.

Argon gas was used for most tests. However, some tests were made with nitrogen and air.

Three electric circuit arrangements were investigated. They were:

1) Electrode as cathode, expansion nozzle as anode.
2) Constrictor and expansion chamber removed, arc sustained between electrode and expansion nozzle.
3) Arc sustained between electrode and constrictor.

Arrangement (1) produced a quite stable arc in argon at power levels below 10 kw. At higher power levels a double arc formed with the constrictor resulting in damage to that part.

With arrangement (2) it was found that the emerging jet had large axial and lateral fluctuations. The potential varied between 40 and 50 volts at a power input of 18 kw. The anchoring of the arc on the nozzle was not fixed.

Arrangement (3) proved to be the most satisfactory of the three arrangements tested. It was successfully tested with argon, nitrogen, and air. In all cases the jet was quite stable. Rough estimates based on a heat balance indicated that 25 to 50 percent of the input power appeared as energy in the jet stream. Table 1 gives typical values of potential drop, current, and power input for argon, nitrogen, and air.

TABLE I

MODEL "B" PLASMA GENERATOR OPERATING DATA

Gas	Potential Drop Volts	Current Amperes	Power Input Kilowatts
Argon	30	435	13
Nitrogen	80	340	27
Air	60	620	37

The arc was initiated with argon and gradually switched over to nitrogen or air. Counting tests of 5 minutes duration and longer the generator was tested in excess of two hours. Negligible evaporation of the tungsten electrode was experienced with argon and nitrogen. With air the erosion was greater but still small.

Lai, Gustavson, and Talbot concluded that the equalizing chamber was a very desirable feature for damping out disturbances in the jet. They also concluded that the divergence angle of the constrictor should be kept quite small to prevent flow separation. It was also believed that design of the expansion nozzle could be based on the same considerations as design for conventional flow.

The authors state that future investigations will be directed towards diagnosis of the flow produced by the plasma generator.

CHAPTER III

DESIGN OF THE PLASMA GENERATOR AND AUXILIARY EQUIPMENT

Due to the almost complete lack of correlation among the various operating parameters, no attempt was made to design the plasma generator from an analytical standpoint. Instead, the design was based on the findings and experience of some of the more recent investigators summarized in Chapter II.

Approximately 15 kw of d-c power was available at the time of this study. Since Lai, Gustavson, and Talbot (4) achieved satisfactory operation with argon at a power level of 13 kw, it was decided that the basic dimensions of their design would be used for the plasma generator described in this thesis. These dimensions were: inside diameter of chamber 4 inches, length of chamber $4\frac{1}{2}$ inches, and the minimum section of the constricting nozzle 5/16 inch. The remainder of the design was governed by standard engineering practices, availability of materials, and ease of manufacture and assembly.

The principal components of the plasma generator test facility are: the plasma generator, instrument and control panel, gas piping and controls, water piping and controls, power supply, and instrumentation facilities.

Each of the above listed components will be described separately.

Plasma Generator

The plasma generator is composed of 6 assemblies. They are: the chamber, nozzle, electrode, electrode support, gas manifolds, and traversing mechanism. An assembly drawing showing the relative location of the above assemblies may be seen in Figure 5.

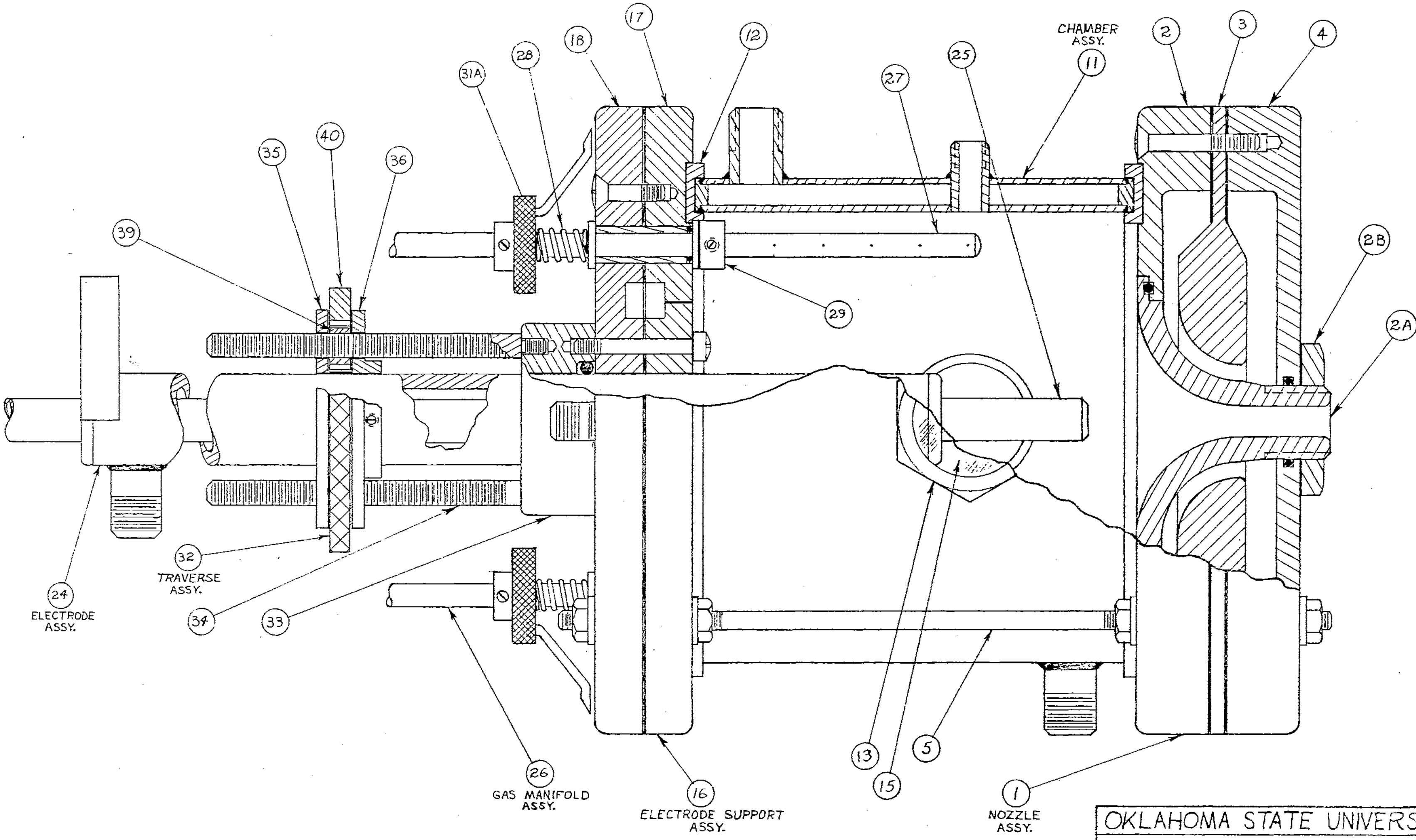
Chamber Assembly. The principal function of the chamber is to contain the stabilizing gas. Figure 6 is a detailed drawing of the chamber assembly. It was designed as an annulus so that cooling could be accomplished by circulation of water. As a matter of convenience in positioning the retractable electrode, two observation ports were provided. These ports were covered with double-strength plate glass 1/8 inch thick, held in place by retaining nuts. One pressure tap was provided for preliminary operation of the generator.

The material used for the chamber was cold drawn, seamless, mechanical, steel tubing. In addition to having the desired shape, this material has excellent welding and machining characteristics, and was therefore well suited to this application.

The ends of the chamber were fitted with phenolic insulating rings to isolate the oppositely charged parts of the generator. Figure 7 shows details of the insulating ring design. Phenolic sheet was used for the insulating rings because of its excellent dielectric properties and ability to be machined.

Nozzle Assembly. The nozzle assembly consists of the nozzle, nozzle support, flow divider, and back plate. Figure 5 gives a cross section of this assembly. The nozzle has two essential functions in the operation of the generator. First, it acts as one electrode for the arc. Second, it serves to direct the gas through the arc and also gives direction to the emerging jet. Details of the nozzle design are given in Figure 8.

Due to the high heat rates expected, hard drawn copper (ASTM:



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OKLAHOMA STATE UNIVERSITY
PROJECT No. 163 MECHEN
PLASMA GENERATOR

PLASMA HEAD ASSY.

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Figure 5. Plasma Generator Assembly

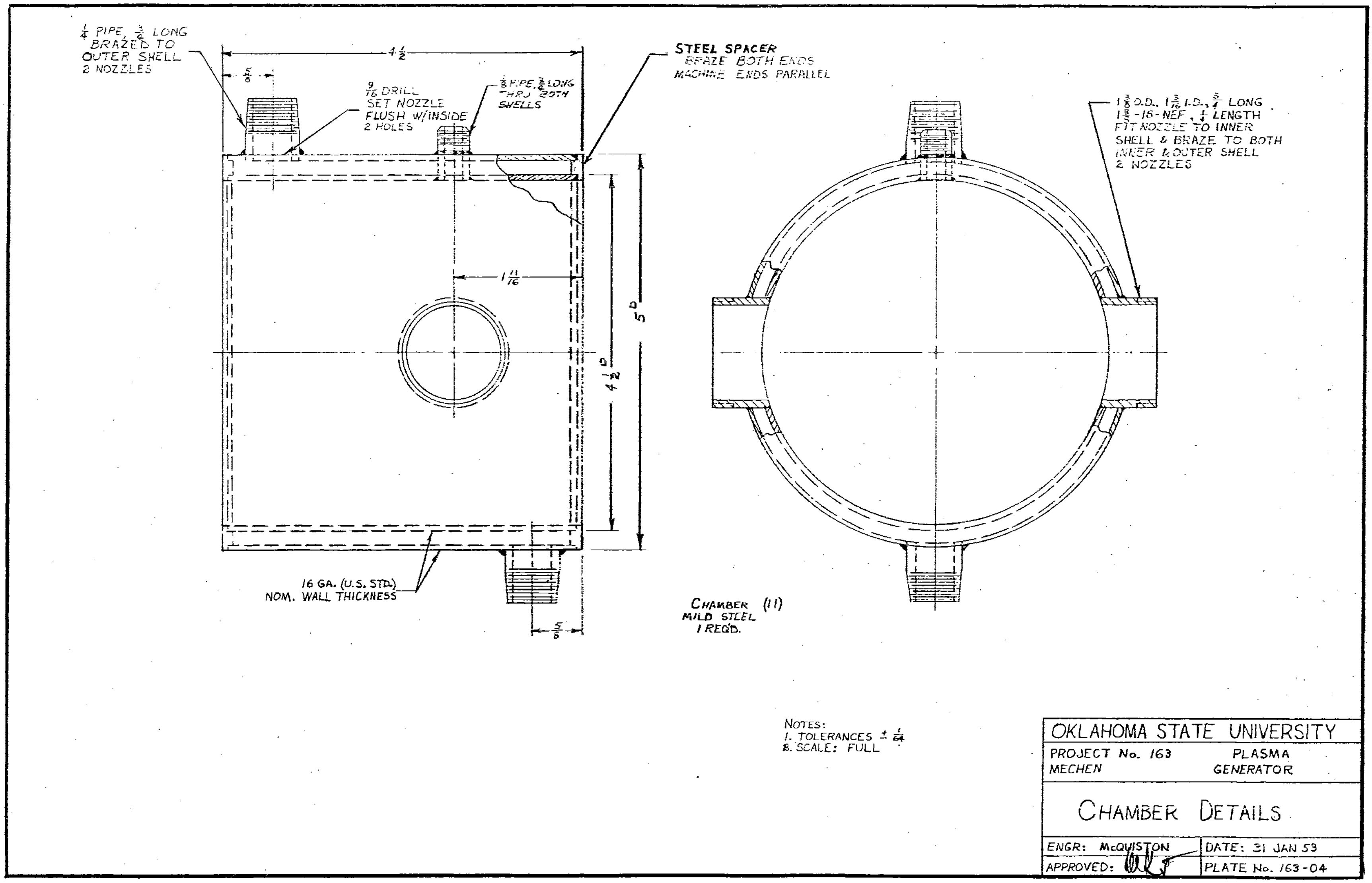
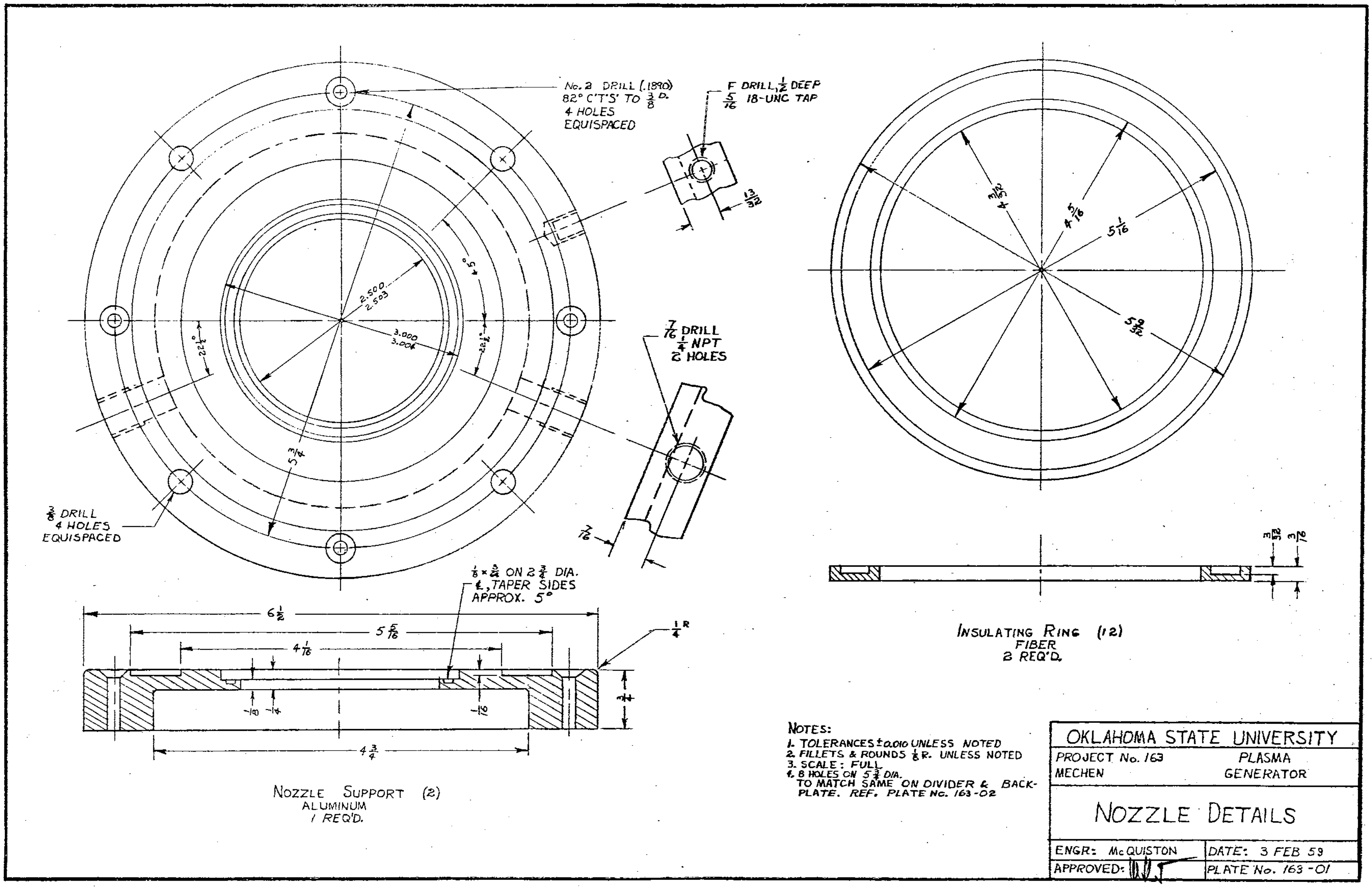


Figure 6. Chamber Details



NOTES:
1. TOLERANCES ±0.010 UNLESS NOTED
2. FILLETS & ROUNDS 1/8 R. UNLESS NOTED
3. SCALE: FULL
4. 8 HOLES ON 5 3/4 DIA.
TO MATCH SAME ON DIVIDER & BACK-PLATE. REF. PLATE No. 163-02

