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INDUCTION PLASMA HEATING: MEASUREMENT OF GAS CONCENTRATIONS, TEMPERATURES, AND STAGNATION HEADS IN A BINARY PLASMA SYSTEM

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16. Abstract

The degree of mixing between an argon plasma and a cool sheath of hydrogen has been found to be markedly different from the mixing measured for an identical gas flow system without the plasma. Temperatures measured show that the plasma virtually separates the argon from the sheath gas. The induction skin effect presents itself as temperature maxima which are not on the plasma axis.

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FOREWORD

The work described herein was done by the TAFA Division of the Humphreys Corporation under NASA Contract NAS 3-11487. Mr. Chester D. Lanzo of the NASA Lewis Research Center, Nuclear Systems Division, was the Project Manager for NASA.

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INDUCTION PLASMA HEATING:

MEASUREMENT OF GAS CONCENTRATIONS, TEMPERATURES,

AND STAGNATION HEADS IN A BINARY PLASMA SYSTEM

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SUMMARY

An experimental investigation has been made of the degree of mixing between a radio-frequency induced argon plasma arc (heat addition region) and a surrounding sheath of air or hydrogen with air/argon mass ratios of 0.6, 5.55 and 19.7 and a hydrogen/argon mass ratio of 1.67. Comparison with mixing experiments conducted without heat addition but with identical gas flows show that the plasma eliminates all turbulent recirculation present in cold gas flow and appears to behave as if it had a definite skin or boundary similar to a gas/liquid interface.

Temperatures have been measured spectroscopically for the air/argon mixing systems. It is interesting to note that the plasma is virtually confined to the argon core gas, with hot mixing patterns resembling those obtained with coaxial flows where diffusion is dominant. The maximum temperatures have been found to be not on the centerline as predicted by theory and observed experimentally by others.

Velocities were not obtained for this complex system since they were extremely low. Nevertheless, stagnation pressure heads were measured with a two liquid manometer sensitive to .001 in. water.

This work presents the first observations of mixing and temperature for an induced low velocity argon plasma operating as a heater for a high velocity annulus of air or hydrogen.

INTRODUCTION

The concept of using a fissioning core of slowly moving uranium gas to heat an annular sheath of high velocity hydrogen in a nuclear propulsion unit for deep space flight was presented by Weinstein and Ragsdale in 1960[1]. Since then, much research has been directed to the problems of radiant heat transfer, fluid mechanics and reactor physics problems that need to be solved before an optimum design can be made.

In the design, the heated hydrogen is expanded through a nozzle to provide the thrust. One important assumption that needs to be experimentally verified and which is the key to the economic realization of the gas core concept, is the degree of mixing between the slowly moving uranium core and the hydrogen propellant. Obviously, the loss of uranium should be zero and it would be most desirable to have a transparent container for it. In practice, however, such a container would be subjected to severe nuclear and thermal radiation. It is therefore likely that some will be lost with the hydrogen through the nozzle. Laminar mixing theory, which is reasonably accurate, at least for isothermal conditions, indicates that the mixing might be at an acceptable level. However, the uranium plasma system is so complex that reliance on theory alone is undesirable.

The fissioning uranium can be simulated quite satisfactorily by the induction plasma system[2]. In the TAFA laboratories, a low velocity argon plasma is induced in the center of a high velocity hydrogen stream. The object of the present studies is to experimentally determine the degree of mixing between the argon plasma and the annular hydrogen sheath, then to measure temperatures and velocities within such a system for certain sheath/core mass ratios. In order to avoid the safety hazards associated with heated hydrogen, air is used in most of the work to simulate the hydrogen.

