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THE PROPERTIES AND USES OF AN ARC PLASMA JET GENERATOR

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by

RICHARD DEAN TURNER

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INTRODUCTION

Since the beginning of World War II there has been a demand for accurate high temperature data for various properties of solids, liquids, and gases. This need has stemmed primarily from three fields of engineering interest, one, the design and development of gas turbines and rocket engines; two, nuclear reactions both fission and fusion; and three, the aerodynamic heating of high velocity missiles. Temperatures in the early part of the century were limited by the amount of energy of the chemical bond of fuels and the conditions under which the energy release was effected. The temperature range was increased to an upper limit of 10,000°F with the development of electric furnaces, solar furnaces, and special cutting flames such as oxy-aluminum and Thermit flames.

The upper limit for elements to exist in the solid phase is approximately 7000°F, and in the liquid phase it is approximately 11,000°F. Above 11,000°F all elements are in the gaseous phase at atmospheric pressure. At this temperature oxygen O_2, for example, consists almost entirely as free atoms i.e., in the dissociated state of O. Above 11,000°F oxygen atoms begin to ionize and exist as a mixture of ions, electrons, and free atoms. A gas that is completely ionized is known as a "plasma." The term plasma has been extended to include partially ionized gases. Thus a plasma is a mixture of molecules, free atoms, ions, and electrons where the ionic charge is numerically equal to the number of electrons in a finite volume of gas.

Various devices which generate a jet of plasma in a temperature range of 10,000 to 35,000°F are being developed by various companies and organizations interested in research at high temperatures. Most of the commercially available plasma generators have undergone several changes during their development but now in their semi-final phase of development they show considerable resemblance to each other. They all have some cylindrical chamber in which the working fluid is introduced tangentially in order to produce a vortex flow pattern around a tungsten cathode. The anode is made of copper, is water cooled, and is generally in the form of a convergent or convergent-divergent nozzle. The vortex flow pattern carries the arc from the back electrode through the anode orifice where the arc attaches itself at some point on the nozzle.

The subject of plasma physics is quite complex and has not yet been sufficiently investigated to determine generator design criteria. The characteristics of an arc discharge depend mainly on how the generated heat is released to the working fluid. This depends upon the particular design chosen and fortunately, this is not very critical, for most of the plasma jet designs show satisfactory performance.

A high temperature plasma is like a universal solvent that cannot be contained, since it can melt all known solids. It is hoped to solve the problems of containment with a "magnetic bottle" i.e., using magnetic fields to contain the plasma. The study of the interaction of an electrically conducting fluid and a magnetic field has recently been given the name magnetohydrodynamics which is a combination of several existing words to describe the phenomenon.

The interest in conducting fluids in various magnetic fields had its beginning in the period of 1900 to 1920 with the astrophysicist and the geophysicist. The interest of the astrophysicist has been to investigate the effects of the magnetic fields of the sun and the stars on the gases which are highly ionized by the extreme temperatures. It has only been within the last five years that other fields of study have become interested in electrically conducting fluids in magnetic fields or, as mentioned previously, magnetohydrodynamics. These fields of interest are aerodynamics, gas dynamics, fluid mechanics, and nuclear research. Each field is investigating the various properties, uses, and problems of the plasmas peculiar to their field. In the field of materials technology the plasma generator is also being used to investigate high temperature spray coatings, ablation rates of various solid materials, transport properties of various gases, and the fusing of metals and ceramics.

The purpose of this report was to discuss the various known properties and uses of the plasma jet generator. This was accomplished by a study of many references which dealt with the development of the plasma generator, the various properties of plasmas, and the present and future uses of plasma generators.

EARLY INVESTIGATIONS OF HIGH TEMPERATURE PLASMAS

The first known laboratory investigations using a plasma were in 1909 when Hugo Spiel produced nitric oxide by means of an electrical discharge in air. McEachron continued the work of Hugo Spiel in the period of 1918-1922. The arc used for the production of nitric oxide was of the low-intensity type (low current and high potential.)

According to Lochte-Holtgreven (11), H. Beck in 1910-1912 used a high-intensity arc (high current - low voltage) in his investigations. The voltage required at the terminals of the Beck arc was 50 to 60v. With a corresponding current flow of 200 to 250 A, a total energy of 10 to 15 KW was supplied to the Beck arc. Beck used anodes that contained oxides and fluorides of cerium. This salted anode allowed a considerable increase in the current density which was several times the maximum normal density without hissing of the arc. The high current density resulted in a very rapid evaporation of the anode surface which produced a high-temperature vapor jet-stream which extended primarily in a direction perpendicular to the anode surface. The jet-stream had a measured initial velocity of 10^3 to 10^4 cm sec^{-1} and an initial temperature of 10,000°K. Of interest, was the fact that there was no further heating by the current of the arc i.e., the velocity did not increase. The temperature dropped continuously along the jet stream and the rate of temperature decrease was calculated from the length and the velocity of the observed jet stream. The time required to cool the gas from 10,000 to 3,000°K was approximately 10^{-3} sec. which was found to agree with Newton's law. The decrease of velocity was measured from little irregularities in luminosity traveling along the flame by Finkelnburg in 1948.

The so-called Beck arc, usually 10 to 30 mm in length, was very unstable because according to (11):

> Furthermore the long (arc) column creates a considerable magnetic field, the lines of force being directed circularly around the arc column. This field causes any curvature in the direction of the current to increase, thus causing an instability of Beck arcs, which are not straight.

In 1922-1924 Gerdin and Lotz worked to increase the current densities of the arc column by forcing the arc to burn through a narrow constriction which was water cooled to withstand the heat. The temperature attained was higher than expected and reached 20,000 to 30,000°K. The Gerdin diaphragm was constructed of a heat-resistant earth-like material with a central bore of a few millimeters in diameter. The arc was confined in the central bore over a length of a few millimeters. Although, a high current density was attained with the Gerdin diaphragm, the most interesting phenomena occurred inside the central bore and could not be observed because of a layer of inhomogeneous temperature on either side of the central bore.

HIGH TEMPERATURE PLASMA GENERATORS

Description of Various Generator Designs

The Free-burning Arc. The interest in the production and properties of high temperature plasmas has led several investigators, according to Lochte-Holtgreven (11), to study arcs burning between various metal rods. The free-burning low current arc (about 5 to 10 A) when burning between two carbon rods reaches a temperature of 6000 to 7000°K. The carbon electrodes attain a temperature of 3600°K at the cathode and a temperature of 4000°K at the anode. The latter value is the temperature of evaporation of pure carbon and has been found to adjust to a constant value of 3995 ± 15°K. This temperature occurred at the maximum value of current just below the hissing point of the arc. One investigator, von Engel in 1955, found the temperature of an arc column between two copper rods in the atmosphere to be about 4700 to 5500°K. Burhorn, also in 1955, found the temperature of an iron arc column between heat insulating iron oxide beads attained a temperature of 6700°K. Lochte-Holtgreven in 1955 found that the emission of a free-burning arc was subject to sudden violent or small variations which were caused by a movement of the cathode spot or by gaseous eruptions from carbon electrodes. The variations also caused variations in the potential drop across the arc.

The temperature of a free-burning arc can be raised a little by increasing the voltage or the current, i.e., the speed or the number of electrons or both. Such an investment of electrical energy, under ordinary circumstances, goes primarily for the production of a larger volume of plasma, not a proportional elevation of temperature.

The Low-Voltage High-Current Arc. The low-voltage high-current arc was investigated by Busz and Finkelnburg in 1953, 1954, and 1956 using a water-cooled tungsten rod as cathode and a water-cooled copper plate as anode, as shown in Figure 1. This arc, only a few millimeters in length, required a total potential across the terminals of about 12v. when burning at 500 A. Depending upon the composition of the plasma, temperature measurements ranged from 18,000 up to 30,000°K. The total energy fed into the arc was about 6 KW as compared to 600 watts dissipated in a free-burning low-current arc; the increased power in this case resulted in a temperature increase from 6000 or 7000°K to 18,000 or 30,000°K. The gas supplied by the concentric tube surrounding the cathode confines the arc thus increasing the temperature of the plasma.

A comparison of the previously mentioned high-intensity Beck arc with this high-intensity confined arc shows that the power requirements of the Beck arc were twice the power requirements of low-voltage high-current arc and yet the temperature reached in the Beck arc was about one-third the temperature obtained by this high intensity confined arc. The higher power requirements of the Beck arc were required to sustain the mechanism of the jet stream and to counteract the cooling of the jet of plasma by convection.

<u>The Water-Pipe Arc</u>. Maecker and Burhorn in 1949-1951 confined an arc column in a tube cooled with running water on the inner surface of the tube and in direct contact with the arc. The water was kept in contact with the inner surface of the tube by centrifugal force, as shown in Figure 2. Tubes of small diameter were chosen, and the arc was confined considerably since the cooling water was between the tube and the arc. A temperature of 30,000°K was produced with an energy input of 140 KW, which was a voltage drop of 700v across the terminals with a corresponding current flow of 200 A. One advantage

EXPLANATION OF PLATE I

Fig. 1. The low-voltage high-current arc.

Fig. 2. The water-pipe arc.

PLATE I

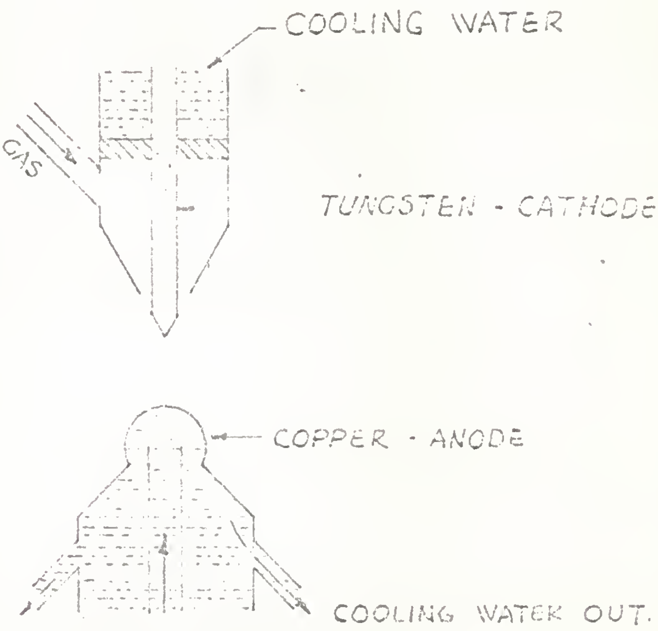


FIG. 1.

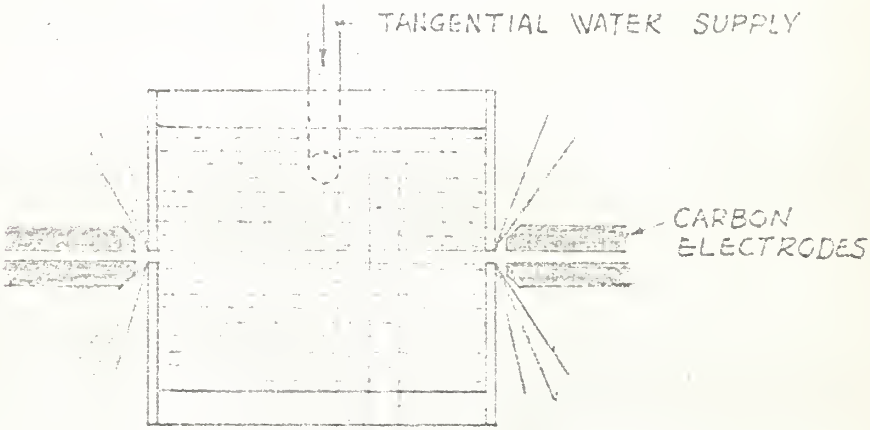


FIG. 2.

of the water pipe arc was that a gas could be introduced into the cooling water which was then introduced into the arc plasma. It was not possible to introduce salts into the plasma arc by injecting a salt solution into the arc because the water evaporated and the salt went into the water jacket. A solution forced through the axis of the hollow electrode traveled unaffected through the hottest part of the arc by the Leidenfrost phenomenon and did not introduce salts to the arc plasma. When a powder was blown into the arc it went into the water jacket by centrifugal force and again kept outside the arc plasma. Only a previously prepared pressed rod could be introduced through the central bore of the electrode into the arc plasma. Thus high temperature data obtained from the water-pipe arc was restricted to gases in the vapor of water and to a limited number of solids that could be introduced into the plasma. Even a greater disadvantage existed in that the arc column was by no means steady but was blown by steam development perpendicular to the axis. Thus an element of volume under observation quickly changed temperature and plasma content allowing only the evaluation of mean values.

Although temperatures in the range of 50,000°K had been produced and maintained by the water pipe arc the problem of obtaining precision measurements of the arc's plasma was still unsolved because of the unsteadiness of the arc column. Therefore, the direct contact of water with the plasma was avoided and the arc was burned inside a number of water-cooled copper diaphragms each only a few millimeters in height (Maecker 1956, Lochte-Holtgreven 1956.) A temperature slightly above 30,000°K was obtained when a current of 400 A was used. The arc column generated in the device was found to be sufficiently steady for precision measurements.

Although the arc technique is still developing, it seems that a definite goal has been reached, namely, the production, maintenance and use of temperatures up to 35,000°K. Higher temperatures in the region of 50,000°K can be obtained practically but are for many purposes not yet sufficiently under control.

