FOREWORD

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This report covers work conducted from June 1959 to September 1960.

It is a pleasure to acknowledge the important contributions of several members of the Fuels Research Laboratory to the work reported here, as follows: N. Y. Chen for active direction of some phases of the project and contributions towards design of both the pyrometer and the plasma generator; Noble M. Nerheim and Walter Niessen for design and construction of the photo-electric pyrometer and for calibration of system components; Herbert A. Passler and Reed C. Fulton, for construction of a plasma jet generator facility.

ABSTRACT

A literature study has been made of methods for measuring temperatures of hot gases and plasmas, with particular emphasis on evaluation of non-spectroscopic techniques. For application to measurements on air stabilized plasma jets at temperatures to 8000°K and in the pressure range from 0.01 to 10 atmospheres, an optical technique has been chosen, modified for fast response by use of a multiplier phototube as the receiver. The technique involves display on a cathode ray oscilloscope of signals alternately representing first a single path and then a double path (by means of a mirror) of the image of a portion of the plasma jet, the alternation being at 13 cycles per second. The double path image is attenuated by means of a neutral filter and the chopped signal is compared with that of a calibrated pyrometer filament, the image of which is made to appear upon the oscilloscope screen, again at a frequency of 13 cps, by means of passage through a glass refraction block. The measurement of integral intensity is made nearly monochromatic by the use of very narrow band interference filters, e.g., a sodium D line filter peaked at 5892 Å, with a half width of 7.5 Å. With an additive producing constant absorption over the range of the filter, the effect on intensity of doubling the path is used to infer the intensity of black radiation - and therefrom the temperature - by conventional use of Beer's law. With an additive producing line emission within the wavelength range of the filter, the interpretation of path doubling becomes more complicated; and the normalized shape of the line must be used in the interpretation of the pyrometer readings. Extension of the range of possible temperature measurement to as high as 10,000°K is made possible by interposition between the target and the pyrometer filament of neutral density glass filters, each having a transmissivity of about 4.5%.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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I. INTRODUCTION

A. THE PROBLEM AND OBJECTIVES

With the advent of hypervelocity flight, the possibility of direct conversion of heat to electricity by magnetohydrodynamic techniques, the possibility of space propulsion with plasma-accelerators, and the development of pinch-controlled plasmas in high energy physics, there has been an explosive growth in the attention devoted to the plasma state. Plasma is simply fluid having a high enough energy content to be at least partially ionized. Depending on the energy level (or the temperature) the plasma consists of a greater or lesser fraction of charged particles, but in any case there is a balance of positive ions against negative ions and electrons with no net charge. This definition allows the term "plasma" to be applied to matter in an extremely wide range of physical conditions. On the low temperature end of the scale is the glowing material of a neon tube, and the ions and electrons in electron tubes. Any electrical discharge produces a plasma. So also do high temperature flames and so does any projectile or missile whose travel through the atmosphere is fast enough to cause dissociation and ionization behind the shock wave it produces. Temperatures in relatively dense plasmas, attainable by laboratory means, are in the range between about 3000°K and 30,000°K, with the upper end of the range confined to the more difficultly ionized inert gases, and the lower end of the range the common diatomic gases. Plasmas of very low density, especially those studied for possible use in controlling fusion reactions, attain temperatures of the order of 10^7°K or more, though in this context the term temperature is not very meaningful and it is more customary to speak of the energy of the plasma in terms of electron volts.

The temperature range between about 3000°K and 10,000°K is the region of great importance for aerodynamic heating, the region of the re-entry problem. During the past five years there has been an increasing concentration of research on the properties of air in this temperature range, and on the heat transfer and ablation problems associated with high temperature air. The radiative properties, dissociation, ionization and recombination reactions that occur in air at high temperatures have been studied most extensively with shock tube techniques and high-speed spectrophotometry (78, 79). The shock tube has the advantage of permitting study of the clean gas. For heat transfer studies and the evaluation of materials, such as ablation materials, the short duration of shock phenomena is not suitable, and the arc-heated plasma jet has gained most wide acceptance. The plasma jet provides a high temperature source capable of relatively long runs, usually with some penalty in the form of contamination of the gas by electrode materials.

The purpose of the research reported here has been to develop means of measuring the temperature of plasma jets, with special attention given to finding non-spectroscopic means. While certain spectroscopic techniques are the first to suggest themselves and have been developed to some extent for application to plasma jet temperature measurements (135, 149, 151), the aim here is to see that other promising possibilities, especially optical techniques, would not be neglected. The range of plasma jet conditions for which temperature measuring means were to

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be sought was 4000°K to 8000°K, at pressures from 0.01 to 10.0 atmospheres and with air specific enthalpies of 4000 to 12000 Btu/lb. The coverage of this range of conditions, especially of pressure, implies considerable variation in plasma properties and thus probably in the details of temperature measuring techniques which may be most suitable.

A survey of the literature on properties of air and other gases at plasma jet temperatures, on design of plasma jet facilities, and on temperature measuring techniques, has been an important part of this effort. The Bibliography in Section VI of this report, with some 178 references, is given as representative of the work in these areas, though no claim is made that this list is all-inclusive.

B. PROPERTIES OF HIGH TEMPERATURE AIR

A necessary basis for finding techniques for measuring the temperature of very hot air and other gases is knowledge of their thermodynamic, transport, and radiative properties. During the past five years the thermodynamic and transport properties of air and argon have been studied intensively by groups at the National Bureau of Standards, NASA, the Cornell Aeronautical Lab, and the Rand Corporation. Results of this work and some other are included in the 27 references of the first section of Bibliography (Section VI A). In most of these studies emphasis was on machine computation of thermodynamic properties, with allowance for equilibrium among as many as 28 components of the dissociated, ionized air. The most comprehensive and probably the most accurate are the tables given by Hilsenrath and his NBS colleagues (21). For certain uses the tables and charts given by others may be easies to use (10, 13, 23, 25). In general the treatment of transport properties has received less detailed attention, (i.e., engineering approximations have been the goal (1)), but the determinations of thermal conductivities, Prandtl and Schmidt numbers for high temperature air have been very revealing and important for heat transfer and ablation studies.

To characterize air properties briefly, the formation of new species by dissociation, ionization and species interaction, attended by departure from ideality, begins at something below 3000°K, proceeds irregularly with increasing temperature, and is also strongly influenced by pressure. Between 3000 and 4000°K most of the O_2 molecules undergo dissociation. Between 4000 and 8000°K the nitrogen dissociates and oxygen atoms begin to ionize. Above 8000°K is the plasma region, with atoms, ions, and electrons but only a very low concentration of molecules. Nitric oxide is a fairly important component at atmospheric density and 3000 to 4000°K (about 4 mol %), but its concentration drops ten fold as temperature increases to 8000°K. The ion, NO^+, amounts to about 10% of the NO concentration at about 6000°K. At 8000°K and normal density nitrogen and oxygen are present mainly in atomic form, but at reduced pressure (< 0.01 atm., $\rho/\rho_o = 10^{-4}$) N^+ ions amount to about 2.3% and O^+ to about 0.5% of the total mixture. Argon ions amount to less than 0.01%, and the oxides of carbon to still less. The carbon is present as C and C^+. At higher densities, CO is always present in larger amounts than CO_2, being between 0.02 and 0.03% in the 4000 - 8000°K range at $10^{-2} < \rho/\rho_o < 1.0$. (21). To summarize, in the range of conditions of present interest the components of equilibrium air go through essentially complete dissociation and at the high temperature, low density end of the range the concentration of ions reaches values of a few mole percent. Throughout the range, however, the presence of at least half a dozen species of ions

has a very important bearing on the radiative properties of the plasma.

It is important to know whether equilibrium is attained in the air which passes through a shock wave to the surface of a missile nose cone, and similarly, the length of time or distance required for thermochemical equilibrium to be attained in air-stabilized plasma jets. Studies of the chemistry, especially the relaxation rates, of high temperature air, have been an important part of the work at AVCO Research Laboratories especially, and at several others in the past five years, as reported in many of the references (28 through 94) in the second part of the Bibliography. According to AVCO workers (93) , air in passing through a normal shock wave attains equilibrium of the rotational and translational degrees of freedom within a few mean free paths. The bow shock ahead of a missile nose is entirely analogous, and the same conclusion should be valid for air-plasma produced by passage through an arc. Thus the translational temperature and the density can be found directly, for shock-heated air, from the Rankine-Hugoniot relationships. Attainment of complete equilibrium is more complicated, however, requiring vibrational excitation, production of new species (e.g., NO), dissociation of some species, and production of some ions. All these processes are interdependent and also dependent on the temperature, density and composition, all of which change as equilibrium is approached. In the AVCO studies of this extremely complex physico-chemical process, emphasis has been given to measuring the order of magnitude of relaxation times to produce equilibrium ionization and radiation, as well as the magnitude of non-equilibrium electron density and radiation intensity. For the case of air, five "thermally significant" chemical reactions have been considered. Experimentally, vibrational excitation and dissociation have been studied by a technique utilizing ultraviolet absorption, which measures the density of molecules in the ground state. Radiation emission and ionization, which result from excited states, do not affect the UV absorption experiment. From the AVCO work (35, 93) it is clear that O_2 vibrational relaxation is much faster than O_2 dissociation or nitrogen vibrational relaxation. Vibration relaxation times of nitrogen in air are of the order of 20 μsec. at about 2800°K (shock Mach No. M_s of 8 with p_1 = 1 mm), down to 1 μsec. at about 4200°K (M_s of 12, p_1 = 1 mm). At 3000°K and 1 atm. vibrational relaxation times of pure O_2 and pure N_2 have been measured as 2 μsec. and 30 μsec. respectively (29). The differences between measurements in different experiments probable are due to differences in effectiveness of O_2 and N_2 as catalysts for the reactions.

Dissociation of oxygen behind shock waves, where the initial pressure was 1 mm, reached 60% of its equilibrium value in about 20 μsec. when M_s was 11.3 ($T \cong 3800$°K) and in about 2 μsec. when M_s was 13.4 (5250°K); but the 20 μsec. test time available was not sufficient for dissociation to reach more than 95% of its equilibrium value even with M_s = 13.4, indicating that the "time constant" of the process is not a constant or that the process is not first order.

Behind a shock wave in either air alone or air-argon mixtures production of NO in about the first 2 μseconds overshoots an equilibrium value by about two fold, then relaxes to equilibrium in about 15 μseconds.

Computed values of chemical relaxation rates, based on the measurements indicated above, have been used (93) for calculating rates of ionization reactions. These are said not to have any appreciable effect on temperature, density, or composition if the equilibrium temperature behind the shock is less than 8000°K

because here the energy invested in ionization is small compared with the total enthalpy of the gas. The most important source of ions and electrons in this region is NO, which has a relatively low ionization potential.

Considering now the non-equilibrium radiant emission, in shock tube experiments it has been found that under some conditions there is initially a pronounced overshoot. For example, O_2 Schumann-Runge radiation shows no overshoot while the first negative band of N_2^+ and the β band of NO sometimes do overshoot. For shock tube initial pressures of 1 mm and 10 mm, respectively, and shock Mach Nos. between about 8 and 18, distance (or time) required for relaxation to within 10% of the equilibrium value is inversely proportional to the density and a strong function of the (changing) temperature. For low density ($\rho_{equil} = 0.015\rho_o$) or low equilibrium temperature (3000°K) the relaxation time may be about 100 μseconds. Radiation overshoot does not occur at high densities and low Mach numbers (low $T_{equil.}$). Comparison of the data for radiative and chemical relaxation distances shows them to be roughly equal where experimental conditions overlapped, suggesting that the radiation intensity is governed by the chemical processes which determine the instantaneous temperature and composition (35). But the non-linearity of the rate equations is a warning against extrapolating relaxation "time" values beyond the range of their experimental verification.

For production of electrons in shock-heated air the most important reaction is that in which an atom of nitrogen combines with one of oxygen to produce an NO^+ ion and an electron, and at equilibrium temperatures of 4000 to 5000°K, the number of electrons increases linearly with distance behind the shock front, attaining equilibrium in about 40 to 70 μseconds (93).

From the above discussion it seems reasonable to conclude that chemical and radiative equilibrium in hot air is attained rapidly enough so that it should not be difficult to design and operate a plasma jet with assurance that except perhaps for the lowest density, lowest temperature conditions the gas would be in equilibrium. Assuming this to be the case, it is next important to consider the radiative properties of equilibrated high temperature air. Here again most of the guidance comes from a series of reports and papers from AVCO (57, 58, 59, 60, 61, 62, 83, 86, 92) with some additional information from other sources (53, 63, 73, 76, 81, 82, 84, 90). In the temperature range 4000 to 9000°K, the density range 0.01 to 10 times normal atmospheric density, and the wave-length range 2000 to 10,000 Å the radiation includes bands due to O_2, N_2, N_2^+ and NO molecules, lines due to N and O atoms, and Kramers continuum radiation from O^-. At lower temperatures electronic bands of triatomic molecules NO_2, CO_2, and O_3, would also be significant. At temperatures above the range cited above, radiation associated with recombination forming excited nitrogen atoms is most important. Going away from the cited wavelength range, both into the UV and the infrared, air becomes more nearly black. In the range 2000 - 10,000 Å, at 8000°K and atmospheric density * the measured emissivity of a one cm. path of air was about 7% that of a black body.

* It has become the practice in plasma and shock tube research to use "atmospheric density" to describe gas having the same MP/T ratio as air at 1 atmosphere and room temperature. In the present application the pressure to give atmospheric density at 8000°K is (8000/293)(29/M) $\cong$ 40 atm.

Kivel and Bailey (61) have summarized the AVCO experimental results and theoretical extrapolations therefrom in a single convenient set of curves of energy radiated per unit volume as a function of temperature and density. The experimental work covered the more dense half of the range of conditions of interest in the present program. From this set of curves one predicts for the region of present interest total emissivities of a 1 cm path ranging from 3×10^{-7} at 4000°K and 0.01 atmosphere to 9×10^{-3} at 8000°K and 10 atmospheres. This makes it plain that the emittance from clean air, in a small plasma jet, can not be high enough for any ordinary optical temperature measurement.

The effects of impurities on the radiative and thermodynamic properties of air have been studied to some extent by G. E. and AVCO personnel (122, 102). Contaminants affect the flowing gas in at least four ways: Firstly, when the electrode material is carbon and this erodes or vaporizes into the air it reacts with oxygen, mainly to form CO, and thus to produce an O_2-starved gas with different thermodynamic properties from those of air and unrepresentative of air, especially in ablation tests of combustible materials. Secondly, the CO and CO_2 formed produce their characteristic radiation mainly in the infrared. This might be useful for temperature measurements (as with use of the 2.7 and 4.3μ bands of CO_2) on a plasma jet, even though it would not be applicable to clean air. Thirdly, some of the carbon (about 10-20%) from plasma generators remains as particulate carbon, thus producing continuum radiation. While formation of CO is exothermic, thus tending to increase the gas enthalpy, the increased radiation, from contanimamts, tends to reduce it. Fourthly, material losses from metallic electrodes (e.g., water-cooled copper) contaminate the stream with metallic vapors which because of their lower ionization potential produce a given concentration of electrons at lower temperatures than the concentration in clean air. The conductivity of the plasma is thereby increased and conversion of electrical to thermal energy reduced, since this conversion is inversely proportional to the conductivity. In a stream contaminated by copper to the extent of 5% of the air mass flow rate, conductivity would increase 6-fold and to offset this would require increasing current density by $6^{0.5}$. It is reported (122) that if the carbon loss is less than 5% and the copper loss less than 1% the situation is acceptable for present applications of plasma jets.

II. DESIGN, CONSTRUCTION AND OPERATION OF PLASMA JET GENERATOR

A. THE PRIOR ART

Perhaps the best way to establish the value of a proposed technique for measuring the temperature of air-plasmas would be not to test the technique on a plasma jet but rather to sight on or otherwise examine a stationary arc free from air flow. For example, at Linde Speedway Labs (162, 163) a spectroscopic technique for temperature measurement has been applied to detailed temperature mapping of an argon arc. At the Bureau of Standards (155) an apparatus has been perfected in which a slowly flowing test gas is heated to plasma temperatures while shielded from the electrodes by being sandwiched between layers of inert gas that minimize electrode erosion. This apparatus permits working with clean plasmas whose properties are essentially nonvariant with time. Since the real problem here, however, is to develop techniques for measuring temperatures of plasma jets it was clear that plasma jet equipment would ultimately be required and that temperature measuring schemes could be initially checked out on simple flames not requiring construction of special equipment for producing the ideally clean, stationary plasmas. It was also plain, however, that all known precautions be taken to make the plasma jets as free as possible of contamination, to make the temperature as nearly as possible represent those of air plasmas.

The history of plasma jet development has been quite adequately covered by Browning (96) and others (105, 121, 123). A fairly comprehensive group of papers on plasma jet design and performance is given in the third part of the bibliography, references (95) through (125). Here it should suffice to say that while the early plasma jets were mainly water-stabilized models current interest is almost wholly in gas-stabilized jets, and design problems have been mainly concerned with extending the life of the electrodes by minimizing erosion and oxidation.

As described by Browning, there are just two design steps in the transition from an open arc to a plasma jet torch. With the open arc the electrical path is directly to the work to be heated, which is made one of the electrodes. In the case of gas shielded welding there is a directed flow of inert gas around the arc. The plasma torch differs from this in that the arc is caused to pass through a nozzle or orifice before reaching the work, which is again one of the electrical terminals. This is the so-called transferred arc and provision is made for gas flow through the nozzle to help confine the arc and cool the nozzle walls. The nozzle is electrically neutral, however. Finally, if the nozzle is made an electrode we have the non-transferred arc or true plasma-jet configuration. All the heating that can be done beyond the plasma jet unit must then be by the arc-heated gas, whereas with the transferred arc considerable heating is due to electron impingment at the work surface. The aim in plasma jet design, however, is to provide efficient heating of the gas and this is accomplished by minimizing the heating of electrodes.

Of three methods used for controlling the arc geometry one is known as "wall-stabilization." Here the plasma-forming gas becomes an integral part of the arc stream, which fills the nozzle from wall to wall. More common than this technique

are those which rely on "vortex stabilization," "gas-sheath stabilization," or perhaps a combination of these. In the case of vortex stabilization the plasma-forming gas is introduced radially at high velocity, setting up a vortex flow which when constrained to pass through the nozzle provides a low velocity core in which the arc is positioned well away from the electrode wall. In this design the nozzle electrode is usually the cathode and a stubby disc projecting a short distance from the arc chamber back wall is the anode. The Giannini "Plasmatron" is probably the most widely known equipment of this design (105, 106).

In gas-sheath stabilization the cathode is a rod electrode and the anode the nozzle, with the latter certainly, and usually also the former, water-cooled. The arc may be started by a high frequency arc starter or by an auxiliary tickler electrode provided simply for breaking down the gap between the cathode and the nearest part of the anode surface. It is also possible, especially with argon as the stabilizing gas, to initiate the arc by shortening the gap between the main electrodes, then increasing it. This tends to cause excessive erosion, at a local spot on the anode, however. The arc, once initiated, is confined by the gas momentum to follow a path down the axis of what is usually a relatively long nozzle. Initially confined mainly to the low velocity gas core, the arc rapidly heats and accelerates this core, then heats the peripheral "sheath" gas and by the time it reaches the anode surface is sufficiently dispersed to impinge over a relatively wide area. Although the gas does not have to be introduced tangentially, it usually is, and it is thus possible to exploit higher arc voltages. The ideal operation described above can be impaired by any of a number of design or operating faults. For example, a too-short nozzle will permit the arc to pass through the entire nozzle passage and strike on the outer surface, thus wasting some of the energy it might have transferred to the gas. Or, most importantly, a small misalignment of the electrodes can cause the arc to strike preferentially at a particular spot on the anode, causing local overheating and burnout. Similarly, a local obstruction in anode cooling passages can cause premature burnout. It is generally found that the arc does not strike the anode uniformly over its entire periphery but rather at a number of points, perhaps randomly. With this in mind a number of designers (103, 113, 121) use a magnetic field to insure and control the rotation of the arc around the anode periphery.