CONCENTRATION PROFILES

The ability to detect the presence of different gases in an unknown flow system by a fast comparison of thermal conductivities of the mixture with a known reference gas is probably the main reason why gas chromatography is now used so widely as an analytical tool. Through the gas chromatography industry, a very sensitive thermal conductivity detector has been developed. For the present studies the detector section of a Perkin Elmer Model 900 research chromatograph was used without modifications. It uses four tungsten-rhenium filaments connected in a bridge circuit and mounted in a stainless steel block, located within a cast aluminum housing. Its temperature can be controlled and maintained by the proportional controllers within the instrument. Of course, the partitioning column of the gas chromatograph is not used since the flow system under investigation consists of just two gases.

There is a linear relationship between thermal conductivity and mass concentration of the minor component of a binary gas mixture providing the concentration of this minor component is below 10 percent[3]. In gas chromatographic analysis, this is no problem since only very small samples are used. However, when using the detector to measure air/argon mixtures, where the air concentration can vary from 0 to 100 percent, precautions are necessary to avoid the detector from seeing anything greater than 10 percent air. A constant bleed of reference gas, argon in this case, is therefore used to dilute the sample continuously just as it enters the detector (see Fig. 11).

The thermal conductivity detector system used has proved to be a most reliable and simple device and has permitted a most detailed investigation of the mixing phenomena between a plasma and a cooler gas.

Induction Plasma Generator

The apparatus used to generate the argon plasma completely within a sheath of cooler gas was a standard TAFA Model 66 sheath torch. It is shown in Fig. 1. It comprises four separate sections. At the rear, the gas mixer section contains three inlets for argon gas and certain water cooling passages. Argon from the three inlets is passed to a specially designed nozzle containing three series of small orifices. One series directs the argon axially into the torch, another permits the argon to flow radially out to the wall of the central tube and then axially into the torch, and a third is designed to impart vorticity to the incoming gas. By selecting various mixtures of these three flows, any degree of vorticity can be created in the central argon gas stream. Figure 3 shows the gas flow arrangement.

The second main torch section houses the metal separator, the water cooled segmented metal wall which isolates the upstream argon from the annular sheath gas. It is shown in Fig. 4. The metal separator is a cylinder of water cooled metal tubes in order to provide a wall which can withstand the enormous heat fluxes (around 2500 Btu/ft^{2}sec) in close proximity to the plasma fireball yet be transparent to the rf field even though made from highly conductive copper. If the wall were a water cooled solid copper cylinder, the rf field would induce a peripheral current in the metal and absorb all the induced power. Sauerisen cement is used to fill the gaps between individual tubes to prevent gas seepage from the core to the sheath.

The third section contains the rf coil and a water cooled quartz tube which forms the containing wall for the plasma/sheath gas system. The main body of this section is made from teflon, noted for having superior dielectric properties that are necessary for use in high frequency environments. Figure 5 shows the metal separator located within the torch body, which, for the sake of clarity in the photograph, is made from transparent acrylic.

The final section is the water cooled copper nozzle. In this case the nozzle serves to hold the water cooled quartz tube and is the same diameter.

The plasma device is connected to the tank circuit of a radio-frequency generator supplied at 90 kW plate power and operating at 2.5 - 4.5 MHz. A simplified circuit is shown in Fig 6. A triode oscillator tube is fed with a dc plate voltage, which, at full power, is 12 kV. Feedback to the grid of the tube from a tuned plate tank circuit, part of which is the plasma generator rf coil, produces the required oscillating conditions. The tube operates in "Class C Telegraphy" and conducts for only 110° of each cycle. A high rf current is induced in the tank circuit and flows through the plasma generator rf coil. This, in turn, produces an even higher current in the plasma skin which can be likened to a single turn secondary within the torch rf coil. The inductance and capacitance in the tank circuit are adjusted to produce an impedance match. Various filter networks are provided to prevent rf power from reaching the rectifier section of the power supply and to prevent dc leakage from the oscillator plate. The plasma generator was tested for the three designed air/argon mass ratios of 0.6, 5.55 and 19.7. Power lost to various sections of the whole system were recorded by calorimetric methods and are shown in Table I. In each case approximately 13-16 kW of energy was delivered to the plasma.