OKLAHOMA STATE UNIVERSITY
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MECHEN GENERATOR
NOZZLE DETAILS
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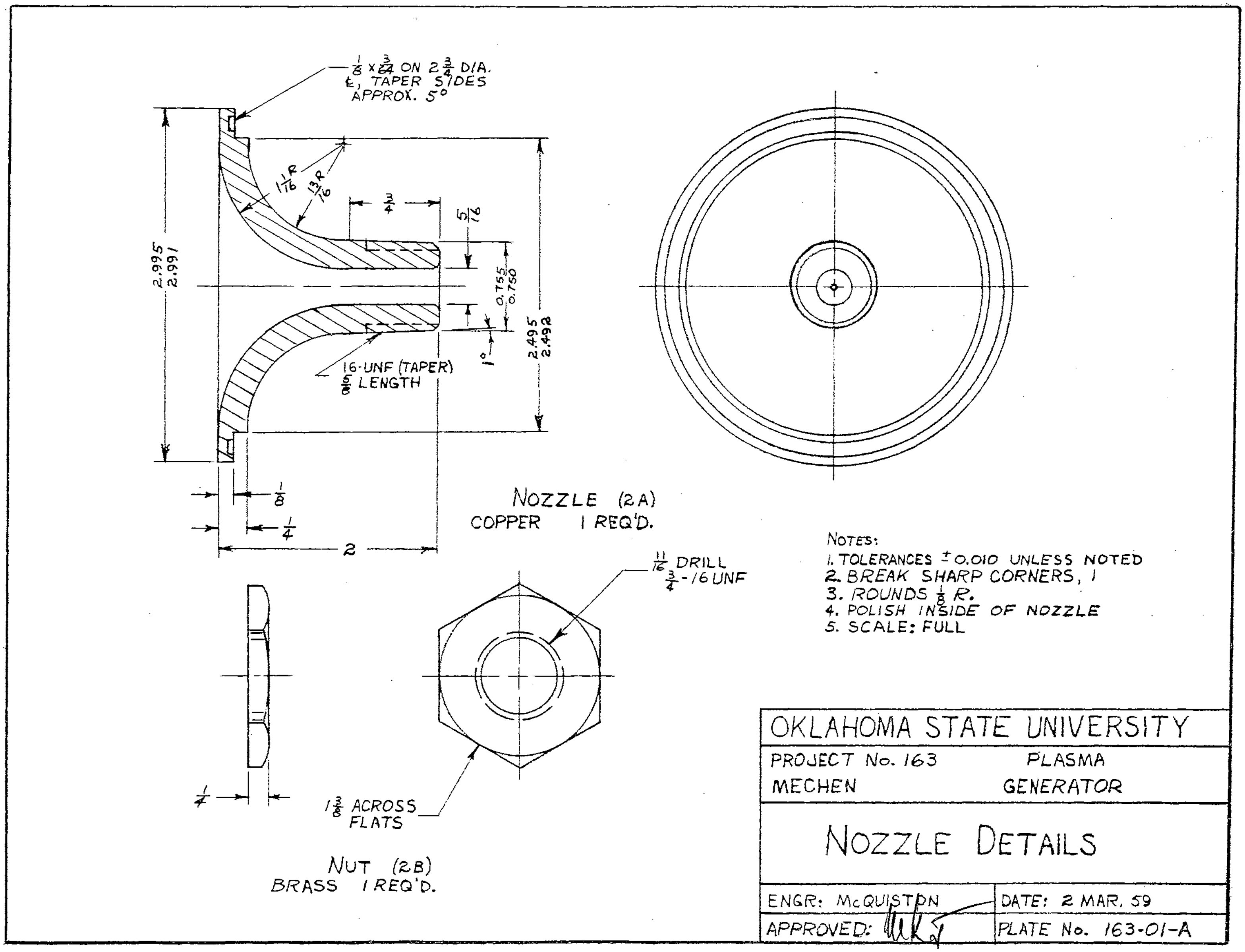
Figure 7. Nozzle and Insulating Ring Details



NOTES:
1. TOLERANCES ± 0.010 UNLESS NOTED
2. BREAK SHARP CORNERS, 1
3. ROUNDS $\frac{1}{8}$ R.
4. POLISH INSIDE OF NOZZLE
5. SCALE: FULL

OKLAHOMA STATE UNIVERSITY
PROJECT No. 163 PLASMA
MECHEN GENERATOR

NOZZLE DETAILS

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Figure 8. Nozzle Details

B133-54T) was selected as material for the nozzle. Copper has a high thermal conductivity and therefore can be prevented from melting by cooling one surface. Copper also has a high electrical conductivity which is desirable because the nozzle serves as an electrical conductor.

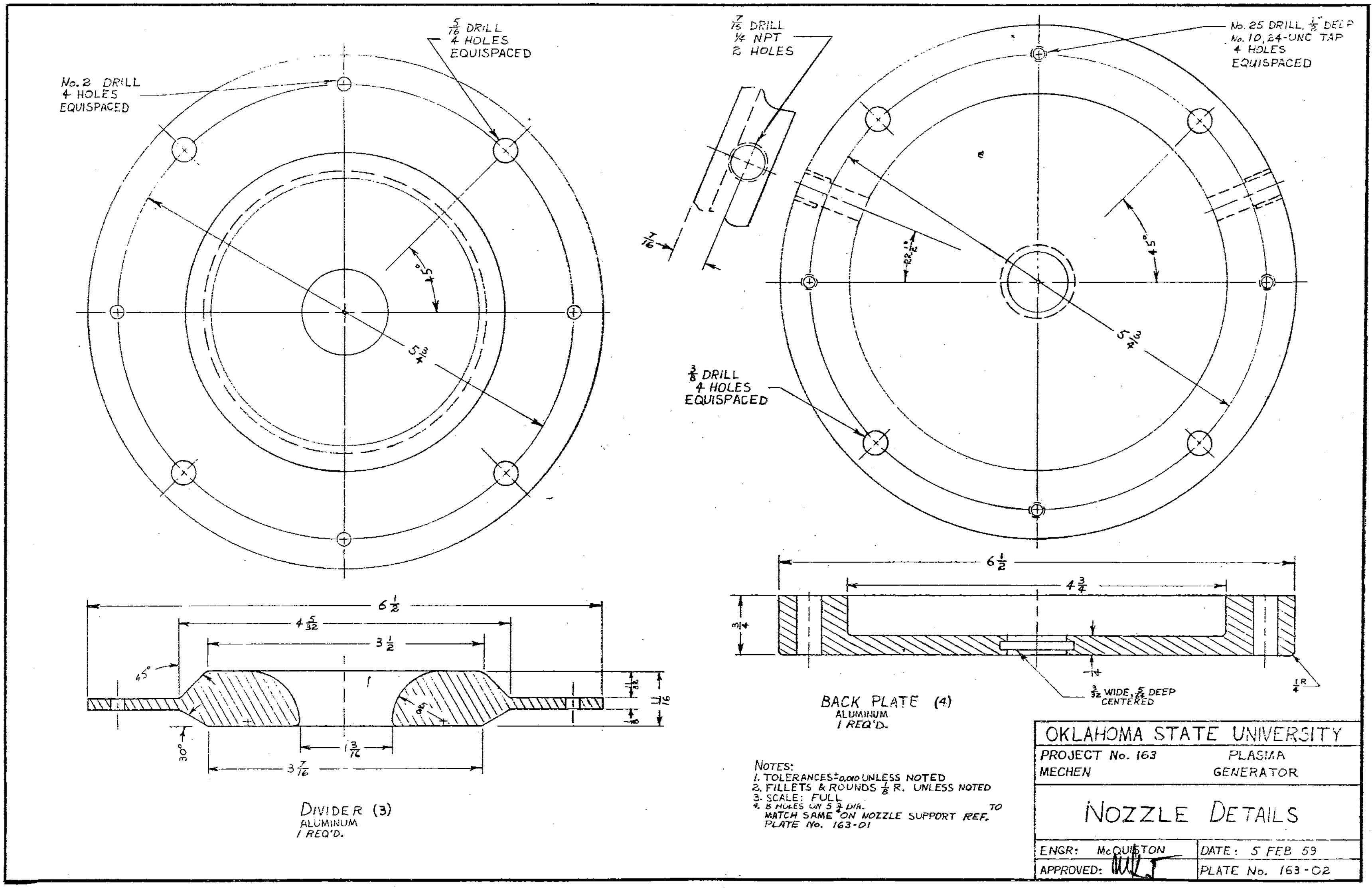
The nozzle support, divider, and back plate shown in Figures 7, and 9, respectively, serve to hold the nozzle in a central position with respect to the chamber, to close one end of the chamber, and to provide a cooling jacket for the nozzle.

Type 32-ST aluminum was selected for these parts due to its good electrical and thermal conductivity, good machinability, and light weight.

The water flow passage in the nozzle assembly was designed to give maximum flow velocity at the throat section in order to promote the heat transfer rate to the water as much as possible.

To prevent leakage of water, wax impregnated paper gaskets were used in assembling the nozzle support, divider, and back plate. The nozzle was sealed in place by neoprene o-rings on each side.

Electrode Assembly. The electrode assembly has a singular purpose, and that is to provide a gap with respect to the nozzle through which the arc is established. Two electrodes were designed and constructed. The first design, shown in Figure 10, was water cooled. A 1 percent thoriated tungsten tip was silver-soldered to the end of a hard drawn copper tube (ASTM: B133-54T). Copper again was selected for its good electrical and thermal conductivity. Tungsten was selected for its high melting point (3900. degrees Kelvin). The flow passage was formed by two concentric tubes. Water enters through the



NOTES:
1. TOLERANCES ±0.010 UNLESS NOTED
2. FILLETS & ROUNDS 1/8 R. UNLESS NOTED
3. SCALE: FULL
4. 8 HOLES ON 5 3/4 DIA. TO MATCH SAME ON NOZZLE SUPPORT REF. PLATE No. 163-01

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MECHEN GENERATOR
NOZZLE DETAILS
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Figure 9. Divider and Back Plate Details

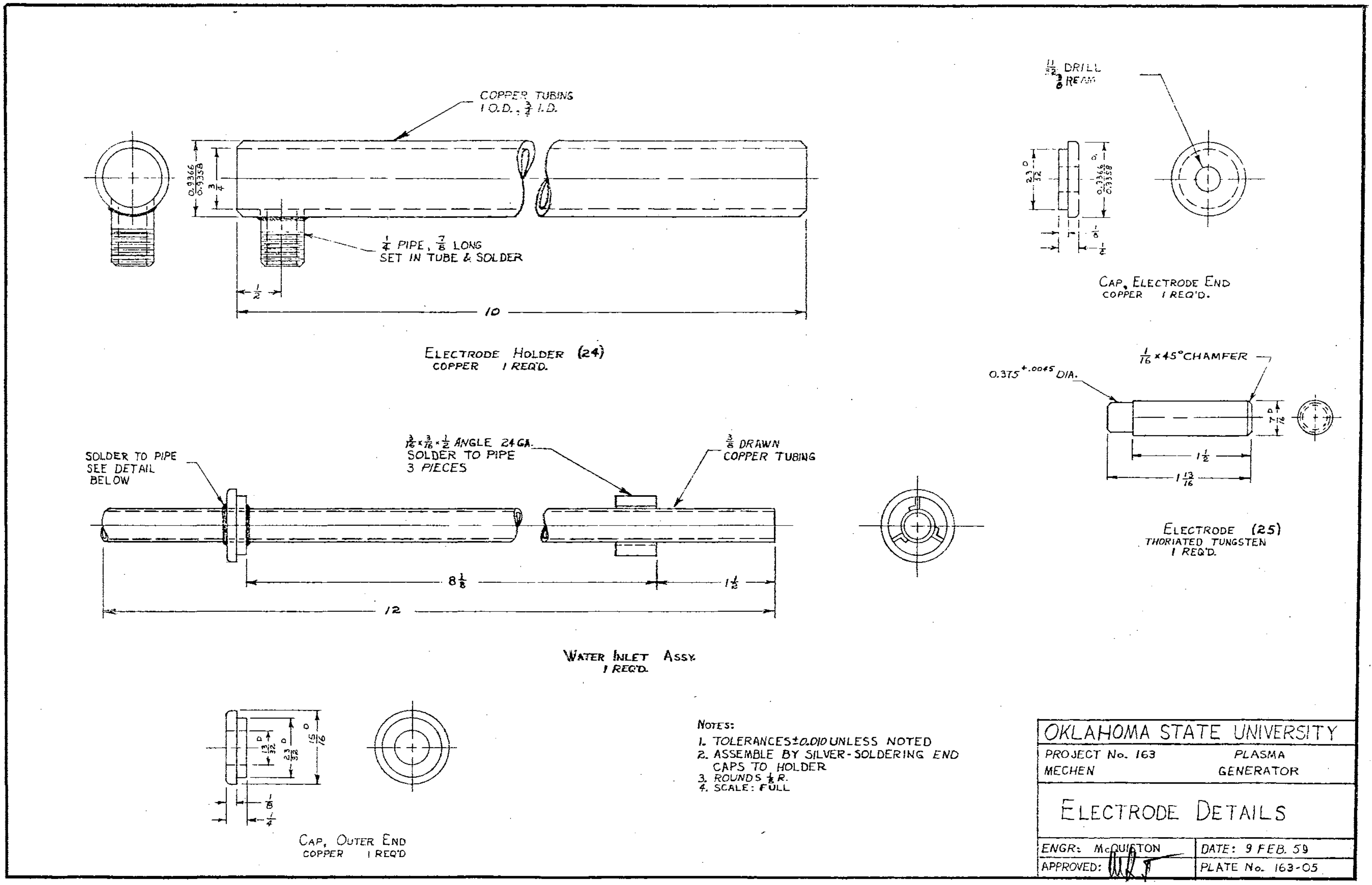


Figure 10. Water Cooled Electrode Details

inner tube, impinges on the tungsten tip, and flows back out through the outer tube. The cross section of the outer tube was designed to carry a current of 550 amperes (14).

The second electrode design, shown in Figure 11, was of solid stainless steel (type 304) with the same tungsten tip as described above. This electrode was designed to test the effect of high temperatures on the tungsten tip without cooling.

Both designs were equipped with lugs for connection of power cables.

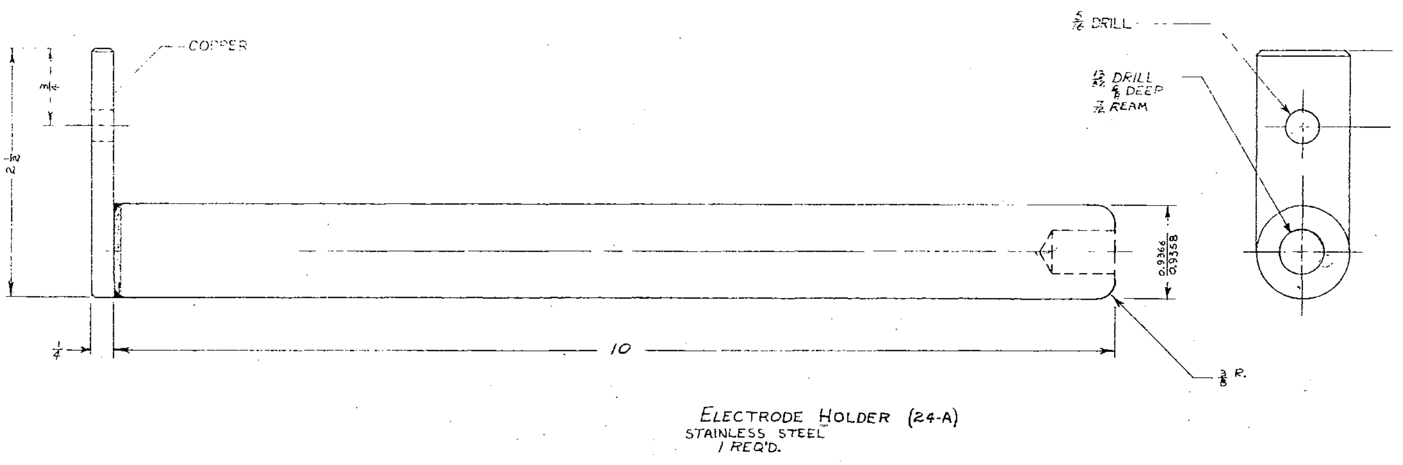
Electrode Support Assembly. The principal function of the electrode support is to guide the electrode along the geometric axis of the nozzle. Other functions are: to close one end of the chamber, to provide a gas manifold for axial flow of gas, and to support two manifolds for tangential flow of gas. The assembly, shown in Figure 5, consists of two halves. Details are shown in Figure 12.

Yellow, half hard, brass (ASTM: B121 Alloy No. 4) was selected as material. This particular type of brass has excellent machinability. Inasmuch as 12 No. 78 (approximately 1/64 inch) diameter holes were drilled in the axial gas manifold, this property was very important.

No cooling was provided other than the flow of gas through the axial gas manifold.