The Gas Stabilized Plasma Jet Generator. A typical gas stabilized design is shown schematically in Figure 3. The various industrially developed plasma generators have undergone several changes in their development but now in the semi-final phase of completion, they each show considerable resemblance to the others. They all have a cylindrical chamber in which one end of the chamber has an orifice in the form of a cylindrical convergent or convergent-divergent nozzle. The nozzle is a water-cooled copper anode and has an orifice diameter from 1/8 to 1/2 inch. Located axially in the center of the chamber is a tungsten cathode of about 1/4 inch in diameter which is also water cooled. The working fluid is introduced tangentially into the chamber in order to produce a vortex flow pattern around the cathode through which the arc is stabilized. McQuiston (12) achieved a more stable operation by putting three thoriated tungsten rods 1/16 inch diameter in the nozzle to which the arc could attach itself. The rods were 120° apart and extended into the nozzle approximately 1/32 inch. The arc appeared to just touch the ends of the tungsten rods.

In addition to vortex stabilized arcs, there are two other methods, discussed by Browning (3), used to stabilize arcs. These are the gas-sheath stabilized and the wall stabilized methods. In the gas-sheath stabilized method the gas momentum sweeps the arc down the nozzle passage. The configuration of the electrode geometry is such that the gas flows as a hollow sheath into the nozzle passage. A low velocity gas core exists beyond the cathode and extends into the nozzle passage. The arc is established within this core.

In the wall stabilized method the plasma forming gas is injected in the chamber in such a way that it becomes an integral part of the arc stream. The arc stream, instead of being constricted as in the previous methods, completely fills the nozzle.

The Water Stabilized Plasma Jet Generator. This generator is a gas stabilized generator in which the working fluid is water. Most designs are operated in a vertical position thus containing the water in the chamber and allowing only plasma to pass through the nozzle. Electrode and nozzle life is measured in minutes in the water stabilized design because of the high electrode consumption in the oxidizing atmosphere. One advantage of the water stabilized generator is that water can produce a greater arc constriction and thus higher plasma temperature. Because of the short electrode life and high oxidizing atmosphere, the water stabilized generator is being used almost entirely in laboratory investigations.

The Transferred Arc Plasma Generator. An adaptation of the gas stabilized plasma generator, as shown in Figure 4, is known as a transferred arc plasma generator. It consists of a gas stabilized plasma generator with a limited current flow to the hollow electrode of 2 to 100 A. The remaining current is passed from the solid electrode, through the nozzle, to a conducting member located in front of the generator. This design is essentially an open arc which has been confined by a small diameter nozzle. The purpose of the pilot arc to the nozzle is to establish a conducting path between the solid electrode and the work through which the main arc can strike when the generator is brought near a conducting member. Since the main arc passes through the nozzle, it is possible to operate this unit at much greater arc current densities than the non-transferred type. The heat transfer rates for equal inputs are

EXPLANATION OF PLATE II

Fig. 3. The gas-stabilized plasma generator.

Fig. 4. The transferred arc plasma generator.

PLATE II

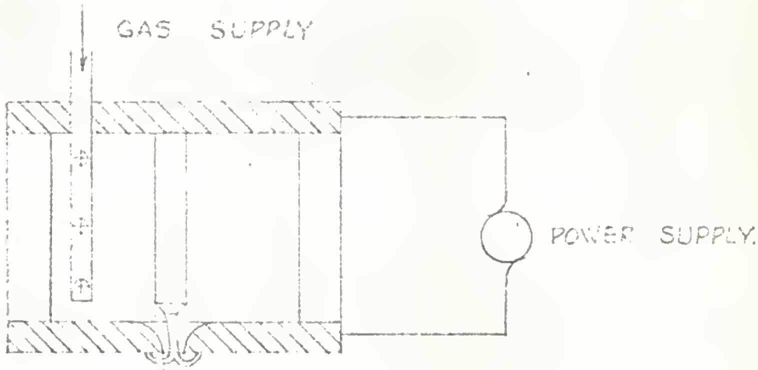


FIG. 3.

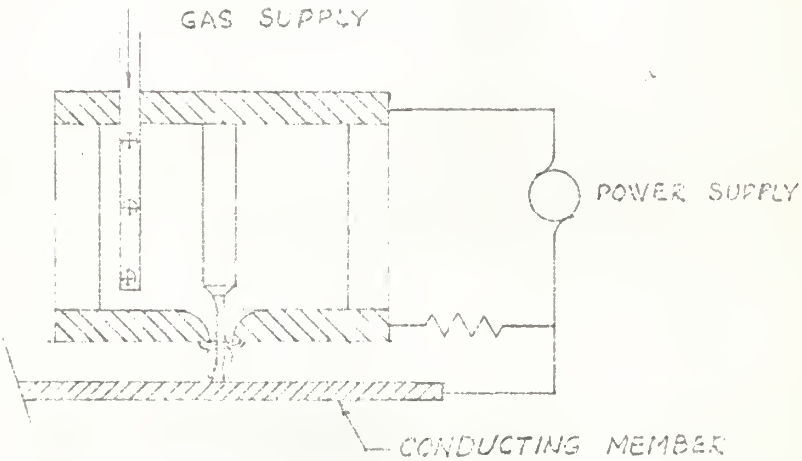


FIG. 4.

considerably greater than for the non-transferred unit due to the electric heating at the work surface caused by electron bombardment. The use of the word plasma to describe the transferred arc generator is a misnomer because the efflux is a combination of both an electric arc and a highly heated gas and not a true plasma. A true plasma, as discussed later, is electrically neutral whereas the jet from the transferred arc generator is a combination of a plasma and opposite flows of the electrons and ions composing the arc.

Design Factors of the Plasma Generator

The subject of plasmaphysics is quite complex and the scientific efforts in the field have not been able to determine the design parameters which allow a straightforward generator design or to permit any detailed discussions of the subject. However, the plasma generators have been operated for periods long enough to allow a discussion of the observed effects on the arc and the working fluids.

One design parameter which is being investigated and is as yet not clearly understood is the mechanism by which the generated heat of the arc is released to the working fluid and the electrodes. This energy release varies with the different electrode-nozzle geometries for, while most of the published plasma generator designs show satisfactory performance, some generators are able to achieve higher plasma temperatures than others for a given energy input.

Various factors influence the selection of the working fluid of the generator. The noble gases like argon and helium have been widely used because of their low ionization energy and reasonable arc voltage requirements. If long anode and cathode life is desired, an inert gas must be used to prevent oxidation of the electrodes. On the other hand, if aerodynamic studies are to be made with dissociated air, the obvious choice is air. A monatomic gas is chosen when a low voltage power supply is required. In applications where the operating cost is of prime consideration, an inexpensive gas and long component life is needed. Then relatively inert gases like hydrogen and nitrogen are selected. Other gas selection factors are pertinent too and are briefly discussed in the section on "High Temperature Test Chambers."

Plasma generators have characteristics which resemble flames in many ways. An open arc resembles an open flame in that both are affected adversely by high gas velocities; the flame can be blown off by increasing the gas velocity; and in a similar manner, the arc may be extinguished by disturbing the conducting path. The gas flow rates for flames can be increased significantly by placing the flame within a properly sized chamber. Confining an arc within a small passage has a similar stablizing effect. Low gas velocities within the plasma generator result in inadequate arc confinement and arcing to the walls; too low a current at a given gas flow results in the extinguishment of the arc because of inadequate arc path ionization. Thorpe (17), noted from experimental observation that the arc diameter remains relatively constant in a gas until a high degree of ionization in the arc conducting region is reached. Once the high degree of ionization is reached, the diameter of the arc begins to grow until it fills the entire nozzle of the plasma generator and then strikes an arc between the electrode and the nozzle wall, thus resulting in nozzle failure. This uncontrolled arcing establishes an upper limit on the temperature or the energy density of a given electrode-nozzle geometry. The upper limit of gas flow is reached when the arc is extinguished. The upper limit for current is not as yet clearly defined or understood. Many tricks can be used in which the electrode-nozzle geometry is changed which results in an increase in the upper current limit for a given gas. From the meager experimental results, to date this upper limit ranges from 25,000°F to 60,000°F depending upon the gas used.

PROPERTIES OF ARC PLASMAS

The discussion of the plasma properties of dynamic viscosity and of electrical conductivity is based on the kinetic theory of gases. A collision cross section which represents a "sphere of action" for the ionized particles is substituted for the "particle size" in the kinetic theory equations. The concept of collision cross sections is a statistical approach used to determine numerical values of these plasma properties at high temperatures. The other properties can only be discussed generally because of the lack of suitable measuring equipment available at the present time for obtaining accurate data. Currently being studied at Avco Research and Advanced Development (2) are microwave, ultrasonic, and spectroscopic techniques for independent measurements of the various plasma properties produced by the plasma generator.

Plasma Composition

The properties of thermally ionized gases are much different than the properties of the same gas at standard temperature. Plasmas generated by the devices discussed in this report are only partially ionized plasmas. The chemical composition of partially ionized plasmas usually contains a large number of species, since molecules, atoms, and ions with single and multiple charges are present in significant quantities. The treatment of various properties for partially ionized gases requires the simultaneous solution of several non-linear algebraic equations. Thus, treatments of ionized gases are based on various assumptions and the resulting solutions are only approximations.

Figure 5, after Lochte-Holtgreven (11), shows the composition of nitrogen as a function of temperature at atmospheric pressure.

Electrical Neutrality

A basic property of a plasma is its tendency toward electrical neutrality. Thus in a given volume of plasma the number of electrons is equal to the number of positive charges on the ions. If over a finite volume of plasma the number of electrons differ appreciably from the number of positive charges on the ions, the electrostatic forces that result yield a force per particle that is much greater than the mean thermal energy. Unless there exists potential differences in the plasma field from external sources to support the electrostatic forces, the charged particles will rapidly move in such a way as to restore electrical neutrality.

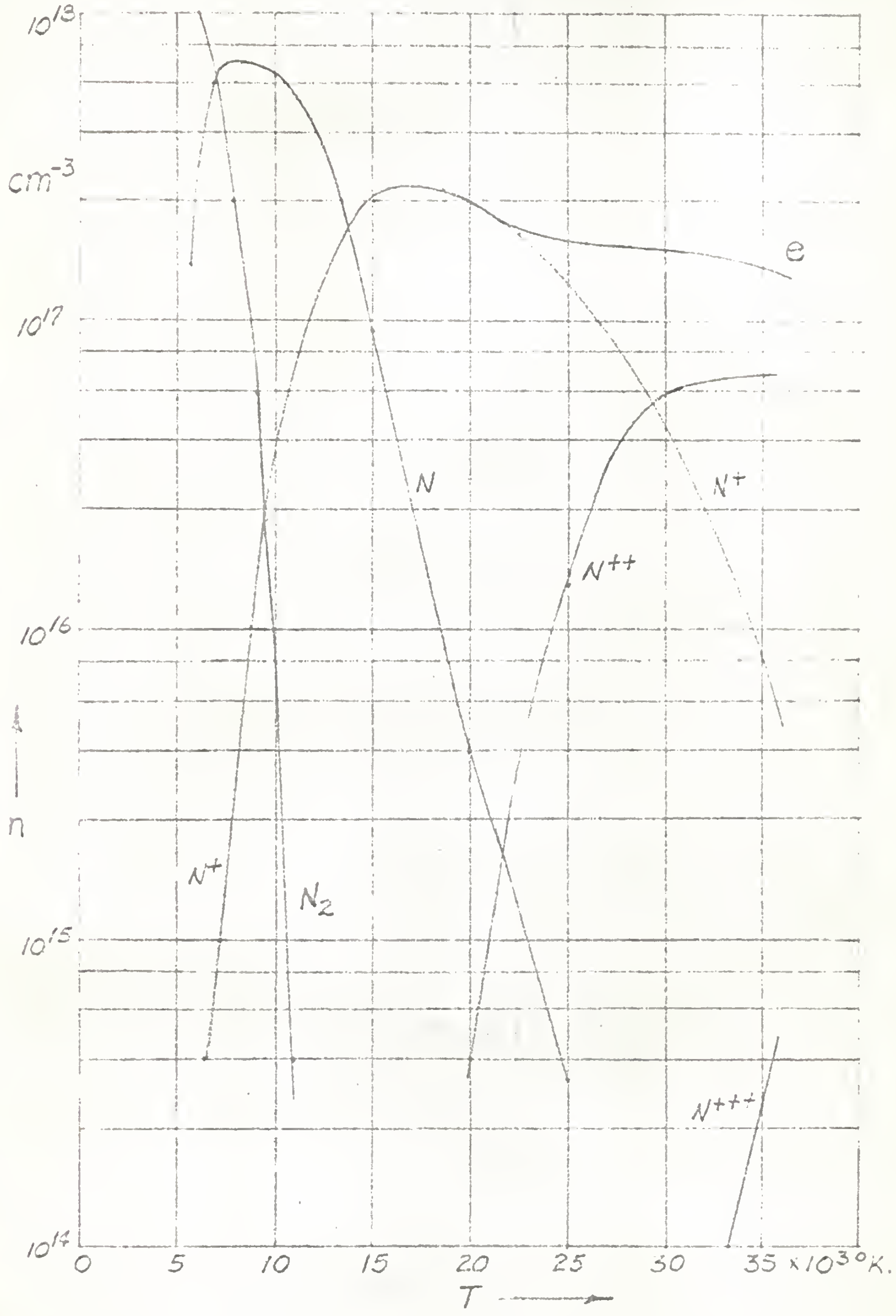
Temperature, Temperature Equilibrium, and Density

Temperature definitions tend to be confusing at very high gas temperatures because heat transfer rates have been related to temperature. The higher the temperature, the greater the rate of heat transfer. One fallacy in this reasoning is the fact that a diatomic gas is much more capable than a monatomic gas for heating. At these extreme temperatures the heat content, as well as the temperature, must be considered. Assuming an essentially constant specific heat, the monatomic gas has a nearly linear enthalpy rise with increasing temperature. At a high temperature the gas begins to ionize and now the enthalpy rises more rapidly for a given temperature increase.