Brogan (95) found that the plasma jet emitted from the 0.6-inch diameter nozzle of his generator had a large spacewise variation in the intensity of its light emission, i.e., the jet had a very hot core and sharp radial temperature gradients. Worse than that however was a 25-fold timewise variation in the intensity of light emission, this variation (at about 2,000 cps) apparently reflecting and amplifying variations in the power input to the arc. To cure these troubles it was found satisfactory to attach a plenum chamber to the anode nozzle, followed by a second nozzle, this one being converging-diverging with the throat small enough relative to that of the first nozzle to assure sonic velocity. The volume of the plenum chamber is made large compared with that of the gas flow in one period of oscillation. The discharge from the supersonic second nozzle is found to be uniform radially and to have had its timewise light-output-variation reduced from 25-fold to 2-fold. Even this seems rather large and perhaps could be improved with a steadier arc power supply. Since Brogan's use of the plenum chamber and second nozzle, all the AVCO plasma generators (114, 115) and many others (113, 97, 110, 123) have incorporated these features.

With reference still to the most common type of plasma jet generator, i.e., one having a rod cathode and nozzle anode, the most important design factors are the choice of electrode material and the details of provision for dissipating the tremendous heat loads to which electrode surfaces may be subjected. Experience has shown that the heat load on the anode is 4 to 5 times as great as on the cathode, so that design for effectively cooling it is most important. Most cathode designs provide for use of either a carbon or a 1%-thoriated tungsten rod, fitted into a water cooled holder. The graphite rods are usable to considerably higher power levels and current densities than are the tungsten but erosion and oxidation of the graphite can cause serious contamination of the plasma jet. At low power levels, the essentially non-consumable 1%-thoriated tungsten is the most common choice. In a NASA study of electrodes (118) (for N_2-stabilized plasma jets) and in some others it has been reported that 1000 amps is about a maximum for tungsten cathodes, with failure due to cracking and ablating at higher currents. The NASA rods were deeply bored for water cooling and probably the thermal shock produced by a steep temperature gradient accounts for the current limitation. Other experience has shown it possible to use tungsten rods at higher current densities than the 2300 amps/sq. in. of the NASA study. It is still probably true, however, that graphite cathodes can be pushed to higher loads to produce jets of higher enthalpy (103, 118). Some designers have suggested protecting the cathode with a sheath-flow of argon, but the use of argon for cathode protection constitutes a form of contamination of an air plasma jet.

The most exacting design problem in plasma generator technology is that of providing suitable geometry and cooling for the anode to maximize service life, minimize erosion (and stream contamination) and provide flow conditions suitable for the use to which the plasma jet will be put. If the arc chamber pressure is not much above atmospheric, the stabilizing gases inert (especially argon or helium), and the power level not above about 75 KW, the anode design is not very critical. In this case service life for many hours is possible with relatively low-velocity cooling water. Designs of this kind often feature replaceable tungsten, copper, or graphite nozzle inserts, usually of a simple cylindrical shape pressed into a water-cooled element (111, 119, 120).

When the plasma generator is required to operate on air, the chamber pressure to be appreciably greater than atmospheric, and the power levels to be into the megawatt range, anode design is extremely difficult. In order to insure efficient cooling the AVCO units designed for operation at 2 MW feature the minimum copper wall thickness (1/8-inch) compatible with strength requirements and thin annular cooling-water passages (40-50 mils) to insure the scrubbing action that can be provided by water at velocities in the neighborhood of 100 fps (95, 114, 115). In these units heat transfer rates have been as high as 10 to 20 $Btu/in.^2sec$. This may be compared with the maximum of 106 $Btu/in.^2sec$. achieved in boiling burnout heat-transfer studies (101) in which vortex flow of water inside a tube could be employed to take advantage of centrifugal force in scrubbing the tube wall to prevent local vapor binding. These anode chambers have been operated at pressures up to 40 atmospheres. Anode life time if usually about 15 seconds, even with the extremely good heat transfer that is achieved.

Because anode cooling is so important, attention is paid to providing good cooling water, free of solids and minerals, to prevent fouling heat transfer surfaces. In some installations distilled, deaerated water is used, with helium

repressurization after deaeration (110). Shepard and Boldman (118) found it possible to extend life by nickel plating the inner anode surface; apparently nickel is less susceptible to concentration of the arc at a small spot.

The most advanced design of air-stabilized plasma generators known to the authors are those developed by a Boeing group (113) and seen in September 1960. (Presumably similar advances have been made at AVCO and G. E. since the units at AVCO were seen a year previously). In the Boeing design of plasma generators to operate at chamber pressures to 500 or 1000 psi and power levels of 500 to 1000 KW a two-nozzle arrangement is employed, with intermediate plenum chamber. In contrast to the AVCO design, however, the anode is considerably longer, and cylindrical for about 80% of its length before a relatively small area reduction (to about 1/2 the cylinder area) at the throat. The cylinder is water cooled and the anode lead is a water-cooled copper tube of square cross-section spiraled around the outer shell of the anode water jacket. Thus the electrical lead provides a magnetic field to rotate the arc around the anode periphery. Since the cathode rod extends only about a third of the way into the cylinder the arc is obliged to spread over the cylindrical rather than the nozzle wall. Usually copper anodes have been used but graphite has also been satisfactory. Anode life for some of these units amounts to over an hour of accumulated run time. Cathodes have usually been copper or tungsten but the latest development is a water-cooled, toroidal copper-tube cathode. The outside diameter of the toroid is about 2 inches, the inside diameter of the anode about 3 1/2 inches, and judging by the absence of pitting on either surface, apparently the arc maintained rapid revolution about the generator axis.

B. FUELS RESEARCH LABORATORY PLASMA JET FACILITY

A question that had to be answered shortly after the start of this research was whether to buy or to build a plasma jet generator. The size of the unit required was dictated by the facility space available, the power supply, and the job to be done. There appeared to be no need for a unit to operate at more that 50 or 100 KW, since the plasma jets required would not have to be large. For the power supply it was found possible to obtain 5 dc generator-type arc welding machines at a nominal cost from the state surplus property office. Not more than two weeks work was required to make these operable. The combined output of these machines, 75 or 80 KW, set the size of plasma generator. At the time, units rated for these power levels were available commercially from Thermal Dynamics Corp. and Giannini Plasmadyne. However, these units were (and are) operated mainly on argon, helium, hydrogen, or nitrogen, usually exhausting to atmospheric pressure or less. Neither manufacturer would give any assurance that operation with air would be satisfactory, though it would be possible with replacement of electrodes after run-times in the order of minutes, perhaps. Thorpe (120) of Thermal Dynamics recommended operation of his plasma "torch" on nitrogen followed by addition in a downstream chamber of sufficient oxygen to exhaust an air-like mixture from a second nozzle. This idea was avoided because it would have added metering and mixing problems. A more important factor in a decision not to buy this equipment was the fact that the commercial units were not designed for operation at arc chamber pressures high enough to permit exhaust pressures up to 10 atmospheres.

At about this time AVCO put two plasma jet units on the market. The larger

of these had been used with air, was rated at 500 KW, had been operated at power levels to 1600 KW, and at high pressures. Because its cost was commensurate with this performance and because of our power limitations this unit was not suitable. The smaller AVCO equipment was rated at 5 KW and had been operated on nitrogen to 20 or 25 KW. There was no record then of its suitability for high pressure operation with air, so this unit did not seen suitable either. Thus there seemed to be no alternative to design and construction of a plasma generator here for this particular program.

The unit constructed is shown in Figure 1. It is patterned mainly after the AVCO model described by Brogan (95), but is on a smaller scale. Two water-cooled cathode holders were made. Each has a 1/2-inch o.d. outer tube of 0.05-inch wall thickness which carries away water that is introduced through an inner tube of 5/16-inch o.d., 0.035-inch wall. Each holder accommodates a 5/16-inch diameter rod. The holder for graphite rods is 4-5/8-inches long, that for tungsten 5-5/8-inches; the shorter holder allows starting with a longer graphite rod, to be moved in as it erodes away. Cathode holders are driven manually by a lathe tail-stock mechanism.

The stabilizing gas is introduced tangentially through two 0.078-inch diameter holes at the upstream end of the 1-7/8-inch diameter arc chamber. This gas feed section is separated by a Teflon insulator and pressure-sealing O-rings from the anode unit.

The anode consists of two copper flanges of 4-1/2-inch o.d. with a shaped, thin-walled copper nozzle connecting them integrally and with a cooling water guide clamped between them and separated from the outside wall of the nozzle by about 0.025-inch. Several different nozzle configurations that have been built are shown in Figures 1 and 2. The one shown in Fig. 1 was contoured to provide positive curvature in an effort to insure the vigorous scrubbing of the metal surface which would prevent bubble formation. Because a need for replaceability of these nozzles was expected, arrangements were made to have them produced by spinning from copper sheet. The spun section was silver soldered to the flanges. As it turned out, however, spinning did not produce a satisfactory unit, because the extreme changes in diameter required over a short length caused work fractures to occur in the metal. A nozzle spun from 1/16-inch copper sheet looked somewhat porous at the throat, the most critical part, and one spun from 3/32-inch sheet looked worse. The former of these was fitted with flanges and tested. It burned out after about 15 minutes operation at about 12 KW, with argon as the gas. Following repair by filling in its defects with silver solder and remachining, it was operated again for some time on argon but failed 10 or 15 seconds after changeover to air.

Subsequently four more anode nozzles have been made, all by machining. This is the M-series shown in Figure 2. These are alike in having 9/32-inch throats, 1/8-inch walls and longer throats than in the spun nozzle. The model M-2 provides the easiest means of assembly, since the cooling water guide is simply slipped over the nozzle, then the downstream flange is fitted and soft-soldered to the nozzle. Cooling is effective enough to prevent melting of this joint, at least for operation at power levels to about 25 KW. A nozzle of the M-1 type has been nickel plated on its inner surfact and will be tested after the M-2 presently installed has failed.

Figure 3 shows schematically the cooling water and gas supply systems. The cooling water system forms a closed loop, to permit use of distilled water. All but two small parts of the system are copper, brass, or glass. The two cast iron parts have been sprayed with a clear lacquer to minimize accumulation of rust that could foul heat-transfer surfaces. Before assembly of anode parts these surfaces are cleaned with dilute nitric acid. Cooling water is metered to each of three plasma-generator sections by rotameters and the total flow is indicated by an integrating water meter. Temperatures of the water to and from the generator sections are indicated on bi-metallic dial thermometers. The working fluid, argon or air as used to date, is metered by a calibrated porous plug flow meter and mercury manometers. Air is supplied from a carbon-ring compressor at pressures to 90 psig. For higher pressure operation bottled air will be used.

A schematic of the electrical system is shown in Figure 4. Only one of the five motor-generator dc welding machines is indicated. These are Lincoln Electric Type SAE 300 machines, rated for 300 amp continuous, 500 amp intermittent service. Their maximum output is about 16 KW each. Heavy copper jumpers are used on a control panel to connect as many as needed in series, parallel, or combinations of series-parallel arrangements. The input to welder motors is 3 phase, 60 cycle, 440 volt. An interlock requires the cooling water pump to be operating before power can be available to the welders. Not shown in Figure 4 is the circuitry for a high frequency arc starter (Miller Electric) which is connected across the plasma generator to aid in starting and stabilizing the arc. The electrical system is instrumented with an ammeter for each generator, another for their combined output to the plasma generator, plus a voltmeter across its electrodes; all these are indicating, not recording devices.

As shown in Figure 1, the plasma generator is mounted on a 1-inch thick flange which forms the end closure of a 5-ft. long, 30-inch diameter pressure vessel. This tank can be connected to the main laboratory vacuum system which can maintain an absolute pressure of 0.04 atmospheres. For operation down to 0.01 atm. a pump having a capacity of 60 CFM will be used.

The photographs of Figures 5 through 8 show the apparatus without the pressure vessel: Figure 5 shows the flange-mounted plasma generator and flow meters. Figure 6 is another view of the same plus the water pump and piping. Figure 7 depicts the power supply and controls. And Figures 8a and 8b show a low-power (9KW) argon plasma jet.

III. REVIEW OF TECHNIQUES FOR GAS TEMPERATURE MEASUREMENT

There are many good reviews of methods that have been used routinely and others that have been tried experimentally for the measurement of gas temperatures. Especially commendable are reviews by Broida (133), Bundy and Strong (134), Gaydon and Wolfhard (144), Kostkowski (155), Margrave (159), Penner (166) (on optical methods) and Warshawsky (176). Freeze (142) compiled an extensive bibliography of material on the subject up to 1951. The foregoing reviews are mainly dated from the period prior to need for measurement of plasma jet temperatures. Later writings, such as those by Dieke (139), Hurwitz (153) and others have been concerned with the high temperature regime. Section 4 of the bibliography at the end of this report lists 52 references on the general subject of gas temperature measurement. It seems fitting here to review essentially all the techniques, with only very brief mention of those which are inherently inapplicable at temperatures above 3000 or 4000°K.

It will be convenient to consider gas temperature measurement under six classifications, according to the bases of the techniques: (a) the thermal properties of a probe or sensing element, (b) the electrical properties of a sensing element, (c) the electrical properties of the gas (or plasma), (d) the thermodynamic properties of the gas, (e) spectroscopic techniques, and (f) optical techniques. In the literature there is often not a clear distinction between spectroscopic and optical techniques. Different authors (and sometimes even the same author writing at different times) have referred to the line reversal method, for example, as being in each of these two categories. Other authors do not use either of the terms. Methods often called optical are classified as "Radiance" methods by Broida (133) and "Radiation" methods by Margrave (159). In this review those methods will be called "spectroscopic" which depend on the changes in characteristics of spectral lines with temperature. These techniques require negligible self absorption of the spectrum lines, i.e., optically-thin gas samples, and usually require high-dispersion spectrographs for their successful use. Optical techniques, on the other hand, are those requiring a fairly high emissivity and absorption, either totally or over a selected spectral band. In general, these methods do not require high resolution spectroscopes. Rather, if a spectroscope is used it is as a filter and in most cases it could be replaced by a filter of suitable band width.

A. METHODS BASED ON THERMAL PROPERTIES OF PROBES

Since these methods all require a probe or sensing element to be immersed in the hot gas stream they cannot be used with very hot gases. These methods include some that are very common at lower temperatures, including gas thermometry, liquid thermometry, and those which exploit the expansion of metal rods or bimetallic strips.

B. METHODS BASED ON ELECTRICAL PROPERTIES OF PROBES

This category includes resistance thermometers, thermocouples and suction pyrometers, noise thermometers and nuclear resonance thermometers. While these instruments cannot be used for very high temperature pyrometry they do have some

relevance to the subject because of their use in defining that part of the International Temperature Scale from which extension is made by use of the Planck equation. The platinum resistance thermometer serves as a standard instrument between the oxygen point (-182.97°C, or 90.19°K) and the antimony freezing point (630.5°C, or 903.7°K). For the region between 630.5°C and the gold point (1063°C, or 1336°K) a platinum platinum-10% rhodium thermocouple serves as the standard. At present some authorities propose extending the range of the resistance thermometer to 1063°C as the standard interpolation instrument. The thermocouple would be eliminated in favor of an instrument capable of better reproducibility (and to eliminate a discontinuity in the scale). Aside from their use as standard instruments platinum resistance thermometers have been used at temperatures as high as 1870°K. Certain alloys have been used, in protecting atmospheres, for temperature measurements to nearly 3000°K. The normal range of platinum/platinum-rhodium thermocouples goes to about 2050°K for brief use. Iridium/iridium-rhodium couples have been used to measure engine exhaust temperatures as high as 2700°K. Some refractory metal thermocouples are capable of use at still higher temperatures (and a graphite-clay couple to 4000°K, reportedly (159)) but always with difficulty and with limitations due to uncertainties in corrections for radiation and conduction losses. The noise thermometer and nuclear resonance thermometer are capable of measurements to very high accuracy but limited to a low temperature range.

C. METHODS UTILIZING ELECTRICAL PROPERTIES OF THE GAS

These methods depend on the degree of ionization or the presence of free electrons in a gas or plasma, thus are limited on the low rather than the high end of the temperature range, i.e., to a range in which ionization is important.

1. Ionization Method.

If the gases in a flame or plasma are in equilibrium, if the concentration of ionizable constituents and their ionization potentials are known, and if the concentration of free electrons can be measured, as by determination of the conductivity of the plasma, then the temperature can be calculated from the Saha equation:

$$\log K = \log\left(\frac{x^2}{1-x^2}\cdot P\right) = \frac{-U}{4.573T} + \frac{5}{2}\log T - 6.49 + \log\left(\frac{g_A^+ \cdot g_e}{g_A}\right),$$

where U is the ionization potential of atom A, in cal/mol, g_A^+, g_A and g_e are the statistical weights of the ion, the atom and the electron, x is the fraction of the initial amount of A which is ionized and P is the sum of partial pressures, in atmospheres. Since in an air plasma the ionization potentials of all the constituents save NO are relatively high, total ionization will be strongly affected by the presence of any impurities, such as alkali metals, having low ionization potentials. For exploitation of this method of temperature measurement, it is customary to add potassium, sodium or cesium in small, controlled amounts, because their low ionization potential assures a supply of ions that will be a high fraction of the total. Measurement of the conductivity is made difficult by space charges and high potential gradients near the electrodes (144).

Furthermore, the accurate metering of metal into the plasma and accurate knowledge of the degree of ionization of all the components that may furnish ions pose difficult problems. In the region between 4000 and 8000°K, formation and ionization of NO in air is one of the processes that could materially affect the ion concentration, as would ionization of oxygen atoms in the high-temperature, low-density part of the range to be investigated. Further difficulty would be encountered if equilibrium among the ionized and non-ionized species were not attained.

2. Microwave Attenuation

This method is closely related to the previous one in that measurement of the attenuation of a microwave beam directed normal to an ionized jet is one method of evaluating the concentration of free electrons, for use with the Saha equation. Sugden and his associates used both the attenuation and conductivity methods to measure temperatures in rifle flashes and found values within 50°K of each other at about 2000°K (144). Others have claimed an accuracy of ± 60°K for temperature measurements by microwave attenuation in the 2000 - 3000°K range.

Descriptions of NACA microwave attenuation apparatus for measurement of flame temperatures has been given by Warshawsky (176) and by Rudlin (166a). They point out that the amount of injected alkali necessary to produce enough free electrons for attenuation is only about 1% of the amount required in line-reversal pyrometry. The attenuation equation, modified from the Saha equation, is:

$$\log (P'/P'') = F_M L \nu (\nu^2 + \omega^2)^{-1} \sqrt{N}\ T^{3/4} \exp (-q/2kT)$$

where P' and P" are the microwave power before and after passage through the flame or gas of depth L and temperature T, ω is the microwave frequency, ν is the electron-molecule collision frequency, N the volume-concentration of electron-producing atoms, q their ionization potential and k is Boltzmann's constant. Various methods of measuring L agree within about ± 10%. The calibration constant F_M is constant only under ideal conditions, but the temperature indication is relatively insensitive to variations in F_M, L, ν or N. The system is capable of high sensitivity and high frequency response, but on the other hand the range over which the response is linear with temperature is limited. Using an operating frequency of 24000 megacycles, Rudlin measured flame temperatures in the 2000-3000°K range. Warshawsky estimates the probable error in absolute temperature measurement by this method as about ± 3% of the measured value, if all systematic errors are carefully studied and appropriate corrections applied.

Rudlin chose 26K megacycles as an operating frequency assuming that attenuation would be greatest near the free-electron collision frequencies found in the medium. This frequency corresponded to a wavelength of 1.25 cm and Rudlin therefore studied flames of 4.5cm diameter, 50 to 75 cm long, to surround a microwave beam of 3 to 4 cm width. His temperature measurement was therefore an integrated average one. The beam width could certainly not be reduced to less than the wave length and to reduce the wavelength would mean, in view of their reciprocal relationship, increasing the microwave frequency. This is not feasible because at much above

the collision frequency the flame or plasma jet would be transparent to the microwave beam. Furthermore, the required wavelength would be greater at reduced pressure. Thus Rudlin's technique would be applicable only for finding an integrated temperature of a very large plasma jet. With a more elaborate set-up this difficulty might be overcome; for example, if the microwave beam greatly overflows the plasma jet, that part of it which passes through the jet should undergo phase shift as well as attenuation, so that it could presumably be examined without regard to the remainder of the beam. Also, the scattering of the beam by the plasma jet electrons might be made the basis of the electron-density measurement.