Wax impregnated paper gasket material was used in assembling the two halves of the support. A gas tight seal between the electrode and the support was achieved by an o-ring as shown in Figure 5.

Gas Manifold Assemblies. Two identical gas manifolds located near the periphery of the chamber and diametrically opposite one another were used for the tangential gas supply. These manifolds were designed so that the gas discharge could be adjusted from a radial direction to



NOTES:
1. TOLERANCES ± $\frac{1}{64}$ UNLESS NOTED
2. SCALE: FULL

OKLAHOMA STATE UNIVERSITY

PROJECT No. 163 - PLASMA
MECHEN GENERATOR

ELECTRODE DETAILS

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Figure 11. Uncooled Electrode Details

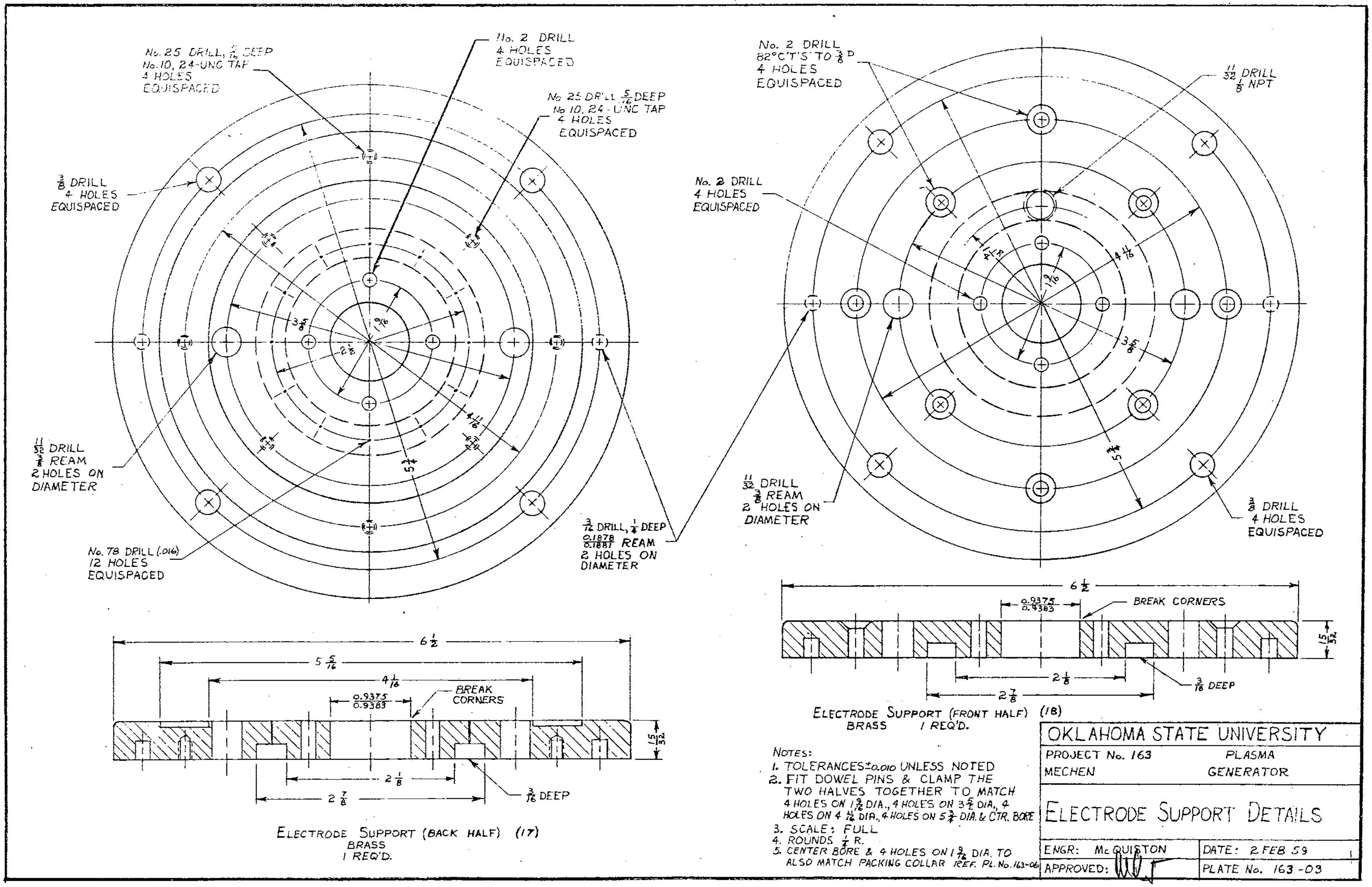


Figure 12. Electrode Support Details

a tangential direction with respect to the chamber. Manifold details are shown in Figure 13.

The manifolds were constructed of cold drawn, seamless, mechanical steel tubing. They were isolated (electrically) from the electrode support assembly by plastic (polyethylene) sleeves with fiber washers on each side. A gas tight seal was achieved by use of an o-ring and the collar-spring arrangement shown in Figure 5.

Traversing Mechanism. The traversing mechanism, shown in Figure 5, serves to advance or retract the electrode assembly. Movement of the electrode is accomplished by turning the knurled ring (actually an internal gear) which meshes with two small pinions threaded on the traversing shafts. Circular motion is changed to axial motion through this arrangement. Figure 13 gives details of design. To complete this design, one internal gear (Boston Gear G 666) and two spur gears (Boston Gear G 166) were purchased.

Final Assembly of The Plasma Generator. The six subassemblies described above were combined into one complete assembly by the use of 4 bolts $8\frac{1}{4}$ inches long by $\frac{1}{4}$ inch in diameter. For convenience, these bolts were threaded on both ends. Plastic sleeves were used to isolate the bolts from the nozzle assembly and the electrode support assembly. Fiber washers were used under each nut to complete the electrical insulation. The bolts were spaced 90 degrees apart around the assembly as shown in Figure 5.

To insure a gas tight seal between the chamber, the nozzle assembly, and the electrode support assembly, the phenolic insulating rings were cemented to the nozzle and electrode support assemblies. Three-M Brand rubber cement, manufactured by the Minnesota Mining and Manufac-

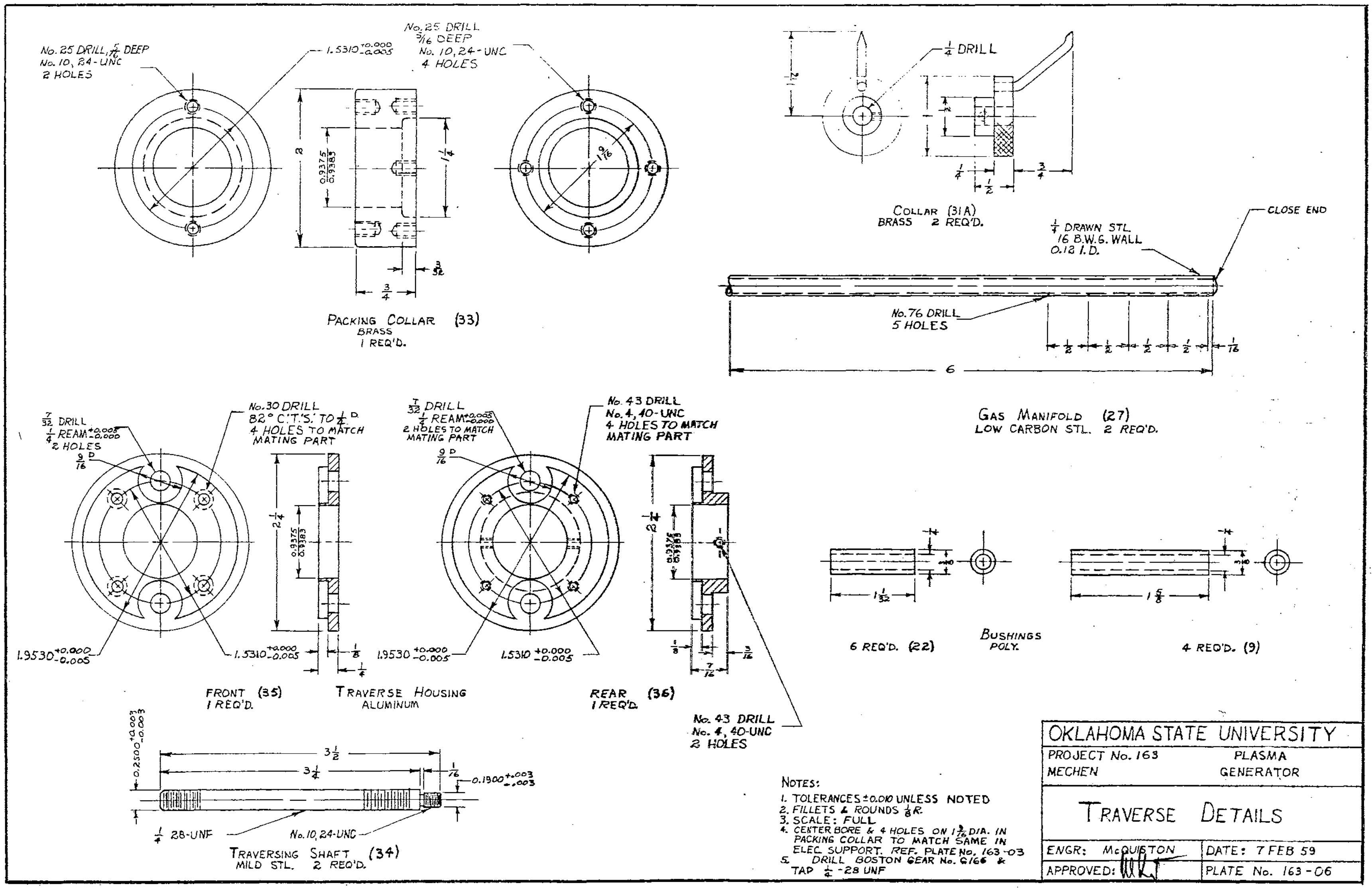


Figure 13. Gas Manifold and Traversing Mechanism Details

turing Company, was used for this purpose. Wax impregnated paper gaskets were used between the insulating rings and the chamber. These gaskets were sealed with No. 2 Permatex, manufactured by the Permatex Company, Incorporated.

Instrument and Control Panel

To facilitate operation of the plasma generator, a control panel was designed and constructed as shown schematically in Figure 14.

The framework was fabricated, by welding, from 1 inch angle. The upper front of the panel was covered with 3/4 inch plywood and the remainder with $\frac{1}{4}$ inch plywood. To accommodate portable instruments, note paper, etc. a formica covered shelf was provided at a convenient height just beneath the instruments and controls.

Space on the panel was divided in the following way: gas instruments and controls were installed in the right hand portion; electrical instruments and controls were installed in the center, with the temperature recorder and water controls on the left.

Gas Piping and Controls

The function of this apparatus is to provide for the selection of a particular type of gas, to meter the gas, and to distribute the gas to 3 different manifolds on the plasma generator. Figure 15 is a schematic diagram of the gas piping and controls. Gas selection was accomplished by use of 3 $\frac{1}{4}$ inch globe valves which discharged into a common manifold. Each valve controlled the flow of a particular type of gas from a regulated supply. The gas was metered by means of a sharp edged orifice located between the inlet manifold and the outlet or distributing manifold. Needle valves were used on the outlet manifold to regulate the flow to the generator.

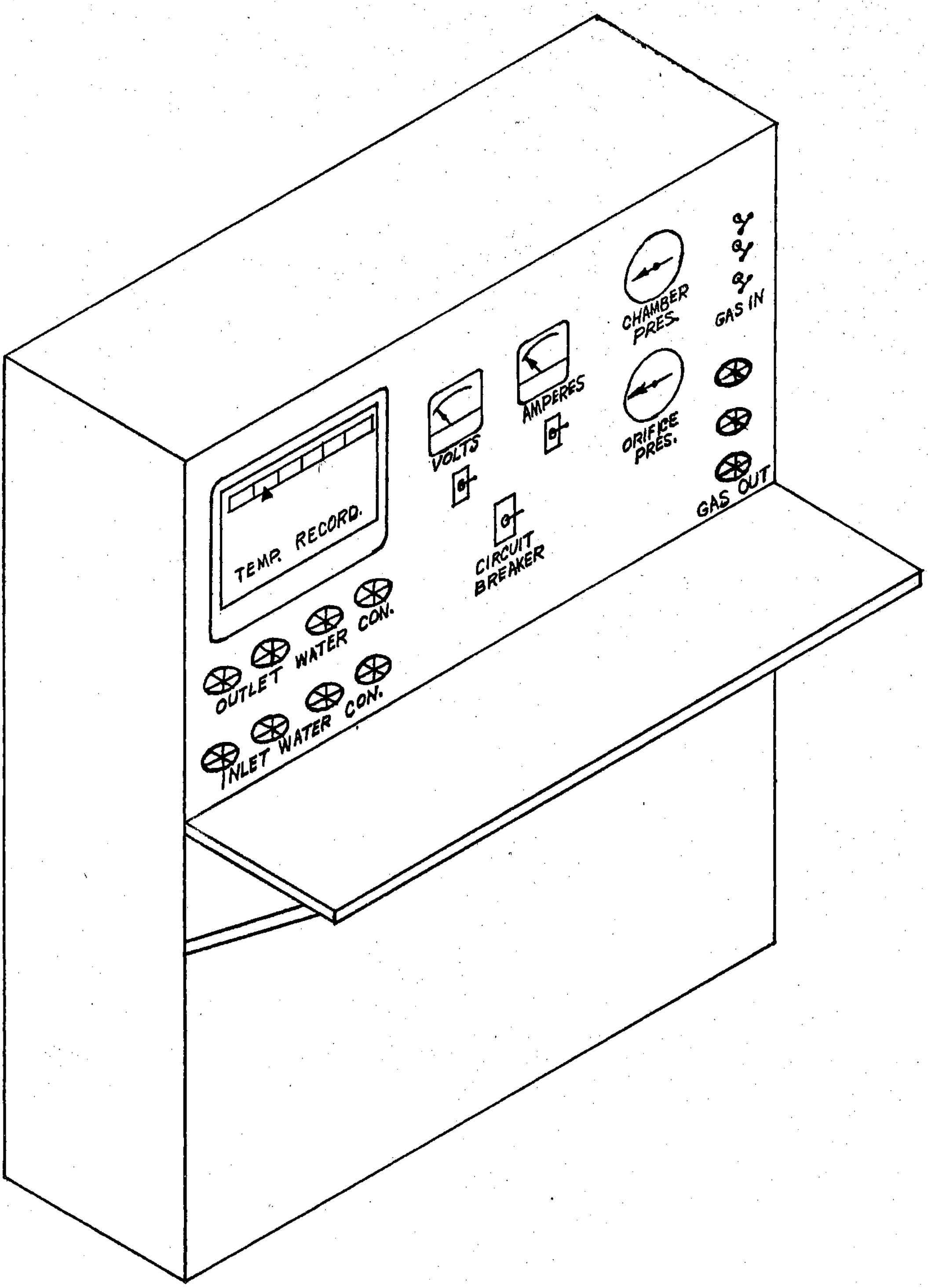


Figure 14. Instrument and Control Panel

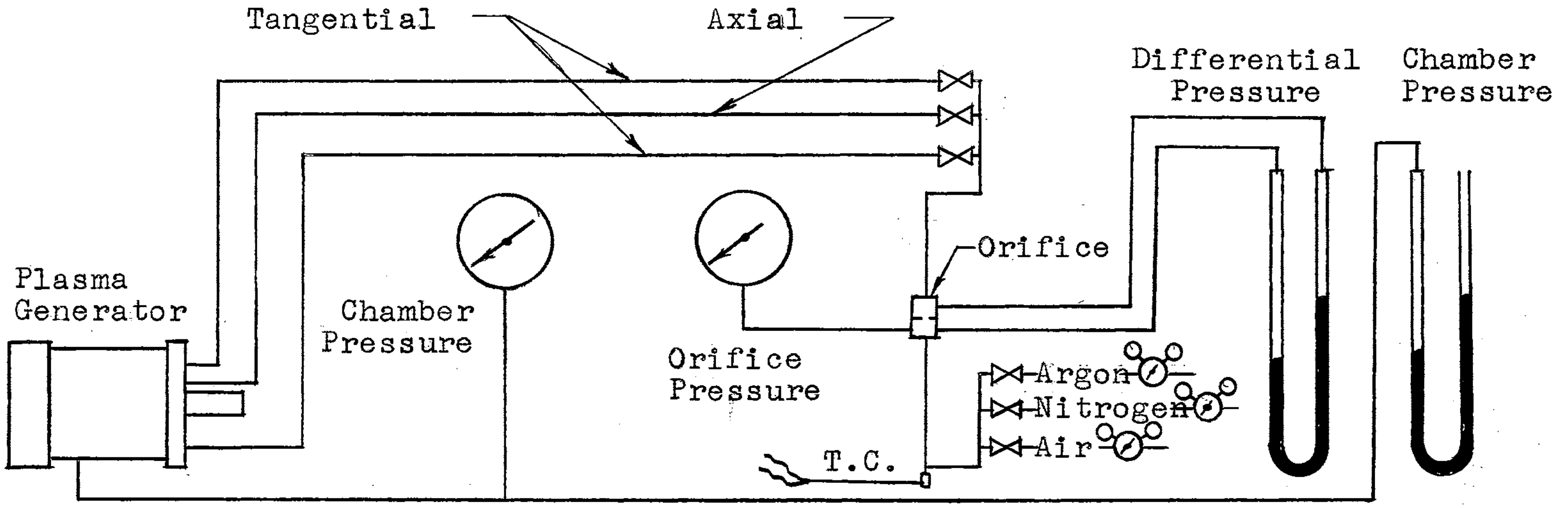


Figure 15. Gas and Instrument Piping

Plastic tubing was used for all the piping except the two manifolds which were $\frac{1}{4}$ inch steel pipe, and the straight sections on each side of the orifice which were 3/8 inch copper tubing. Flared fittings were used with the plastic tubing which was flared by heating until pliable and then shaped by screwing together the mating parts of the fitting.