EXPLANATION OF PLATE III

Fig. 5. Composition of nitrogen gas at atmospheric pressure versus temperature.

PLATE III



10^{18}
cm^{-3}
10^{17}
10^{16}
10^{15}
10^{14}
n
e
N
N^+
N^{++}
N^{+++}
N_2
0
5
10
15
20
25
30
35 × 10³ °K.
T

A diatomic molecule begins to dissociate at a temperature below 10,000°F and for most gases, dissociation is complete at 12,000°F. The energy required for dissociation of the diatomic molecules allows the plasma to contain large amounts of heat at lower temperatures. For example, Browning (3) indicates that nitrogen at 10,000°F contains as much energy as argon at 25,000°F. Thus diatomic gases are more suitable than monatomic gases for heat transfer applications because, as the gas cools through the dissociation range large quantities of energy are released per unit temperature drop.

Results from limited investigations indicate that a point is reached with increasing temperature where the rate of heat transfer ceases to increase. Although the cause of the plateau of the heat transfer rate is not known, it is thought that heat transfer is due to the translational mode of energy for the particle. As the temperature is increased, the rotational and vibrational modes of the particle energy are excited with the added energy input to the gas being distributed between these modes. The vibrational energy is probably radiated rapidly and is not available for convective heat transfer. According to the heat transfer thought model, the object being heated can only "see" the translational mode of energy of the particles. Thus, according to Browning (3), the extreme energy levels of the plasma "decay" to a lower form before the energy can be transferred to a surface in the form of heat. The higher energy modes would act as a heat source and supplement the kinetic energy of the particles as they tend to cool. If this model is correct, then the heat transfer rates must be related to some critical temperature instead of the total value of energy contained within the gas.

In a classical thermodynamic sense, temperature is defined only for a system in thermal equilibrium from Wolfe (1). Temperature measurements in hot gases are uncertain because of temperature gradients and the possible lack of equilibrium among the various energy modes. However, it is possible to define temperature on the basis of the average energy of the molecules or the probability distribution among various energy states. Thus the temperature of a plasma is defined by an energy distribution over all the particles present in the plasma i.e., molecules, atoms, ions, and electrons. For example, Mohler, F. L. (1), concluded that; four different kinds of temperature and the gas pressure are required to describe the conditions of a discharge in a monatomic gas. These temperatures are one, the electron temperature which gives the kinetic energy of the electrons; two, the gas temperature which gives the number of atoms per cm^3; three, the concentration temperatures which determine the population of the excited states; and four, the ionization temperature which gives the number of electrons per cm^3. If the plasma of the monatomic gas is in thermal equilibrium, the four temperatures will give the same value. For the case where equilibrium does not exist, the different temperatures may still be convenient parameters to describe the physical state of the system.

Temperature equilibrium implies that the number of excitations of atoms by electrons is equal to the number of collisions of the second kind; that events of ionization by collision are equal to the events recombination between three colliding particles and that the radiation emitted is equal to the radiation absorbed. In plasma generators with plasma temperatures of $20{,}000^{o}F$, instead of such a state of equilibrium, there can only exist some sort of stationary state where a supply of energy balances the inevitable losses by radiation, by convection and by diffusion.

In the 1920's, Irving Langmuir (10) investigated electron discharges in low gas pressures from a hot tungsten cathode (at zero volts) to an anode at a potential of 10 volts. The bulb contained saturated mercury vapor at room temperature. There existed regions of strong space charge called "sheaths" which covered the cathode and anode. The cathode sheath was a positive space charge and the anode sheath was a negative space charge. The relatively field-free regions between the sheaths contained positive and negative space charges in nearly equal magnitudes i.e., a plasma. The electrons in the plasma had an energy distribution corresponding very closely to a Maxwellian distribution. The ion energy distribution, however, was not a Maxwellian distribution. The ions depend upon elastic collisions with electrons or forces from electrostatic fields to attain their energy distribution. In the low pressure discharges the ions acquire practically all the kinetic energy they possess from the electric fields within the plasma. The momentum of the electrons is so small that ionizing collisions of electrons with gas molecules cannot impart to the ions appreciable kinetic energy. Measurements with perforated collectors near the cathode indicated that the normal components of velocity of the ions were roughly that of a Maxwellian distribution corresponding to a temperature T_p which is about 1/2 that of the electron temperature T_e.

Thus at low pressures and low current densities the electron temperature is high and the gas temperature is low. If the temperature of an arc plasma is to be increased, the frequency of collisions between the electrons and the ions must be increased. This reasoning is supported, in reverse, by the cool temperature of the neon tube where the collision rate is low because of the low gas density. With increasing current density and with increasing pressure, the electron temperature drops and the other particle temperatures rise until all temperatures approach the temperature of thermal equilibrium.

In the case of electrical discharges at atmospheric pressure, the electrons, because of their small mass, attain their equilibrium energy almost instantaneously. Atoms and ions attain an equilibrium energy condition through elastic collisions with electrons. According to Lochte-Holtgreven (11) the time required to attain equilibrium for various plasmas may vary from 10^{-5} to 10^{-8} sec., and provided the energy loss due to radiation is not too large, a uniform Boltzmann distribution has been observed for these plasmas.

The plasma generators described previously normally produce a partially ionized plasma at atmospheric pressure in a temperature range of 10,000 to 35,000°F. These temperatures are considered as being only an "average" value for the flow as a whole.

Viscosity

From the kinetic theory of gases, the dynamic viscosity of a gas is given by

$$\mu = \frac{1}{3} n m \lambda \bar{c} \tag{1}$$

where n is the number density of the particles, m is the mass of the particles, λ the mean free path, and $\bar{c}$ is the mean velocity of the atoms or molecules. λ based on kinetic theory of gases for molecules with an energy distribution that is Maxwellian is given by

$$\lambda = \frac{1}{\sqrt{2}\; n \pi d^2} \tag{2}$$

where d is the spherical diameter of the gas molecules. $\sqrt{2}\pi d^2$ the so-called "particle size" is now replaced by a collision cross section Q which indicates a sphere of action for the charged particles, thus

$$\lambda = \frac{1}{nQ} \tag{3}$$

Substitute eqn. (3) into eqn. (1).

$$\mu = \frac{m\bar{c}}{3Q} \tag{4}$$

The factor n has disappeared from eqn. (4) which indicates that the viscosity, according to kinetic theory, is independent of pressure, but instead varies inversely as the collision cross section Q. The values of Q (Table 1) change considerably with temperature. In kinetic theory this change is due to a higher stability of the path of a particle with increasing velocity. The values of Q decrease as the temperature increases. The values of the cross sections at temperatures T_1 and T_2 are given by

$$\frac{Q_1}{Q_2} = \frac{1 + C/T_1}{1 + C/T_2} \tag{5}$$

where the values of the Sutherland constant C are given in Table 1.

Table 1. Values of Q and C for various gases.

Gas	C	Q (related to 273°K)	Q_{a}^{e} ($Q\uparrow$)
He	80	38×10^{-16} cm^2	6×10^{-16} cm^2
H_2	80	6×10^{-16} cm^2	12×10^{-16} cm^2
Ar	165	10×10^{-16} cm^2	24×10^{-16} cm^2
Air	115	10×10^{-16} cm^2	16×10^{-16} cm^2

With increasing temperature, however, a certain portion of the gas becomes ionized. In this case, several collision cross sections, atoms against atoms, electrons, and ions, are now required to calculate the viscosity. Thus equation (1) becomes

$$\mu = \sum \frac{1}{3} n_i m_i \overline{c_i} \lambda_i \tag{6}$$

where the suffix i refers respectively to atoms, ions, and electrons. The various λ's are given by

$$\lambda_{atom} = \frac{1}{n_a Q_{\dagger a}^{a} + n_i Q_{\dagger a}^{i} + n_e Q_{\dagger a}^{e}}$$

$$\lambda_{ion} = \frac{1}{n_a Q_{\dagger i}^{a} + n_i Q_{\dagger i}^{i} + n_e Q_{\dagger i}^{e}} \tag{7}$$

$$\lambda_{electron} = \frac{1}{n_a Q_{\dagger e}^{a} + n_i Q_{\dagger e}^{i} + n_e Q_{\dagger e}^{e}}$$

Now the number n_i does not cancel and the viscosity is dependent upon pressure because the ionization equilibrium depends upon pressure.

From the plasma of an electric arc the collision cross sections $Q_{\dagger a}^{e}$ of atoms for electrons have been obtained as given in Table 1 after Maecker (1956). Since the cross sections of the various gases were obtained from a plasma, the values given are mean values. The true values increase by a factor of about two when the temperature of the gas is just high enough for the dissociation of the molecules; this is shown in Figure 6.

Similar curves are expected for Q values of molecules colliding with ion and likewise for molecular-molecular collisions, though these curves are not yet known in detail (11).

As the temperature of the gas is further increased, the collisions between two charged particles become important. The coulomb forces between charged particles now become much greater than the van der Waals forces that exist between molecules. Therefore, larger collision cross sections are obtained for the electron-ion collisions and are given by the modified Grosdover cross section formula

$$Q_+ = \frac{e^4}{(kT)^2} \ln\left(\frac{KT}{e^2 n_+^{1/3}}\right) \qquad (8)$$

which is in agreement with experiment (Maecker, Peters, and Schenk 1955.) In eqn. (8) e is the charge of an electron and n_+ is the number density of the ions. The cross section Q_+ is dependent only on the magnitude of the charge on the ion, e.g., all singly charged ions at 10,000°K, where n_+ is equal to 25×10^{13}, Q_+ is found to be 2×10^{-14} cm^2.

An increase of temperature to 20,000°K results in almost perfect ionization. Hydrogen gas at this temperature, consisting of nuclei and electrons cannot be further ionized. The viscosity of hydrogen gas in this temperature range is given by

$$\mu = \frac{m\bar{c}}{3Q_+} \qquad (9)$$

and will continue to increase because of the variation of the $\bar{c}$ and Q_+ values.

Electrical Conductivity

A plasma is an electrically conducting fluid, even though it is

EXPLANATION OF PLATE IV

Fig. 6. Plot of collision cross section of atoms for electrons versus temperature.

PLATE IV

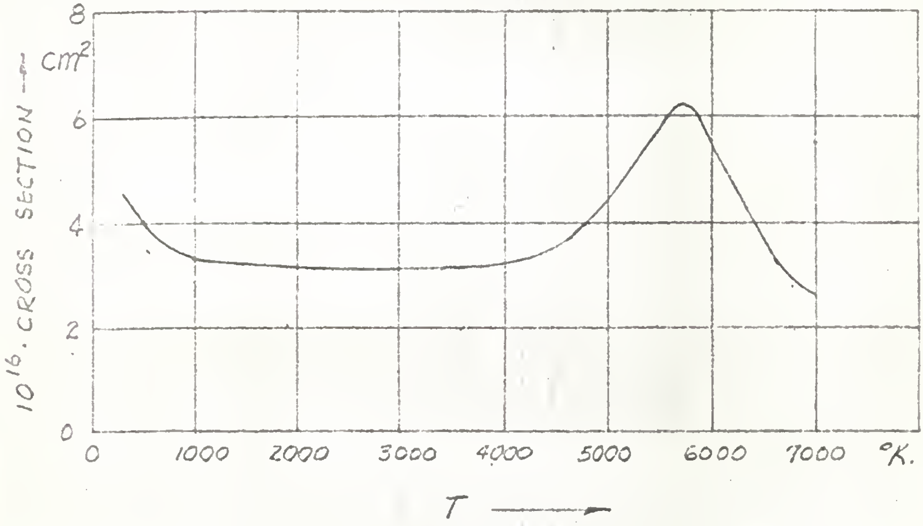


FIG. 6.

electrically neutral, because of the diffusion that exists between the electrons and ions. Diffusion occurs because of the relative velocity between the electrons and the ions. If the plasma is in thermal equilibrium, then because the mass of the ion is greater than the mass of the electron, the velocity of the electron is greater than the velocity of the ion. Thus, the electrical conductivity σ is related to the mobility b_e of the electrons according to the following equation from Lochte-Holtgreven (11).

$$\sigma = e\, n_e\, b_e \tag{10}$$

where b_e is given by

$$b_e = \frac{e\,\lambda}{m\,v} \tag{11}$$

and substituting eqn. (11) into eqn. (10)

$$\sigma = \frac{e^2 n_e \lambda}{m\,v} \tag{12}$$

As seen in equation (12) the electrical conductivity is again dependent upon the mean free path λ given by

$$\lambda = \frac{1}{n\,Q} \tag{13}$$

where the cross sections to be considered are only those for electron collision. The velocity term of equation (12) can be expressed in terms of temperature

$$v = \sqrt{\frac{8KT}{\pi m}} \tag{14}$$

The mean free path λ is dependent upon the temperature which establishes the degree of ionization and dissociation for a particular gas, and the pressure of the gas. Nitrogen, for example, as shown in Figure 5, is almost completely dissociated at 12,000°K; and the number of ions is increased to about one-seventh of the number of atoms. The mean free path for nitrogen in an ionized state is given by

$$\lambda = \frac{1}{nQ + n_+ Q_+} \tag{15}$$

where n is the number density of free atoms, Q is the collision cross section of electrons for atoms; n_+ is the number density of ions; and Q_+ is the collision cross section of electrons for ions.