D. METHODS UTILIZING THERMODYNAMIC PROPERTIES OF THE GAS.

1. The relationship between vapor pressure P and temperature being given by the relationship:

$$\frac{d\ \ln P}{d(1/T)} = -\frac{\Delta H}{R} \quad ,$$

it is possible to base a vapor pressure thermometer on this equation and calibration at two points. Practically, however, such devices are limited to low temperature work, the highest temperature being about 1000°K, with mercury vapor as the working fluid.

2. Chemical equilibria shift with temperature in the same way as does vapor pressure, so it is theoretically possible to base a temperature measurement on the state of an equilibrated chemical reaction. No way to apply this principle to measurement of high temperatures appears to have been found, however.

3. Pneumatic pyrometers are devices with which advantage is taken of the flow relations for gases to obtain a temperature measurement. Using a critical flow nozzle the mass flow is limited by sonic velocity at the throat to a value dependent only on the entrance temperature T_e:

$$w_e = K_N \left(\frac{p_e}{\rho_e}\right) T_e^{-1/2}$$

where K_N is characteristic of the gas and the throat area, and p_e, ρ_e and T_e are the pressure, density and temperature at the entrance. In a more advanced form of this instrument two critical flow nozzles are used in series, with a cooling space between, to permit the mass flow to be determined at a lower, more convenient temperature in the second nozzle. This instrument is of course limited to temperatures that the first nozzle can withstand.

4. Calorimetry is surely the easiest and most used technique for obtaining an approximate value for the bulk temperature of a plasma jet. It requires simply an energy balance on the system and knowledge of the thermodynamic properties of the plasma, which is assumed to be in thermal equilibrium. Electrical energy input to the system is readily measurable and losses to the cooling water can be quite accurately evaluated if the water flow is low enough to assure

an appreciable temperature rise. Heat loss by radiation from the jet will be low unless contaminants or additives make it unusually opaque. Thus the accuracy of the bulk temperature measurement is largely limited by the accuracy of flow meter, and temperature, voltage and current indicators. It is assumed that all the energy not accounted for by measured losses goes to increase the enthalpy of the stabilizing gas. For argon and for air at temperatures of interest here the temperature-enthalpy relations are known to better than 1%. Calorimetry should, therefore provide a good check on other means of temperature measurement.

5. The interferometer and sometimes Schlieren apparatus, have been used in a limited way to determine temperatures in flames. These techniques depend on the relation between gas density, refractive index and temperature. The flame or hot gas is placed in one beam of an interferometer and the displacement of the parallel interference fringes may be photographically recorded. Theoretically the method should be applicable for measuring temperatures of plasma jets but there would be many practical difficulties.

6. The absorption of α-particles and X-rays is a function of gas density, thus of temperature and this phenomenon has been investigated in a limited way as a basis for flame temperature measurement (144, 159). In these experiments the methods have yielded mean flame temperatures with an accuracy of ± 5 to 10 percent. Theoretically it should be possible to use these methods with higher temperature gases or plasmas, but complications would be introduced by need to know the local effects of dissociation and ionization.

7. Velocity of Sound Methods. In an ideal gas medium the velocity of sound is given by the well-known expression:

$$C = \sqrt{\frac{\gamma RT}{m}}$$

where R is the universal gas constant, γ the specific heat ratio, m the molecular weight and T the absolute temperature. Temperature measuring techniques exploiting this relationship have been quite extensively developed and reported (134, 144, 147, 157, 159, 171) . The most commonly used arrangement has a transmitting transducer separated by a known distance from a receiver with circuitry for measuring continuously the delay time of an ultrasonic wave passing between them. These systems have the advantages of (a) a short time constant, i.e., capability of following rapid temperature changes and requirement of non-variant gas conditions for times in the order of, say, 10 to 100 μseconds, (b) freedom from errors due to radiation of the "thermometer" element (because it is the gas itself), and freedom from lag such as that due to the heat capacity of other kinds of thermometric elements. Among possible disadvantages is the fact that an average temperature over the path is measured. The biggest difficulty, however, is in establishing the relationship between sound velocity and temperature, i.e., in determining or estimating γ, R, and m of the gas when the temperature is high enough to cause appreciable dissociation and some ionization.

Most experimenters have used ultrasonic frequencies in these devices,

(in the megacycle range) though Gaydon & Wolfhard warn that too high frequencies may cause alteration in the specific heat ratio due to delay of the molecules in taking up vibrational energy. The frequency of oscillator output can be very accurately known. One method of determining the wavelength in the gas is to use shadow photography. Then c, the sound velocity is the product of λf. In an alternative to the photographic determination of λ, the repetition rate of a train of sound pulses is determined by the delay time between transducers, this delay being a function of spacing and sound velocity. The temperature measurement is made by comparing the phase difference of transmitted and received signals at a known initial temperature and following the manner in which the phase changes as temperature varies. These techniques have the disadvantage of needing transducers close to the high temperature gas. Presumably they could be water-cooled for work with plasma jets, but another method, developed by Suits for temperature measurement of arc discharges (up to 5500°K) seems superior for work with plasma jets as well (134). In this technique a photographic record is made on film in a cylindrical holder of the passage of a single sound pulse which passes through the hot medium. A rotating mirror sweeps the film with an image of the arc. The compression part of the sound wave front appears as a line of increased brightness on the film; from the slope of the wave front line and the known scan rate the sound velocity could be calculated. With a very fast spark discharge a sharp line was obtained and temperatures could be determined within ± 100°C at 5500°K.

E. SPECTROSCOPIC METHODS

Good discussions of the application of spectroscopy to measuring temperatures of flames, arcs, and other hot gases are given by Gaydon and Wolfhard (144), Broida (133), Dieke (139), Margrave (159) and Lochte-Holtgreven (157 a and b). Application to plasma jet temperature measurement has been reported in detail by Greenshields (145), Pearce (165) and Olsen (162).

1. Rotational Intensity Distribution

The most common spectroscopic thermometric technique depends on the distribution of intensities among the lines of the rotational fine structure of a band spectrum. The intensity I of a line is given by

$$I = CP\nu^4 e^{-E_r/kT}$$

where C is a constant for all lines of the same band, P is the rotational transition probability, ν is the wave number, E_r is the rotational energy of the initial state, k is Boltzmann's constant and T the temperature. With P and E_r determined experimentally or calculated from theory, it is possible to determine T from the measured intensities of two lines. In practice three methods have been used: (a) From the position of the maximum intensity in a single branch of the band the temperature may be determined, but seldom is because the results are of very low accuracy. (b) In the iso-intensity method, lines of equal intensity are found near the beginning and the tail of a branch; a "temperature" may be found even if self absorption precludes the use of other techniques, but this method also is not frequently used because it requires very high dispersion and

does not indicate whether a Maxwell-Boltzmann distribution exists. (c) The most popular method is to plot $\ln I - \ln(P \nu^4)$ against E_r, which should yield a straight line of slope -kT, as can be seen from the foregoing equation. This last method loses accuracy if line self-absorption is significant because this weakens the strong lines. But it shows up departures from equilibrium (by departures from linearity) and since it makes use of a number of lines it is not hurt by the chance blending of one or two lines.

Gaydon and Wolfhard (143, 144) have measured rotational temperatures of flames and hot gases extensively, finding OH-rotational temperatures equal to or a little below the theoretical flame temperature for H_2-O_2 and for alcohol and aldehyde flames with O_2. But for hydrocarbons and higher organics and especially for low-pressure flames very high rotational temperatures were measured; the extreme case was 10,000°K indicated for the low pressure oxy-hydrogen flame spiked with a trace of acetylene. They conclude that rotational measurements are useful for indicating the state of equilibrium and indicating the nature of reactions occuring but that true temperatures in reacting systems are not given. In equilibrated hot gases, however, OH bands do give a measurement of temperature, provided that self-absorption is substantially absent.

2. Vibrational Intensity Distribution

In a manner similar to that for rotational temperatures, the "vibrational" temperature may be determined from plots of $\ln(I_1/I_2)$ vs E_{vib}, if the vibrational transition probabilities are known from experiment or theory. The relative transition probabilities may be measured experimentally using a source of known temperature, a technique used for the CN violet bands (144). The method requires comparison of resolved rotational lines from different vibrational states, with the rotational distribution in each of the various states being the same Boltzmann distribution.

3. Translational Temperature by Doppler Broadening

The position of a spectral line is displaced to longer or shorter wavelengths depending upon whether the emitter is moving away from or towards the observer, a phenomenon known as the Doppler effect. In a hot gas the random movement of the emitters is a function of the temperature (among other things) so that by reason of the Doppler effect a spectral line becomes broader with increased temperature, thus:

$$b = 2\nu\sqrt{\ln 2}\sqrt{2RT/Mc^2} = 0.71(10)^{-6}\,\nu\sqrt{T/M}\ \text{cm}^{-1}$$

where b is the line half-width, M the molecular weight, R the gas constant, c the velocity of light and ν the wave number of the spectral line. Theoretically the method looks attractive for determining an effective translational temperature. It suffers, however, because in most cases pressure broadening, self-absorption and hyperfine structure of the spectral lines due to nuclear spin mask the Doppler effects. Gaydon and Wolfhard, (144) have experimented successfully with the method, at low pressure, using a Fabry-Perot interferometer

crossed with a large spectrograph. They conclude that the method is not suitable for normal temperature measurement.

4. Ornstein's Two-Line Method

If two spectral lines of the same element have excitation energies E_1 and E_2 and transition probabilities P_1 and P_2, then according to the Boltzmann distribution law the ratio of their intensities will be:

$$\frac{I_1}{I_2} = \frac{P_1}{P_2} \quad e^{-(E_1-E_2)/kT}$$

The transition probabilities are first determined by measuring the relative strengths of the two lines in a source of known temperature. Then the measurement can be used on unknown sources at any temperature theoretically but practically those of very high temperature. The method is not usually used with resonance lines because of self-absorption. It is hard to get sufficient excitation of the non-resonance lines at the temperatures of flames but readily possible with the high temperatures of arcs and plasma jets, and indeed Ornstein devised the method for measurement of arc temperatures (144). Use of the non-resonance lines is thought to make the method particularly subject to errors due to abnormal excitation and to self-absorption of emitted light by other molecules in the system.

In a modification of the technique applied to arc plasmas the emission strengths of several lines were compared quantitatively, using a reference carbon arc, followed by measurement of the absorption strength of the lines with a flash-tube as background. Then T was determined from a plot of the relation

$$\log \frac{J}{W \nu^3} = \text{const} - \frac{h\nu}{kT}$$

where J is the intensity in emission, W the equivalent breadth of the line in absorption and ν the wave number. This technique does not require independent knowledge of transition probabilities and is applicable to strong self-absorbed lines, e.g., resonance lines.

F. OPTICAL METHODS

These are methods based on the Planck distribution law and Kirchhoff's law. The former states that the radiant energy, $W_{B,\lambda}$ emitted by a black body at temperature T and wavelength λ is:

$$W_{B,\lambda} = c_1 \lambda^{-5} \left[e^{c_2/\lambda T} - 1\right]^{-1}$$

where c_1 and c_2 are first and second radiation constants. Easier to use is the

Wien equation:

$$W_{B,\lambda} = c_1 \lambda^{-5} e^{-c_2/\lambda T}$$

which for values of λT less than 0.312 cm°K is accurate to better than 1 percent but which can be seriously inaccurate for λ in the visible and temperatures in the plasma-jet range. For example, with λ = 5893 Å (centered on the NaD line doublet) the Wien "temperature" and the true temperature vary as follows:

True Temp.	3000	4000	5000	6000	7000	8000	°K
"Wien Temp."	3000.02	4001.4	5008	6026	7062	8129	°K

Kirchhoff's law relates the radiant flux density emitted or absorbed by a body at temperature T and wavelength λ to that emitted or absorbed by a black body at the same temperature and wavelength:

$$\frac{W_{\lambda T_g}}{W_{B,\lambda,T_g}} = \epsilon_{g,\lambda,T_g} = \alpha_{g,\lambda,T_g}$$

where ϵ_g and α_g are the emissivity and absorptivity of the gas at wavelength λ and temperature T_g and where it is assumed that the reflectivity of the gas is negligible.

1. Reversal Methods

In this most widely used type of gas temperature measurement a variety of techniques have been developed, some employing a continuous radiation over a fairly wide wavelength interval and others using discrete spectral lines, but in either case involving the observation of a standard comparison source through the hot gas. When continuous radiation is observed the method is called absorption-emission pyrometry, total reversal or the Kurlbaum method, after its first practitioner (1902), who proved the technique satisfactory for measuring the temperature of luminous flames. When a discrete spectral line is observed it is known as line reversal pyrometry. The line most commonly used is the NaD-line doublet at 5890 - 5896 Å although the lines of other alkali metals and also the OH radical have also been used. Good descriptions and evaluations of the technique are in the literature (131, 133, 134, 135, 142, 143, 144, 159, 166, 167, 169, 176, 177).

The method consists basically in focusing radiation from a comparison source of variable brightness at a point in the hot gas where the temperature is to be measured. With a second lens, this image, modified by absorption and emission of the hot gas through which the beam passes, is focused into a spectral dispersing unit, usually a spectroscope of medium resolving power. The radiation is detected

usually by eye but in some designs photographic film or a photocell is used. If the brightness of the comparison radiator is greater than that of the gas, absorption by the gas causes the lines to appear dark; and if the comparator is less bright its image will be reinforced by emission from the gas, to appear as a bright background line. Adjustment of the comparator brightness to the reversal or null position gives a brightness equaling that of black-body radiation at the gas temperature, as shown in the following relationships:

$$\epsilon_{\lambda,T_c} J_{\lambda,T_c} = \epsilon_{\lambda,T_g} J_{\lambda,T_g} + \left[1 - \alpha_{\lambda,T_g}\right] \epsilon_{\lambda,T_c} J_{\lambda,T_c} \qquad (1)$$

where $\epsilon_{\lambda,T}$ is the emissivity at temperature T and wavelength λ; $\alpha_{\lambda,T}$ similarly the absorptivity; $J_{\lambda,T}$ is the radiant intensity of a black-body at T and λ, and subscripts c and g refer to the comparison radiator and the gas. From eq. (1) it follows that

$$\alpha_{\lambda,T_g} = \frac{\epsilon_{\lambda,T_g} J_{\lambda,T_g}}{\epsilon_{\lambda,T_c} J_{\lambda,T_c}} \qquad (2)$$

By definition of a nonblack-body, $\epsilon_{\lambda,T_c} J_{\lambda,T_c}$ equals $J_{\lambda,T_{c,Br}}$ where $T_{c,Br}$ is the brightness temperature of the comparator. And from Kirchhoff's law $\alpha_{\lambda,T_g} = \epsilon_{\lambda,T_g}$, so that from eq. (2),

$$J_{\lambda,T_g} = J_{\lambda,T_{c,Br}} \qquad (3)$$

and the true temperature of the gas must be the same as the brightness temperature of the comparison radiator. If the Wien equation is applicable,

$$T_{c,Br} = \frac{T_c}{1 - \frac{\lambda T_c}{c_2} \ln \epsilon_c} \qquad (4)$$

and if λT is high enough to require the Planck equation,

$$T_{c,Br} = \frac{c_2/\lambda}{\ln\left[1 + \frac{\exp(c_2/\lambda T_c) - 1}{\epsilon_c}\right]} \qquad (5)$$

Comparing the Kurlbaum and line-reversal techniques, Penner (166) concludes: "1. Absorption-emission pyrometry will usually not give an exact value of the flame temperature because complete statistical equilibrium for all of the emitters may not be reached. However, even in the presence of some luminescence the

temperature measurement will usually not be greatly in error if a sufficiently wide wavelength band is used. 2. The line-reversal technique will give a correct value for the temperature if the emitters of radiation are excited thermally and are therefore in statistical equilibrium with the remaining gases. If statistical equilibrium does not exist, then the line reversal method may lead to results which are greatly in error."

Since use of any kind of reversal technique requires a comparison radiator capable of attaining a brightness temperature at least as great as that of the flame or gas being studied, it is necessary to consider what kind of background sources might be usable for measuring plasma jet temperatures. For most reversal applications a tungsten strip lamp is used. This is good for brightness temperatures as high as 2800°K, although calibration cannot be maintained reliable to that high a temperature, so the working lamp is compared, through suitable neutral filters, against a standard lamp that is not run above about 2000°K. For temperatures above 2800°K a carbon arc background has been used. In this laboratory Shipman (167) used a carbon arc bathed in mixtures of helium and argon for measuring reversal temperatures slightly above 3000°K. Variation of the He/Ar mixture ratio determined arc temperatures between 3000 and 3500°K; use of the inert atmosphere improved the stability and prolonged the life of the arc. (For achieving reversal it is more customary to use a wedge filter of varying optical density to attenuate the arc brightness.) Others (144) have found it possible to use carbon arc backgrounds to 3800°K. This would be in the range necessary for low temperature plasma jets.

For still higher temperatures some have used the sun as a background source, as Wilson et al (177) did to measure fluorine-hydrogen flame temperatures. The technique is not simple. Because sodium appears in the sun's spectrum, lithium instead was the additive used. The effective temperature of the solar disk is about 6000°K but this value is a mean for all wavelengths over the whole disk. There is a variation from 6700°K at the center to 5400°K at the outer edge, but these temperatures can be realized for reversal measurements only in ideal weather where absorption by the earth's atmosphere is minimal. However, Wilson was able to image the heliostat-controlled image of the sun onto a spectrometer slit and even to use the center-to-edge variation (along with a neutral filter) for finding a reversal point, thus determining the maximum flame temperature for $H_2 - F_2$ at 4300 ± 150°K. The technique appears reasonable as a secondary check on plasma jet temperature measurements, where the primary measurement would necessarily be one not dependent on good weather.

The reliability of NaD-line reversal measurements has been strongly challenged in the past on the grounds that the electronic excitation temperature it measures is not necessarily the same as the translational temperature of the gases. In the case of flame zones where equilibrium does not prevail among the several degrees of freedom the objection is often valid and reversal temperatures are sometimes higher than theoretical flame temperatures. But in this non-equilibrium case, the term "temperature" either is meaningless or needs to be qualified with respect to the type of temperature meant. In this case "temperature" measured by other methods would have to be similarly qualified. When equilibrium prevails, as in the region above a flame zone, or in a plasma jet, departure from equilibrium specific to the sodium may still be possible. For one example, when the metal is added in small amounts to an optically thin gas the Na atoms

will lose energy by radiation; Gaydon & Wolfhard (144) estimate from comparisons of the radiative life and the collision life for deactivation of excited Na that the reversal temperature would thus be too low by about 3^{o} at 1 atm, 27^{o} at 1/10 atm, and 160^{o} at 1/100 atm., for a gas at 2000^{o}K. The error would be reduced by abundant addition of sodium. Finally, the reversal temperature depends on the relative populations of excited and unexcited Na atoms, so that the time required for excitation and de-excitation is important. On this point Gaydon and Wolfhard indicate that the time lag would not be more than a few microseconds. At the higher temperatures of plasma jets there can be little doubt that a sodium additive would be in equilibrium with the plasma constituents in a matter of a few microseconds.

2. Two-Color Pyrometry

When the gas emits continuously over the range of each of two narrow-pass filters and the relation of the absorption coefficients in the two ranges is known, the determination of brightness temperature at each of the wavelengths suffices to determine gas temperature. The method was developed by Hottel and Broughton (151) for measuring temperatures of luminous flames. The absorption coefficient $\overline{k_\lambda}$ of luminous flames was found to be a simple power function of wavelength.

$$k_\lambda = k/\lambda^{\alpha}$$

Then, for a flame path of length L

$$\epsilon_\lambda = 1 - e^{-kL/\lambda^{\alpha}}$$

Using a filter that transmits over only a fairly narrow band width, in the red, say, λ_r, it follows from the Wien equation (when it applies) that

$$\frac{1}{T_r} - \frac{1}{T} = -\frac{\lambda_r}{c_2} \ln (1 - e^{-kL/\lambda_r^{\alpha}})$$

where T is the true and T_r the red-brightness temperature of the flame. A similar equation for T_g, the green-brightness temperature at λ_g, gives the second relationship necessary for eliminating kL and determining T, if α is known. Hottel and Broughton found $\alpha = 1.39$ from measurements by the two-path method on various numbers of amyl acetate flames arranged to give a known kL variation. The method was used on flames with an emissivity as low as 5% with good accuracy; the permitted lower limit of ϵ was not established.