Water Piping and Controls

The function of the water piping is to provide cooling for the nozzle, chamber, and electrode assemblies. Figure 16 is a schematic diagram of the water piping and controls. Water enters a distributing manifold, fabricated from $\frac{1}{2}$ inch galvanized steel pipe, through a $\frac{1}{2}$ inch garden hose which was connected to the laboratory water supply. The manifold was equipped with four $\frac{1}{4}$ inch gate valves. Two valves control the flow of water to the nozzle, and the remaining two control flow to the chamber and electrode assemblies, respectively. Four $\frac{1}{4}$ inch globe valves were provided in the return lines to regulate the flow of water. Downstream of these valves the piping led to the sink. Provisions were made at the inlet manifold and in each water line on the outlet side of the plasma generator for the insertion of thermocouples.

Plastic tubing was used to pipe the water to and from the generator and to the sink. Brass tube fittings of the flared type were used in the manner described in the preceding section.

Power Supply

An electric welder was used as a source of d-c power. The machine was a "Lincoln Shield Arc", type SAE 300, manufactured by the Lincoln Electric Company, Cleveland, Ohio. The welder was rated at 400 amperes with 40 volts potential difference.

The welder was connected in series with the plasma generator as

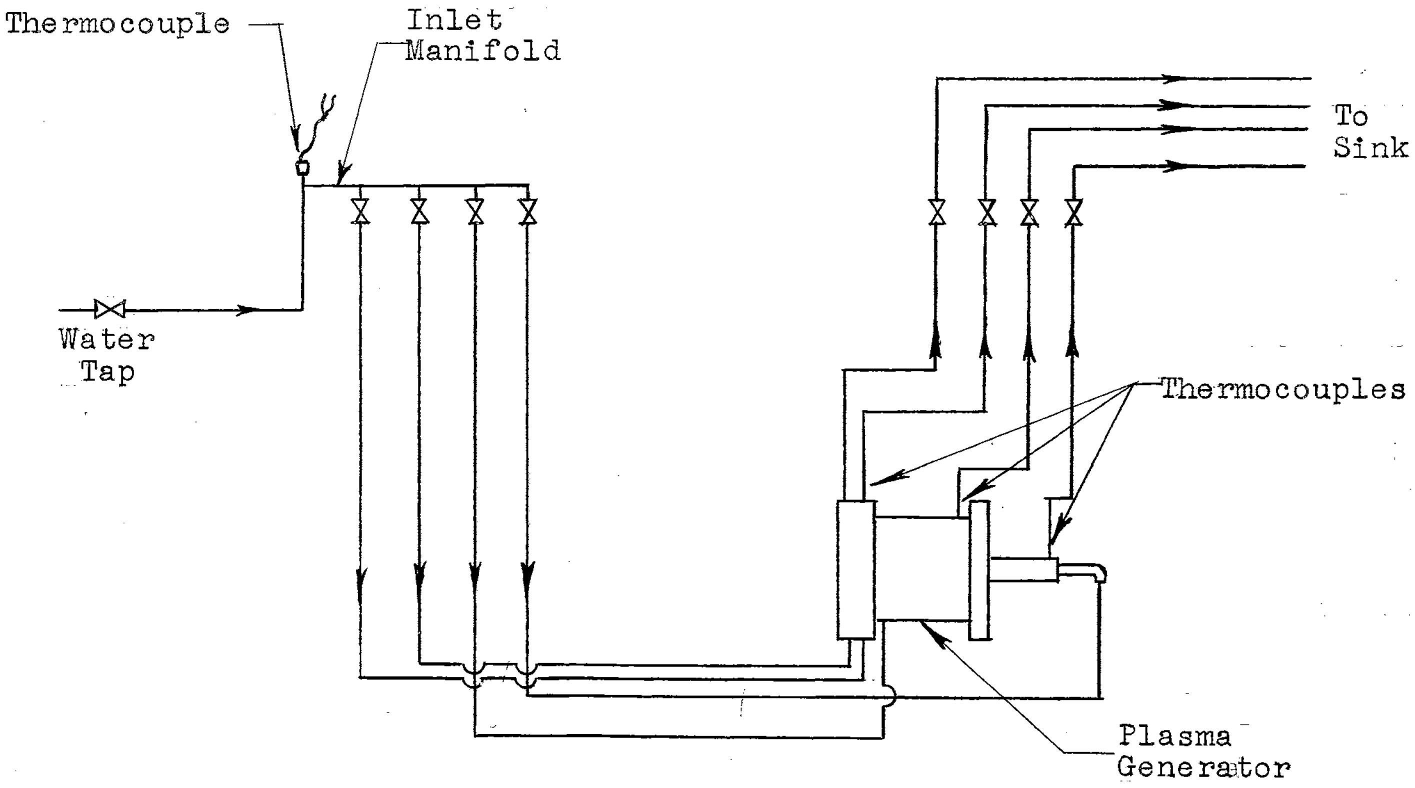


Figure 16. Water Piping and Controls

shown in Figure 17. Provisions were made for the measurement of current and potential difference at the welder terminals, and a circuit breaker was installed for instantaneous opening and closing of the circuit. The current and voltage controls on the welder were used to regulate the power input to the plasma generator. To prevent electrical shock while making adjustments on the generator, the electrode assembly of the plasma generator was grounded.

The cable used for the main circuit was rubber insulated copper (AWG 4/0). For the ground cable as well as the actuating circuit of the circuit breaker, rubber insulated copper cable (AWG 4) was used. Soldered copper terminals were used to make all connections.

Instrumentation

The plasma generator apparatus was instrumented to make the following measurements: electrical, gas flow rate, pressure, and temperature. Most of the instruments necessary for these measurements were mounted on the central control panel. The various instrumentation facilities will be discussed separately according to the above listing.

Electrical Instrumentation. The voltage was measured at the output of the electric welder, and the current was measured by means of a 500 ampere meter with a 50 millivolt shunt as shown in Figure 17. Switches were installed in the leads to both meters so that the instruments could be disconnected from the circuit during periods of large and unpredictable fluctuations. The voltmeter and ammeter are incorporated into a portable low voltage circuit tester manufactured by Joseph Weidenhoff, Incorporated, and are noted more for their durability than for their accuracy. It was believed that this type of instrument was more suitable for preliminary operations than more delicate and refined instru-

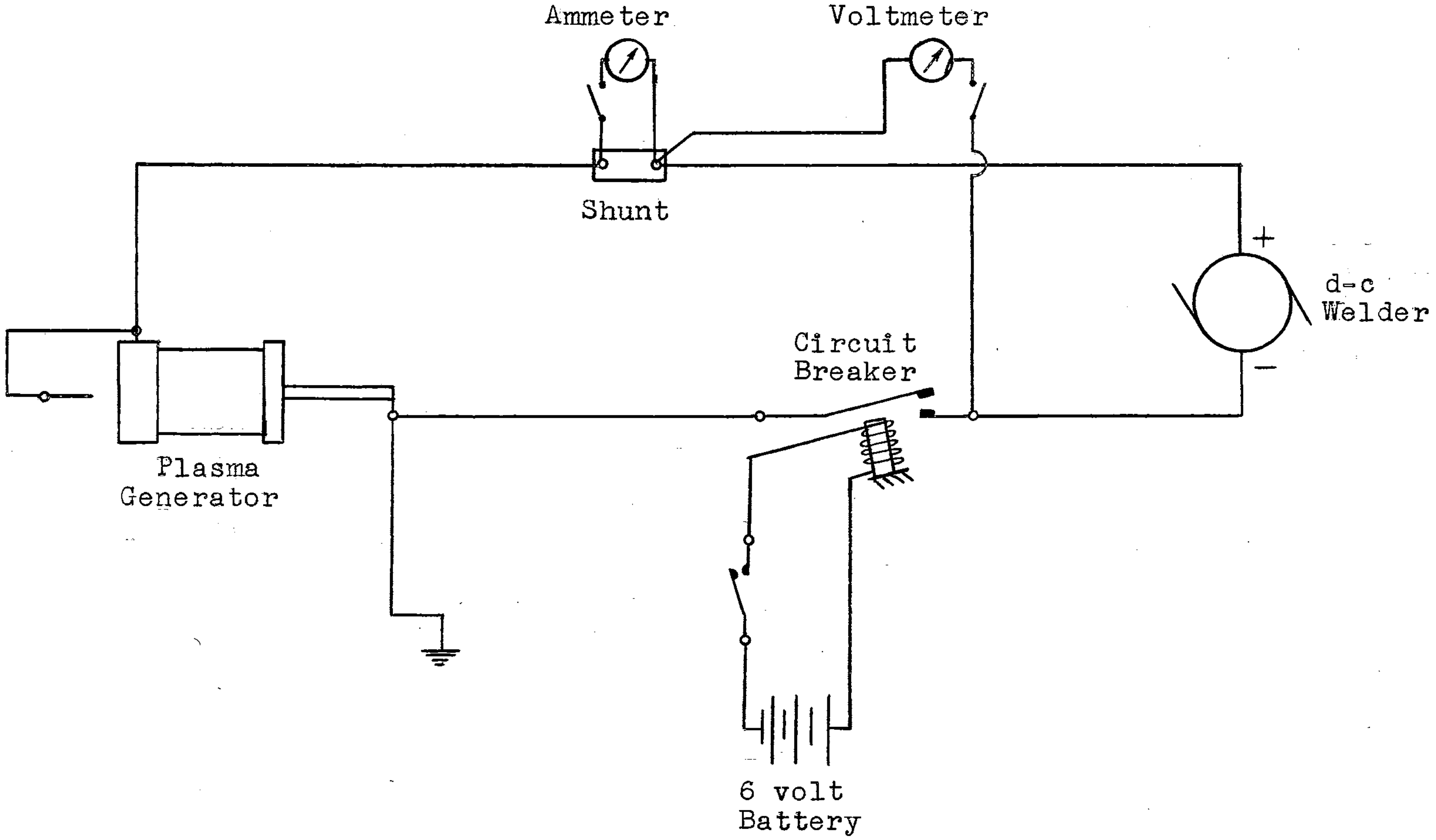


Figure 17. Electrical and Instrument Wiring

ments. The range of the voltmeter was 0-100 volts and the range of the ammeter was 0-500 amperes.

An ammeter and a voltmeter manufactured by the Triplett Electric Instrument Company were originally installed in the control panel for the measurement of current and voltage. However, these instruments were not used because of their delicate construction.

Measurement of The Gas Flow Rate. A sharp edge orifice, shown in Figure 18, is used as the primary element for measuring the gas flow rate. The orifice was installed in a vertical position, as shown in Figure 15, with a straight section of 3/8 inch copper tubing 7 inches long on each side. The upstream pressure tap was located 1 pipe diameter from the orifice, and the downstream tap 1 pipe radius from the orifice. Flanges for the orifice were machined from brass. The orifice plate was machined from stainless steel.

Pressure Instrumentation. The pressure instrumentation includes the measurement of differential pressure across the orifice, upstream pressure at the orifice, and the pressure in chamber of the generator. Figure 15 shows a schematic representation of the pressure instrumentation.

The orifice differential pressure and the chamber static pressure were measured by means of single tube manometers, the wells filled with Meriam Unity fluid (specific gravity of 1). The manometers were connected to the orifice and chamber taps through plastic tubing and brass fittings.

An Ashcroft bourdon tube pressure gage was used to measure the upstream orifice static pressure. The range of this gage was 0-100 psi in 1 pound subdivisions. A tee was inserted in the tube to the up-

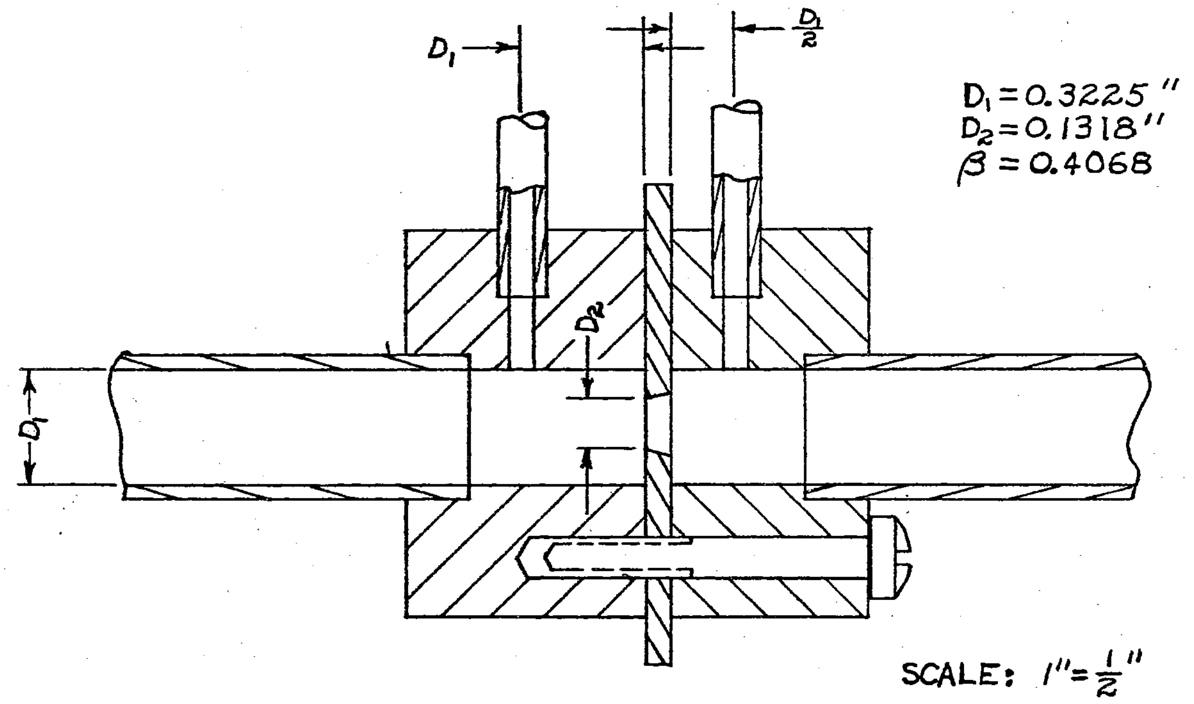


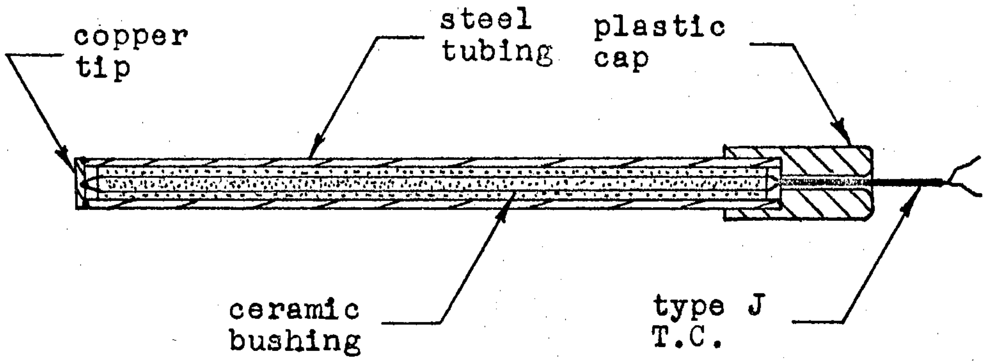
Figure 18. Orifice Meter

stream pressure tap of the orifice for this measurement.