As the temperature increases, more of the gas becomes ionized and this increases the conductivity of the gas. Upon substituting equations (14) and (15) into equation (12), the following equation is obtained

$$\sigma = \frac{e^2 n_e}{[8mKT/\pi]^{1/2}} \left[\frac{1}{nQ + n_+ Q_+}\right] \tag{16}$$

Divide both numerator and denominator of equation (16) by $n_+ Q_+$ and assuming that nitrogen behaves as a "hydrogenic gas" i.e., the ions are singly charged and the number of electrons n_e is equal to the number of ions n_+, then equation (16) is given by

$$\sigma = \frac{e^2}{Q_+[8mKT/\pi]^{1/2}} \left[\frac{1}{1 + (nQ/n_+ Q_+)}\right] \tag{17}$$

Substituting equation (8) for Q_+, equation (17) becomes

$$\sigma = \frac{(KT)^{3/2}}{e^2\left[8m/\pi\right]^{1/2} \ln\left[KT/e^2 n_+^{1/3}\right]} \left[\frac{1}{1 + (nQ/n_+ Q_+)}\right] \tag{18}$$

In the temperature range of 15,000 to 20,000°K, as seen in Figure 5, nQ is small compared with $n_+ Q_+$ so the quotient $nQ/n_+ Q_+$ can be neglected compared with unity. Thus, the value of the terms in the last bracket in equation (18) is equal to unity. By choosing some arbitrary value of temperature T and for a given ion number density the logarithm term can be considered as a constant over a temperature range, and equation (18) becomes

$$\sigma = A(T)^{3/2} \ cm \ \Omega^{-1} \tag{19}$$

where A is the particular constant value determined by the conditions of the problem.

The electrical conductivity of a plasma that can be considered fully ionized varies directly with the temperature to the three halves power.

The resistivity of hydrogen gas at 50,000°K was determined by (11) and was found to be $7 \times 10^{-3}\ \Omega\ cm^{-1}$.

Plasma Instabilities

Pinch Effect. A plasma in motion through a constriction such as a nozzle or an orifice behaves like an electric current. The electric current generates a magnetic field circularly around the plasma. The pressure of the magnetic field produces a force which confines the plasma within a finite cross section. This confinement of the plasma by its self-magnetic field is known as the "pinch effect." This pinch effect is responsible for holding the plasma away from the walls of the nozzle or orifice.

Observations of the pinch effect in gas discharges have indicated that the pinch tends to have only a brief transient existence (9). The discharge initially fills the tube but quickly pulls away from the tube walls and pinches as desired. However, no sustained pinch is obtained, and the plasma undergoes a series of contractions and partial expansions which are then followed by a succession of turbulent waves, and quickly, the detail of the structure is lost and breakup is complete within a few microseconds.

For the purposes of investigation, the instabilities which cause the breakup of the pinch have been divided into modes. Presently, only two modes can be identified in the photographs of the breakup of the pinch. According to H. J. Karr in (9), these two modes are the most serious instabilities of the simple pinch. The two modes are identified as the sausage mode and the helical mode because of their physical appearance.

Plasma instabilities have been under extensive investigation by several investigators (4), (8), (9), (14), (15). The sausage mode instability is observed as a pattern of bulges and constrictions which develop along the pinch giving it a sausage-chain appearance. This instability, according to (9), is caused by a local increase in the magnetic field at the surface of the plasma at a region adjacent to the constriction i.e., the nozzle or orifice. Thus, the magnetic pressure is increased causing a further confinement to the plasma cross section. This further confinement causes an axial flow of the plasma that expands the adjacent region of the plasma. Thus, the sausage-chain pattern develops along the pinch. According to the instability theory developed by Kruskal and Tuck, which is summarized in (9), the sausage mode of instability would be stabilized by a magnetic field, the lines of which are parallel with the flow streamlines of the plasma. The suppression of the sausage mode instability by a longitudinal magnetic field was verified by experiments as given by H. J. Karr (9).

The other mode of instability has the appearance of a helix. This instability develops at a displacement or bend of the discharge in a similar manner as the instability of the Beck arc. The magnetic flux is concentrated on the concave side of the bend and is small on the convex side. The resulting difference in magnetic pressure causes a further growth of the deformation. This instability persists no matter how large an external stabilizing field is applied.

The pinch effect has been under considerably more investigation than other types of instabilities because the pinch effect has been hopefully considered as a possible basis for the production of a plasma at temperatures high enough for a thermonuclear fusion reactor.

The general experimental approach has been to study the unstable pinch under various conditions and to detect the onset of the instability; to determine the nature or type of perturbation leading to the breakup; and to investigate the parameters that might correct or control the instability. Other investigators have been seeking answers based on the simultaneous solution of Maxwell's electromagnetic equations with the appropriate gas dynamic equations. These equations which govern the interaction between a plasma and the electromagnetic field, however, are so complex that simplifying assumptions must be made to arrive at solutions. A detailed analysis of the development of a self-pinched plasma has apparently not been carried out.

Containment Instabilities. It has been hoped to be able to contain a high temperature plasma within magnetic fields (13). If the plasma was allowed to contact any solid boundary, it would either melt the boundary or the plasma would be cooled to such an extent that very high temperatures could not be attained.

The problem involved in fusion research is to be able to contain a plasma at a very high temperature for a period of time long enough to sustain a controlled release of nuclear energy by thermonuclear fusion. As the plasma temperature is increased, a charge separation is produced within the plasma and the existing magnetic fields are unable to support the electrostatic charge, and the plasma then drifts across the magnetic field and is lost to the system. It is not known whether magnetic fields can adequately contain a neutral plasma even at low temperatures. Although it is known that a plasma can be controlled by a magnetic field, investigations are being conducted to determine the mechanisms by which the control is effected and to determine if it is adequate to contain plasmas under any given conditions.

Since the 1958 Fusion Conference at Geneva, the efforts have been to investigate the various instabilities that are causing the high temperature plasmas to drift across their containing magnetic fields and to be lost to the system.

USES OF PLASMA JET GENERATOR

Materials Technology

Plasma Cutting. A plasma generator of the transferred arc type is used for metal cutting. Any material that is electrically conducting can be cut in this fashion. The cutting speed of an aluminum plate 1/2-inch thick is approximately 100 inches per minute. The cut face of the aluminum plate is comparable to a high grade oxygen cut in steel. A 3/4-inch thick steel plate can be cut by a 40 KW plasma generator at twice the maximum speed of an oxy-fuel torch. An inert atmosphere is provided around the cut when argon is used as the working fluid in the plasma generator. Many metals such as copper, stainless steel, and inconel have been cut by this method. In comparing oxygen cutting with plasma cutting, the oxygen cutting relies on a continuous chemical reaction at the metal-oxygen interface whereas the plasma supplies the necessary heat electrically. In oxygen cutting the speed is also limited by the diffusion rate of oxygen at the interface, whereas no such limit seems to exist in plasma cutting. A comparison of the hourly operating cost of the plasma generator and an oxygen cutting torch is made on an equal output basis (Btu's/hr) by Browning (3). The total operating cost per hour of the plasma generator is $7.76 as compared with a total operating cost for the oxy-acetylene torch of $14.38 per hour. As the plasma generator and its component equipment become more specifically designed, it is very likely that plasma cutting will be used extensively for metal cutting operations.

With the high temperatures now available it is now possible to machine refractory metals in a much shorter time and to fuse and shape ceramics for the first time. Investigations are being made of the possibility of alloying metals in the vapor phase and allowing them to condense in a controlled manner. Also, another prospect is the production of scarce material in fairly pure form from its ore by direct vaporization.

The ability of the plasma jet to fuse all known materials might lead to its being used to work difficult minerals. Granite, taconite, and similar hard minerals are currently quarried by high intensity "rocket" flames at above sonic velocity. The high temperatures and velocities of the plasma generator may extend the thermal working of minerals.

High Temperature Coatings. Another use of the plasma jet generator is the application of various elements or compounds as coatings by spraying them on some base material. The art of spraying is well developed and it is very simple to substitute a plasma heating source for oxy-fuel flames. In the coating procedure, the spray material is injected as a powder into a plasma, melted and/or vaporized and deposited on the base material. Materials such as titanium carbide, tungsten, chromium, or titanium can be sprayed on most ceramic base materials or metals without metallurgical, crystallographic, or chemical changes, Giannini (6). The high temperature coating process allows the coating of practically any element with a base material without oxidation of either the base material or the coating. It is now known (3), (6), that this new technique produces better coating properties than those produced conventionally. In addition, many materials which are not fusible with the oxy-fuel flame are readily sprayed by a plasma generator as the heat source.

These coatings permit substantially improved performance of refractory metals (16), for example, the resistance to abrasive erosion of carbon is greatly increased when coated with tungsten and is being considered for use as leading edge of airfoils, re-entry bodies, and rocket nozzles.

High Temperature Test Facilities

Hyperthermal Wind Tunnel Test Facility. The plasma jet generator is being used to supply a continuous flow of gas at high temperature to an evacuated tunnel. With sufficient vacuum in the tunnel a plasma of argon can be injected from the plasma generator at the velocity of sound into the tunnel at a temperature of 21,000°F. The gas recombines as the temperature drops and the velocity of the gas at the test section reaches Mach 12 at a temperature of $80^{o}F$. The density being very low, these conditions are used to study the effects of high speed flight at extreme altitudes. The shock wave generated at the test object momentarily ionizes the gas back into a plasma, thus allowing studies of heat transfer rates from a high temperature ionized atmosphere to a high speed body.

Because the plasma generator has the capability of producing very high temperatures on a continuous basis, the tunnel can be operated at a Mach number of 2.5 or 3.0 but simulate, temperature-wise, flight conditions which correspond to Mach 15 or 20. By keeping the test section Mach number low, the density of the gas is increased by many orders of magnitude thus giving heat transfer rates corresponding to the range of missile re-entry conditions. For blunt models, hypersonic flow conditions are simulated quite well in the Mach number range of 2.5 to 3.0 over the critical forward portion of the blunt body. However, the shape of the standing shock wave and its detachment distance is quite different in the two cases. The plasma generator produces conditions that seem adequate at the present time to investigate blunt body ablation rates and to study the boundary layer behavior of an ablating body.

Table (2) gives characteristic re-entry conditions of the Avco Model 500 plasma generator from (2).

Table 2. Characteristic re-entry conditions.

Vehicle	Heat flux (Btu/Ft^2-Sec)	Pressure (Atms)	Enthalpy (Btu/lb)
Hypersonic glider	50 to 500	.01 to .50	2500 to 12,500
Re-entry vehicle	1000 to 4000	.10 to 50	2500 to 12,500

High Temperature Test Chambers. A plasma generator is discharged into a chamber or small tube in which conditions can be controlled to conduct various high temperature experiments. One experiment that can be performed in this manner is to determine the various transport properties of different gases i.e., heat transfer, electrical conductivity, and diffusion coefficients and other properties of gases such as relaxation times and recombination rates at high temperatures. The gases that have been used (16) are air because it is a free flight medium; nitrogen because it is encountered in space and has properties similar to air but is free of oxygen; and argon because it is truly inert, thus isolating heat transfer from chemical effects. The determination of the various mentioned properties is still in the initial stage because the measurements are very difficult to obtain, for they depend upon a jet of plasma that is uniform and accurately calibrated. The plasma instabilities mentioned previously have so far prevented the production of a uniform jet of plasma for obtaining consistent data.

The test chamber has also been used for a number of experiments on ablating bodies of different materials. Most materials erode in various configurations while ablating. Graphite, however, in a high density, high temperature plasma sublimes into a needle-like configuration and retains this configuration while ablating. Graphite ablation in air is approximately 20 times faster than in argon because of the oxidation (burning) involved in the boundary layer. Because graphite has been observed to retain a stable configuration while ablating, it is being considered for leading edges of reentry bodies. The ablation rate of graphite in air is too excessive, and a solution to the problem may be found in a high temperature coating, as the example given previously.

By using various coil geometries with the test chamber, the plasma generator can be used to study the theory and application of magnetohydrodynamics. Magnetohydrodynamics is the study of the interaction of an electrically conducting fluid in the presence of a magnetic field. The interaction is described as follows: The motion of a conducting fluid in the magnetic field will induce electric currents in the fluid, thus altering the magnetic field, and the magnetic field also produces mechanical forces which modify the flow. Plasma instabilities and the magnetic pinch effect, as discussed previously, are part of the theory that is now under study in the field of magnetohydrodynamics.

At the present time plasma instabilities have prevented the attainment of controlled thermonuclear fusion. The problem is to be able to confine deuterium or tritium isotopes at a temperature in the range of 200,000,000°F for approximately one second to allow sufficient fusion reactions to occur. In thermonuclear research confinement times have only lasted a few milliseconds. The theoretical and experimental work in fusion research is being directed toward obtaining reliable data on confined plasmas and an understanding of how a plasma can slip through a confining magnetic field and be lost to the system. This information is needed to determine what magnetic field configurations are required to confine deuterium plasmas long enough to permit sustained thermonuclear fusion.

DESIGN OF A PLASMA GENERATOR

Since the subject of plasmaphysics is very complex, the design parameters which would allow a straightforward generator design have not been determined. Thus the generator design described in this report has been developed primarily as a demonstration model. However, the design is basic enough to allow modification of any of the assemblies used. The design of the generator was based on various descriptions of recent generator designs; availability of materials; and its use as a demonstration model.