Diagnostic Apparatus

For the present diagnostic studies the plasma torch was arranged to burn horizontally into a water cooled chamber which contained the probe system. The apparatus is shown in Figs. 7-9. A 12 in. section of 6 in. diameter clear fused quartz electrically isolates the plasma unit from the main chamber which is constructed from a standard 12 in. pipe cross. The sampling probe is supported in one of the flanges.

The degree of mixing between the argon plasma core and the outer sheath gas was recorded by continuously withdrawing point samples through a water cooled probe and thence to a calibrated thermal conductivity cell. The diagnostic probe is shown in Fig. 10. It consists of three concentric copper tubes fabricated in such a way that the central tube which carries the gas sample can be water cooled. The end section is .187 in. o.d. and the sample gas passes through a tube .030 in. i.d. This section is supported 3 in. off a rotation axis by a 1.625 in. o.d. water cooled copper cantelever system. Since the probe end is in contact with the plasma it picks up an rf potential and must be isolated from ground. Teflon bushings accomplished this. It was found during the course of the work that at least 1 in. of teflon surface and not less than 0.2 in. of teflon thickness was required between any point on the probe unit and the grounded 12 in. cross chamber to prevent random arc-over.

The probe is moved across the plasma containment tube by a gearing system driven by a dc motor. Microswitches fitted to the probe reverse its motion at the end of each traverse. The motor and gearing system are mounted on a lathe table so that the probe can be moved to prescribed axial positions within the plasma torch. The probe end traces an arc as it moves across the plasma tube. Figure 2 shows the mechanics of this system.

The gas sample passes from the probe to a flow system and then to a calibrated thermal conductivity cell, part of a Perkin Elmer Model 900 research gas chromatograph. This is shown in Fig. 11. A preset flow of argon reference gas dilutes the sample so that the concentration of air delivered to the thermal conductivity cell never exceeds 10 percent even though the actual sample at times contains over 90 percent. This is to assure that there is a linear dependence between air mass concentration and electrical output of the cell. Samples were checked by calibration with standard mixtures and are described below.

Calibration Procedures

The thermal conductivity cell was calibrated for the air/argon experiments using argon as the reference gas. Pre-calibrated mixtures of air and argon were fed to the plasma equipment and the probe was used to withdraw a continuous sample. The sensitivity of the instrument was adjusted so that 100 percent argon produced no output and 100 percent air produced a full scale deflection. It was found that there was a linear relationship between the recorded deflection and the mass concentration of air, providing sufficient argon was bled into the sample stream at a constant rate to dilute the air concentration to a mixture of 10 percent.

For the hydrogen/argon experiments, hydrogen was used as the reference gas and the above procedures repeated.

Experimental Procedure

These studies were conducted at an approximately constant input plate power of 35 kW. Start-up procedure was routine and accomplished in the following manner. The power was activated and allowed to go through its preset timed warm up cycle. Pressure interlocks were provided in all external water cooling and gas supplies so that the high voltage to the plate of the oscillator tube could not be applied until the plasma equipment was ready to receive power. The argon core flows were adjusted to about 135 SCFH with 60 percent of this as tangential input. The plate voltage was then applied in readiness for plasma ignition.

The plasma was ignited with an externally applied dc arc. A 50 volt 100 amp dc welding generator was connected to an insulated holder that contained two 0.25 in. diameter graphite electrodes. The holder was constructed so that the electrode ends could be moved apart under a spring force from a rest position where they were in contact. The holder was held within the rf coil, with dc applied to the electrodes. A dc arc was formed by separating the electrodes. At this moment the rf power was applied and the output control advanced slowly. As soon as the rf power had coupled to the dc arc and was self sustaining, the dc arc holder was removed. This self sustaining point was evident from the current and voltage readings of the rf power generator and a characteristic 360 cycle modulation note of the rf plasma. The rf power controller was then advanced to approximately 35 kW and the core and sheath flows adjusted to the particular requirements of the experimental run. Gas flows were measured at 50 psig with calibrated rotometers.