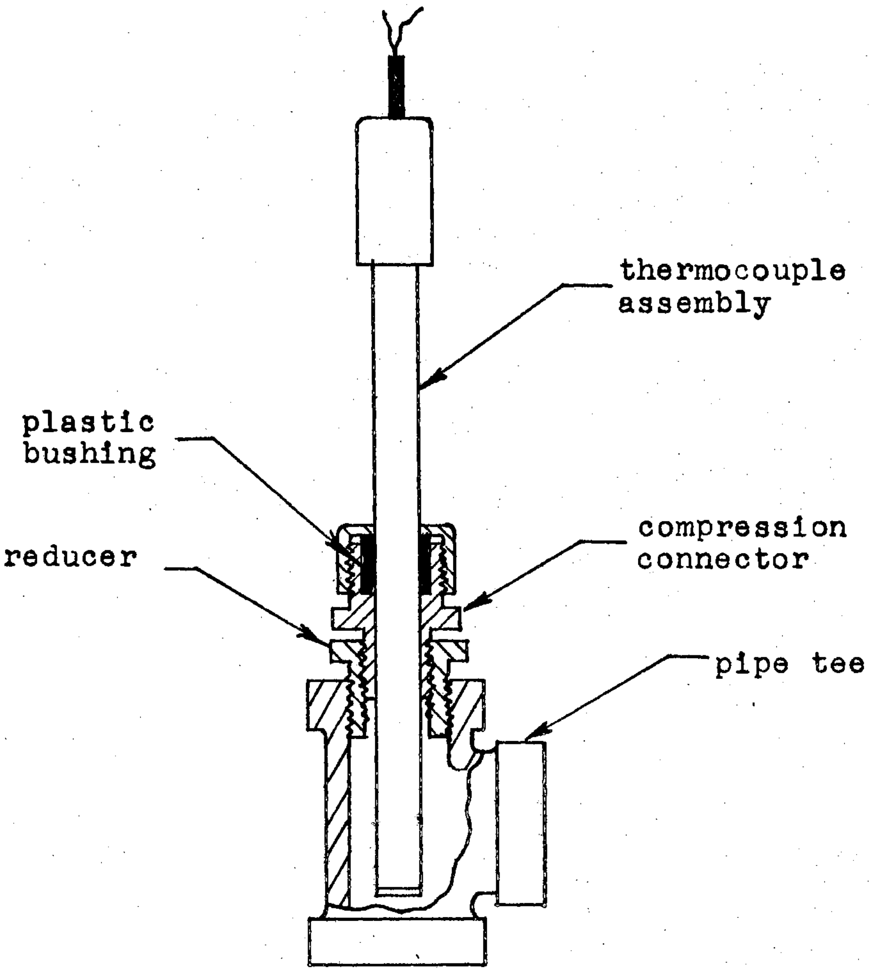
Temperature Instrumentation. Temperature was measured at the following points: gas temperature upstream of the orifice, inlet water temperature at entrance to the distributing manifold, and outlet water temperatures at the four water outlets on the plasma generator.

Minneapolis-Honeywell Type J iron-constantan thermocouple wire was used to fabricate thermo-well assemblies as shown in Figure 19a. The thermo-wells are inserted in the gas and water piping by means of pipe tees and brass compression type connectors as shown in Figure 19b.

Measurement and recording of temperature were performed by a Brown, Type 153X65 Electronik Multipoint recorder. This instrument has a range of 0-600 degrees Fahrenheit, and the manufacturer gives the accuracy as ±0.375 per cent of scale span.



(a) Thermocouple Assembly



(b) Thermocouple Well Details

Figure 19. Thermocouple and Thermo-Well Details

CHAPTER IV

CALIBRATION OF INSTRUMENTS

During this preliminary study of the plasma generator, the intention was not to make precise measurements. However, all instruments were calibrated to insure reasonable accuracy.

The Brown temperature recorder did not require calibration since the manufacturer gives the accuracy as ±0.375 percent of scale span when the recorder is placed in operation according to instructions. This recorder periodically corrects itself for changes in reference temperature. Calibration was required for the orifice meter, the two Ashcroft pressure gages, the voltmeter and ammeter, and the 6 thermocouple assemblies. Each of these calibrations will be discussed separately.

Orifice Calibration

The orifice calibration consisted of determining the orifice discharge coefficient by measuring the pressure differential across the meter caused by a fluid of known flow rate. By knowing the pressure differential and flow rate, it was possible to calculate the discharge coefficient by the following equation:

$$Q = \frac{C_d A_2}{\sqrt{1 - \left(\frac{D_2}{D_1}\right)^4}} \sqrt{2g \frac{\Delta p}{w}} \qquad \text{IV - 1,}$$

in which, Q = volumetric flow rate, cfs;

C_d = coefficient of discharge;

A_2 = orifice area, ft^2;

D_2 = orifice diameter, ft;

D_1 = inside tube diameter, ft;

Δp = pressure differential, lb/ft^2

w = specific weight of flowing fluid, lb/ft^3; and

g = gravitational acceleration, feet per sec^2.

The calibrated orifice was then used to measure the flow rate of the stabilizing gas by inserting the measured pressure differential and the predetermined value of the discharge coefficient into Eq. IV-1, and calculating the flow rate.

For reasons of simplicity water was used to calibrate the orifice instead of a gas as it was a simple matter to weigh the water discharged by the nozzle over a period of time. The arrangement of the calibrating apparatus is shown in Figure 20.

The flow rate was controlled by the valving shown in Figure 20. The gate valve upstream of the orifice remained in the open position while the flow rate was varied by the globe valve located downstream providing undisturbed flow through the orifice.

The mass flow rate was determined by diverting the flow of water into a receptacle and simultaneously starting an electric timer. After a specified time the flow was diverted away from the receptacle. Knowing the mass flow rate and the density, it was possible to obtain the volumetric flow rate.

Water temperature was measured at the outlet of the flow line, and any difference in temperature between the point of measurement and the orifice was assumed negligible. The physical properties of the water were evaluated at this temperature.

The differential pressure was determined by connecting the orifice

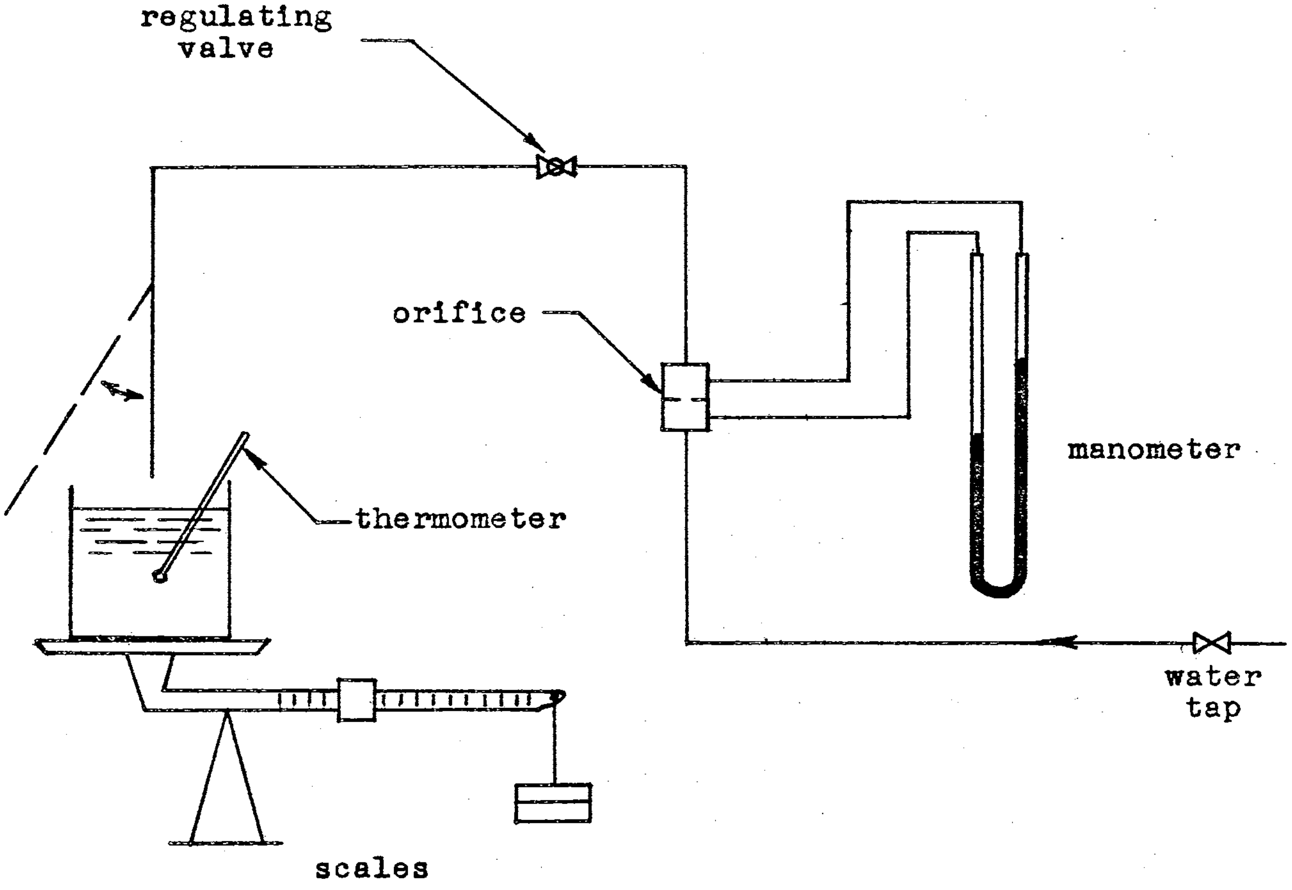


Figure 20. Orifice Calibration Setup

pressure taps to a U-tube manometer using as the measuring liquid either Meriam Unity fluid (specific gravity of 1) or Meriam No. 3 fluid (specific gravity of 2.95). The Unity fluid was used at the lower flow rates and was replaced by the No. 3 fluid at higher flow rates.

Provisions for water supply were made by connecting the orifice to the municipal water line. It was possible to obtain flows with Reynolds numbers greater than 1.2×10^5. However, fluctuations in pressure became pronounced. To avoid pressure surges the calibration runs were made at night which eliminated most of this trouble. Runs were repeated when variations in the differential pressure occurred.

The calibration data was represented by C_d versus Reynolds number (N_{Re}) plot as shown in Figure 21. It was not known why the discharge coefficient showed a gradual increase above a Reynolds number of 5×10^4. However, it was possible that the position of the vena-contracta changed as the flow increased which affected the pressure differential.

A value of 0.64 was used for the coefficient of discharge. This was justifiable since the range of operation was in the neighborhood of $N_{Re} \cong 4 \times 10^4$. A trial and error process using the pressure drop was used in the low N_{Re} range to determine the discharge coefficient. This process was necessary because the velocity of the fluid could not be measured directly.

Pressure Gage Calibration

The pressure gage calibration consisted of comparing the pressure indicated by the calibrated gages with a pressure produced by a known weight on a known area (15). A Crosby dead weight tester was used for

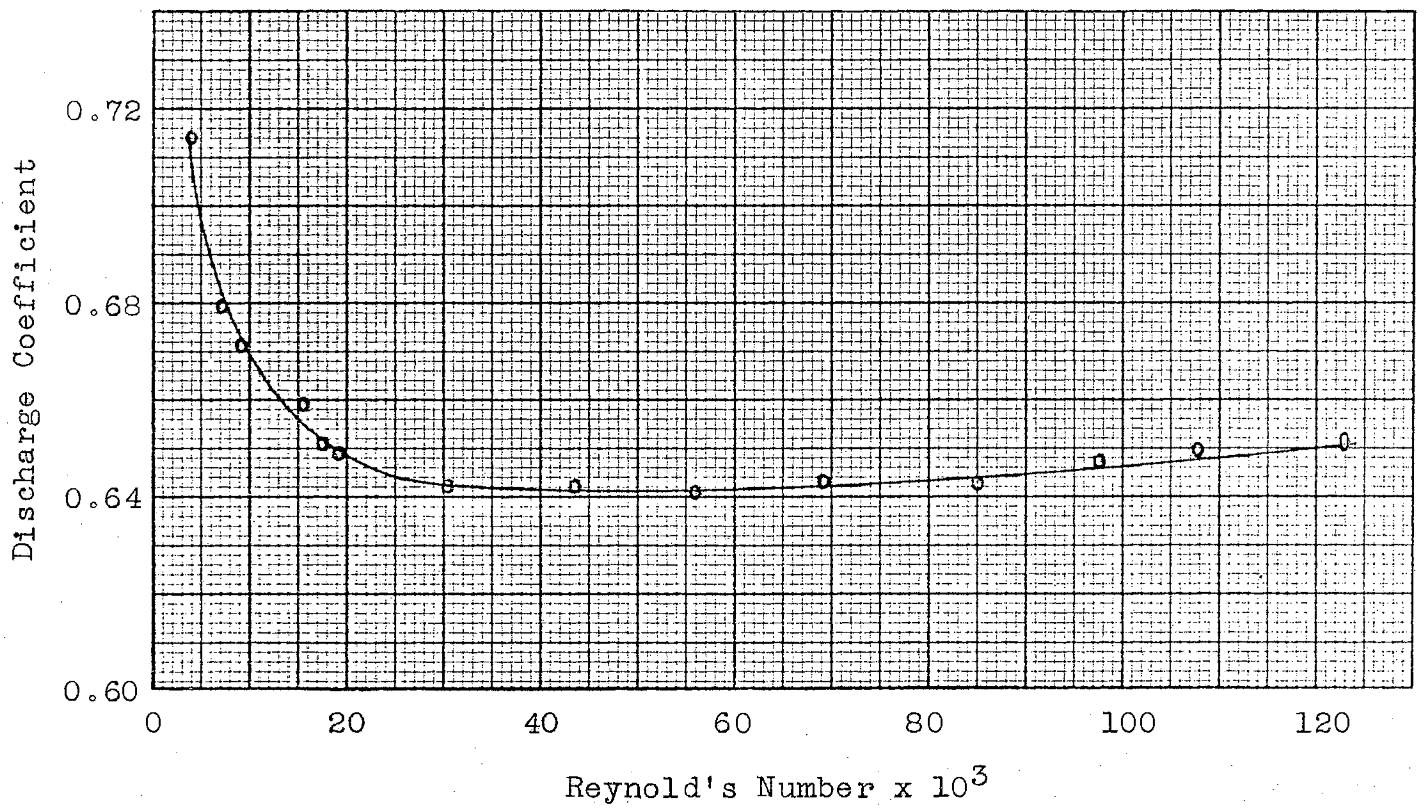


Figure 21. Orifice Calibration Curve

this purpose. The gage to be calibrated was connected to one end of a tube which was closed at the other end by a piston and cylinder arrangement. The space between the gage and piston was filled with oil.

Two gages were calibrated; one was used to measure the chamber pressure, and the other was used to measure upstream orifice static pressure.

Weights were placed on the piston of the dead weight tester in amounts necessary to increase the pressure in increments of 5 psi. Each gage was calibrated over its complete range by progressing up the scale and then back down to zero.

Below 50 psi both gages were found to be accurate. Above 50 psi each gage had a slight positive error which increased to 1 psi at a full scale reading of 100 psi.

In view of the fact that the gages were to be used for measuring pressures below 50 psi, the error was taken as zero and no calibration curves plotted.

Calibration of Voltmeter and Ammeter

The voltmeter calibration consisted of comparing the indicated voltage of the calibrated meter with the voltage indicated by a Simpson precision voltmeter of accuracy ±0.2 percent of scale span.

The calibration was made in increments of 4 volts up to 50 volts and in increments of 10 volts on up to 100 volts, the full scale deflection.

A calibration curve of correction versus voltmeter reading was plotted and is shown in Figure 22. In the range of operation with argon the error was ±1 volt.

Ammeter calibration was accomplished by measuring the potential difference across a standard shunt with a Twing-Albert potentiometer.