Gaydon and Wolfhard (144) rate the two-color method as less reliable than the two-path, Kurlbaum or line-reversal methods, mainly because of the difficulty of knowing the dependence of emissivity on wavelength. They point out, however, that if brightness temperatures at three colors, i.e., three wavelengths, are

measured it is possible to eliminate α among the three equations, so that only the form of the ϵ_λ, α relationship is assumed, and not the absolute values. Although Gaydon and Wolfhard recommend this procedure for use with optically rather thin flames the α value for which is hard to determine, this recommendation appears to be misleading. Accuracy goes down with decreasing optical depth regardless of whether two or three wavelengths are used; but three readings of brightness should of course yield higher accuracy than two.

A group at the University of Wisconsin (126) has perfected the two-color and three-color techniques for measurement of the rapidly varying temperatures of gases in an I.C. engine cylinder. They used a monochromator to disperse the beam from the gases onto either two or three separate photomultiplier tubes the signals from which were displayed on a CRO. The amplifier-oscilloscope system was calibrated by use of a standard tungsten strip lamp at known brightness temperatures. For the three-color procedure this group added iodine to the gases, since it gives three nicely located lines free from interference by other emitters and since it apparently does not affect the reactions going on in the gas.

Since two-color pyrometry does not require a background source brighter than the gas, it should be applicable for plasma-jet temperature measurement, provided that the plasma jet is opacified by the addition of an agent that would either make it a gray body or provide strong emission in two or three selected bands.

3. Two-Path Method with Comparison Source

This method, though requiring a comparator, does not require it to be as bright as the gas, so it too could be applied to plasma jet temperature measurement. The exact techniques have been varied by different workers, using different means for isolating a relatively narrow spectral band (monochromators, filters), different sensing devices (the eye, bolometers, thermocouples, photocells) and different regions of the spectrum, through the visible and into the near infrared. Three separate brightness or intensity measurements are made: (a) One of the comparison source alone, I_c (b) the comparator plus the hot gases, I_{cg}, and (c) the hot gases alone, I_g, each at the same wavelength, λ. Thus:

$$I_{cg} = I_c (1 - \alpha_g) + I_g$$

from which

$$\alpha_g = \frac{I_c + I_g - I_{cg}}{I_c}$$

Since monochromatic absorptivity equals emissivity if the system is in equilibrium, $\alpha_g = \epsilon_g$. Also $I_{Bg} = I_g / \epsilon_g$, where I_{Bg} is the intensity of a black body at gas temperature. Then

$$I_{Bg} = I_c \frac{I_g}{I_c + I_g - I_{cg}}$$

and from this plus the Planck equation,

$$T_g = \frac{c_2/\lambda}{\ln\left\{1 + \frac{I_c + I_g - I_{cg}}{\epsilon_c I_g}\left[\exp\left(c_2/\lambda T_c\right) - 1\right]\right\}};$$

or if λT is small enough to make the Wien equation hold:

$$T_g = \frac{T_c}{1 + \left(\frac{\lambda T_c}{c_2}\right) \ln \frac{I_c + I_g - I_{cg}}{\epsilon_c I_g}}$$

The comparator source would be one of known emissivity and its brightness temperature is most readily obtained by comparison, using a disappearing filament pyrometer, with a standard lamp. But it is important to note that although the background does not have to be as hot as the gas, no accuracy is obtained unless I_{cg} is significantly greater than I_g, which means that T_c cannot be very much lower than T_g.

The above technique is sometimes called the "Schmidt" method, after an early practitioner. Silverman (170) used this technique for measuring flame temperatures, taking advantage of the high emissivity of CO_2 in the near infrared and employing a tuned 10 cps chopper-amplifier arrangement so that his bolometer detector responded only to the oscillating signal. Tourin (173) and his coworkers at Warner and Swasey Co. have perfected this type of measurement, using it for measuring temperatures of combustion chamber exhausts. Arrangements for automatic recording have been incorporated. Their use of infrared emission has the advantage of assured freedom from errors due to nonequilibrium effects. It was pointed out in the discussion of D-line reversal that in the visible the time required for radiative decay is only about 100 times as long as that required for equilibration between vibrational and translational excitation, so that an error in temperature measurement would result, the greater the lower the pressure. In the infrared, however, the radiative time constant is on the order of 10,000 times longer than that required for the vibrational-translational equilibration.

4. Two-Path Method with Mirror

Placement of a mirror behind the gases makes it possible to measure the radiant energy first from the gases directly, I_g and also that of the gases reflected by the mirror, I_m. The intensity of the double-path radiation, I_m, depends upon the absorptivity of the gases α_g and the reflectivity, ρ, of the mirror. The following relationship then holds:

$$I_m = I_g \left\{ 1 + \rho \ (1 - \alpha_g) \right\} .$$

Then

$$\alpha_g = 1 - \frac{I_m - I_g}{\rho I_g}$$

For a narrow wavelength region if the emitters are in equilibrium, $\alpha_g = \epsilon_g$, the gas emissivity; and I_{Bg}, the intensity of a black body at gas temperature, is given by

$$I_{Bg} = \frac{I_g}{\epsilon_g} = \frac{I_g}{1 - \frac{I_m - I_g}{\rho I_g}}$$

If intensity is identifiable with a black body brightness temperature, the above constitutes an answer. Using the Planck equation gives

$$T_g = \frac{c_2/\lambda}{\ln \left[1 + \left(\frac{A}{\lambda 5} \right) \left(\frac{I_g + I_{go} - I_m}{\rho I_g^2} \right) \right]}$$

A separate determination of A, which incorporates the first radiation constant with an instrument constant, must be separately determined from calibration against a standard source (132).

Hett and Gilstein (147a) have described a photoelectric pyrometer incorporating the mirror doubling of path length and an interference filter of 150 Å half width, which they used successfully for measuring the rapidly varying temperature of a pulse-jet flame. Two photomultiplier tubes were used, placed in slightly displaced paths so that the view of one tube only was conjugate to a front-surfaced mirror behind the flame.

As with descriptions of other optical (and spectroscopic) methods given here there is an implicit assumption that the gas being studied constituted an isothermal region. Actually, of course, most flames and plasma jets are far from isothermal but can be fairly well approximated by a model in which two, three or more isothermal zones are assumed. (By use of a converging-diverging nozzle it is possible to get a supersonic jet of essentially uniform temperature downstream of a plasma generator plenum chamber). Measurements made on non-isothermal regions introduce considerable complications with any method if the temperature is too high to permit introduction of either a probe or a device for local introduction of an opacifying additive. In consideration of the two-path method however, Penner (166) reports that calculations by Bundy permit the conclusion that the method would yield results corresponding closely to the actual temperature of a hot central core of gas if the product $k\rho L$ (gas emission

coefficient x emitter density x path length) was small enough so that the intensity ratio of the double and single path would be of the order of $\sqrt{2}$.

5. One Wave Length Interval Pyrometer

This method is simply the use of an optical pyrometer, of the disappearing filament type, in much the same way that it is used for measuring temperatures of liquids and solids which are gray bodies. If the spectral region chosen is narrow and the gas emissivity does not vary too markedly with temperature this technique can be used at least for getting relative temperature measurements, after the pyrometer has been calibrated against a source of known temperature and emissivity. The method has been used for measuring temperatures of jet engine exhausts saturated with sodium for complete opacification, and by measuring the energy at the center of the D-line doublet. The blackbody assumption can of course be checked by comparing the intensity of a single and a mirrored path through the gas.

6. Wavelength of Maximum Radiant Energy (134)

If the Planck equation is differentiated with respect to λ and the derivative set equal to zero one obtains the following relationship between the temperature and the wavelength of maximum radiant energy emission:

$$T = \frac{ch/k}{4.9656\lambda_{max.}} = (0.2898/\lambda_{max.})\ 10^8, \text{ (where } \lambda \text{ is in } \mathring{A}).$$

It has been suggested that this relationship can be used as a means of temperature measurement, but serious drawbacks suggest that it will never become a popular technique. Most serious is that the above relation is valid only for a gray emitter, and that there is consequently need for independent knowledge of the variation of emissivity and instrument response as functions of both temperature and wavelength. A second serious difficulty is sufficiently accurate determination of the wavelength of maximum intensity. The peak of the curve is rather flat, so that a 6 percent change in wavelength produces only a 1 percent change in intensity. The above equation shows that the temperature can be known only as accurately as $\lambda_{max.}$. It is apparent that if at each of two temperatures, say 2500° and 8000°K, $\lambda_{max.}$ can be located within 200 $\mathring{A}$, the error at 2500° will be 40° and at 8000°, over 400°.

7. Total Intensity Method

The temperature of an emitter of known total emissivity ϵ may be determined by measuring the total radiant flux density per unit solid angle, since, by the Stefan-Boltzmann law,

$$I_{total} = \epsilon\, \sigma\, T^4$$

where I_{total} is for all wavelengths. Since the total emissivity of plasma jets

is presently an unknown function of their operating variables, the utility of the method is restricted to its use as a control after empirical establishment of the relation of its reading to that of a valid measuring device.

8. Residual-Ray Pyrometry

If the value of $\lambda T \geq 77$ cm°K the Rayleigh-Jeans approximation for emission from a blackbody is good within one percent:

$$I_\lambda = c_1 T / c_2 \lambda^4$$

Thus for 1% accuracy at 4000°K one would have to work at $\lambda = 192$ microns. Since it would be difficult to find a suitable spectrometer-detector combination for this far infrared wavelength it would probably be advisable to use a wavelength of 25μ or less, recognizing that the Rayleigh-Jeans relationship would be only a first approximation, to be improved by the Planck law. Early in this program it appeared there would be a great advantage in utilizing the far infrared for temperature measurement, because of a report that relatively small volumes of air (say, 1 cm thick) gave blackbody radiation. More recent and more complete evidence from AVCO (private communication with Dr. Raymond L. Taylor) negates this possibility. If in some relatively narrow band of the IR a strong emitter were found it might be usable, but at present none is known for sure. The 15μ CO_2 band is strong at about 3000°K but how well it would survive at the higher plasma jet temperatures is not known.

A convenient way to isolate radiation in a fairly narrow band at long wavelength would be to take advantage of the peculiar reflectance characteristics of certain crystalline materials, i.e., to use "Reststrahlen" or "Residual-Rays". For many years a number of materials have been known to exhibit this property of selective reflectivity, being highly reflective in one or more narrow wavelength bands and highly absorptive in the remainder of the IR spectrum. Bell (127) has experimentally determined the reflectivity of a number of common materials in the near infrared, 1 - 15μ, as a preliminary to the study of far IR reflectivity; he found reststrahlen for some of the materials, but only the well-known 9μ band for quartz that might be useful. Kimball (154) recently presented an analytical study showing how electromagnetic theory applied to the interaction of radiation with the electrons and molecules of a reflecting substance could be used to predict probable reststrahlen. He then proved the point by experimentally finding the predicted reststrahlen for some half a dozen newly prepared synthetic crystals, in the 1 - 25μ region. He found, for example, that titania oxidized is .7% reflective at 4μ, 3% at 10.5μ and 80 - 85% at 16 to 19μ. For isolation of a narrower band, quartz would still probably be better since its 93% reflective band at 9μ has a half-width only a little over 1μ wide and the reflectivity at shorter wavelengths is only 2 to 10%. Quartz shows another residual ray peak at 20.75μ which might be used. In any case, isolation of the reststrahlen simply requires successive reflections from polished surfaces of the crystalline material. The isolated residual ray would then be focused onto an IR detector.

9. Photoelectric Pyrometers

This heading does not imply a temperature-measuring technique per se, but rather the use of photoelectric detectors for improving the sensitivity, shortening the time constant or signaling a recorder in measurements by the methods already described.

(a) Silverman (170) used a Perkin-Elmer 12c spectrophotometer with a Baird ac bolometer and a 10 cps chopping arrangement in his modification of the 2-path method with a comparison source.

(b) The Wisconsin group (126) made a high-speed 2-color pyrometry arrangement for measuring IC engine gas temperatures by using a Zr lamp source, a prism spectrograph, selected 931A photomultipliers as detectors at different wavelengths, and a 1P22 tube as a monitor of the continuum at 7200 Å.

(c) Hett and Gilstein (147a) applying the 2-path with mirror method to measurement of rapidly varying pulse-jet gas temperatures, used two 1P21 photomultipliers. Their signals from the single and double paths were displayed on 5-inch dual-beam oscilloscopes and recorded by a 35-mm drum camera. The monochromator was an interference filter of 150 Å half width.

(d) Warshawsky (176) describes a self-balancing line reversal pyrometer developed by Buchele at the NACA Lewis Labs. In this a phototube actuates a servo system to vary the brightness of a comparison lamp until a match is achieved.

(e) Chicago Midway Labs (172) photoelectric pyrometer is used mainly for measuring surface temperatures of materials exposed to plasma jets. In this system a selenium detector feeds its signal to a Consolidated recording galvanometer which has three overlapping channels, to permit covering a brightness range of 1000-fold variation. The technique for making the system monochromatic is not clearly described.

(f) Blum's (130) recording optical pyrometer was also built for measuring brightness temperatures of materials exposed to plasma jets. Its milliseconds response time is made possible by use of a 6570 phototube (not a photomultiplier) and a Philbrick K2-W amplifier, the output either being read on a meter on the instrument or fed to an external recorder. It is said to be good to ± 20°K at > 2200°K routinely, and good to ± 10°K in the spectral region of a recent calibration.

(g) Trombe (174) has indicated that several researchers in France have perfected photoelectric pyrometers, but he does not give details.

(h) Of greatest interest here are the photoelectric pyrometers under development at the National Bureau of Standards, because we have adopted one feature of an NBS design. In the model described (briefly) by Kostkowski (155) the classical disappearing filament pyrometer was modified in two respects. One was reception of the signal by a high quality photomultiplier tube, the 7237, with recording of its output on a strip-chart recorder. The other was the insertion into the light beam of a rotatable glass block. In its normal position the block allowed the

light beam from the pyrometer filament and from the target to fall on a slit which precedes the photomultiplier. In its rotated or tilted position the filament image is thrown off the slit and only the target image passes. The Bureau people subsequently abandoned the glass block idea, wishing to avoid the need for corrections due to its uncertain optical properties. The main aim of the NBS work is to improve the precision and accuracy of temperature measurement to the limit that photosensitive devices make possible; extension of the upper limit of their pyrometry to about 6000°K is a secondary aim. In the pyrometer shown by R. D. Lee of NBS to one of the authors the glass block is not used and instead the pyrometer filament is moved into and out of the beam from the target. The movement required is only a few thousandths of an inch and is made by hand; the system is a dc one.

IV FUELS RESEARCH LABORATORY PYROMETER

A. PRINCIPLES OF THE METHOD

Presently favored here as the primary method of measuring temperatures is a modification of the 2-path method with a mirror. The modifications on older versions of this optical technique consist of (1) use of a multiplier phototube for fast response and greater sensitivity than is possible with the human eye; (2) attenuation of the energy from the mirror-doubled path by use of a neutral filter of about 50% transmissivity; (3) alternating display of the signals from the single path and the attenuated double path on an oscilloscope, together with display of a pyrometer filament signal to match one of these; and (4) use of a very narrow band interference filter, 7.2 Å half width, to get a close approximation to monochromaticity. The most important modification is the second one, since it provides a nearly null method for comparing the brightness of the single and doubled path. A chopper is used to provide an ac square wave at 13 cps (or at other frequencies or dc as desired).

The technique provides the means necessary for measuring emissivity and temperature of the plasma jet or flame. In the absence of sufficient opacity due to continuum radiation, - and this is the expected case if the plasma jet is not exceedingly "dirty", - it will be necessary to introduce an opacifying additive. Sodium has been selected, to be introduced by means of a NaCl vaporizer. The spectrum interval chosen for the measurement is therefore a band centered between the peaks of the sodium D-line doublet. The doublet peaks occur at 5889.97 and 5895.93 Å. A Baird interference filter used in our pyrometer peaks at 5892 Å and has half-width of about 7.2 Å. The filter will thus pass part or most of the energy from each of the doublet lines.

Assuming for the present that the plasma jet region observed is an isothermal gas at temperature T, the radiant emission, I_1, from it at wavelength λ is:

$$I_1 = I_B \epsilon_g$$

(The subscript λ has been omitted from the terms, which are monochromatic values) where I_B is the emission from a black body at λ and T and ϵ_g is the emissivity of the gas.

With mirror doubling of the path length the intensity is not doubled, but modified by the reflectance, ρ of the mirror and the transmittance, τ_g, of the gas. In the present application of the technique the emission signal is further attenuated by a neutral filter τ_{50}, having approximatedy 50% transmittance at the λ of 5892 Å. Thus:

$$I_2 = \tau_{50} \left[I_B \epsilon_g + I_B \epsilon_g \rho \tau_g \right]$$

The gas transmittance, τ_g, is equivalent to $1 - \alpha_g$ if the gas reflectance is negligible and, if the emitters are in equilibrium, to $1 - \epsilon_g$. Then

$$I_2 = \tau_{50}\left[I_B\,\epsilon_g + I_B\,\epsilon_g\,\rho(1 - \epsilon_g)\right] = \tau_{50} I_B\,\epsilon_g\left[1 + \rho(1 - \epsilon_g)\right]$$

The ratio of the double and single path signals is then:

$$R \equiv \frac{I_2}{I_1} = \tau_{50}\left[1 + \rho(1 - \epsilon_g)\right]$$

The gas emissivity, ϵ_g at λ, is

$$\epsilon_g = 1 - \frac{R/\tau_{50} - 1}{\rho} = \frac{\rho + 1 - R/\tau_{50}}{\rho}$$

Given the emissivity, the gas temperature can be found by comparison of its radiant intensity with the brightness of a tungsten pyrometer filament. Let T_B be the brightness temperature of a filament having the same brightness as the flame viewed through any neutral high range filter(s) of transmittance τ_H:

$$c_1\lambda^{-5}\left[e^{c_2/\lambda T_B} - 1\right]^{-1} = \epsilon_g\,\tau_H\,c_1\lambda^{-5}\left[e^{c_2/\lambda T_g} - 1\right]^{-1},$$

This yields

$$\frac{c_2}{\lambda T_g} = \ln\left\{\epsilon_g\,\tau_H\,(e^{c_2/\lambda T_B} - 1) + 1\right\}$$

$$T_g = \frac{c_2/\lambda}{\ln\left\{\epsilon_g\,\tau_H\,(e^{c_2/\lambda T_B} - 1) + 1\right\}}$$

or

$$T_g = \frac{c_2/\lambda}{\ln\left\{\tau_H\left(\frac{\rho + 1 - R/\tau_{50}}{\rho}\right)(e^{c_2/\lambda T_B} - 1) + 1\right\}}$$

B. ERROR ANALYSIS ON THE MODIFIED MIRROR-BACKGROUND METHOD

The special merit of the idea leading to the last equation above is apparent only when an error analysis of the method is made. That analysis depends on carefully distinguishing two sources of error. When the pyrometer lamp filament is matched against a target there is a random error in brightness matching which

is of the order of 1% with the human eye, 0.1% with a photocell. With careful calibration using a tungsten ribbon secondary standard, a pyrometer filament temperature-current relation may be established which minimizes the effect of this matching error, but it may contain a systematic error in the temperature scale; and the change in this error over a moderate interval of brightness temperature T_1 to T_2 may be assumed proportional to the interval. That is to say that the temperatures of two targets which are reported by optical pyrometry to be the same may both be in considerable error, but their difference is known with a small probable error ϵ_m (the "matching" error); whereas when two temperatures are reported to be T_1 and T_2, their difference is known with a much larger probable error, proportional to $\epsilon_m + \alpha(T_1 - T_2)$. Changing from use of the human eye to use of a photocell greatly reduces ϵ_m, but it has no effect on most of the factors contributing to α. To develop some feeling for the magnitude of α assume that the calibration curve of an optical pyrometer operating with an effective wavelength of 0.589μ is correct at 1900K and 1°K in error at 2000K, a not unreasonable assumption. The ratio of filament brightness at the two temperatures is

$$\left[\frac{I_{2000}}{I_{1900}}\right]_{true} = e^{-\frac{14388}{0.589}\left(\frac{1}{2000} - \frac{1}{1900}\right)} = e^{+0.643} = 1.9$$

$$\left[\frac{I_{2000}}{I_{1900}}\right]_{apparent} = e^{-\frac{14388}{0.589}\left(\frac{1}{2000} - \frac{1}{1900}\right)}$$

$$= e^{+0.643\ (1.01 \times 2000/2001)} = 1.9116$$

By letting $(I_2 - I_1)_{apparent} = (I_2 - I_1)_{true}\ (1 + \alpha)$, one finds that α based on the above example is 0.013. We shall use 0.01 in the numerical example later. If R is the ratio I_2/I_1 of two intensities, application of the above discussion gives, with all errors assigned positive,

$$R_{apparent} - R_{true} \equiv \Delta R = R\,\epsilon_m + \alpha(R - 1).$$

Although the mirror-background principle yields

$$\frac{1}{e^{c_2/\lambda T_B} - 1} = \frac{\tau_H \epsilon_g}{e^{c_2/\lambda T_g} - 1},$$

where ϵ_g and τ_H are the gas emissivity and high-range-screen transmittance, respectively, it will suffice for the present error-analysis to use Wien's rather than Planck's law, giving

$$\frac{1}{T_g} - \frac{1}{T_B} = \frac{\lambda}{c_2} \ln \tau_H \epsilon_g \qquad (1)$$