The axial position of the probe was noted. The first axial position was generally at the entry plane just ahead of the metal separator. The probe motor was then controlled to move the probe across the plasma tube at two inches per minute, corresponding to the recorder chart speed. This enabled full scale concentration profiles to be generated continuously. Microswitches were adjusted to reverse the probe direction when it reached the plasma tube wall. At the end of two traverses at each axial position, the probe was moved to the next designated axial position and the concentration profiles were generated continuously as before. Two traverses were made to test the reproducibility of the data. However, no problems were encountered. The thermal conductivity cell calibration points were checked with argon and air at the beginning and end of each run.

Generally, five axial positions were chosen at half inch intervals. Data from these five positions were used to construct the mixing maps described below. For each set of gas flows the probe was used to investigate the mixing within the plasma tube without the plasma present. Thus, "hot flow" and "cold flow" mixing maps were constructed for several sheath/core gas mass ratios.

Results

Mixing maps of both "hot" and "cold" profiles were generated for three air/argon mass ratios, 0.6, 5.55 and 19.7, and one hydrogen/argon mass ratio, 1.67. They are shown in Figs. 12 through 19 and certain relevant data is summarized in Table I and is self explanatory. An approximately constant input power was applied in all plasma runs. However, as the calorimetry shows, this does not result in constant power in the plasma due to changing plasma resistivity and diameter. Nevertheless, the plasma power levels are of the same order of magnitude and give meaningful data when referenced to the simulation requirements of the gas core reactor motor.

Discussion and Conclusions

The amazing difference between the "hot" and "cold" mixing profiles is readily apparent from Figs. 12 through 19. It can be seen that the gross recirculation pattern of the isothermal flow systems is completely eliminated when the plasma is present even though the upstream flow conditions are identical for both experiments. The recirculation of the "cold" profiles is due to the vorticity imparted to the argon core gas. This vorticity was used, however, because it was found to produce the argon core upstream flow pattern necessary for optimum plasma stability at ignition. An additional "cold" flow experiment was performed to test this hypothesis. A 0.6 mass ratio air/argon flow system was set up and every effort was made to eliminate vorticity. The tangential argon inlet was not used and glass wool diffusers were used upstream of the probe unit to insure axial laminar flow. The result is shown in Fig. 20. This pattern is similar to that predicted by diffusion equations for laminar flow. It can be seen that the "hot" profiles, even at a mass ratio as high as 19.7, are similar to this laminar pattern even though a high degree of vorticity exists in the upstream flow. What is the explanation?

The main conclusion which may be drawn is that the plasma possesses a well defined boundary or interface similar to a gas/liquid interface. This boundary allows diffusion but not gross recirculation. Movie photographs taken axially show no plasma rotation at 24 frames per second or at 3000 frames per second and, in fact, show remarkable stability. The "cold" flow experiments show that the mixing is a strong function of the vorticity present whereas the "hot" flow experiments show the opposite. One must therefore be wary of extrapolating "cold" flow data to yield meaningful "hot" flow conclusions.

TEMPERATURE PROFILES

Introduction

The measurement of plasma temperatures has been the subject of several books[4]. For gases such as argon, oxygen, nitrogen and hydrogen, the concensus of opinion is that temperatures are most accurate when they are derived from measurements of absolute intensities of certain spectral lines. This method can be used only when absolute oscillator strengths are known for the lines in question. Argon plasma has been studied in great detail by a number of researchers. A recent publication[5] presents the latest data for argon, oxygen and nitrogen. Temperatures were measured using several spectral lines for plasma at various power levels. The continuum radiation as a function of wavelength, was then calibrated against these values. As a result, it was possible to estimate plasma temperatures accurately by measuring the continuum intensity at a particular wavelength that contained no spectral lines. Previously, a scan had to be made across the chosen spectral line so as to determine the intensity of the continuum at either side of the line. This continuum measured as a deflection on a recorder chart was then subtracted from the deflection due to the line plus the continuum. This gave the line intensity.