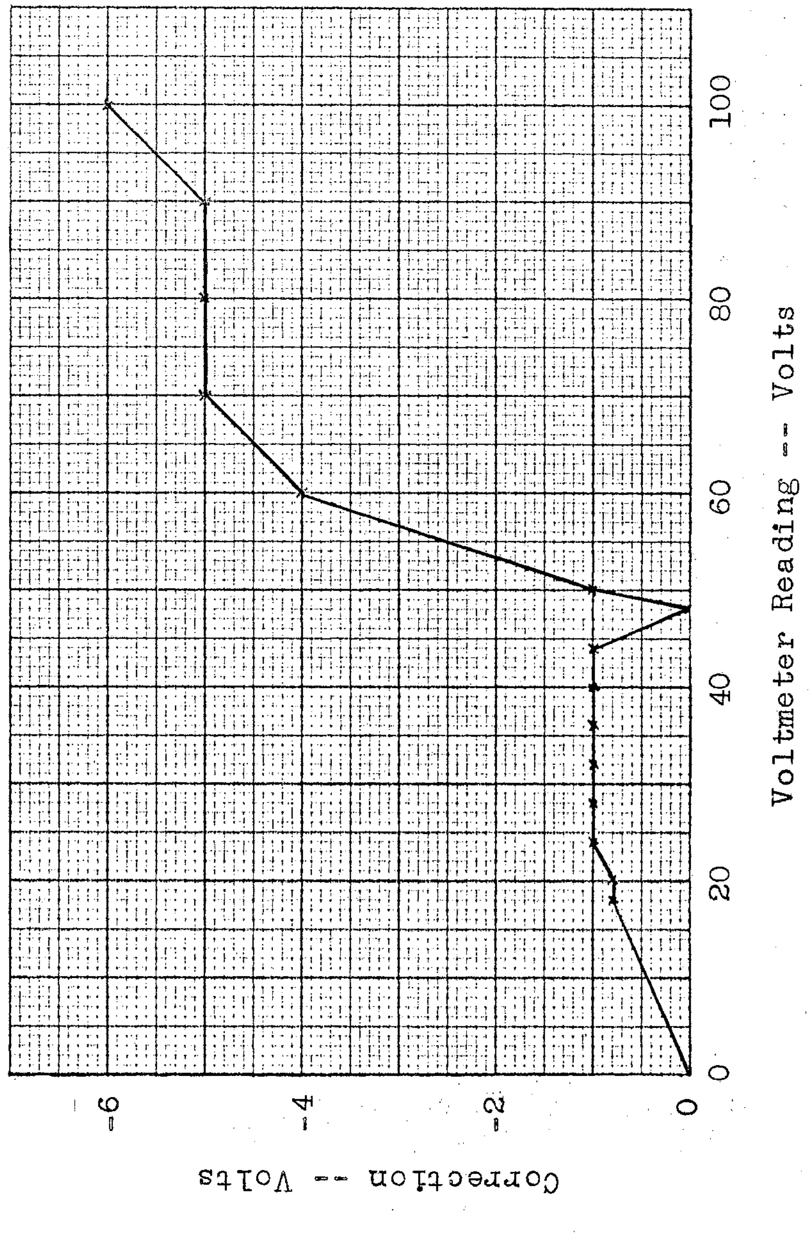


Figure 22. Voltmeter Calibration Curve

The meter and shunt to be calibrated were connected in series with the standard shunt, and a d-c rectifier as described by Sweeney (15). Two standard shunts were used; for the lower range a 150 ampere 50 millivolt shunt was available, and for the higher range a 300 ampere 50 millivolt shunt was used. At the time of this calibration the 300 ampere shunt was the largest available. This was deemed adequate, as currents above 300 amperes were not to be expected with the limited power source available.

Calibration data was taken in increments of 10 amperes up to 150 amperes. Above 150 amperes data was taken in increments of 25 amperes up to and including 300 amperes. The current was calculated for each value from the known values of resistance of the shunt and the potential difference across it. The test meter was then compared with the calculated currents and the data represented as a correction versus current plot as shown in Figure 23. In the range of operation with argon the meter error varied between -5 and -12 amperes.

Thermocouple Calibration

The range of temperatures to be measured by the 6 thermocouples was expected to be between the ice point and the steam point of water at atmospheric pressure. Calibration then consisted of measuring the electromotive force (emf) produced by each thermocouple at the above points and comparing with the emf that should have been produced (15). Temperature versus emf charts published by Minneapolis-Honeywell, Incorporated (16) were used to convert temperature to emf and vice versa.

For calibration, each thermocouple was connected as shown in Figure 24. The reference junction was maintained at the ice point by

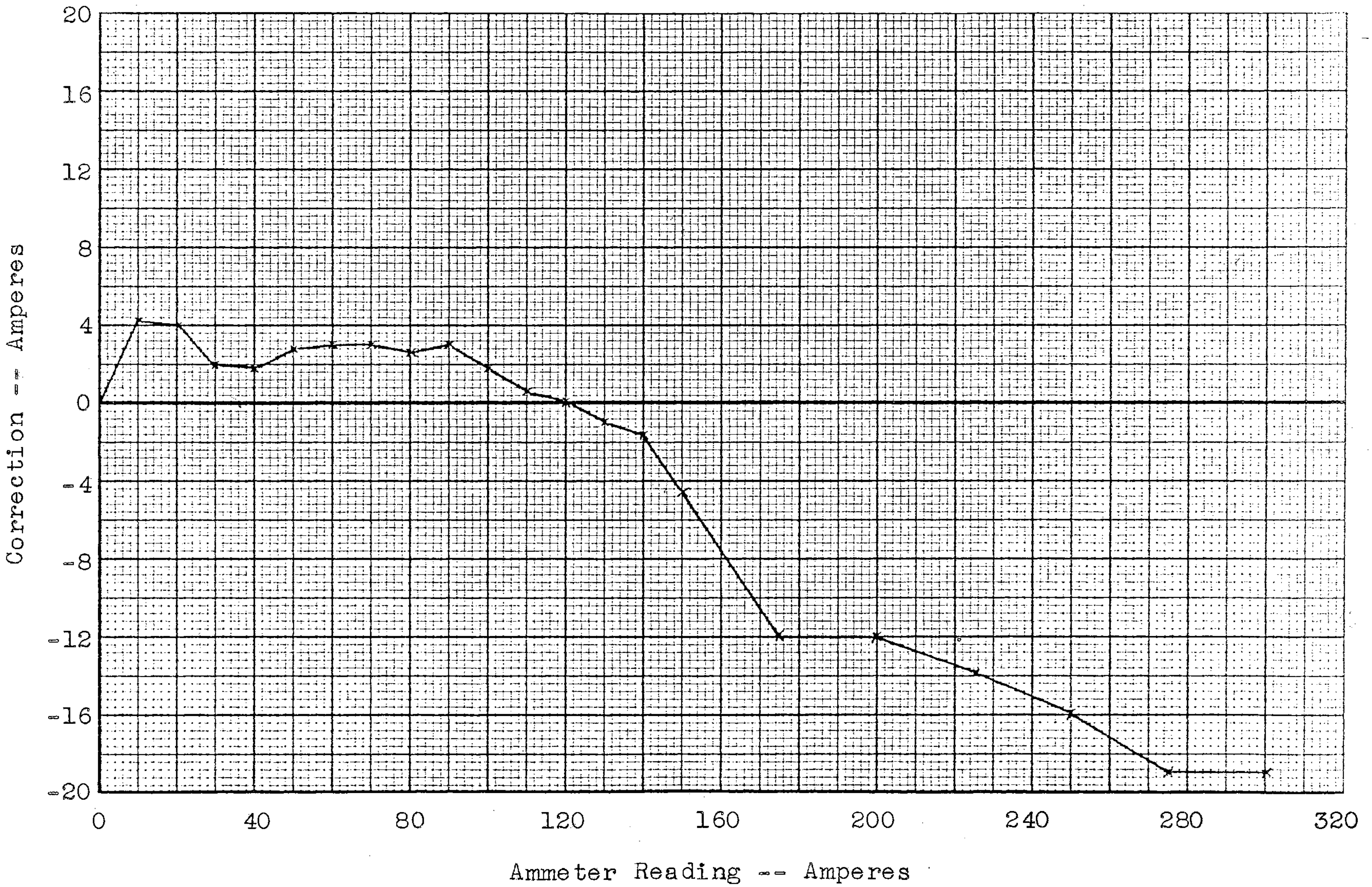


Figure 23. Ammeter Calibration Curve

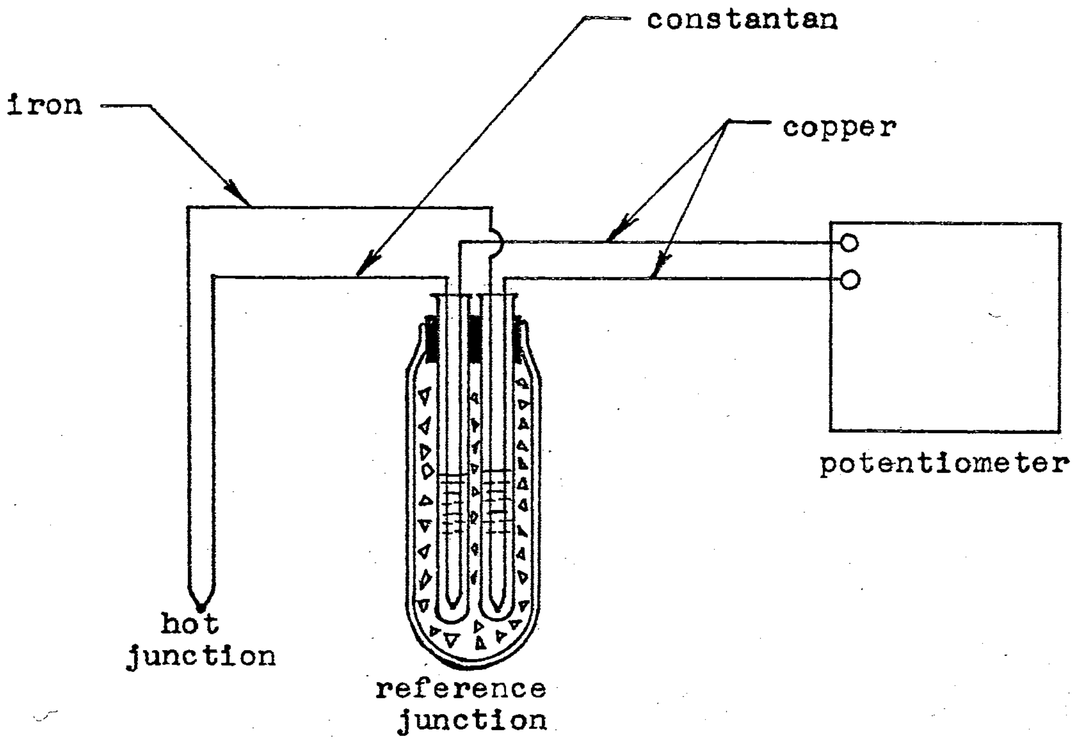


Figure 24. Thermocouple Calibration Setup

inserting the thermocouples in test tubes partially filled with diesel fuel, and then inserting the test tubes in a Dewar flask filled with a mixture of ice and water. The top of the flask was closed to the atmosphere by inserting the test tubes through rubber corks, and the top of each test tube was closed by filling with cotton waste material. The copper leads from the reference junctions were connected to the terminals of a Twing-Albert potentiometer.

To calibrate each thermocouple, the hot junction was first inserted in a Dewar flask filled with a mixture of ice and water, to simulate the ice point, as described above. The thermocouple was allowed enough time to reach equilibrium, then the potentiometer was balanced and the emf recorded. Next, the hot junction was placed in a hypsometer (used to provide the steam point), allowed to reach equilibrium, the potentiometer balanced, and the emf recorded.

At the time of the calibration the barometric pressure was 29.24 inches of mercury. The ice point, being practically independent of pressure in this range, was taken as 32 degrees Fahrenheit. The steam point obtained from Keenan and Keyes, Thermodynamic Properties of Steam (17) by linear interpolation was 210.84 degrees Fahrenheit.

All of the thermocouples were within 1 degree of the above standard temperatures. In view of the negligible error and the fact that differences of temperature were to be used, calibration curves were not plotted. The temperatures as indicated by the Brown recorder were used without correction.

CHAPTER V

OPERATION AND EVALUATION OF THE PLASMA GENERATOR

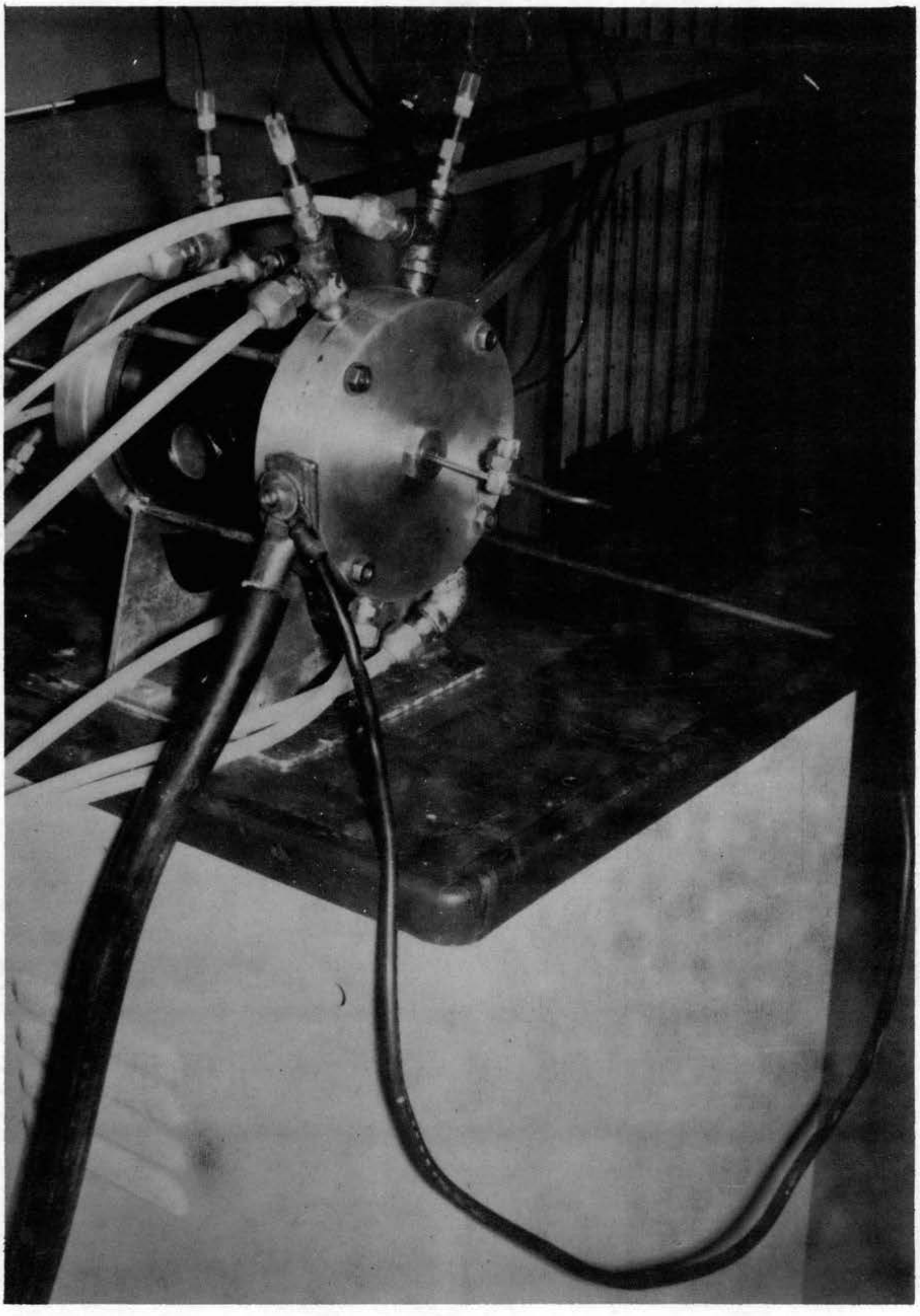
Preliminary to discussing the operation of the plasma generator, considerations concerning the starting procedure will be outlined.

The methods of starting plasma generators vary considerably among the various investigators. In practically all cases it was reported that starting of the generators was much more difficult than maintaining them in operation. As a result, many elaborate methods were devised.

To establish an arc between the electrodes, it is necessary to initially bridge the gap in some way. Two methods are available. The potential difference across the gap may be increased until the dielectric strength of the gas between the electrodes is overcome and a spark will jump, initiating the arc; or second a momentary short circuit between the electrodes may be formed by a conductor of some sort and then gradually withdrawn until the arc is established between the electrodes. The first method requires an extremely high voltage and was not used because of the complexity of the necessary equipment. Instead, a starting device utilizing the second method above was developed and proved very satisfactory.