Gas emissivity is given, as before, by

$$\epsilon_g = 1 - \frac{R/\tau_{50} - 1}{\rho}$$

Inserting error terms, without regard to sign, gives

$$\frac{1}{T_g + \Delta T_g} - \frac{1}{T_B + \Delta T_B} = \frac{\lambda}{c_2} \ln \left\{ \tau_H (1 + \epsilon_H) \left[1 - \left(\frac{\frac{R + R\,\epsilon_m + \alpha(R-1)}{\tau_{50}(1+\epsilon_{50})} - 1}{\rho(1+\epsilon_\rho)} \right) \right] \right\} \qquad (3)$$

Here ϵ_H, ϵ_{50} and ϵ_ρ are the fractional errors in the transmittance of the high-range screen, the transmittance of the "50%" screen, and the reflectance of the background mirror, respectively; and ΔT_g and ΔT_B are the errors in T_g and T_B. Replacing $1/1 + \epsilon$ by $(1 - \epsilon)$, ignoring signs, replacing $\ln (1 + \epsilon)$ by ϵ, and subtracting (2) from (3) gives

$$\frac{\Delta T_g}{T_g^2} - \frac{\Delta T_B}{T_B^2} = \frac{\lambda}{c_2} \epsilon_H + \frac{(\epsilon_{50} + \epsilon_m)(R/\tau_{50}) + \alpha[(R-1)/\tau_{50}] + \epsilon_\rho[(R/\tau_{50}) - 1]}{\rho - (R/\tau_{50}) - 1} \qquad (4)$$

Since $[(R/\tau_{50}) - 1]/\rho$ is, from the derivation, equal to the gas transmittance, $(R/\tau_{50}) - 1$ lies between ρ (when the gas is transparent) and 0 (when the gas is black); and the effects of the various errors vary greatly with variations in R/τ_{50}, τ_{50} and ρ. The worst situation, -and unfortunately the one anticipated, -occurs when the gas transmittance is very high. For purposes of discussion assume mirror reflectivity $\rho = 0.9$, gas emissivity $\epsilon_g = 0.04$ (making $[(R/\tau_{50}) - 1]/\rho = 0.96$, or $R/\tau_{50} = 1.864$) (this is perhaps too low a gas emissivity to make the method under discussion operable); and since the measurement of T_B is conventional and subject only to the usual errors of pyrometry, the contribution of its error will be omitted from the numerical analysis. From (4)

$$\frac{\Delta T_g}{T_g^2} = \frac{0.589}{14387}\left[\epsilon_H + \frac{(\epsilon_{50} + \epsilon_m)1.864 + \alpha(1.864 - 1/\tau_{50}) + \epsilon_\rho(0.864)}{0.9 - 0.864}\right]$$

$$\Delta T_g = 0.41(T_g/100)^2\left[\epsilon_H + 51.8(\epsilon_{50} + \epsilon_m) + 27.8\,\alpha(1.864 - 1/\tau_{50}) + 24\,\epsilon_\rho\right] \quad (5)$$

One now sees the merit of the use of the τ_{50} transmission glass as well as the demands on the accuracy with which the characteristics of the system must be known. For example,

(1) A one percent error in knowledge of transmittance of the high-range screen ($\epsilon_H = 0.01$) at a gas temperature of 8000°K introduces an error of 0.41 x 6400 x 0.01 = 26°K, entirely acceptable but capable of reduction.

(2) But similar error in the transmittance of the "50%" screen would introduce a temperature error 52 times as great, or 1360°K; and a fractional error of 0.001 in τ_{50} would introduce 136°, 76°, and 34°K errors at gas temperatures of 8000, 6000, and 4000°K.

(3) The "matching" error ϵ_m must be kept lower than is possible with the eye, and a photocell matching is necessary.

(4) The error due to α could be eliminated completely by use of a "50% screen" with a transmittance of 1/1.864 = 0.536; and the optimum transmittance would increase to 0.56 if the mirror reflectance were 0.8 instead of 0.9. The screen planned for use has $\tau_{50} = 0.48$. The temperature error due to α at T_g= 8000°K is then 0.41 x 6400 x 27.8 x .01(1.864 - 1/0.48) = 157°K. This would probably be excessive, and either the brightness-current relation of the pyrometer filament would have to be determined with enough more care to bring α down to below 0.01, or the gas would have to be more nearly opaque. One sees the disastrous consequences of having no 50% transmission screen present; without it ($\tau_{50} = 1.0$) the α-error would be nearly 9 times its already excessive value. This discussion suggests that we may need to replace the present 50% screen by one with a nearer-optimum transmittance of about 0.55.

(5) The temperature error due to mirror reflectance error would be 63°, 35°, and 16°K at gas temperatures of 8000°, 6000°, and 4000°K, if $\epsilon_\rho = 0.001$.

The above example indicates that the transmittance of the high-range screen need be known to about 1/2%, that the reflectance of the mirror and the transmittance of the "50%" screen, however, should be known to 1 part in 1000. Such accuracy is at the limit of present spectrophotometer performance. Different laboratories claiming 0.1% accuracy are differing by 2% in values reported for the transmittance of our screen; and we are having to develop a technique of doing it ourselves. The example also indicates that the matching error ϵ_m must be kept down to as near 0.001 as possible; and this presents difficulties when a narrow-band-pass interference filter is used to give a near-monochromatic measurement because the light available is so weak that photo-tube noise becomes a problem.

The difficulties are greatly reduced if the gas emissivity is increased; and the above example suggests that measurements on a gas made 10% black in the wavelength-range of the filter by an additive should be relatively straight forward. In a sense the problem becomes one of finding to what limiting value of gas opacity the modified-mirror is applicable.

C. PYROMETER CONSTRUCTION

Figure 9 shows schematically the temperature-measuring arrangement and the physical relationship of pyrometer components to the pressure-vessel end-flange on which the plasma generator is mounted. The optical path for a direct signal from the plasma jet proceeds past chopper disc B and is reflected by a 45°, front-surfaced mirror into the telescope of the pyrometer. The doubled path goes from the plasma jet past chopper disc A, to the front-surfaced mirror normal to the path, then back past disc A, thru the jet and disc B to the 45° mirror and into the pyrometer telescope.

Chopper discs A and B are mounted on a single shaft which is rotated by a small synchronous motor and a belt drive to make a chopping frequency of 13 cps. This chopper assembly was adapted from its original use in a Perkin Elmer Model 12C IR Spectrometer. It is equipped with switches which may be useful in synchronizing signal outputs with chopper positions. As shown in Figure 5 each chopper disc has one semicircle of 1 7/8-inch radius and one of 1 1/4-inch radius. Their mutual shaft is mounted 1 5/8-inches below the axis of the plasma jet and the two discs are so mounted that the small semicircle of one is aligned with the large semicircle of the other. Both sides of the aluminum chopper are covered with a dull black felt to prevent stray reflected signals. The entire chopper-mirror assembly can be moved about 2-inches, parallel to the plasma jet axis, for the purpose of traversing. A one-inch vertical traverse is also possible.

Chopper disc B is a neutral density glass filter made by Schott in Germany and imported by Fish-Schurman Co. of New Rochelle, New York. Because the transmittance of this filter is so important a factor in the temperature measurement (as indicated by error analysis, above), much time and effort has been spent in getting as accurate measurements of this value as possible. The first measurements, made with a Beckman DK2 spectrometer, gave a general indication of transmittance in the region between 4500 and 8500 Å, showing between 40 and 49%, and 44 - 45% at 5892 Å. Repeat runs were not reproducible, however, and the base and 100% transmission lines were so erratic as to make the uncertainty of τ about ± 2 or 3%. Much better reproducibility was obtained by use of the spectrometer in Prof. Hardy's Color Measurement Lab. The range covered was 4000 to 7000 Å; the τ value averaged for 2 positions at different points on the disc was 46.57% ± .1% (estimated error). Another spectrophotometer, a Cary instrument, has also been used, again covering the 4000 to 7000 Å range. This instrument accommodated the filter disc more readily, allowing measurements at seven positions on the larger semicircle. At 5880 Å and 5900 Å these seven measurements ranged from 47.64% to 48.08% transmittance and 47.42 to 47.86 respectively giving an average of 47.6%. The machine's readout is a 3 place logarithm of absorptivity with an estimated accuracy of ± 0.002, which corresponds to ± 0.2%, -essentially the variation found in the seven measurements at each

wavelength. The difference between readings on the CML and Cary instruments, however, is very disturbing. As mentioned previously, our own measurements by an optical technique, at the 5892 Å wavelength, are under way.

The pyrometer itself has been made partly from a Micro-Optical Pyrometer supplied by the Pyrometer Instrument Co. The fore-optics have been retained intact. This includes the interchangeable and adjustable lenses of the telescope, as shown in Figure 10. The lens combinations allow focusing at targets between 8" and infinity. The original instrument contained a single holder for two high-range screens, one having a transmittance of about 4.5% and the other about 0.1%, for measurements of brightness temperatures to 3500°K. Since it is difficult to measure low transmittances accurately, the 0.1% filter will not be used. Instead, a second filter holder has been installed in line with the first, to accommodate combinations of the 4.5% filters. One of the holders has a single filter in one receptacle, two in the other; the second holder has two filters in one receptacle. Thus one, two, three or four filters can be interposed in the optical path, to permit measurements of brightness temperatures to over 10,000°K without exceeding a brightness temperature of 1680°K for the pyrometer filament. Determinations of the transmittances of these filters have been made with the Beckman DK 2 (Courtesy of Dr. M. Ihnat of AVCO) and with the CML spectrophotometer. One only of these filters was scanned from 4000 Å to 40,000 Å, with the DK 2. Transmittance in the infrared was 8 - 10% between 7000 and 12,300 Å; increasing to about 36% at 26,000 Å, dropping to 3% at 27,700 Å and rising again to 33% at 40,000 Å. In the visible, transmittance varies between 2.5% at 4000 Å and 8.5% at 7000 Å, but is nearly flat at 4.2 to 5% between 4700 and 6500 Å. There are slight variations at any one wavelength, among τ values for the five filters in use, probably due to slight differences in thickness of the glasses. In addition to spectrophotometer measurements which are believed to be good to $\pm$ 0.1 percentage units, τ values have also been checked, in the red, by use of the pyrometer as a photometer.

The filament normally supplied with the Pyro Micro-Optical has a circular cross-section and is formed in a loop. In order to minimize the effects of diffraction caused by passage of light around the circular element, the filament lamp was replaced by one which had a filament of semicircular cross-section and a straight-line configuration horizontally disposed. This is the Leeds and Northrup No. 13301-AQ-1 standard 1 mil. tungsten filament lamp for the L & N optical pyrometer. The L & N lamp filament is straight, as required in the present application where its image is to fill a horizontal slit alternately with the image of a plasma jet section.

The Pyro instrument provided for filament current adjustment by means of a variable resistor mounted in the pyrometer body. To gain flexibility for remote operation this has been replaced by a separate battery-operated power pack. The current is adjusted by a 10-turn Borg micropot variable resistor and determined by measuring, with a null-type potentiometer, the voltage drop across a NBS type standard resistor certified to provide 1.00001 ohms $\pm$ 0.005% resistance at 298°K.

The eyepiece objective lens of the Micro-Optical Pyrometer has been moved closer to the lamp in order to increase to 4-fold the magnification of the filament at the plane of a slit which replaces the eyepiece of the original

instrument. In accordance with the recommendations of Fairchild and Hoover (J. Opt. Soc. Am. 7, 543 (1923)) the exit diaphragm, a 0.078-inch hole in a brass disc, has been located at the second focal point of this eyepiece objective lens. The lens focal length is 1.475" and the exit angle 0.078/1.475 = 0.053 radians.

The slit through which the light beam passes to reach a photomultiplier has a fixed width of 75μ (=0.00295 in) and a length of nearly an inch. It was donated by Baird-Atomic, Inc. The slit is mounted with its long direction horizontal and the slit length can be varied from 1/8-inch to 3/4-inch by means of micrometer adjustment of a V-shaped opening in a masking piece. Since the system magnification is 4-fold the minimum slit size permits examination of a target 0.00074 x 0.031-inches in size. Since the pyrometer filament is 1 mil wide, only 3/4 of its image will pass through the slit. This is intentional, to reduce the influence of edge effects. At the Bureau of Standards only half of a filament width is used.

The light beam that passes through the slit will come either from the target plasma jet or from the pyrometer filament, depending upon the position of an oscillating glass block located as shown in Figure 6. The idea for this beam-deflection system came from a description by Kostkowski (155) of the NBS photo-electric pyrometer. The rotating glass block of the NBS device, however, did not rotate through 360° to produce an a.c. alternation of the target image and the filament image. Instead it was rotated through only a small angle, by hand, to move the filament image into and out of the beam. In a later version of the NBS pyrometer the deflector glass is eliminated entirely and instead the lamp itself is moved into or out of the optical path by movement of a few mils distance along an arc.

After the decision to use the glass block deflector it soon became apparent that 360° rotation would give awkward effects as corners went through the beam. It appeared, also, that a smaller target width (about 0.008") could be examined if the deflector block were simply caused to oscillate through a small angle, rather than to rotate in a full circle. The block is 10 mm long, 9 mm in diameter, and is mounted in a brass ring that pivots on two horizontal shafts secured to the outside of the ring. A vertical arm extending down from the ring carries a 1/4-inch ball bearing which bears, under spring loading, against the surface of a cam. As the bearing follows the rotating 3/4-inch cam wheel the axis of the glass beam-deflector oscillates through an angle of 4.58° and the light beam is deflected by nearly 0.011-inches from the straight-through path. Thus the filament image is moved off the slit and the target image onto it.

In a brass housing beyond the exit slit a 931 A Multiplier Phototube is mounted, horizontally. The cathode surface is approximately 3 1/2 inches from the slit, so that with an exit aperture of 0.053 radians the light projected through the slit falls as a 3/16-inch wide band on the 5/16 wide cathode-surface. The length of used portion of the cathode is from 5/16 to about 3/4-inch, out of a total usable length of 1 3/16-inches. Use of a fairly large fraction of the cathode surface is desirable for minimizing local fatigue. The phototube is powered by a Northeast Scientific Corp. Model RE 1602 regulated high voltage supply. The voltage can be varied continuously from 300 to 1600 volts ± 2%, with ripple of only 1 mv peak to peak, and with stability of 0.01

to 0.02% per hour.

Figure 11 shows an early version of the phototube circuit. In present use is a set of 100K ohm dynode resistors potted in an epoxy resin. The output resistor is no longer fixed at 200 K as shown, but can be selected at 20, 110, 180, 370, or 660K, depending on the output voltage desired. The output selection is incorporated with a 13 cps twin-T tuned filter, the circuit for which is shown in Figure 12. The filter effectively cuts out all frequencies other than those of the choppers in the optical system. From this filter the phototube signal is fed, sometimes amplified by a Tektronix type 122 Preamplifier, to a cathode ray oscilloscope. The CRO most used to date is a Dumont 304A. Alternatively, and especially in connection with calibration of optical filters, the signal is fed to a digital voltmeter.

The interference filter which provides monochromaticity in the optical system was made by Baird Atomic, Inc. This is a rather special filter of narrower band pass than most and having its transmission peak between those of the D-line doublet. In order to determine its characteristics several curves of its transmission of tungsten light were made by Baird Atomic. A 1-meter grating spectrograph (5000 lines/inch) was used and the several transmission curves were made with spectrograph slit widths of 50μ, 75μ, 100μ and 200μ. Theoretically the "absolute" value of filter band width at half the peak transmission (i.e., the "half width") should be obtained if one extrapolates to zero slit width the "half widths" obtained with various slit widths. In this case, there was not much variation, the variation was not very regular, and the best estimate of absolute half width is about 7.5 Å, not much less than that obtained with various finite slit widths. The peak transmission of the filter appears to be about 20%, located at approximately 5891.7 Å, These values represent averages obtained from seven curves such as that of Figure 13. Location of the peak on each was determined by comparison with locations of the doublet peaks produced by sodium light in runs whose signals were superimposed on the same charts with the transmission curves. Because of instrument instabilities, and perhaps because of very slight differences in alignment of the filter in different runs, the peak location was not perfectly reproduced but showed a variation of ± 0.5 Å about the average (and a 2.3 Å deviation in one run, which is thrown out). Alignment of an interference filter to insure normal incidence of the light which strikes it is an important factor in use of such devices. It is usually achieved by aligning the beam reflected from its surface back onto the light source. A misalignment causes the transmission peak to be shifted toward a shorter wavelength (about 5 Å for 1° tilt) and the half width to become broader. In order to prevent transmission by the filter of energy at wavelengths which are harmonics of the design fundamental, blocking filters of colored glass are cemented to the interference filter surface. In the present case this makes the whole assembly about 3/8-inch thick. The filter is 0.6-inch square, this small size being chosen for easy fitting into the pyrometer barrel between the lamp and the eyepiece objective lens.

The sodium chloride vaporizer depicted in Figure 14 is patterned after one described by Collard (135). It consists simply of the fuel bowl from an automobile fuel pump, fitted with inlet and outlet nipples for air flow and with an electric heater for vaporizing the salt. The heater is a half section of

alundum tubing wound with chromel heating wire. The unit is located in a by-pass line of the plasma-jet air supply, so that control of the amount of sodium added to the stream can be adjusted by both the fractional by-pass regulation and by variac-control of heat input to the vaporizer. For pressure operation of the plasma jet a high-pressure version of this vaporizer will be constructed.

Figures 15 and 16 show the pyrometer on its mounting mechanism, which provides for a variety of adjustments necessary for facilitating optical alignment and for traversing the plasma jet area. This mechanism is probably more massive and rugged than would be desirable for a portable device but it has the advantage of stability and required only minor modification of available equipment. Adjustments for elevation and tilt are obvious from the drawing. Horizontal adjustment of the optical bench assemble is achieved by sliding it along a hub which fits into the pillow block, the hub being an integral part of the elevating mechanism. Experience has shown the need for very rigid components in this entire assembly. For example, the original optical bench (a stock item) had to be reinforced with a steel bar because minor adjustments caused bowing of the bench by a few thousandths of an inch, enough to make a marked difference in optical alignment and the resulting phototube signal.

Figure 17 shows a circuit diagram typical of the set-up used for calibration of the pyrometer lamp. Automobile batteries are used to get noise-free power and at least half a dozen are required to make the output sufficiently stable.

V SUMMARY AND CONCLUSIONS

An extensive literature survey on high-temperature gas pyrometry has been assembled and presented. From it the conclusion was reached that a mirror-backed optical pyrometer was attractive, but that it would probably be necessary to add an opacifying agent to the gas. The pyrometer has been designed and constructed, and is still in process of calibration and check-out. An error analysis, presented here, indicated the unusual limits of accuracy and precision necessary to make valid measurements on a gas of low opacity, and the substantial impossibility of doing it unless the mirror method is modified by use of a roughly 50 percent transmission screen placed in the optical path when the mirror is behind the gas. In consequence an accurate comparison of single and double-thickness readings which are nearly the same is possible. The method thus makes possible the interpretation of readings under conditions normally beyond the capacity of conventional optical pyrometry; but it also demands an accuracy of determination of transmittance and reflectance of the rotating parts which has introduced some difficulties. These are in the process of being overcome.