The plasma generator is composed of six assemblies. They are: the chamber assembly, the nozzle assembly, the electrode support assembly (front), the electrode support assembly (rear), the electrode assembly, and the gas manifold assembly. Plate V is an assembly drawing of the plasma generator.

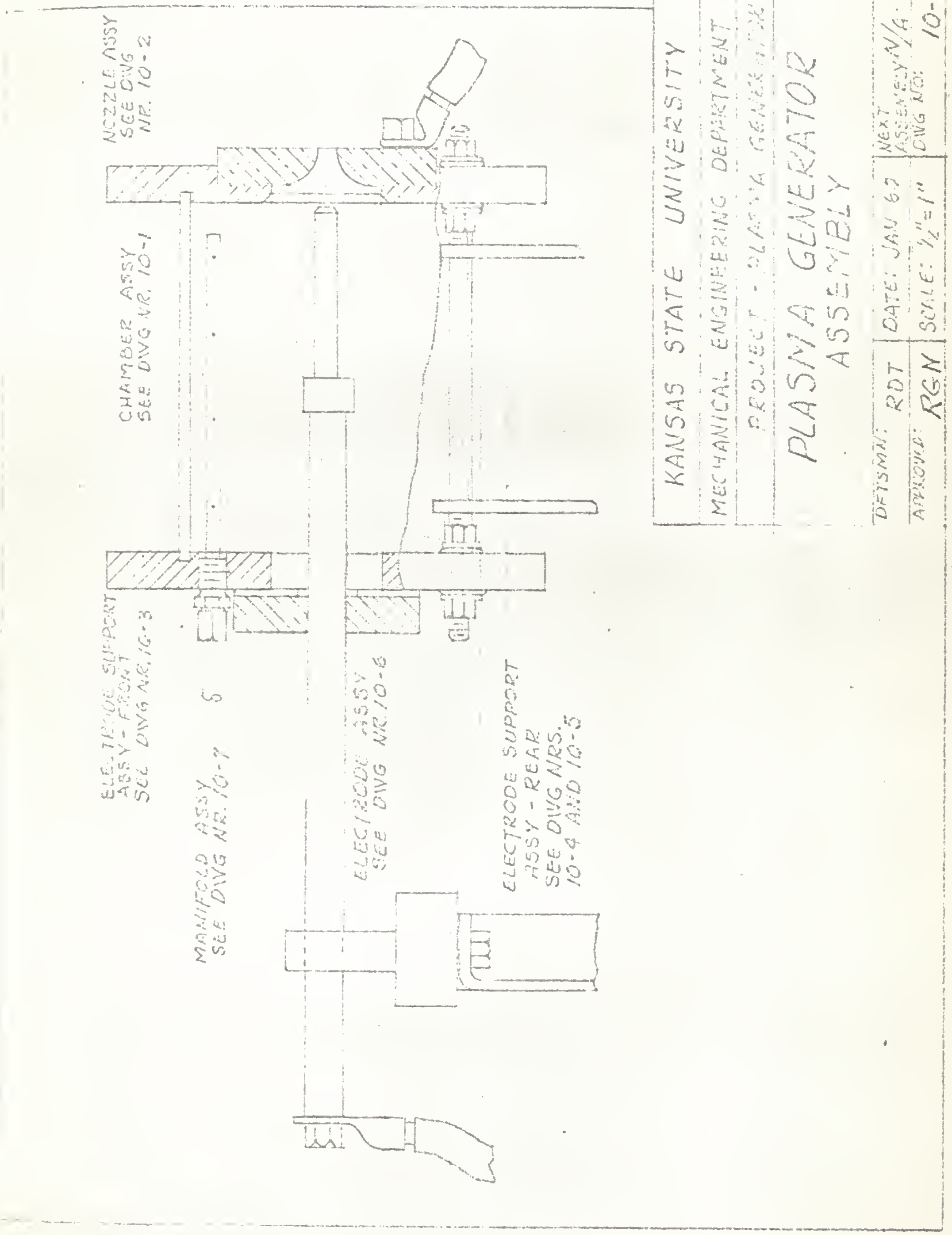
The chamber assembly shown in Plate VI was made of a 4-inch O.D. plastic tube to allow observation of the gas manifolds, the rear electrode and the arc discharge. The function of the chamber in this design is to contain the working gas and to cause the working gas to form a vortex flow pattern which contains the arc from the cathode to the anode.

The nozzle assembly shown in Plate VII consists of a nozzle and a nozzle holder. The nozzle has a three-fold function in this design. First, it is the anode for the arc. Second, it forces the vortex flow of gas into contact with the arc, thus heating the gas. Third, it directs the flow of plasma as it leaves the chamber. The nozzle holder was made of aluminum (2024-T4). The nozzle was made from a solid piece of brass. The nozzle assembly closes one end of the chamber.

The electrode support assembly (front) is shown in Plate VIII. The support assembly positions the rear electrode in the center of the chamber; supports the two gas manifolds; and closes the other end of the chamber. The material used in the assembly was aluminum (2024-T4).

The electrode support assembly (rear) is shown in Plate IX and X. This assembly was required to adequately support the rear electrode. The electrode support is aluminum (2024-T4) and is insulated electrically from the mounting board.

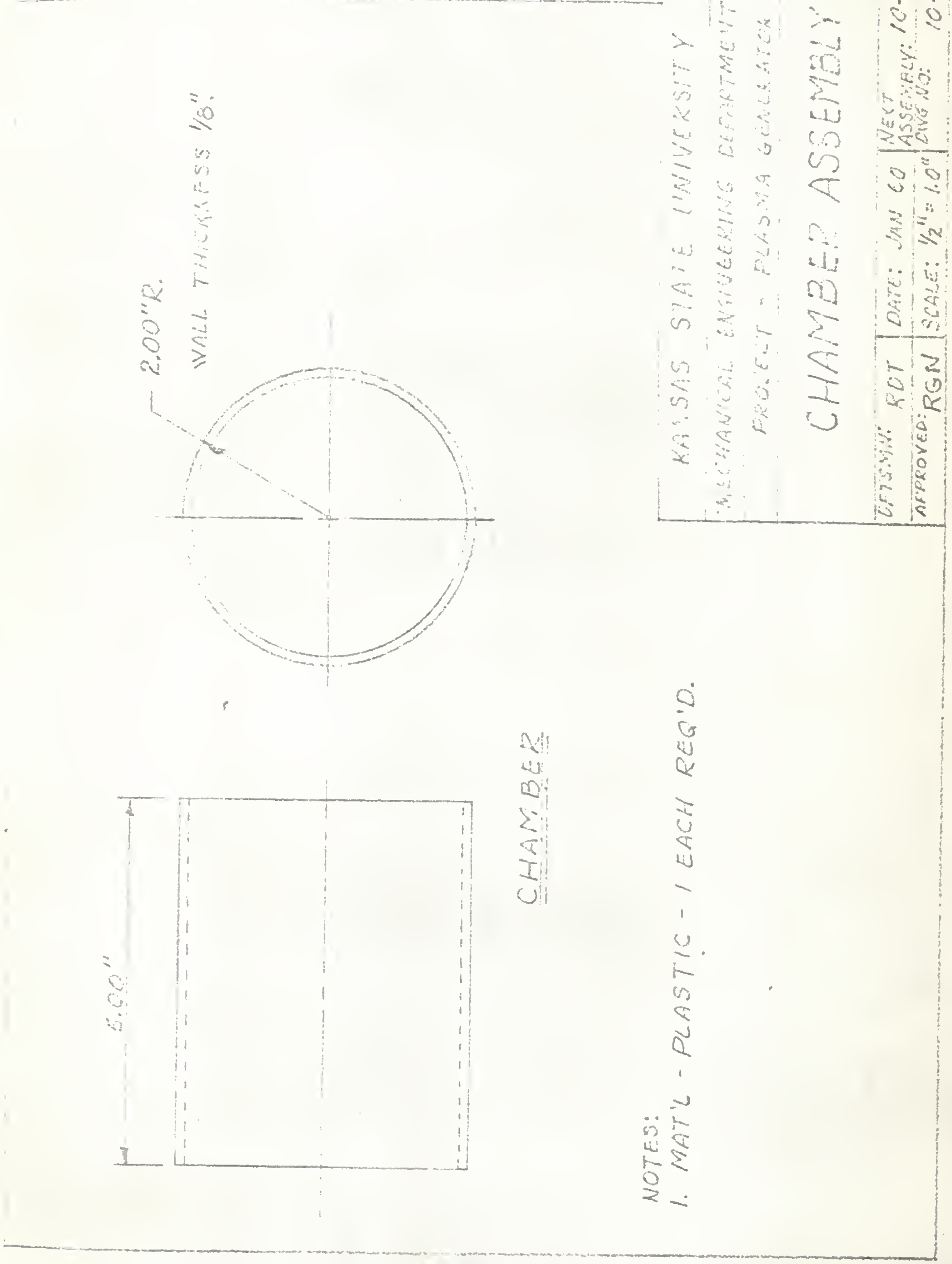
PLATE V


NOZZLE ASSY
SEE DWG
NR. 10-2
CHAMBER ASSY,
SEE DWG NR. 10-1
ELECTRODE SUPPORT
ASSY - FRONT
SEE DWG NR. 10-3
MANIFOLD ASSY
SEE DWG NR. 10-7
ELECTRODE ASSY
SEE DWG NR. 10-6
ELECTRODE SUPPORT
ASSY - REAR
SEE DWG NRS.
10-4 AND 10-5
KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PLASMA GENERATOR
ASSEMBLY
DFTSMN: RDT
DATE: JAN 63
NEXT ASSEMBLY: N/A
APPROVED: RGN
SCALE: 1/2"=1"
DWG NO: 10-0

EXPLANATION OF PLATE VI

Drawing of chamber assembly.

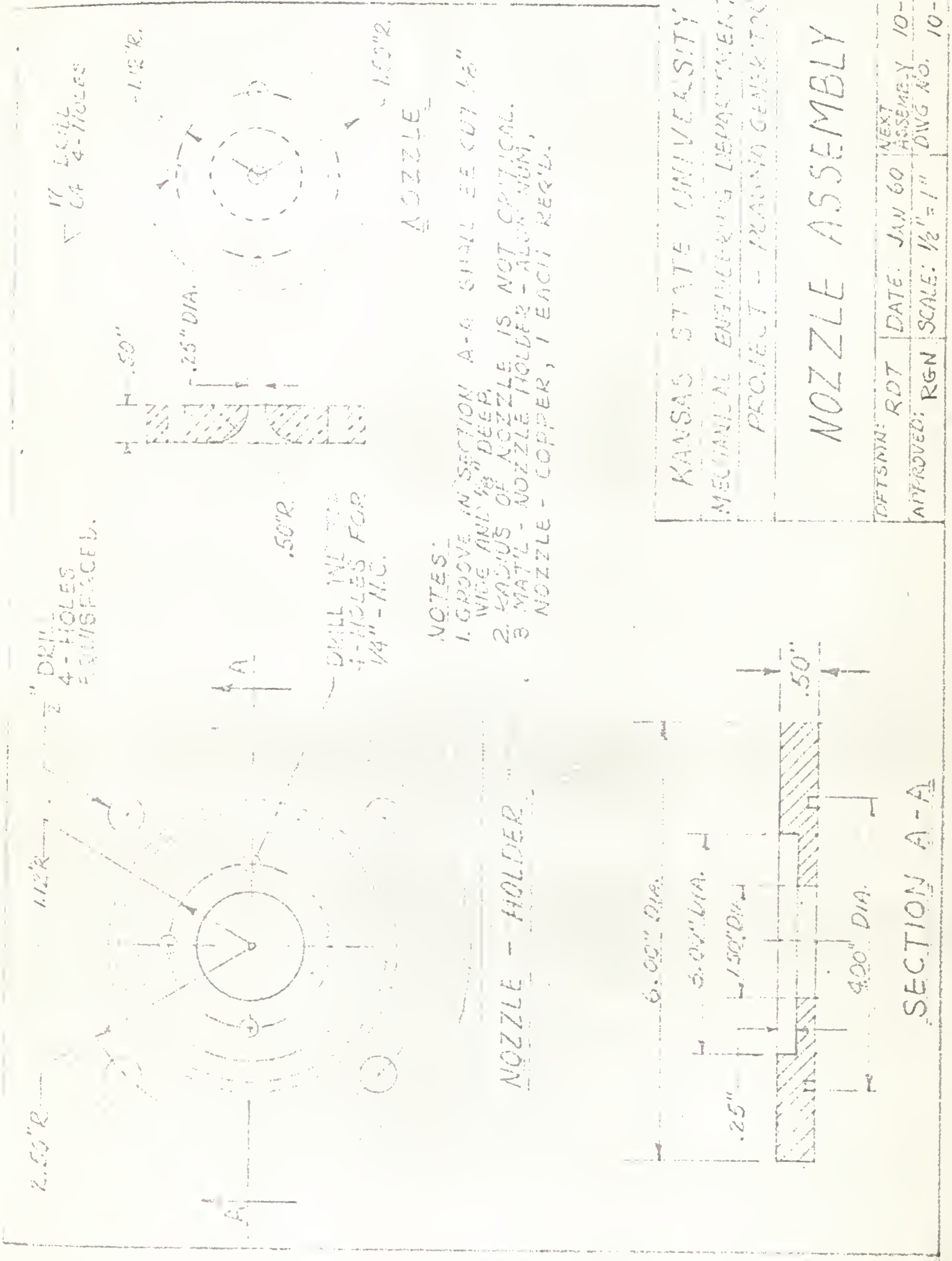
PLATE VI


KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR
CHAMBER ASSEMBLY
DFTSMN: RDT
DATE: JAN 60
NEXT ASSEMBLY: 10-0
APPROVED: RGN
SCALE: 1/2" = 1.0"
DWG NO: 10-1
2.00" R.
WALL THICKNESS 1/8"
5.00"
CHAMBER
NOTES:
1. MAT'L - PLASTIC - 1 EACH REQ'D.