A tungsten rod 1/16 inch in diameter and 3 inches long was clamped to a rubber insulated copper cable (AWG 4). A terminal was soldered to the free end of the cable and connected to the power terminal of the nozzle. Plate I shows this arrangement with the tungsten starting

PLATE I - STARTING ELECTRODE



electrode inserted in the nozzle. To aid the use of the starting electrode, a length of rubber hose was slipped over the cable and taped in place.

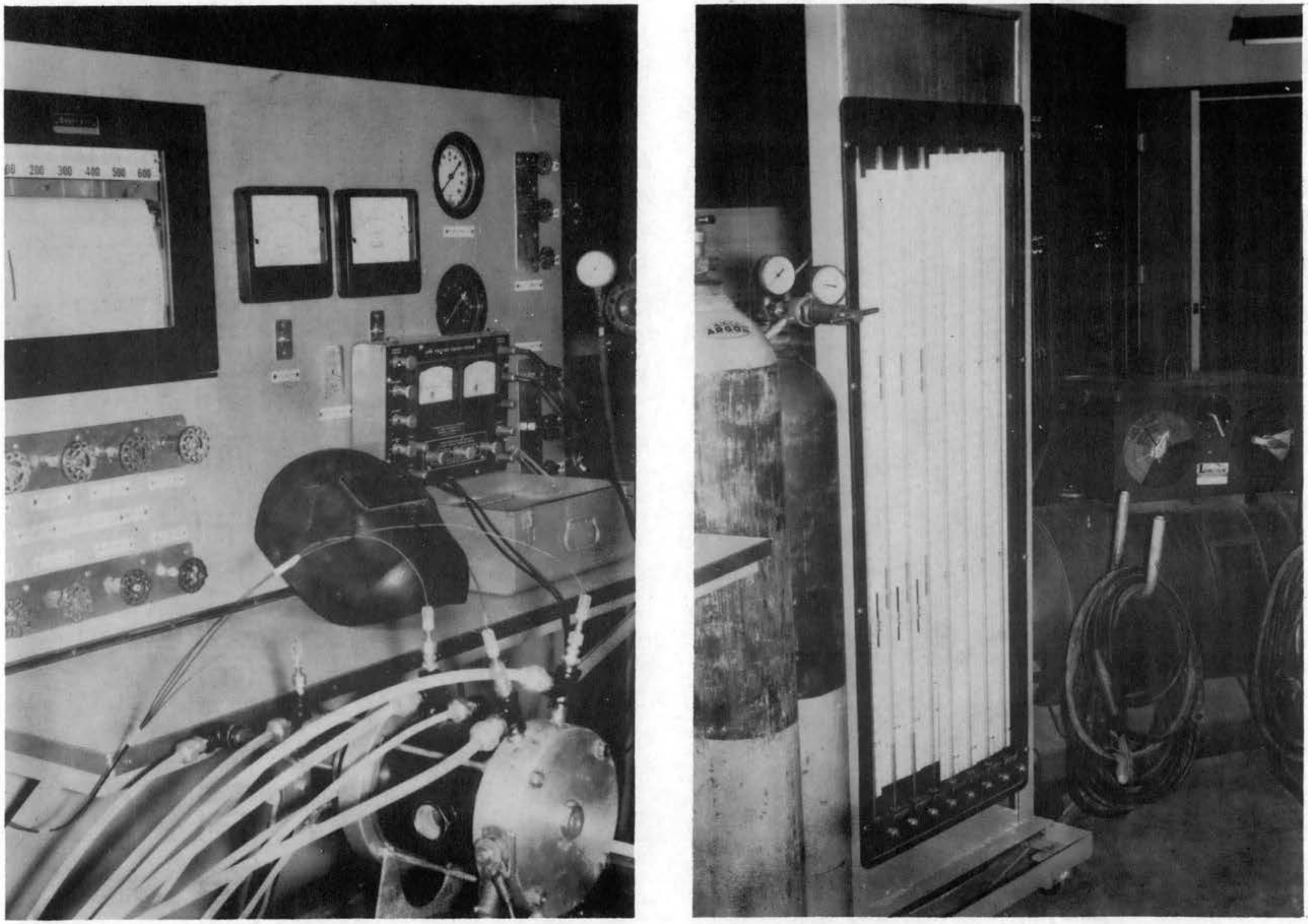
By connecting the starting electrode to the nozzle, any possibility of arcing between these parts was eliminated, thus preventing damage to the nozzle. In establishing the arc, the starting electrode was to be put in direct contact with the movable electrode, then withdrawn until the arc anchored on the nozzle. Subsequent use of the above starting method proved very successful.

Detailed instructions for operation of plasma generators were not available. Therefore, a step by step procedure was adopted in an effort to minimize the possibility of damage to the apparatus. The starting procedure is given in Appendix A. Plate II shows the arrangement of equipment for starting.

The generator was started on the first attempt, as described above, and was operated at a power level of 2 kw for a period of 5 minutes. Two subsequent runs of 5 minutes each were made at power levels of 3.5 and 7.5 kw. The potential difference across the arc was between 45 and 50 volts with a $\frac{1}{4}$ inch gap, and the movable electrode was the cathode. The tangential gas manifolds were used exclusively with an argon flow rate of between 0.05 and 0.10 pounds per minute. The emerging jet was relatively stable even though the arc was traveling down the center of the nozzle and anchoring on the outlet of the nozzle.

The generator was disassembled after the test and each part inspected. The tungsten starter (electrode) had almost entirely melted or vaporized. Some deposits of tungsten from the starter were evident on the retractable electrode, also there was a slight melting effect,

PLATE II - ARRANGEMENT OF EQUIPMENT



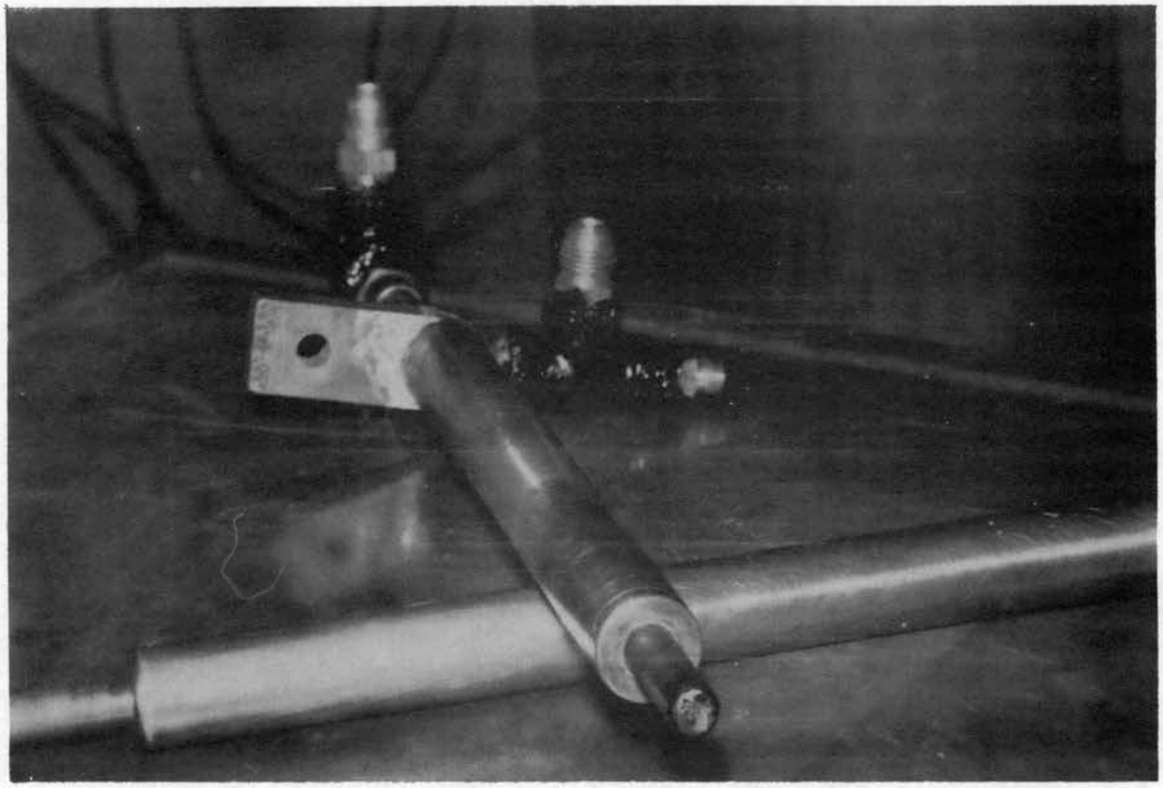
but no appreciable metal has been removed. The copper nozzle showed only a slight erosion around the outlet and an etched effect in the minimum section. All other components of the generator, including o-rings and gaskets, were unchanged from their original condition.

Before reassembling the generator, the nozzle was sanded to remove tarnish and the movable electrode was ground to its original shape. The tangential gas manifolds were extended as far as possible into the chamber (approximately $4\frac{1}{4}$ inches). Previously the tangential gas manifolds were inserted 3 inches into the chamber.

The next series of runs of approximately 20 minutes duration were much more stable. The arc appeared to anchor somewhere in the minimum section of the nozzle, but had a tendency to move around the axis of the nozzle. Power input was 6 kw. The potential difference was 30 volts with a gap of 5/16 inch. Again, only the tangential gas manifolds were used with an argon flow rate of 0.04 pound per minute. Inspection of the generator components revealed no appreciable change in condition from the previous examination. No additional erosion was evident at the outlet of the nozzle. The starting electrode was again practically destroyed, leaving some small deposits of tungsten on the retractable electrode as well as the nozzle. Plate III gives a typical example of the condition of the nozzle and electrode after $\frac{1}{2}$ hour of operation.

At this time, the generator has been operated in excess of 3 hours with only negligible erosion of the nozzle and electrode tip. All operation was with argon as the stabilizing gas and the power input was between 4 and 6 kw. The gap between the electrode and nozzle (nearest point) was approximately 5/16 inch with the electrode as the

PLATE III - NOZZLE AND ELECTRODE



cathode for most of the runs.* Representative operation data is given in Appendix B. Plate IV shows the plasma generator in operation. A number of changes and adjustments were made during the testing, many of which proved to be beneficial.

After the first two series of runs, the tungsten starter was replaced by a carbon starter which proved to be superior. The carbon did not stick to the tungsten electrode tip and instead of melting, it was vaporized. Fouling of the nozzle was therefore eliminated. Carbon also had the advantage of being much less expensive.

In all, 3 configurations of electrode tips were tested. The generator was first tested with the tip shown in Figure 25a which was ultimately selected as the superior design. The tip shown in Figure 25b melted excessively after a few minutes of operation. With this design, the arc could not be stablized. Instead, a short, small diameter arc moved erratically around the convergent part of the nozzle. The melting was attributed to the resulting high local current densities. The tip shown in Figure 25c operated satisfactorily, but had a greater tendency to melt than the tip designed as shown in Figure 25a. Apparently the reduction in mass seriously impaired the cooling of this tip.

It was noted that in regrinding the Model "A" tip, care should be taken to insure that the end is as flat as possible. The arc is then directed along the axis of the nozzle.

The uncooled stainless steel electrode was tested with the Model

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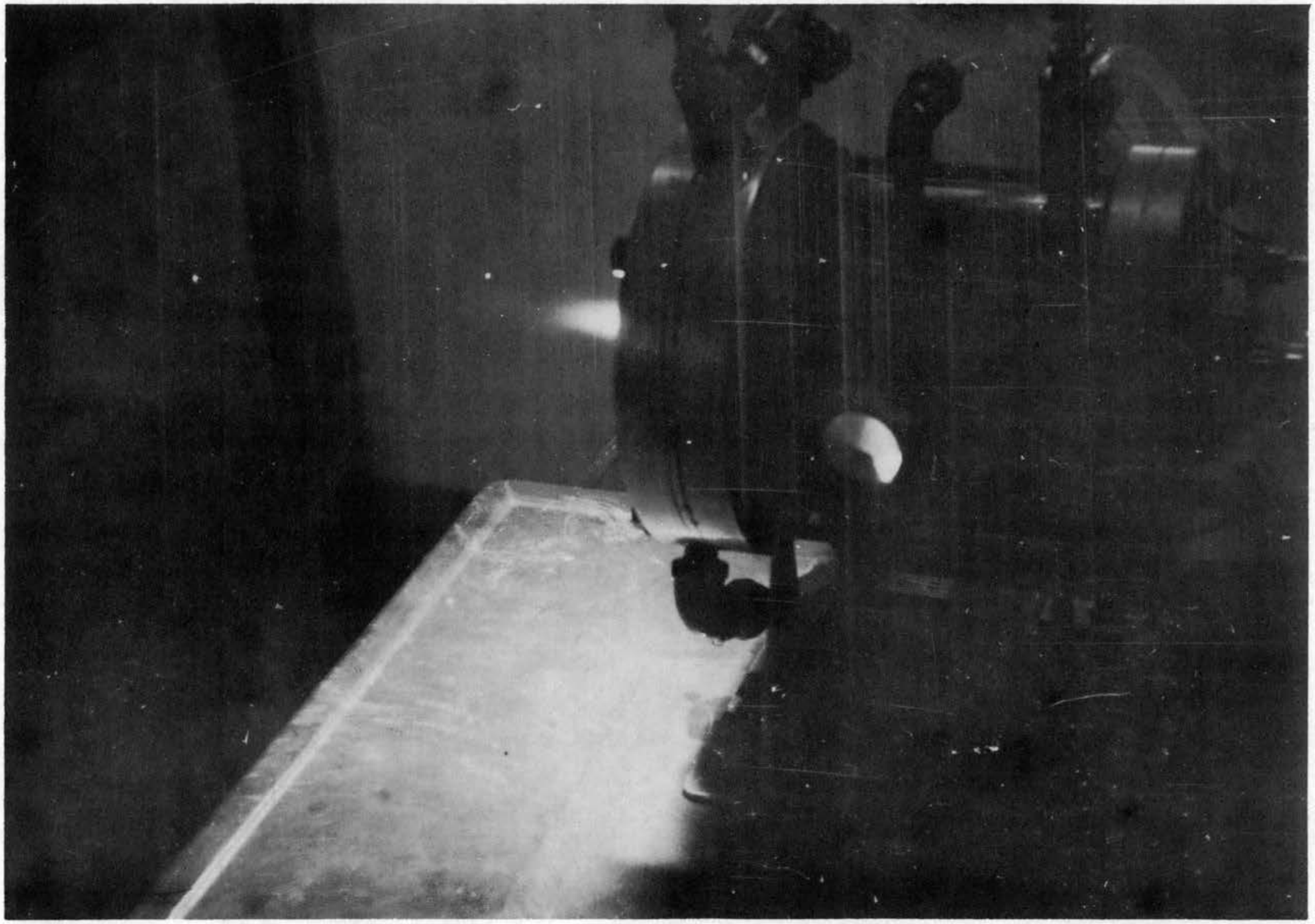
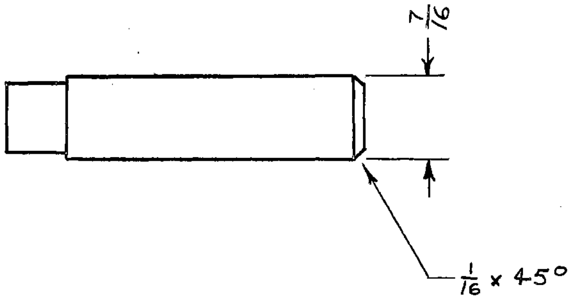
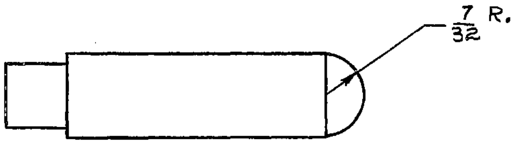
*In some cases the polarity of the electrode was reversed.

PLATE IV - PLASMA GENERATOR IN OPERATION

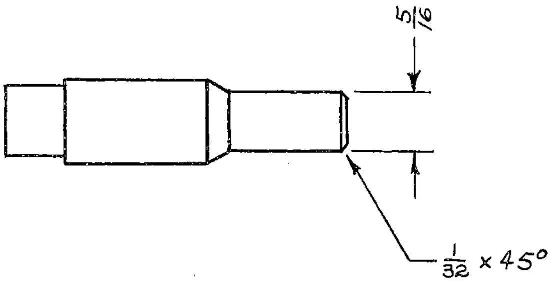




(a) Model "A"



(b) Model "B"



(c) Model "C"

Figure 25. Electrode Tip Configurations

"A" tip. Two runs of 10 minutes each were made at a power level of 5 kw. The electrode was glowing, the tip being white in color whereas the stainless steel was red for a distance of about 2 inches back from the tip. This appeared to be an equilibrium condition. The opposite end of the electrode was only warm to the touch. After stopping the generator, the gas flow was maintained until the electrode and tip cooled. Subsequent inspection revealed no harmful effects to either the electrode or tip.