A phase of the problem still requiring study is the feasability of using an opacifier which is not gray in the range of transmission of the band-pass filter used. In principle, knowledge of the shape of the absorption coefficient-wavelength relation for the opacifier should suffice, without knowledge of absolute magnitudes. What has not yet been established is the sensitivity of the resultant temperature to errors in knowledge of shape.

A plasma-jet has been designed, constructed, and operated. Its use awaits completion of the check-out of the pyrometer.

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APPENDIX I

Figures one to seventeen inclusive.

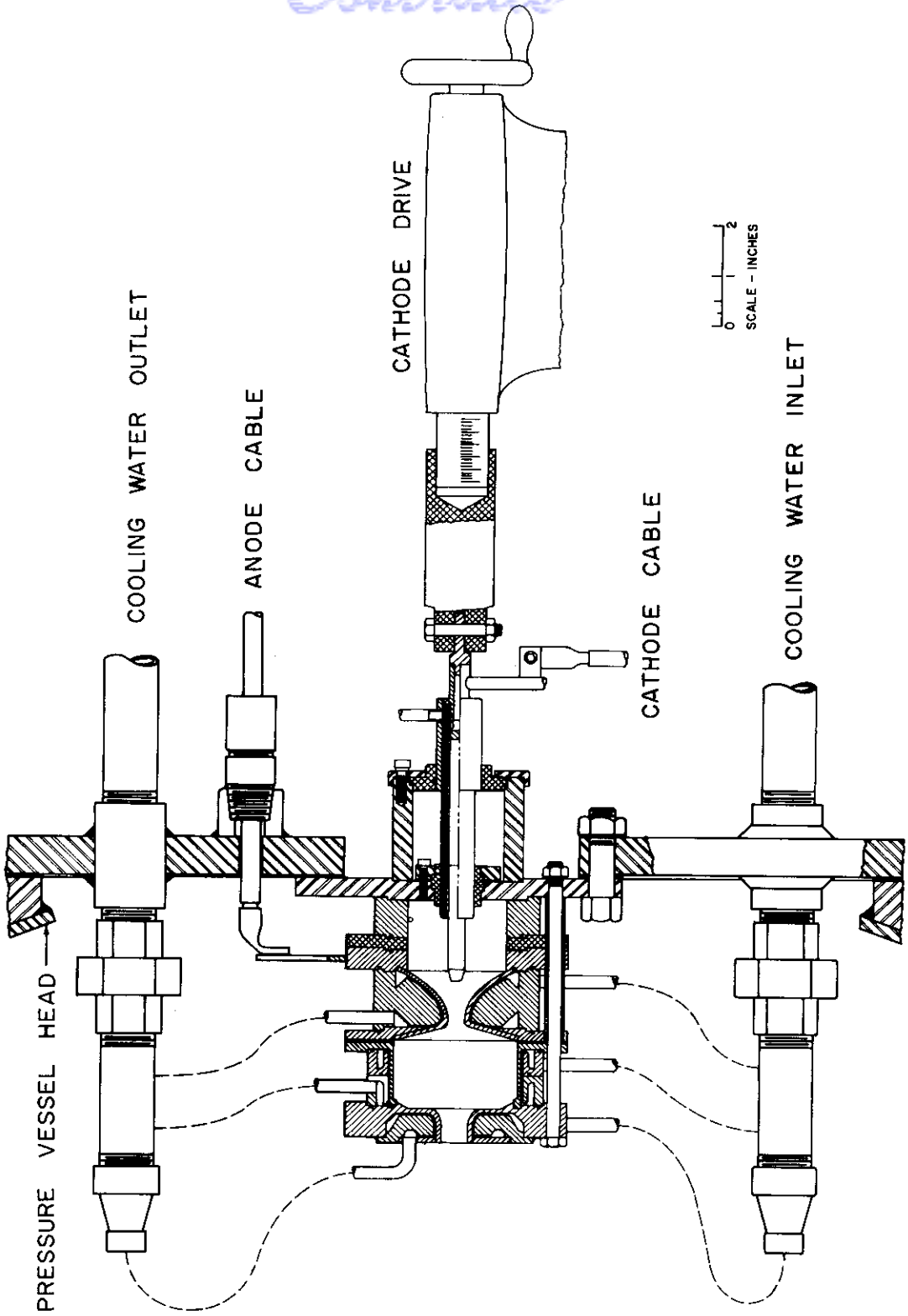


FIGURE 1.— PLASMA GENERATOR ASSEMBLY

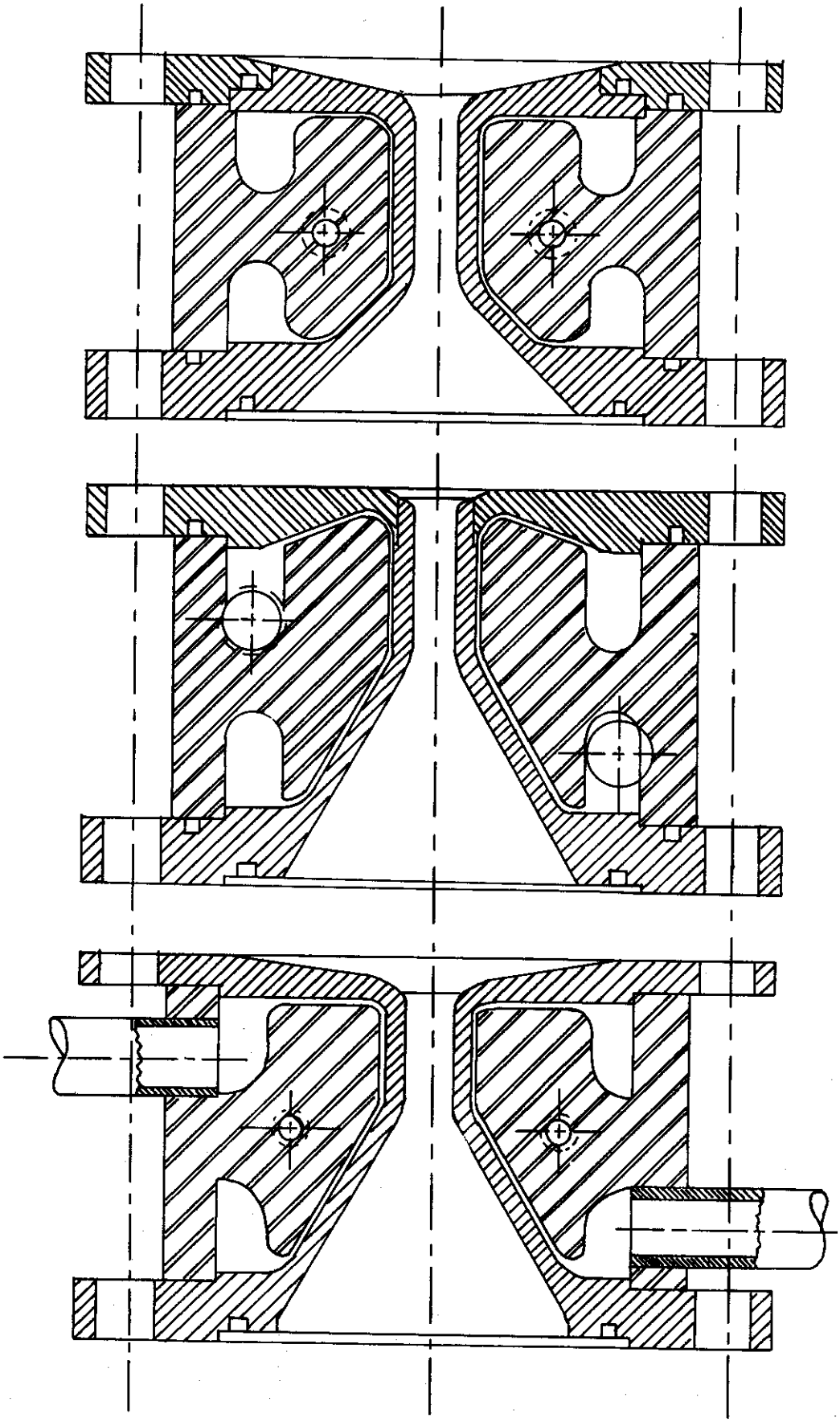


FIGURE 2. - PLASMA GENERATOR ANODE VARIATIONS

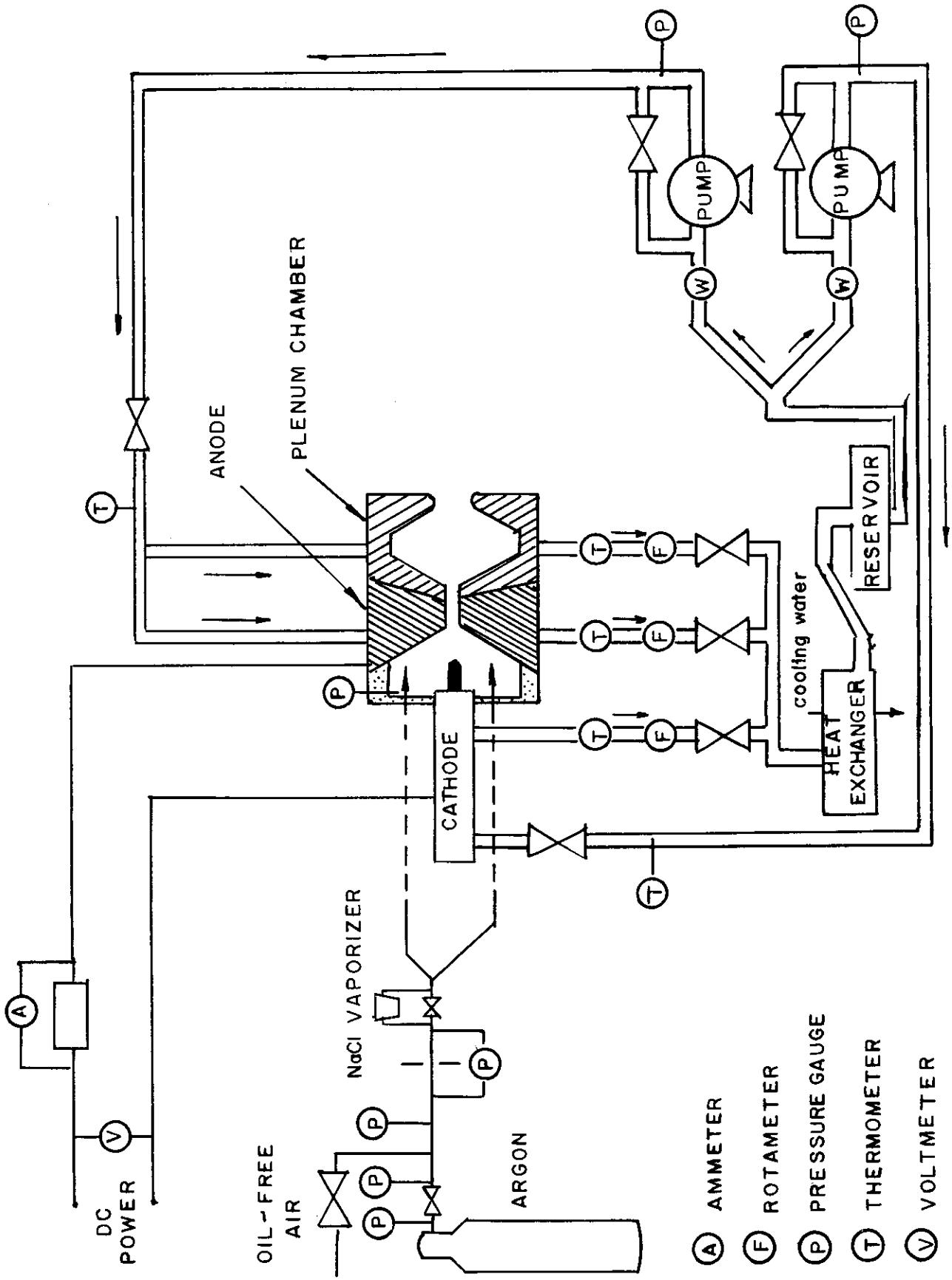