It can be seen that the new data of Morris, Krey and Garrison[5] greatly simplifies the measurement of argon plasma temperatures. Only one intensity measurement at a predetermined fixed wavelength is required compared with a time consuming scan over a particular spectral line. The only prerequisite is that the spectrometer used in the data acquisition is capable of resolving the spectrum so that the actual continuum measurements are not influenced by nearby lines. In the present studies a Beckman DK1-A instrument was used. The slit width of the unit was adjusted so that measurements taken of the argon continuum at 428.5 mμ were not influenced by neighboring lines at 427.2 mμ and 430.0 mμ.

The temperatures measured in this study were all derived from argon continuum measurements at 428.5 mμ. Various chordal intensities were measured and then converted into radial intensities by the Abel inversion technique. The mixing data determined earlier was then incorporated to give actual radial intensities of the argon. These intensities were then referenced against a standard tungsten/iodine lamp to yield plasma temperatures.

Apparatus

The plasma generator used in the temperature studies was similar to that described in connection with the mixing experiments. The central section of a standard TAFA Model 66 induction torch, however, was modified to allow visible inspection of the plasma fireball (arc). The modified system is shown in Fig. 21. A double quartz wall arrangement was used to provide an annulus of water for cooling. A five turn rf coil around the outer quartz tube was adjusted to leave sufficient space between turns to allow intensity measurements to be made at several longitudinal positions. The plasma generator was mounted horizontally as in the mixing studies and connected to the 12 in. cross chamber by a 6 in. diameter clear fused quartz tube.

A fiber optics system was used to transport radiant energy from the plasma to the entrance slit of the spectrophotometer. It is shown in Fig. 22 and 23. A collimator head was mounted on a heavy duty movie camera tripod specially fitted with a 2 in. micrometer dial gauge. It was thus possible to move the collimator accurately and reproducibly to preset chordal positions. Five longitudinal positions were provided to coincide with the spaces between the rf coil. Measurements taken of chordal intensities at these five positions constituted the raw data for the temperature maps to be presented later. The collimator head was connected to a six foot length of 0.25 in. diameter fiber optics. Since it is a characteristic of this device to disperse energy at its end over a 60° angle, a high quality lens system was used to reimage the end of the fiber optics tube on the entrance slit of the spectrophotometer. The 60° dispersion required the use of f:1 lenses to ensure maximum capture of the available energy.

The spectrophotometer used was a Beckman DK-1A instrument. It contained a quartz prism monochromator and had a resolution of 2 angstrom with an entrance slit width of 0.1 mm as used in the present studies at a wavelength of 428.5 mμ. A 1P28 photomultiplier was used to detect the selected 428.5 mμ radiation.

Calibration Procedures

Certain calibration and feasibility studies were necessary at the onset of the temperature studies to ascertain the optimum procedures to be adopted. The fiber optics scheme eliminated many alignment problems but it was not known whether its wavelength "window" was wide enough to accommodate the particular wavelength region under study nor whether the attenuation associated with multiple internal reflections would be so drastic as to render it useless. A transmission scan was made as is shown in Fig. 24. It shows that there is a sharp cutoff around 400 mu but sufficient transmissivity at 428.5 mμ to allow its use in this work.

Another question arose early in these investigations. The water cooled annulus in the plasma generator device was thick enough to produce discernible refraction effects so that chordal positions measured at the collimator head did not truly represent the chordal position within the plasma. A laser operating at 632.8 mμ was used to plot the light path through the plasma system. No appreciable refraction effect was observed until one inch from the centerline. Figure 25 and 38 shows the calibration arrangement. The index of refraction is a function of wavelength but its difference at 428.5 mμ from 632.8 mμ amounts to about half of one percent, within experimental error.

A small standard source was placed within the plasma generator to directly simulate the plasma. It consisted of a standard Sylvania quartz-iodine (Model No. 500Q/CL) lamp with a coiled tungsten filament supplied at 120 volts, 60 cycle. It was calibrated by measuring its brightness temperature with a Leeds & Northrup optical pyrometer certified by the National Bureau of Standards. It had a brightness temperature of 2740^{O}K at 120 volts ac input.