EXPLANATION OF PLATE VII

Drawing of nozzle assembly.

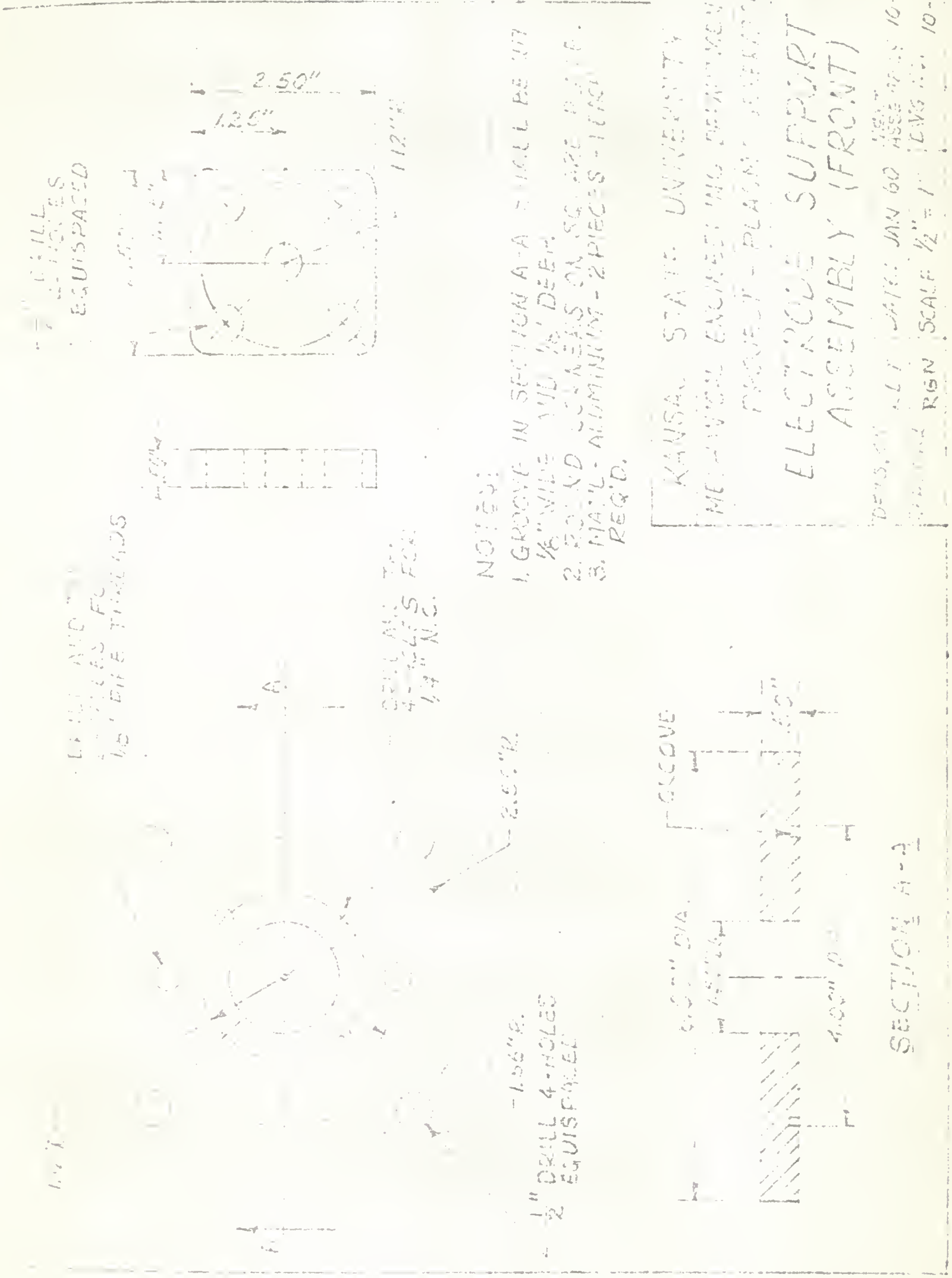
PLATE VII


KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR
NOZZLE ASSEMBLY
DFTSMN: RDT
DATE: JAN 60
NEXT ASSEMBLY 10-0
APPROVED: RGN
SCALE: 1/2" = 1"
DWG NO. 10-2
NOTES:
1. GROOVE IN SECTION A-A SHALL BE CUT 1/8" WIDE AND 1/8" DEEP.
2. RADIUS OF NOZZLE IS NOT CRITICAL.
3. MAT'L - NOZZLE HOLDER - ALUMINUM, NOZZLE - COPPER, 1 EACH REQ'D.
NOZZLE
NOZZLE - HOLDER
SECTION A-A
DRILL 4-HOLES EQUISPACED
DRILL IN THE 4-HOLES FOR 1/4" - N.C.
2.50"R
1.12"R
.50"R
.25" DIA.
.50"
6.00" DIA.
3.00" DIA.
1.50" DIA.
.900" DIA.
.25"
.50"
1.12"R.
1.50"R.
A
A

EXPLANATION OF PLATE VIII

Drawing of electrode support assembly (front).

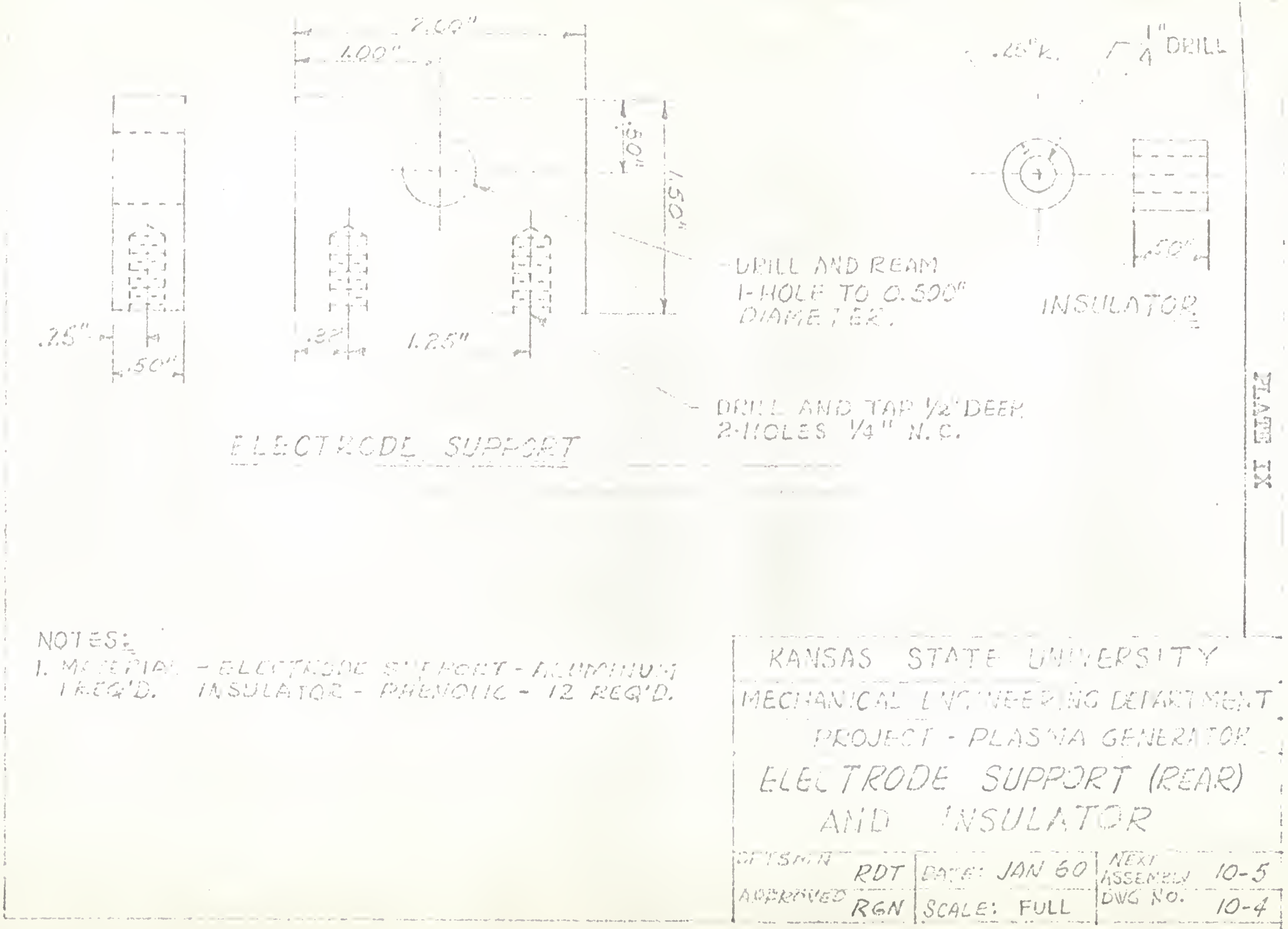
PLATE VIII


NOTES:
SECTION A-A
KANSAS STATE UNIVERSITY
ELECTRODE SUPPORT
ASSEMBLY (FRONT)
2.50"

EXPLANATION OF PLATE IX

Drawing of electrode support assembly (rear) and insulator details.

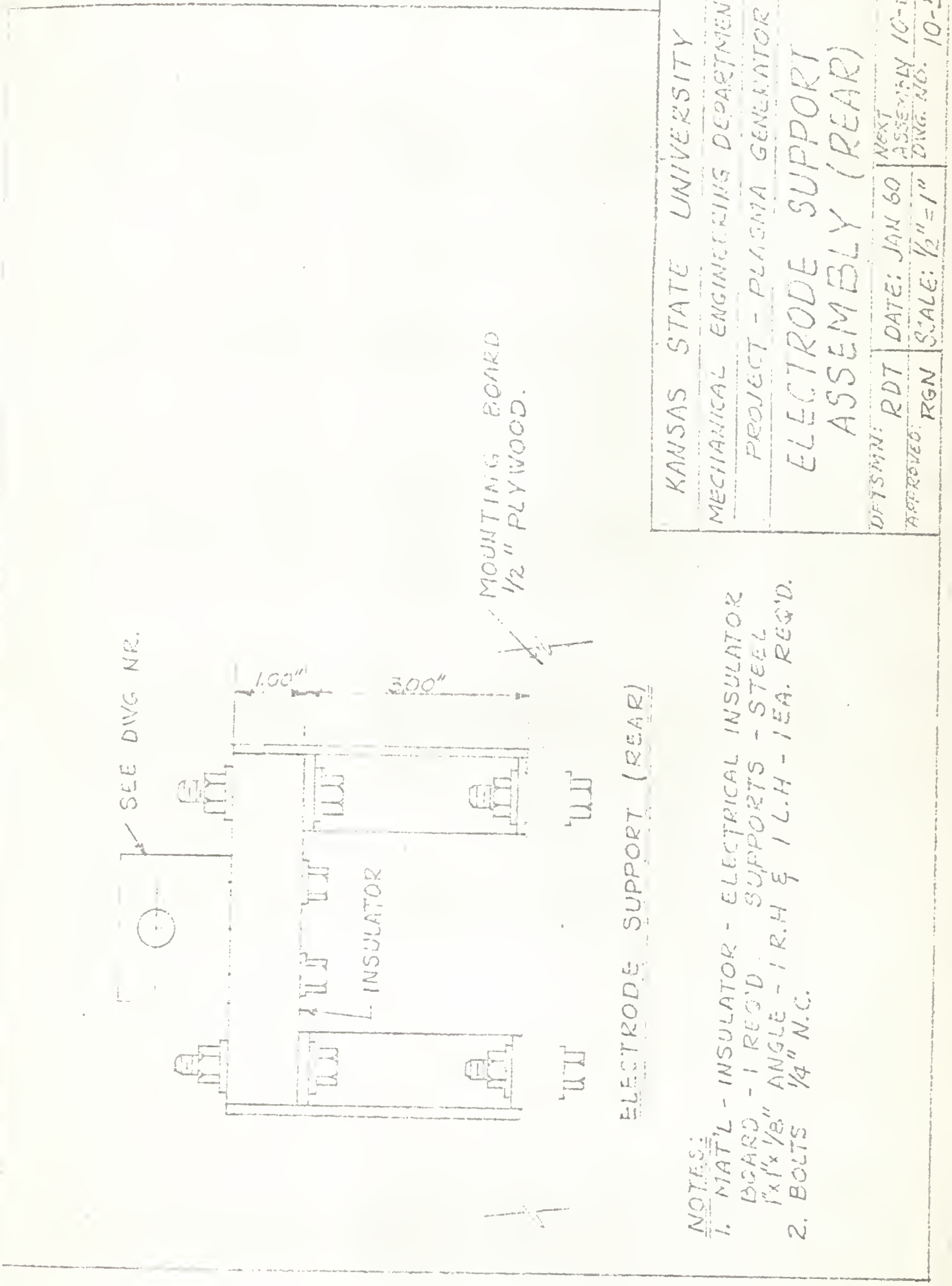
PLATE IX


2.00"
1.00"
.50"
1.50"
.25"
.50"
.38"
1.25"
DRILL AND REAM 1-HOLE TO 0.500" DIAMETER.
DRILL AND TAP 1/2" DEEP 2-HOLES 1/4" N.C.
ELECTRODE SUPPORT
.25"R.
1/4" DRILL
.50"
INSULATOR
NOTES:
1. MATERIAL - ELECTRODE SUPPORT - ALUMINUM 1 REQ'D. INSULATOR - PHENOLIC - 12 REQ'D.
KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR
ELECTRODE SUPPORT (REAR) AND INSULATOR
RDT
DATE: JAN 60
NEXT ASSEMBLY 10-5
APPROVED RGN
SCALE: FULL
DWG NO. 10-4

EXPLANATION OF PLATE X

Details of electrode support assembly (rear).