FIGURE 3.- COOLING WATER AND GAS SUPPLY SYSTEMS FOR PLASMA GENERATOR

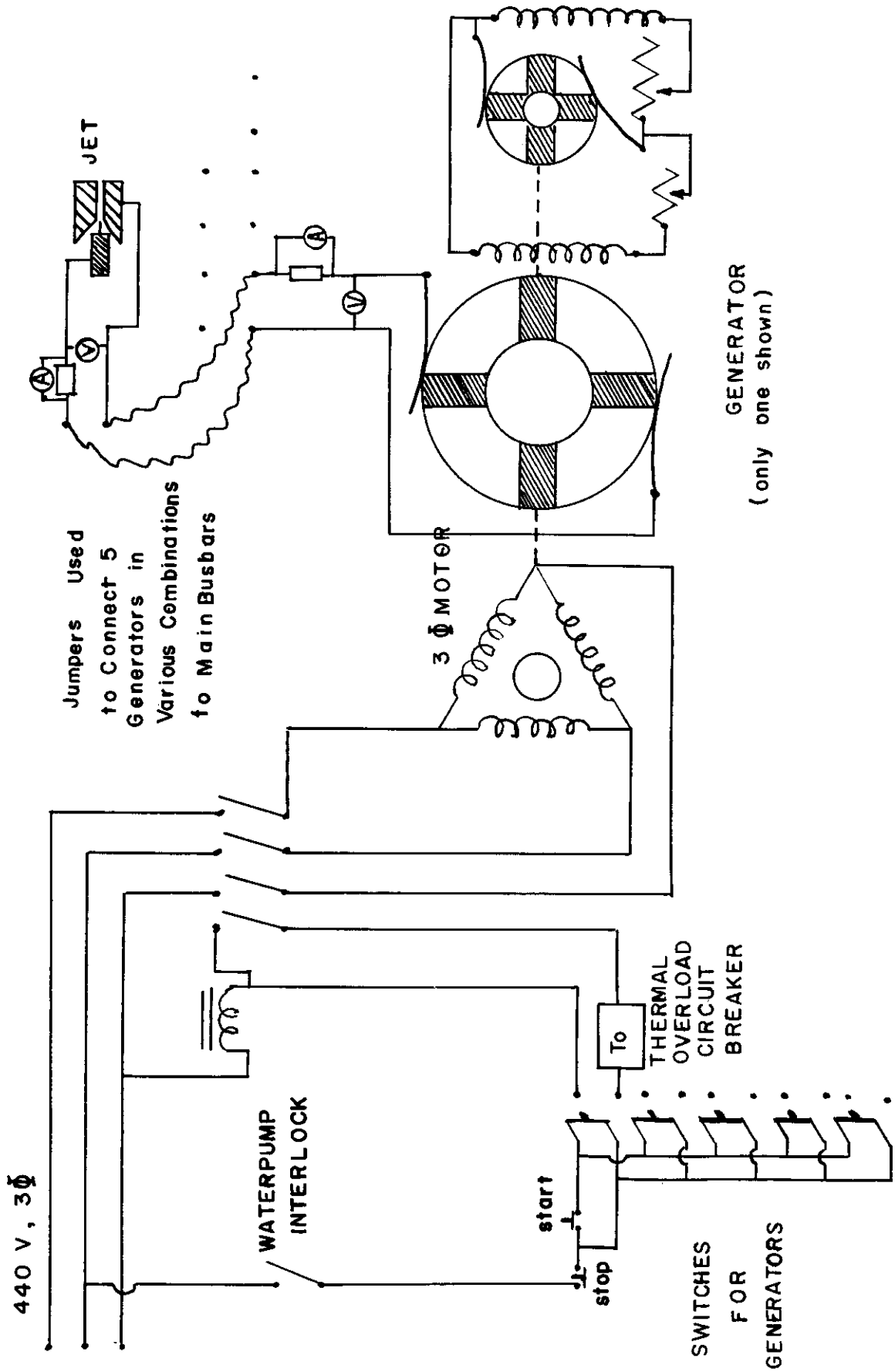


FIGURE 4.- PLASMA GENERATOR WIRING DIAGRAM

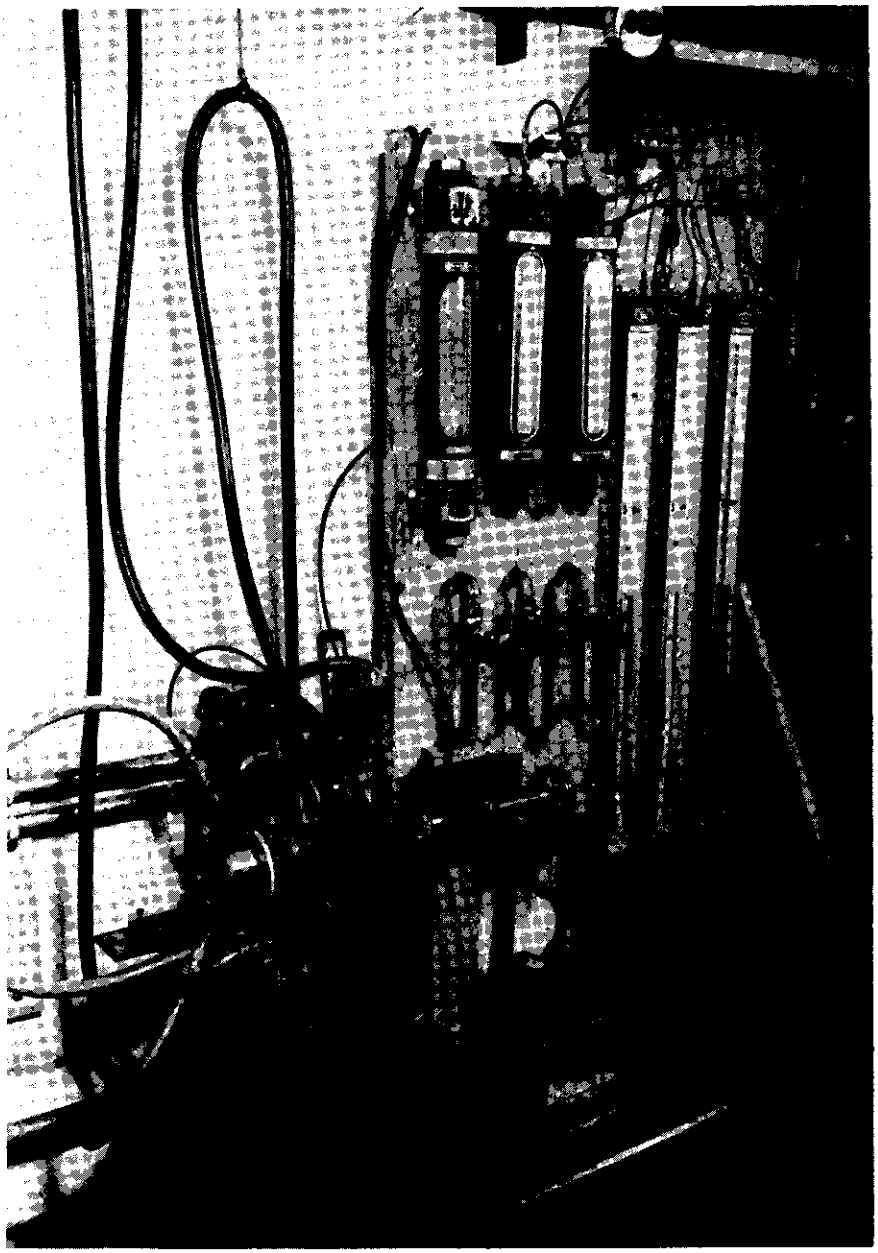


FIGURE 5.- PLASMA GENERATOR AND FLOW METERS

FIGURE 6.- COOLING WATER SYSTEM

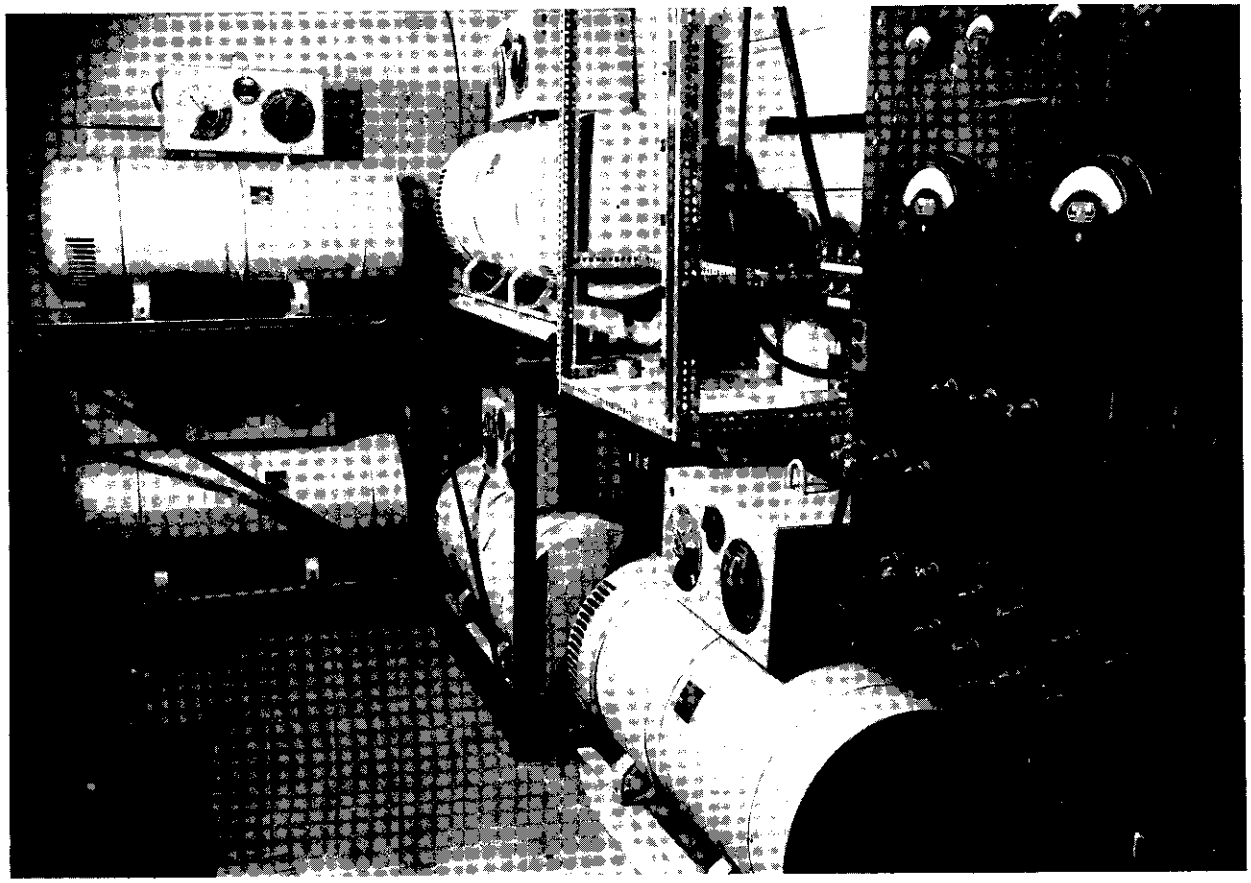


FIGURE 7. – PLASMA GENERATOR POWER SUPPLY

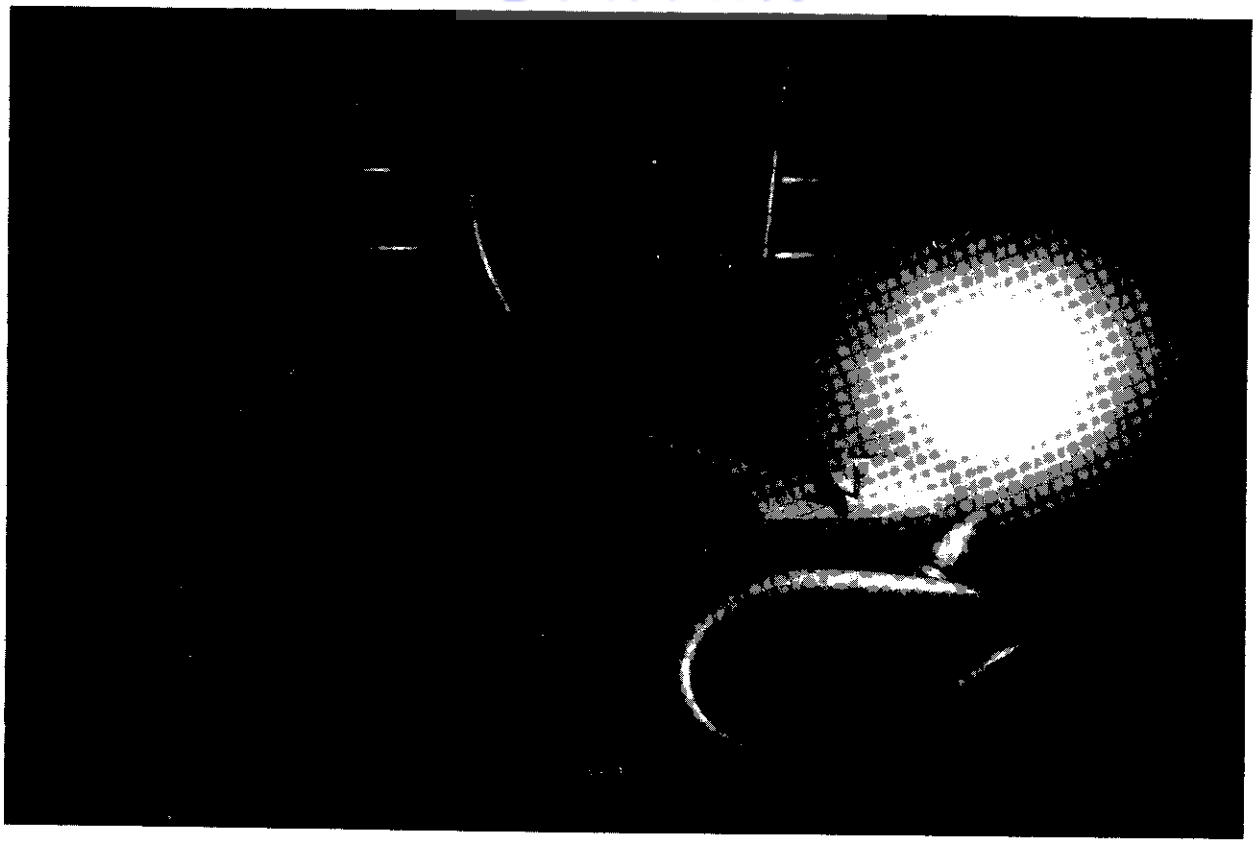


FIGURE 8a. – ARGON PLASMA JET – 1/100 SECOND EXPOSURE

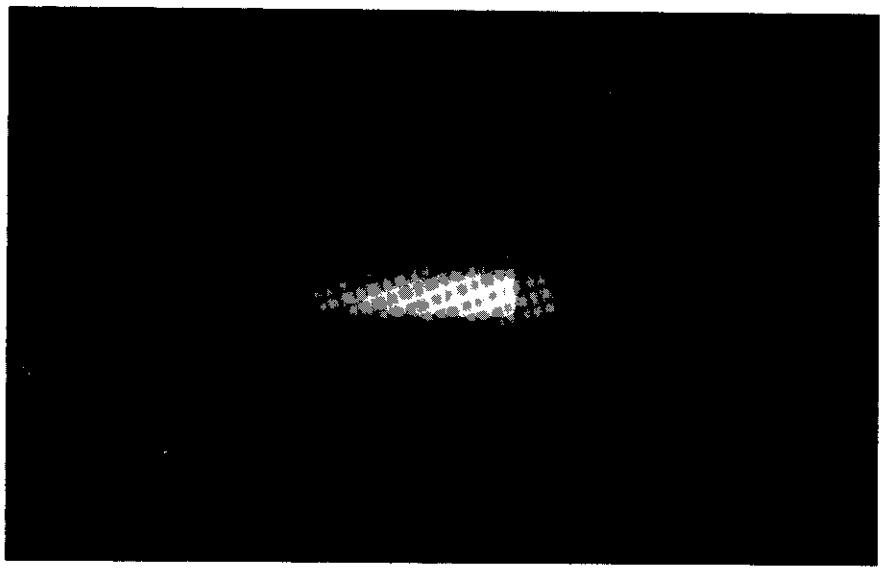


FIGURE 8b. – ARGON PLASMA JET – 1/500 SECOND EXPOSURE

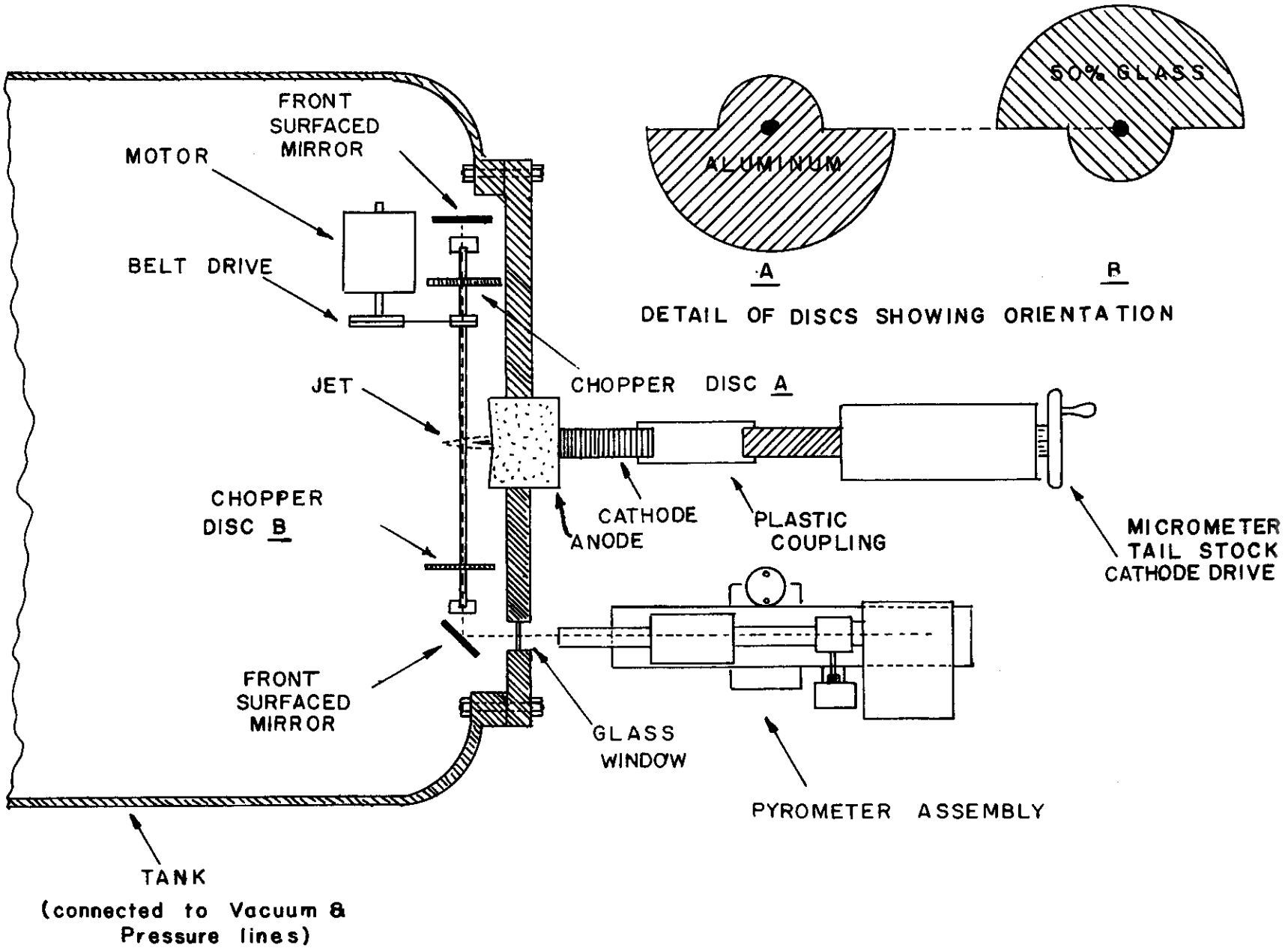


FIGURE 9.- PYROMETER POSITIONED FOR JET TEMPERATURE MEASUREMENT

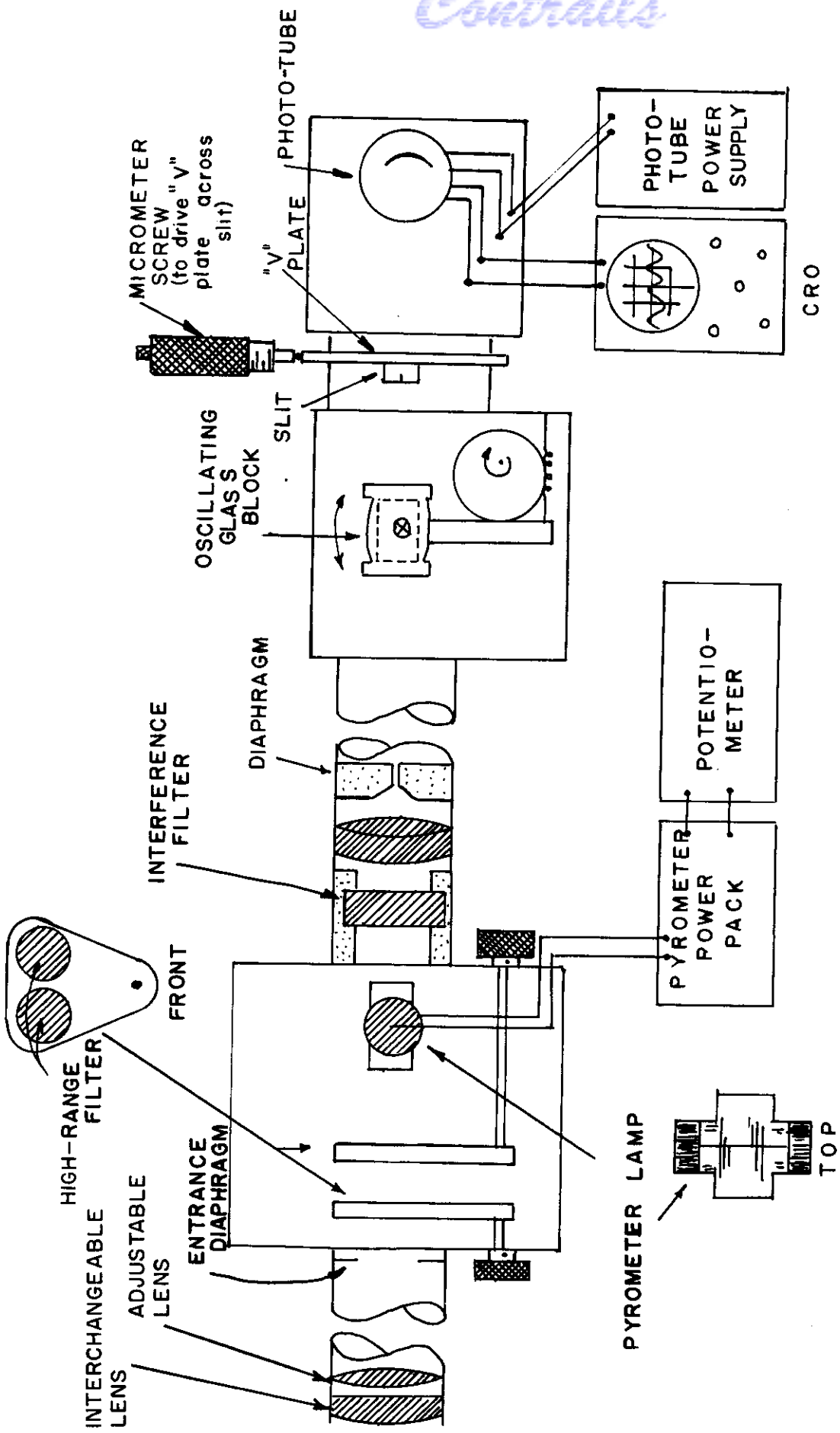


FIGURE 10. – SCHEMATIC OF PYROMETER CONSTRUCTION

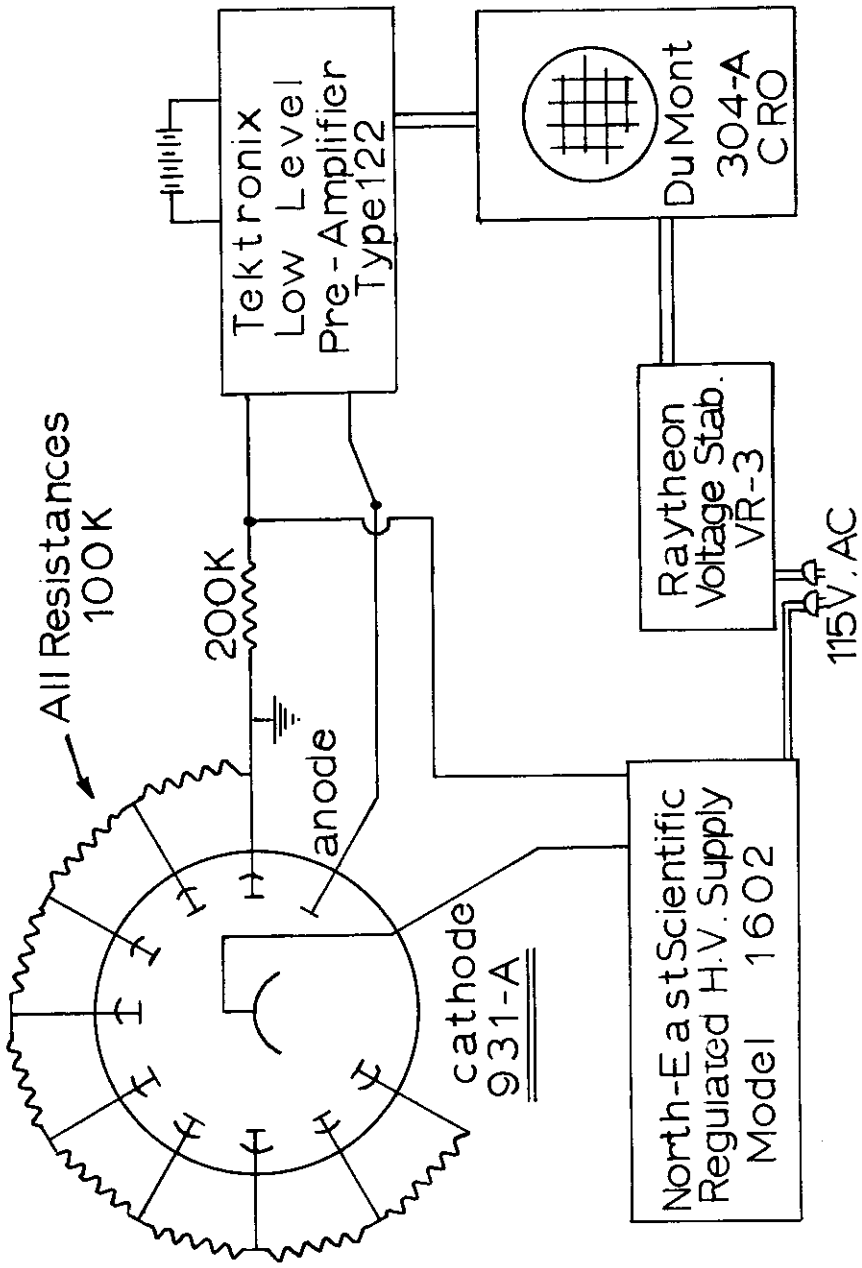
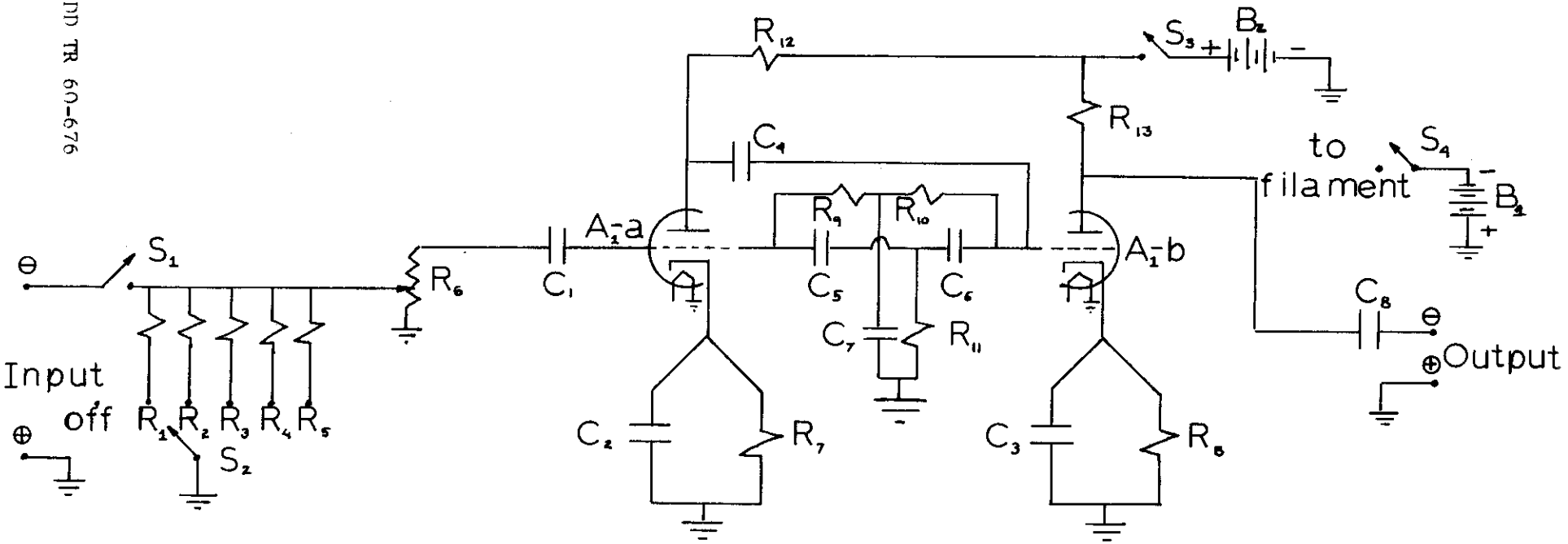