Several spectral scans were taken of the plasma to find an appropriate wavelength to use for the temperature measurement experiments. A scan measured with the fiber optics in situ is shown in Fig. 26. It shows good resolution, especially with the group of argon lines around 420 mμ. The point marked at 428.5 mμ was chosen for subsequent experiments as the continuum wavelength used to determine plasma temperatures. The spectrophotometer entrance slit was set to .01 mm. and after initially scanning the argon plasma the wavelength was set to 428.5 mμ using the argon lines at 427.2 mμ and 430.0 mμ as calibration points.

Experimental Procedures

The plasma was initiated as described earlier in the mixing studies. Gas flow rates and power levels were adjusted to conform to exact duplicates of the mixing runs. Chordal intensities were measured at each of five longitudinal positions at intervals of 0.25 cm. The fiber optics collimator head was moved vertically to a series of positions, calibrated with a laser previously for refraction effects. These vertical positions were accurately reproduced by using the micrometer dial gauge arrangement shown in Fig. 25 and 26. Before each longitudinal position the plasma was extinguished and the standard lamp intensity reco rded under identical fiber optics/spectrometer conditions.

The chordal intensities were fed into an IBM 2741 communications terminal linked to a 360 computer in New York City. A program system, described later, converted these chordal intensities, entered as recorder chart divisions, into radial intensities. These radial profiles were then converted to absolute radiant flux profiles by comparison with the tungsten standard. Finally, the radiant flux values were converted to absolute plasma temperatures using the calibrated argon continuum data of Morris, Krey and Garrison[5]. The continuum intensity at 428.5 mμ as a function of temperature from reference 7 is shown in Fig. 27.

Analysis

The collimator pick-up head insures only the energy from a particular column of plasma reaches the spectrophotometer detector. Thus, the energy from such a columnar volume of plasma has units watt/cm^3.μ.sr. When the plasma is simulated by the tungsten filament, the energy reaching the spectrometer comes from a surface and has units watt/cm^2.μ.sr. At first it seems impossible that one set of units can reference another set, however, the chordal intensity of each columnar segment is made up of an infinite number of point sources at an infinite number of radial positions. The Abel integral transform enables one to determine the radial profile of such point sources from a series of chordal intensities and thus yield radial point intensities with units of watt/cm^2.μ.sr.

The Abel inversion techniques and its use in the determination of plasma temperatures is well documented[6]. The proven method of Freeman and Katz[7] was used in this work. The computer is used to fit a six or seven term polynomial to the input data such that it can be integrated when incorporated in the Abel equation. Such a form is

$$F(z) = \sum_i C_i (R^2 - x^2)^i$$

where x is the chordal displacement from the centerline and C_i are the computed coefficients. When inverted by the Abel technique, a second polynomial is generated

$$G(r) = \sum_{i} \lambda_i C_i \left(R^2 - x^2\right)^{i - \frac{1}{2}}$$

where $$\lambda_i = (2^{2i}/\pi)\left[(i!)^2/(2i)!\right]$$

The parameter R in the above equation is the radius at which the plasma intensity is less than .5 percent of maximum. This value varies with the plasma system and is not a constant as suggested by Freeman and Katz, who chose it to be the tube radius. They were investigating a more homogeneous system. It was found that when R was made to equal the plasma containing tube radius a seven term polynomial would fit only the central data points and the wings were not well represented. Choosing R as described above solved this problem.

Computer Program

A computer program called TAFA1 was written in BASIC language to solve a system of simultaneous equations in order to produce the desired polynomial described above. Then it computed the coefficients of the Abel inversion and printed out the converted radial profile. Figure 28 shows the section of the program which performs the inversion. A typical computer printout is shown in Fig. 29. Input parameters can be changed to print out the chordal and radial profiles at any desired interval. In the example shown in the figure, this interval is 0.1 cm. A second program, called PLOT1, available from the computer library was used to actually plot the chordal or radial polynomials. Examples of this are shown in Figs. 30 and 31.