PLATE X


SEE DWG NR.
1.00"
3.00"
MOUNTING BOARD
1/2" PLYWOOD
INSULATOR
ELECTRODE SUPPORT (REAR)
NOTES:
1. MAT'L - INSULATOR - ELECTRICAL INSULATOR
BOARD - 1 REQ'D. SUPPORTS - STEEL
1"x1"x1/8" ANGLE - 1 R.H & 1 L.H - 1 EA. REQ'D.
2. BOLTS 1/4" N.C.
KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR
ELECTRODE SUPPORT
ASSEMBLY (REAR)
DFTSMN: RDT
DATE: JAN 60
NEXT ASSEMBLY 10-0
APPROVED: RGN
SCALE: 1/2" = 1"
DWG. NO. 10-5

The electrode assembly shown in Plate XI was made from a solid copper rod 1/2 inch in diameter. The actual electrode is a carbon rod 5/16 inch in diameter. This movable electrode is the cathode for the arc when the generator is connected to a D. C. power supply and is used to provide a gap with the nozzle to establish the arc.

The gas manifold assemblies are shown in Plate XII. The manifolds are 3/16 inch O.D. brass tubing approximately 4-1/4 inches long. The manifolds each have four No. 60 diameter holes drilled equispaced along the manifold. The manifolds are located near the outside of the chamber and are diametrically opposite one another. The holes are directed tangentially with respect to the chamber to produce the vortex flow pattern in the gas.

The generator was assembled by combining the various assemblies as shown in Plate V. The various parts of the generator were insulated electrically by phenolic sleeves (shown in Plate IX) and plastic washers.

The gas piping was connected as shown in Plate XIII. Copper tubing was used from the pressure regulator to the distribution manifold. Control valves were placed in the distribution manifold to regulate the gas flow. Plastic tubing which could be easily disconnected was used from the control valves to the gas manifolds in the chamber.

Plate XIV shows the plasma generator connected to an A. C. power supply.

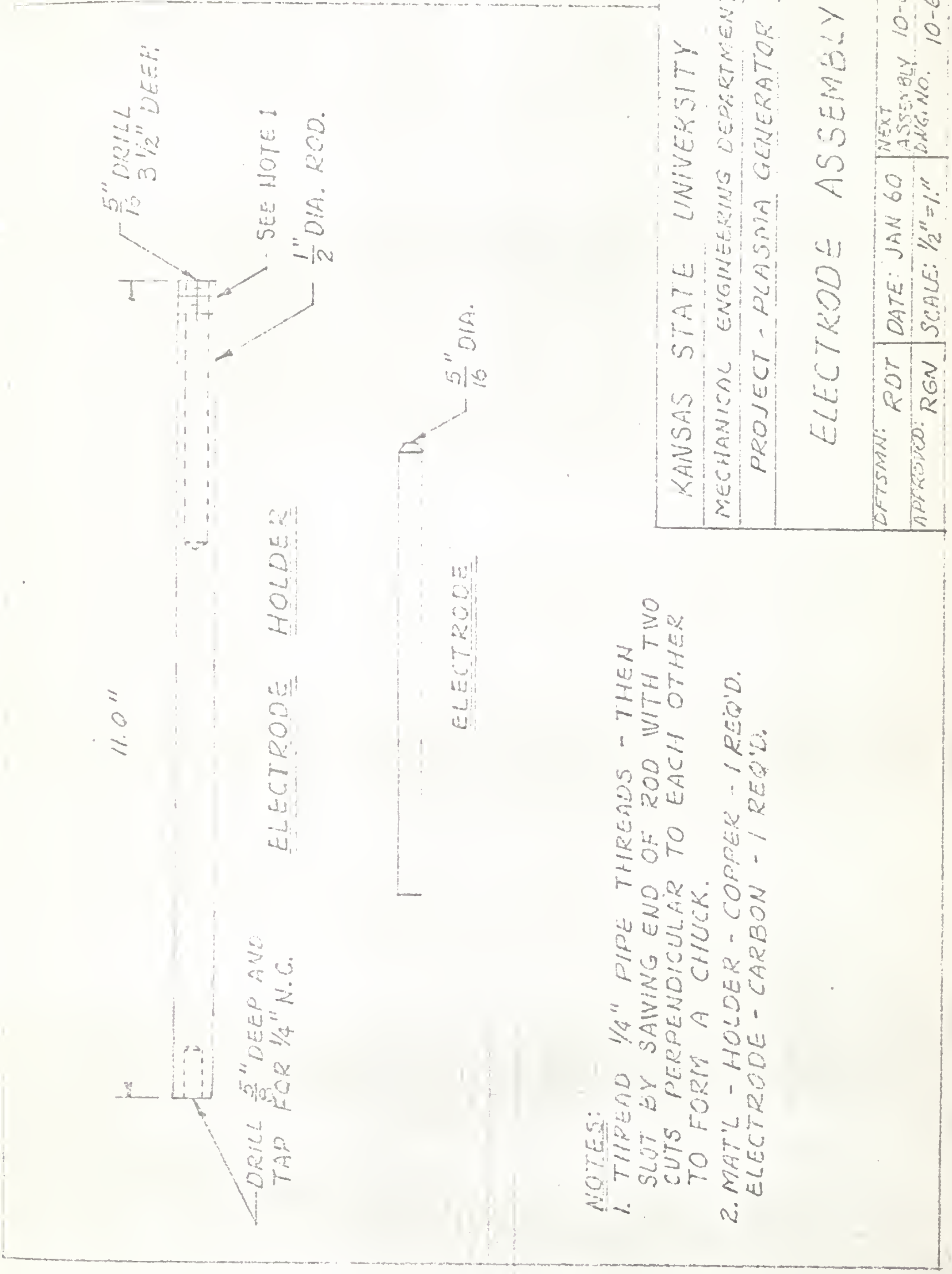
Plate XV shows a close-up view of the plasma generator.

The generator was mounted in a vertical position as shown in Plate XV to facilitate movement of the electrode assembly and for its use as a demonstration model.

EXPLANATION OF PLATE XI

Drawing of electrode assembly.

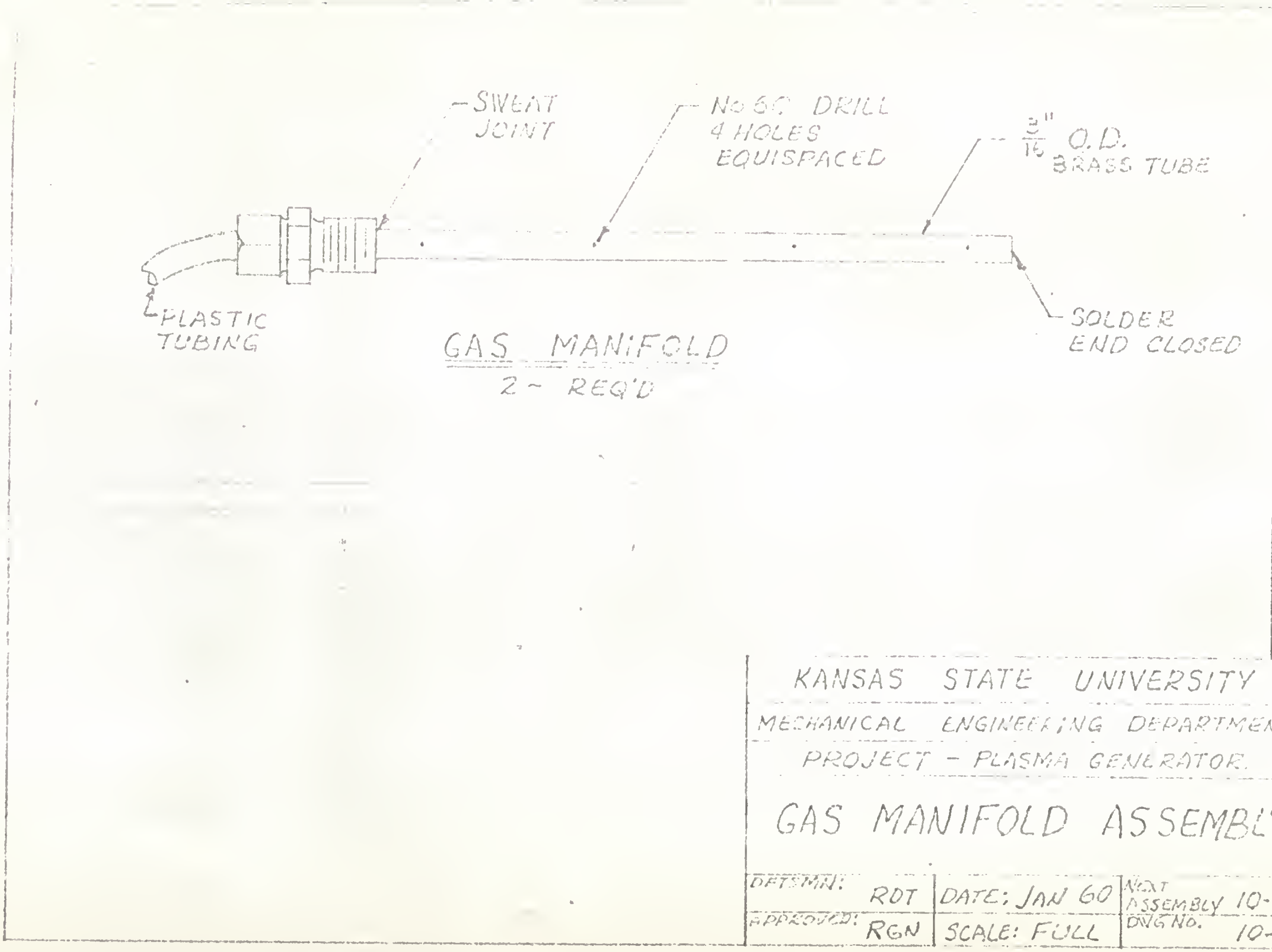
PLATE XI


5/16" DRILL 3 1/2" DEEP
SEE NOTE 1
1/2" DIA. ROD.
11.0"
ELECTRODE HOLDER
DRILL 5/8" DEEP AND TAP FOR 1/4" N.C.
5/16" DIA.
ELECTRODE
NOTES:
1. THREAD 1/4" PIPE THREADS - THEN SLOT BY SAWING END OF ROD WITH TWO CUTS PERPENDICULAR TO EACH OTHER TO FORM A CHUCK.
2. MAT'L - HOLDER - COPPER - 1 REQ'D. ELECTRODE - CARBON - 1 REQ'D.
KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR
ELECTRODE ASSEMBLY
DFTSMN: RDT
DATE: JAN 60
NEXT ASSEMBLY 10-0
APPROVD: RGN
SCALE: 1/2"=1"
DWG. NO. 10-6

EXPLANATION OF PLATE XII

Drawing of gas manifold assembly.