FIGURE 11.- PHOTOTUBE CIRCUIT DIAGRAM



R_1	660K	R_8	1K	C_3	250 mfd
R_2	370K	$R_9 R_{10}$	11K	$C_4 C_5 C_6$	1 mfd
R_3	180K	R_{11}	5.6K	C_8	0.5 mfd
R_4	110K	R_{12}	250K	C_9	———
R_5	20K	R_{13}	50K	B_1	6 V
R_6	0-1M	C_1, C_7	2mfd	B_2	250 V
R_7	10K	C_2	50 mfd	A_1-a,b	12-AT7

FIGURE 12.– CIRCUIT FOR 13 CPS TUNED FILTER

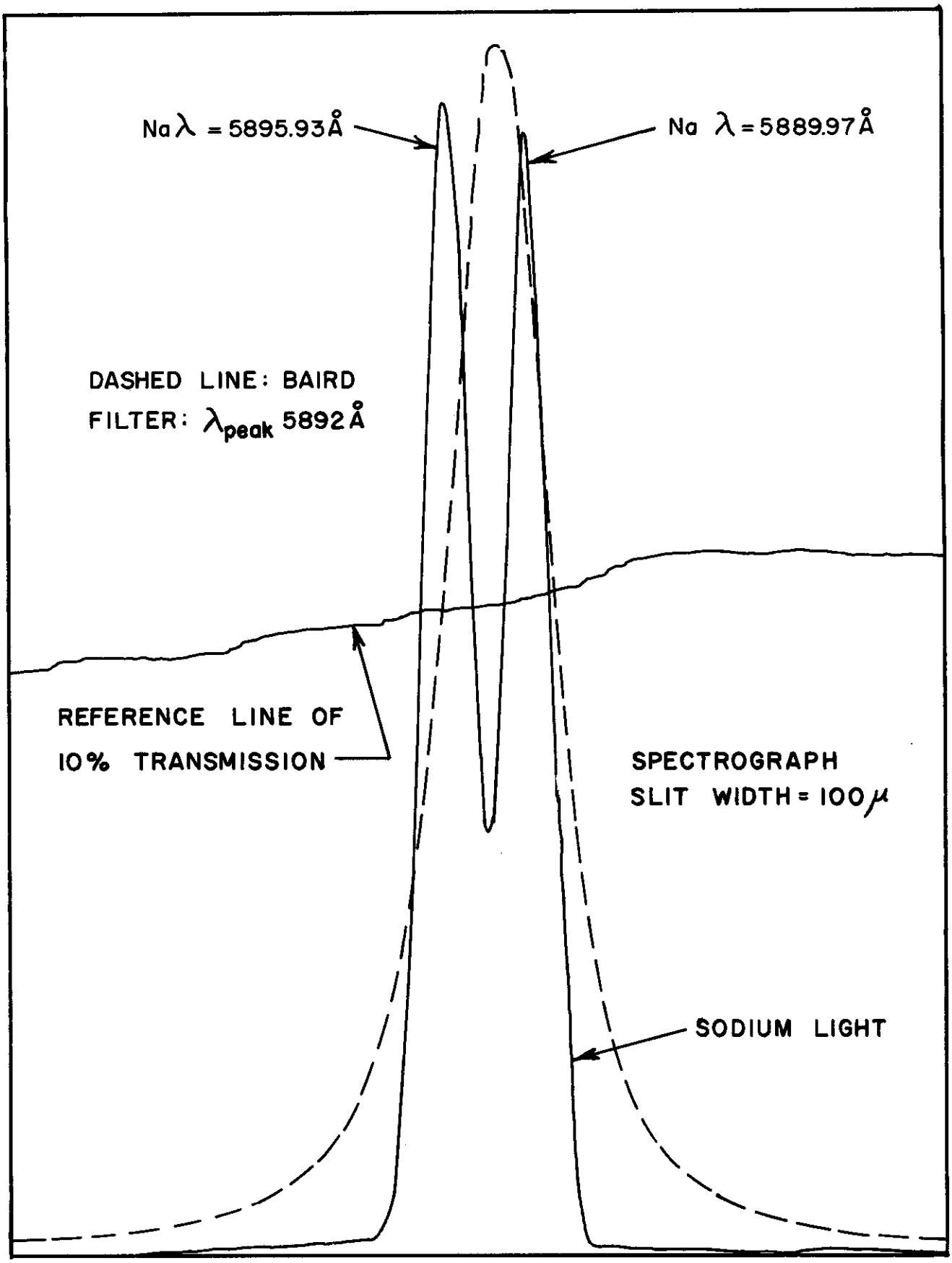


FIGURE 13.– INTERFERENCE FILTER CHARACTERISTIC

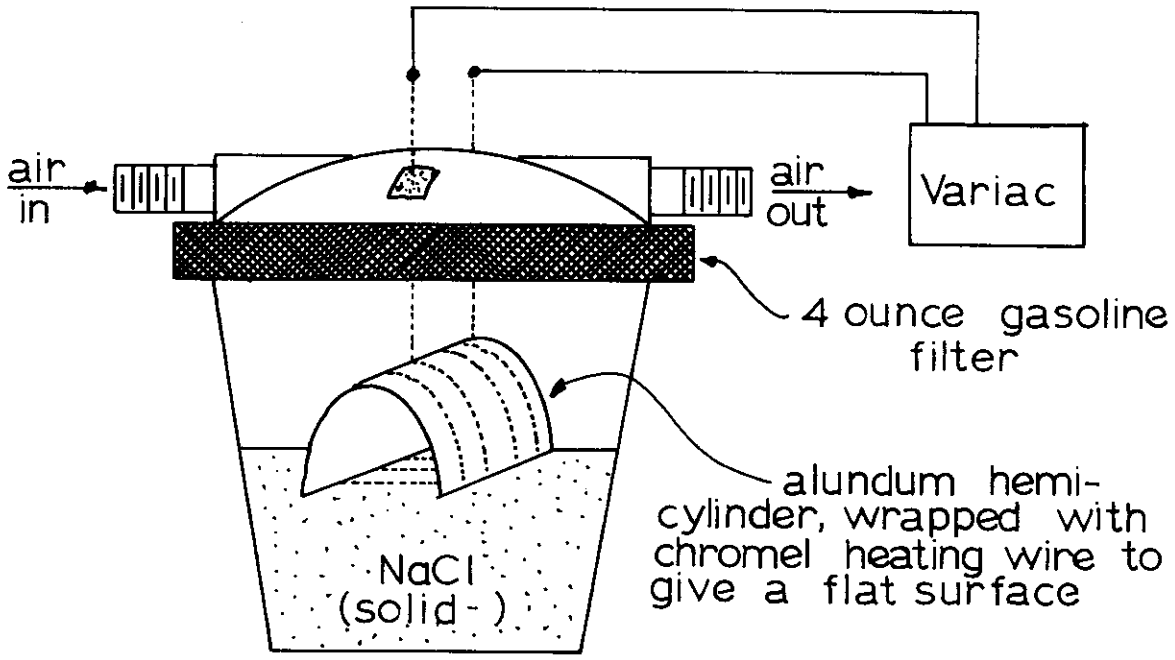


FIGURE 14.– SODIUM CHLORIDE VAPORIZER

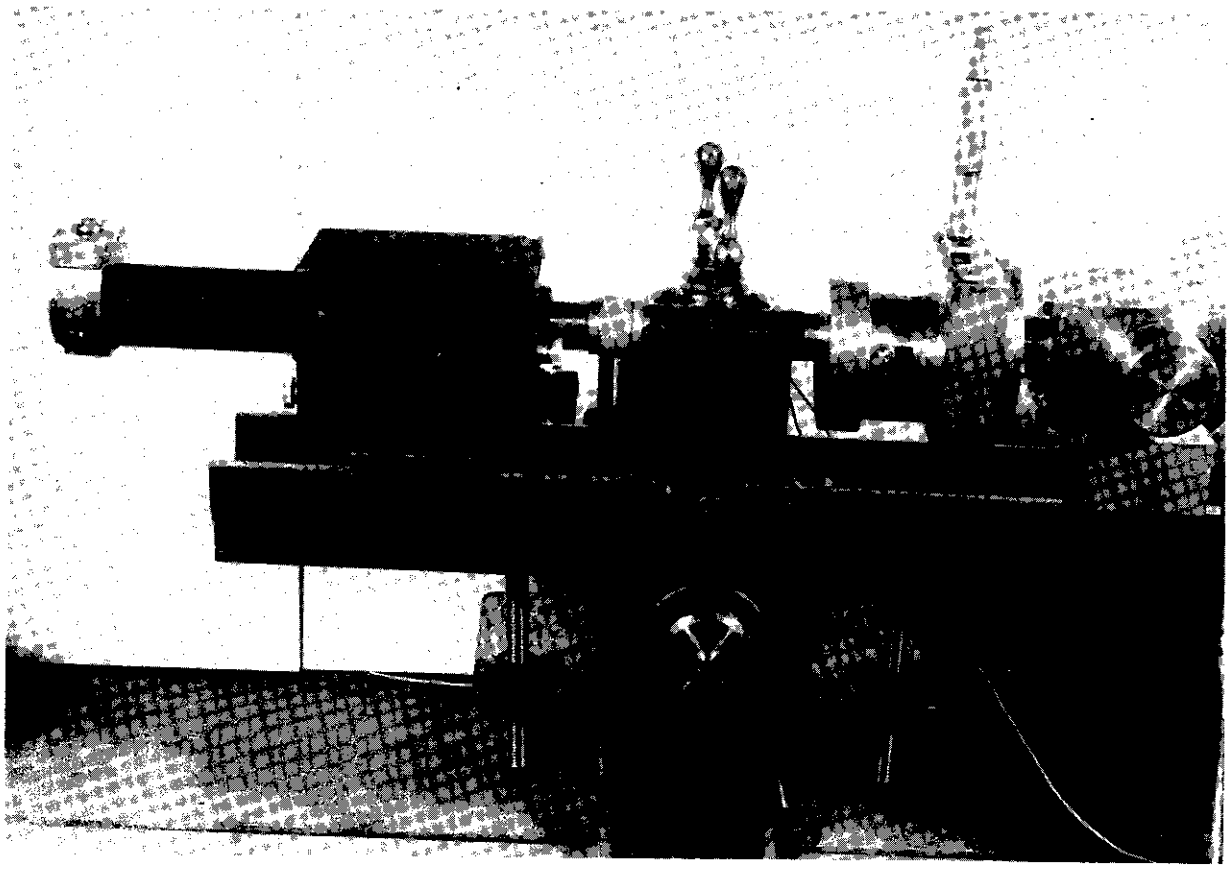


FIGURE 15.– PHOTOGRAPH OF PYROMETER AND ITS MOUNT

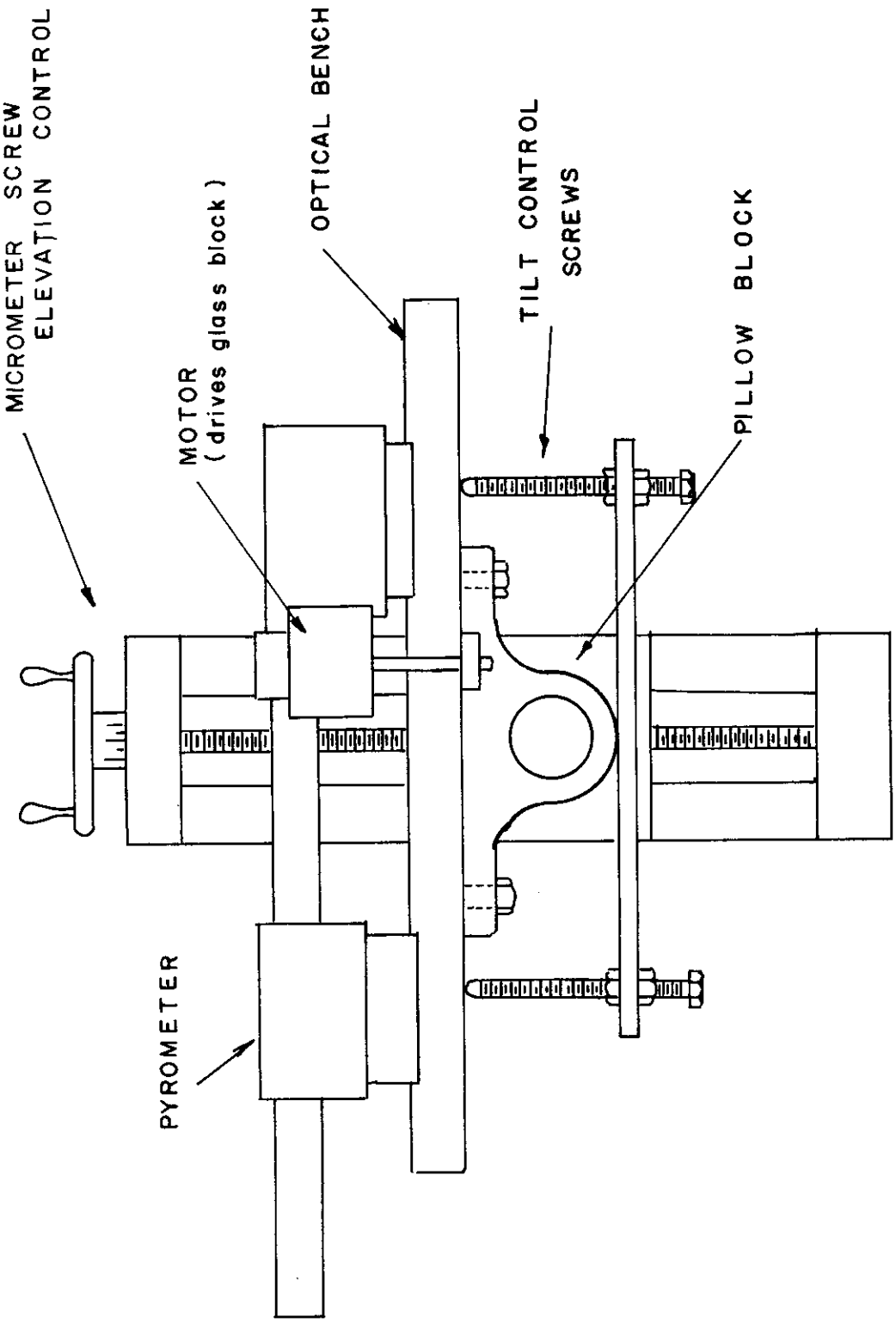


FIGURE 16.- PYROMETER MOUNTING MECHANISM

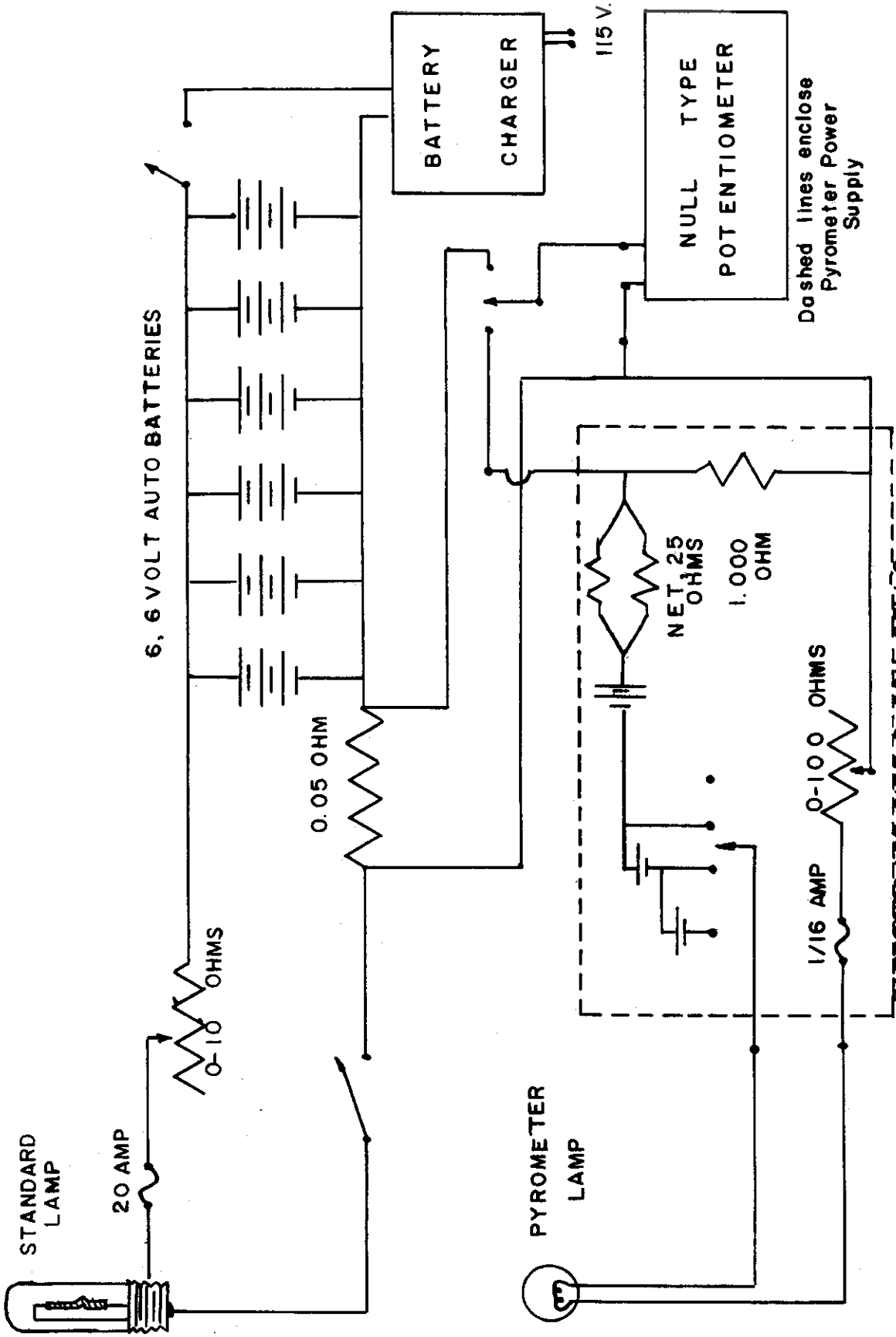


FIGURE 17.- CIRCUIT FOR PYROMETER CALIBRATIONS

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