In all cases, the computer generated chordal polynomial was checked against the plotted raw data. It was found from preliminary studies that experimental errors in observation prevented the use of polynomial with a degree greater than seven. In fact, gross instabilities were produced when the data were fitted by high degree polynomials. It was soon evident that such instabilities could be avoided by limiting the degree of the polynomials to seven.

Results

Figures 32 and 33 show chordal and radial profiles at the five preset longitudinal positions for the gas system comprised of 135 SCFH argon core and 111 SCFH air sheath, a sheath/core mass ratio of 0.6. The radiation intensity, recorded as recorder chart paper divisions, was calibrated with a standard source as described earlier. It was found that the 2740°K source produced a deflection of 6 divisions at 428.5mμ, indicating that each division of the recorder chart paper was equivalent to 0.474 watt/cm^2.μ.sr. The radial profile data was then replotted as shown in Figure 34 to yield an isotherm map of the plasma within the apparatus. Similar temperature maps are presented in Figs. 35 and 36 for air/argon mass ratios of 5.55 and 19.7 corresponding to the systems studied earlier to yield concentration profiles.

Hydrogen/argon runs were not made. An explosion hazard existed due to possible arc out of the plasma during the relatively long length of running time needed to produce the chordal profiles.

Discussion and Conclusion

The temperature maps reveal the off center temperature maxima similar to those reported by Donskoi[8], Johnston[9], and Dymshits and Koretskii[10]. Although the plasma axis is cooler and appears dark to the eye when viewed end-on through a dark filter, it is, in fact, only about 10 percent lower than the maximum. Temperatures below 8500°K isotherm, however, serves as a good plasma boundary. The effect of increasing the mass ratio of air sheath to argon core is dramatically portrayed in the difference between Fig. 35 and 36. It is interesting to note that the mixing data was not needed for the first two cases. Only with the high mass ratio did the air sheath reach high plasma temperatures and influence the radial profile of the argon continuum at 428.5 mμ. An important conclusion is that for the most part the plasma is confined to the argon core gas and the differential point concentration of the air within the plasma rarely exceeds five percent. At the high mass ratio of 19.7, however, the plasma is severely constricted and air sheath concentrations do rise at certain points to as high as 20 percent.

The magnitude of the temperatures derived from the 0.6 mass ratio run were checked by estimating total argon radiation based on these temperatures using the radiation data of Emmons[11]. Radiation amounting to 2.4kW was calculated using Emmons' data. Heat balance data indicates that 13.4kW were induced corresponding to a 17 percent radiation. This agrees with that found for other one atmosphere argon plasma at these temperatures.

VELOCITY PROFILES

Introduction

The determination of velocities in a non-isothermal binary gas system requires knowledge of the density at each point in addition to the measured static and stagnation pressure heads. It was hoped that gas concentrations from the mixing studies together with densities from the temperature studies would be used in this way. However, the induction plasma is a low velocity system and the pressure heads developed amount to 0.1 in. of water maximum. Measurement of velocities was not achieved. However, interesting measurements of stagnation heads are presented.

Apparatus

In order to measure small pressure heads accurately two methods are available. A micromanometer can measure to .001 inches of water. A two liquid manometer depends on density difference[12]. Thus, if two immiscible liquids are placed in a "U" tube as shown in Fig. 38 and there are large reservoirs situated at the top so that the level of the top liquid changes very little, the pressure head recorded by a change of the interface is given by

$$\Delta P = h_m(\rho_1 - \rho_2)g$$

where h_m = interface head
ρ_1 = density of bottom liquid
ρ_2 = density of top liquid
g = acceleration due to gravity

If $\rho_1 - \rho_2 = 0.1$, the interface head is 10 times that read on a water manometer. These instruments can be made very sensitive. Ower[12] suggests that when the liquids are benzyl alchohol (ρ =1.048) and a 5 percent calcium chloride solution (ρ =1.037) the most satisfactory results are produced, yielding a device about 100 times as sensitive as a water manometer.