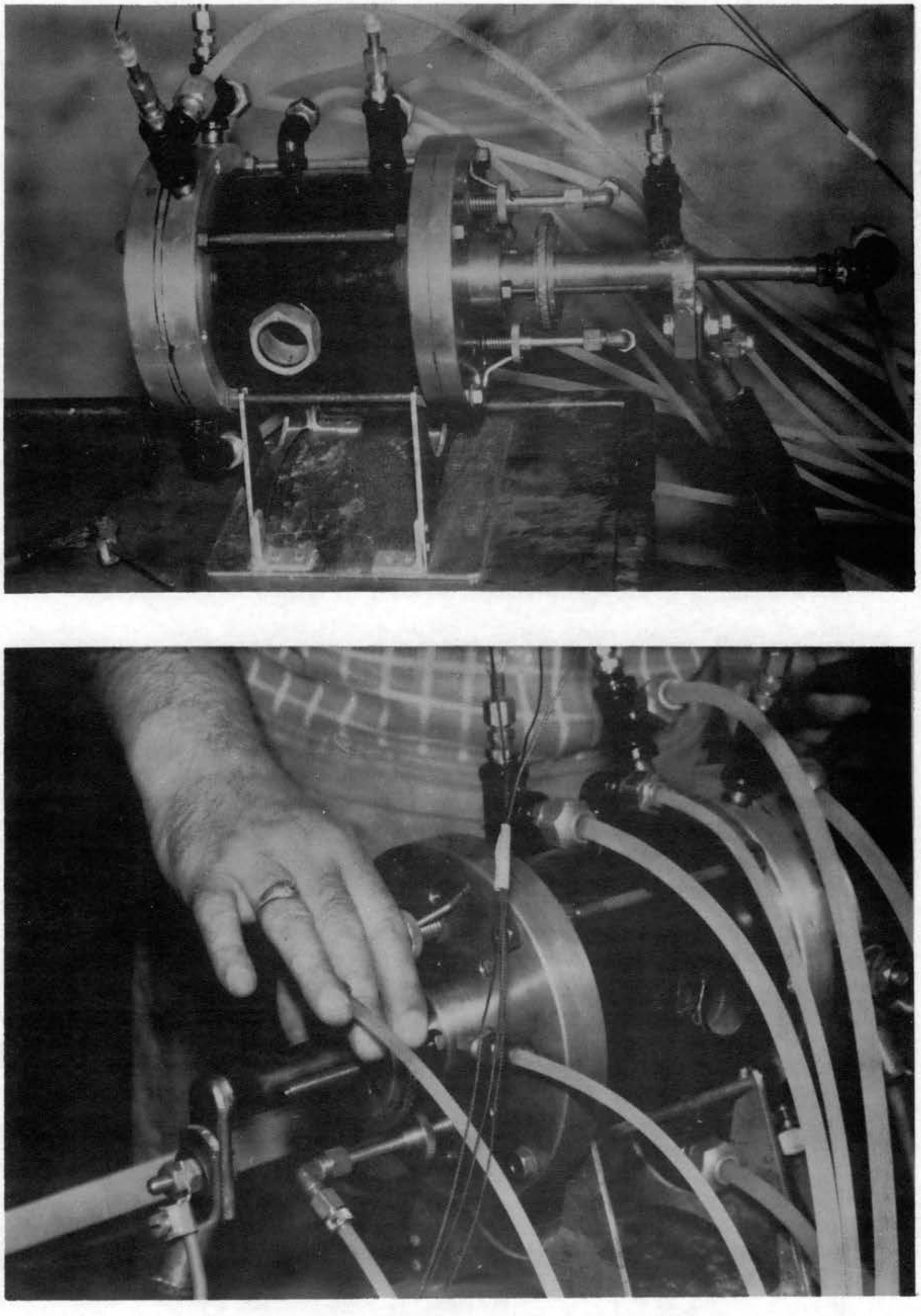
Plate V illustrates the use of the two different electrode designs.

During the course of the testing it was found very difficult to reproduce data. The reason was that on different occasions the arc would anchor at a different place in the nozzle, changing the voltage and current. In an attempt to anchor the arc, without otherwise affecting the generator, the nozzle was modified by inserting three 1/16 inch diameter tungsten rods located radially and spaced equally as shown in Figure 26. These auxiliary electrodes protruded only 1/32 inch into the nozzle and were silver-soldered on the water side.

The above described modification of the nozzle resulted in increased stability of the jet, and insured that the arc would always anchor at the same location. The arc appeared to just touch the auxiliary electrodes lightly as it passed. Addition of the auxiliary electrodes also eliminated the slight tendency of the nozzle to erode at the point where the arc anchored.

Cooling of the plasma generator proved to be more than adequate. With the control valves fully opened, the temperature rise of the water was approximately 4 degrees Fahrenheit for the nozzle, and only 2 degrees Fahrenheit for the chamber and electrode. Water flow rates

PLATE V - PLASMA GENERATOR



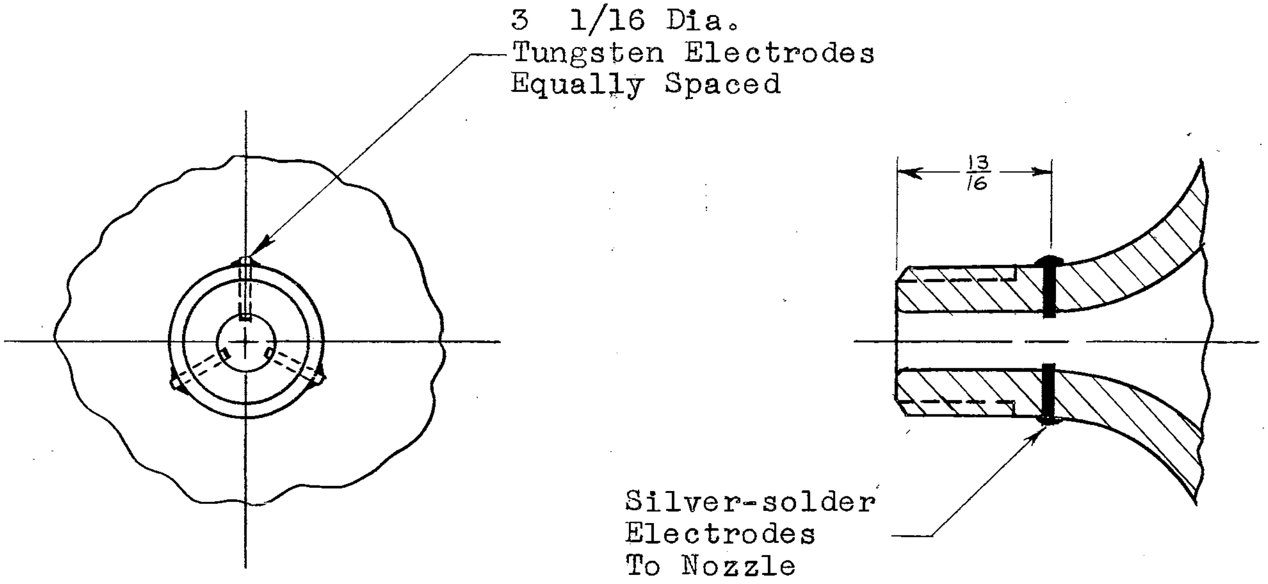


Figure 26. Nozzle Modification

were approximately 25 pounds per minute for the nozzle and approximately 12 pounds per minute for the chamber and the same for the electrode.

Use of the axial gas manifold was found to improve the operation of the generator. Superposition of the axial and tangential flow fields apparently improved the symmetry of the stabilizing vortex which resulted in a more stable jet. For best operation, the flow was divided 30 percent axial to 70 percent tangential.

Several attempts were made to operate with nitrogen, but were unsuccessful.* It was not possible to increase the potential difference to the necessary level with the power source available to produce a stable arc. If a higher voltage could be produced, no difficulty should be encountered in producing a plasma with nitrogen.

The gasketing and o-rings used throughout the generator proved to accomplish their intended purposes. There were no water or gas leaks and in every case the gaskets and o-rings were unaffected by temperature.

The two glass observation ports in the chamber were invaluable in operating the generator and showed no ill-effects at the conclusion of testing.

Adjustment of the retractable electrode was easily accomplished by the traversing mechanism shown on Plate V. This mechanism also added stability to the protruding part of the electrode.

The plastic tubing used in conjunction with the flare type brass fittings was very satisfactory. Plate V shows some of the connections

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*By changing slowly from argon to nitrogen short periods of operation were obtained (10 to 20 seconds).

at the generator. There was no leakage of gas or water, and the tubing could be easily removed as the flare nuts were only finger tight.

The instrumentation facilities previously described were adequate for this preliminary study. A malfunction of the Brown temperature recorder was discovered early in the testing. Due to the nature of the switching mechanism in the recorder, it was possible to form a series d-c circuit with the plasma generator, provided two adjacent measuring points on the recorder were connected to the nozzle and electrode assemblies which were at different potentials. This was the case as point 1 was connected to the electrode water outlet thermocouple and point 2 was connected to one of the nozzle water outlet thermocouples. No serious damage was sustained by the recorder, and to correct the situation the thermocouples were connected to the recorder in a sequence which eliminated the possibility of a short circuit.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Preliminary operation has proved the plasma generator design described herein to be successful and capable of sustained operation. Although a great deal more testing will be required to determine the maximum capabilities of the generator, much information has been obtained concerning the starting and operation of a plasma generator.

The starting procedure finally adopted is given in Appendix C. This procedure was designed to make starting of the generator systematic, safe for both operating personnel and the equipment, and efficient. The generator can be put into operation within approximately 2 minutes.

The following conclusions were drawn concerning the operation of the generator:

(1) A tangential flow of gas was required to stabilize the arc. It was found that two manifolds located diametrically opposite gave better operation than one manifold.

(2) By superimposing an axial flow of gas on the tangential flow, more satisfactory operation was achieved. Approximately 30 percent of the flow was axial.

(3) Although the uncooled electrode was successfully tested, the water cooled electrode was more satisfactory because the tungsten tip operated at a lower temperature.

(4) The design of the Model "A" tungsten tip given in Figure 25a

was superior because it had less tendency to erode and promoted more stable operation than Model "B" or "C".

(5) A method was needed, such as that shown in Figure 26, to anchor the arc at the same location in the nozzle each time the generator was in operation. Otherwise, it was almost impossible to duplicate operating conditions.

(6) Considerable variation of the gas flow rate was possible without affecting the stability of the arc or emerging jet.

(7) With the available equipment it was not possible to determine the temperatures of the plasma jet, but it was estimated by some rough calculations that the temperatures were of the order of 5,000 degrees Kelvin.

The following recommendations for future operation, testing, and investigation of the plasma generator are suggested:

(1) Test the generator at increased power levels to determine the maximum capibilities of the apparatus.

(2) Acquire a power source capable of producing higher voltages so that operation can be achieved with nitrogen, air, and other gases.

(3) Test the generator using reversed polarity (nozzle as cathode) to determine the better arrangement. In preliminary testing no difference was observed.

(4) Make a heat balance on the generator to determine the specific energy input to the gas.

With the above mentioned tests further work may include improvements concerning different components of the generator as well as new designs of complete plasma heads. Once the best design is found the plasma generator may be used for many various investigations in the field of plasma physics, some of which may be foreseen at the present time whereas others may appear in the future.

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APPENDIX A

TRIAL STARTING PROCEDURE

1. Inspect all water, gas, and electrical connections to see that they are in proper operating condition. Close all gas control valves.

2. Set movable electrode so that there is at least a one inch air gap between it and the nozzle. Make sure the main circuit breaker is open.

3. Open fully the main water supply valve beneath wash basin.

4. Open fully the four water <u>inlet</u> valves on the control panel.

5. Open the four water <u>outlet</u> valves on the control panel. (Full open initially. After generator starts regulate to give desired temp. rise.)

6. Turn temperature recorder on. (Switch on rear of chassis)

7. Open main valve on argon tank and set regulator to approximately 10 psi.

8. Set controls on welder to minimum current and minimum potential and start welder. Set electrode negative and nozzle positive. (Ammeter should indicate zero current; if not switch off welder and check circuit.)

9. Open valve on gas inlet manifold for argon.

10. Start chart on temperature recorder.

11. Open one valve for tangential flow on gas outlet manifold. Flow should be just great enough to purge the chamber of the generator.

12. Close main circuit breaker and be prepared to open it immediately.

13. Insert auxiliary starting electrode through the nozzle and establish arc with the movable electrode.

14. Slowly withdraw starting electrode until arcing begins with nozzle. If arc cannot be started adjust movable electrode for a 3/4 inch gap and repeat the above. If the arc still cannot be established repeat for ½ and ¼ inch gaps. Do not move adjustable electrode closer to the nozzle than ¼ inch.

15. If the arc cannot be started with a $\frac{1}{4}$ inch gap retract the movable electrode to one inch, increase the potential by 10 volts and repeat steps 13 and 14.

16. Repeat steps 13, 14, and 15 until arc is started.

17. Adjust gap, gas flow, and potential to achieve best operation. Be watchful for overheating of nozzle.

    (a) Try holding potential constant at 30 volts and adjust gas flow and gap to get highest current.

    (b) Use only the tangential gas manifolds initially as the most stable operation should be achieved.

    (c) Do not allow the chamber pressure to go above 50 psi for initial testing.

18. After correct control settings and electrode gap have been determined increase the current setting on the welder.

19. At the conclusion of testing:

    (a) Open main circuit breaker.

    (b) Close main valve on argon tank.

    (c) Close main water supply valve.

    (d) Turn temperature recorder off. (Two switches)

    (e) Stop electric welder.

APPENDIX B

TABLE II

PLASMA GENERATOR OPERATION DATA

Power Input kw	Potential volts	Argon Flow #/min	Chamber Pres. "H_2O	Electrode Gap inches	Electrode Polarity pos or neg	Remarks	Time min.
2.1	46	0.038	--	¼	negative	cooled elec.	5
3.4	48	0.04	--	¼	negative	cooled elec.	5
7.4	53	0.078	--	¼	negative	cooled elec.	5
6.3	30	0.033	7.2	¼	negative	cooled elec.	5
5.9	28	0.033	6.5	¼	negative	cooled elec.	5
5.5	24	0.040	5.8	3/8	negative	cooled elec.	5
5.6	28	0.037	7.1	5/16	negative	cooled elec.	5
5.6	40	0.028	5.5	5/16	negative	cooled elec.	10
5.2	40	0.028	5.4	3/8	negative	cooled elec.	5
5.9	39	0.022	5.2	5/16	negative	cooled elec.	5
5.9	39	0.018	4.2	5/16	negative	cooled elec.	5
5.3	38	0.024	5.3	5/16	negative	cooled elec.	15
4.6	28	0.032	3.6	5/8	negative	cooled elec.	30
4.8	32	0.037	5.0	5/16	negative	solid elec.	10
4.4	25	0.045	5.9	5.16	negative	solid elec.	10
5.4	34	0.034	5.2	5/16	positive	cooled elec.	10
4.3	26	0.031	4.2	5/16	positive	cooled elec.	10
4.5	29	0.038	5.3	5/16	positive	cooled elec.	10
4.9	30	0.033	5.5	5/16	negative	cooled elec.	15

APPENDIX C

FINAL STARTING PROCEDURE

1. Inspect all water, gas, and electrical connections to see that they are in proper operating condition.

2. Set electrode so that there is at least a 5/16 inch gap between it and the nozzle. Make sure the main circuit breaker is open.

3. Open fully the main water supply valve beneath wash basin.

4. Open fully the four water inlet valves on the control panel.

5. Open the four water outlet valves on the control panel.

6. Turn temperature recorder on. (Switch on rear of chassis)

7. Open main valve on argon tank and set regulator to approximately 6 psi.

8. Set controls on welder to 65 amperes current (red indicator) and 80 volts open circuit voltage, and start welder.

9. Open valve on gas inlet manifold for argon.

10. Start chart on temperature recorder.

11. Open valves for tangential and axial flow (70-30) on gas outlet manifold. Adjust differential pressure on orifice to 3.5 inches of water.

12. Close main circuit breaker.

13. Insert auxiliary starting electrode through the nozzle and establish arc with the electrode.

14. Withdraw starting electrode until arcing begins with the nozzle.

15. Increase orifice differential pressure to 6 or 7 inches of water.

16. To discontinue operation: open main circuit breaker, close main valve on argon tank, stop the welder, turn temperature recorder off, and close main water supply valve.

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