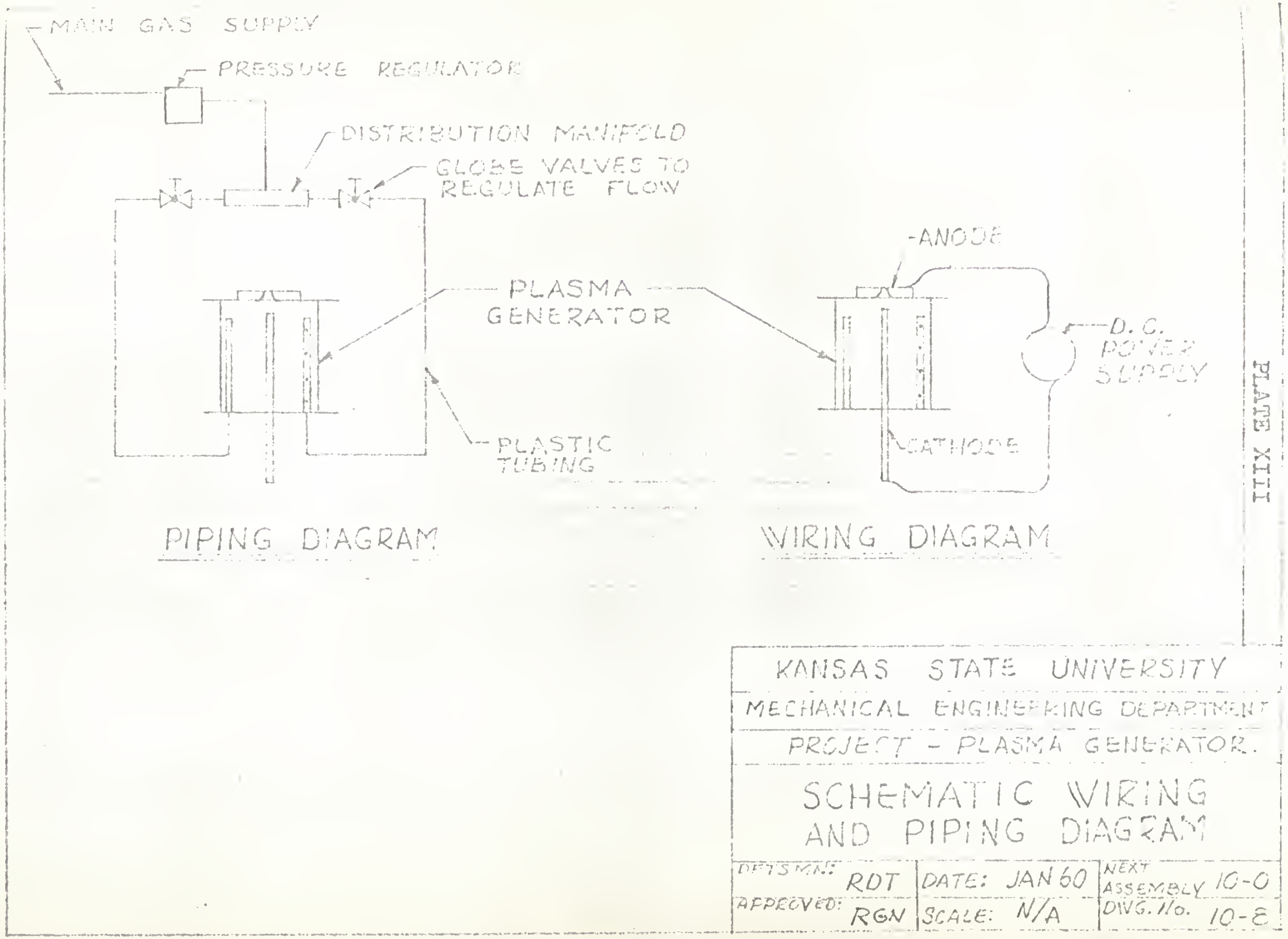
PLATE XII


SWEAT JOINT
No 60 DRILL
4 HOLES
EQUISPACED
$\frac{3}{16}$" O.D.
BRASS TUBE
PLASTIC
TUBING
SOLDER
END CLOSED
GAS MANIFOLD
2 ~ REQ'D
KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR.
GAS MANIFOLD ASSEMBLY
DFTSMN: RDT
DATE: JAN 60
NEXT ASSEMBLY 10-0
APPROVED: RGN
SCALE: FULL
DWG No. 10-7

EXPLANATION OF PLATE XIII

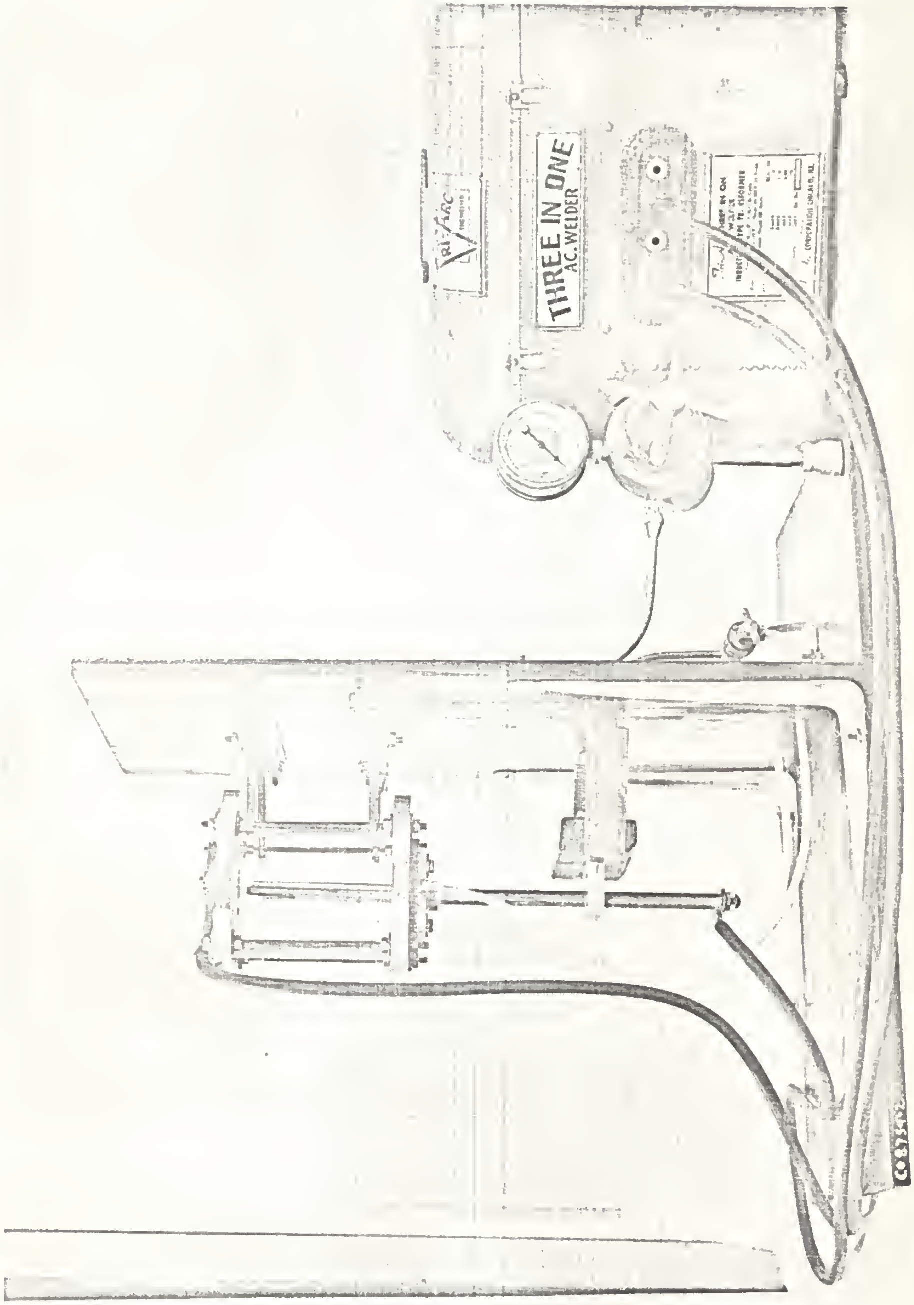
Schematic piping and wiring diagrams.

PLATE XIII


MAIN GAS SUPPLY
PRESSURE REGULATOR
DISTRIBUTION MANIFOLD
GLOBE VALVES TO REGULATE FLOW
PLASMA GENERATOR
PLASTIC TUBING
PIPING DIAGRAM
ANODE
CATHODE
D.C. POWER SUPPLY
WIRING DIAGRAM
KANSAS STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
PROJECT - PLASMA GENERATOR.
SCHEMATIC WIRING AND PIPING DIAGRAM
DFTSMN: RDT
DATE: JAN 60
NEXT ASSEMBLY 10-0
APPROVED: RGN
SCALE: N/A
DWG. No. 10-8

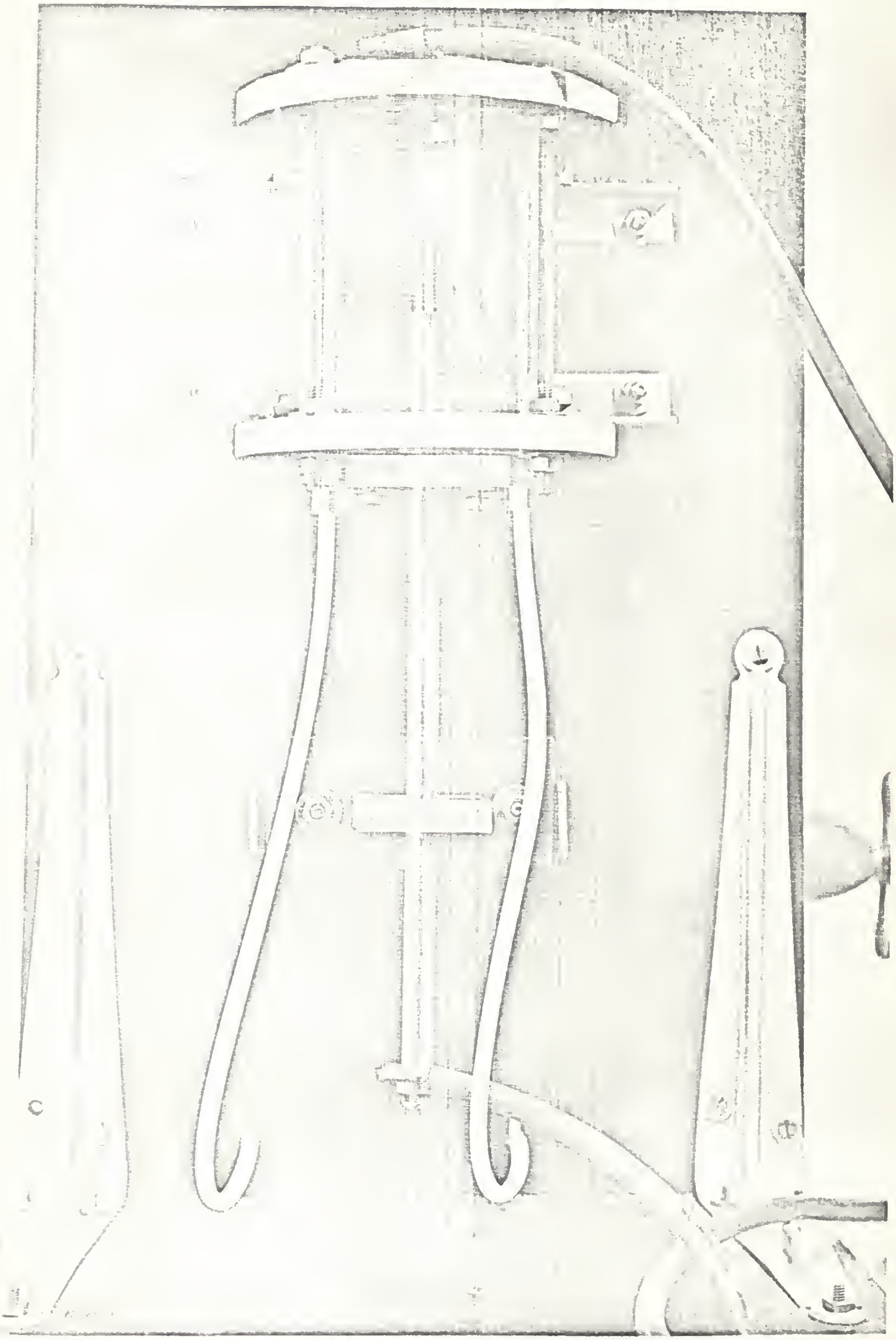
EXPLANATION OF PLATE XIV

View of plasma generator connected to a power supply.


THREE IN ONE
AC. WELDER

EXPLANATION OF PLATE XV

Close-up view of plasma generator.



SUMMARY

The existing industrial plasma jet generator can be classified in one of three categories: a gas-stabilized plasma generator, a water-stabilized plasma generator, or a transferred arc plasma generator.

The properties discussed in this report include plasma composition, electrical neutrality, temperature-temperature equilibrium-density, viscosity, electrical conductivity, and plasma instabilities. The known data for these properties are generally for special cases e.g., a fully ionized gas or a weakly ionized gas, and are only known for a few gases such as air, argon, nitrogen and hydrogen.

The plasma generator is being used in the field of materials technology to spray high temperature coatings; to cut metal plates; and to machine refractory materials; also, as a high temperature test facility to study ablation rates of various solid materials, and the various properties of gases at high temperatures.

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THE PROPERTIES AND USES OF AN ARC PLASMA JET GENERATOR

by

RICHARD DEAN TURNER

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The purpose of this report was to discuss the various known properties and uses of the plasma jet generator. This was accomplished by a study of many references which dealt with the development of the plasma generator; the various properties of plasmas; and the present and future uses of plasma generators.

Since the beginning of World War II there has been a demand for accurate high temperature data for various properties of solids, liquids, and gases. This need has stemmed primarily from three fields of engineering interest, one, the design and development of gas turbines and rocket engines; two, nuclear reactions both fission and fusion; and three, the aerodynamic heating of high velocity missiles.

The field of accessible temperatures has widened considerably due to a change of interest from heated solid matter to the behavior of hot gases. Oxygen O_2, for example, in the temperature range of 11,000°F at atmospheric pressure exists almost entirely as free atoms i.e., in the dissociated state of O. As the temperature is increased above 11,000°F, the atoms begin to ionize. Thus oxygen in this temperature range is a mixture of free atoms, ions and electrons. A gas that is completely ionized is known as a "plasma." The term plasma has been extended to include partially ionized gases. Thus an arc or thermally excited plasma is a mixture of molecules, free atoms, ions and electrons where the ionic charge is equal to the number of electrons within a finite volume of gas.

Various devices have been developed recently which generate a continuous jet of plasma in the temperature range of 10,000 to 35,000°F for periods long enough for any experimental purpose. The plasma generators all have a cylindrical chamber in which the working fluid is introduced tangentially to produce a vortex flow pattern through which the arc is struck from the cathode to the anode. The water cooled anode is made of copper and is generally in the form of a convergent or convergent-divergent nozzle.

The properties discussed include, plasma composition, electrical neutrality, temperature-temperature equilibrium-density, viscosity, electrical conductivity, and plasma instabilities. Most analytical treatments of the various plasma properties discussed in the references considered solutions only for the limiting cases i.e., for the fully ionized gas.

The plasma generator is being used in the field of materials technology to spray high temperature coatings, to cut metal plates, and to machine refractory materials; also as a high temperature test facility to study ablation rates of various solid materials, and the various properties of gases at high temperatures.