The very low velocities present in this TAFA induction plasma system have necessitated the use of a sensitive two liquid manometer capable of recording pressure heads as low as .001 inches of water. A manometer using benzyl alchohol and water was used. Reservoirs seven inches in diameter were placed above the unit in order to maintain the water level. With this arrangement an instrument 20 times more sensitive than a water manometer was achieved. A cathetometer was used to observe the pressure head.

Results

The probe was connected to the manometer and moved to a position two inches downstream from the exit plane. The gas flows were then adjusted to give 135 SCFH argon core (77 SCFH tangential and 58 SCFH radial) and 1035 SCFH air sheath. It was noticed that two to three minutes were required before the manometer head stabilized. The probe was then moved radially to a new position and the pressure head recorded. One complete profile of seven data points from the wall to the centerline was obtained in 16 minutes, the time to consume a #1 cylinder of compressed air at 1035 SCFH. The experiment was then repeated with the plasma present. The results are shown in Table II and in Fig. 39.

The "cold" profile shows a positive head near the wall of .0189 inches of water. This corresponds to a velocity of 9.8 ft/sec. if the local static head is assumed to be zero. This assumption is thought reasonable since the air sheath velocity at the exit plane is 12.95 ft/sec. However, as the profile moves into the argon core, the vortex produced by the tangential flow is revealed by the negative heads recorded.

The "hot" profile is even more complex. The pressure head is directly proportional to the temperature in a ducted system.

$$V = k\sqrt{\frac{\Delta P}{D}}$$

where V = velocity
ΔP = pressure head
D = gas density
k = constant

Rearranging this equation

$$\Delta P = \frac{V^2 D}{k^2} = K V^2 D$$

where K is another constant

Now in a ducted system the velocity is directly proportional to the temperature and the density is inversely proportional to the temperature

So $$V = aT \quad , \qquad D = \frac{b}{T}$$

where a and b are constant.

Therefore $$\Delta P = \frac{Ka^2 T^2 b}{T} = K a^2 b T$$

Significant conclusions may be drawn from the hot profile data. It appears that the maximum temperature in the plasma occurs off center, agreeing with the findings of the temperature studies. Also, if the high velocity sheath is confined to the wall as predicted by the concentration profiles, then the sheath temperature two inches downstream can be estimated. The recorded head at the wall was .0879 inches of water, which is 4.7 times the head recorded without the plasma present. Thus, the temperature should be about 4.7 times the absolute room temperature and equal to $1400^{o}K$ ($1100^{o}C$). This is certainly a feasible value.

Conclusions

The sensitivity of the two liquid manometer can be used only with a specially designed water cooled pitot tube and even then much time is required to obtain the data since the response of the instrument is so slow. An alternative might be the use of a tracer. Perhaps sub-micron particles of a refractory oxide could be injected upstream through a water cooled tube which could be placed in various desired positions. Then high speed movies could be used to document the flight pattern. Individual particles might be located from frame to frame and so reveal point velocities within the plasma system.

GENERAL CONCLUSIONS

These studies have shed light on the mixing mechanism between an argon plasma and a concentric sheath of air or hydrogen. It has been found that an apparent interface exists at the plasma boundary which prevents gross recirculation mixing between the outer sheath gas and the inner core even though such recirculation existed just before the plasma was ignited. Temperature measurements have only enforced the above hypothesis since it was found that the plasma is almost wholly confined to the argon core gas. The hardness of the plasma interfacial boundary has been demonstrated at TAFA[13]. High speed photographs show 250 micron particles of tungsten bouncing off the plasma fireball.

This work presents for the first time a detailed investigation of the interaction of a plasma with a cooler surrounding gas. It shows that plasma is well represented by the phrase, "the fourth state of matter."

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TABLE I

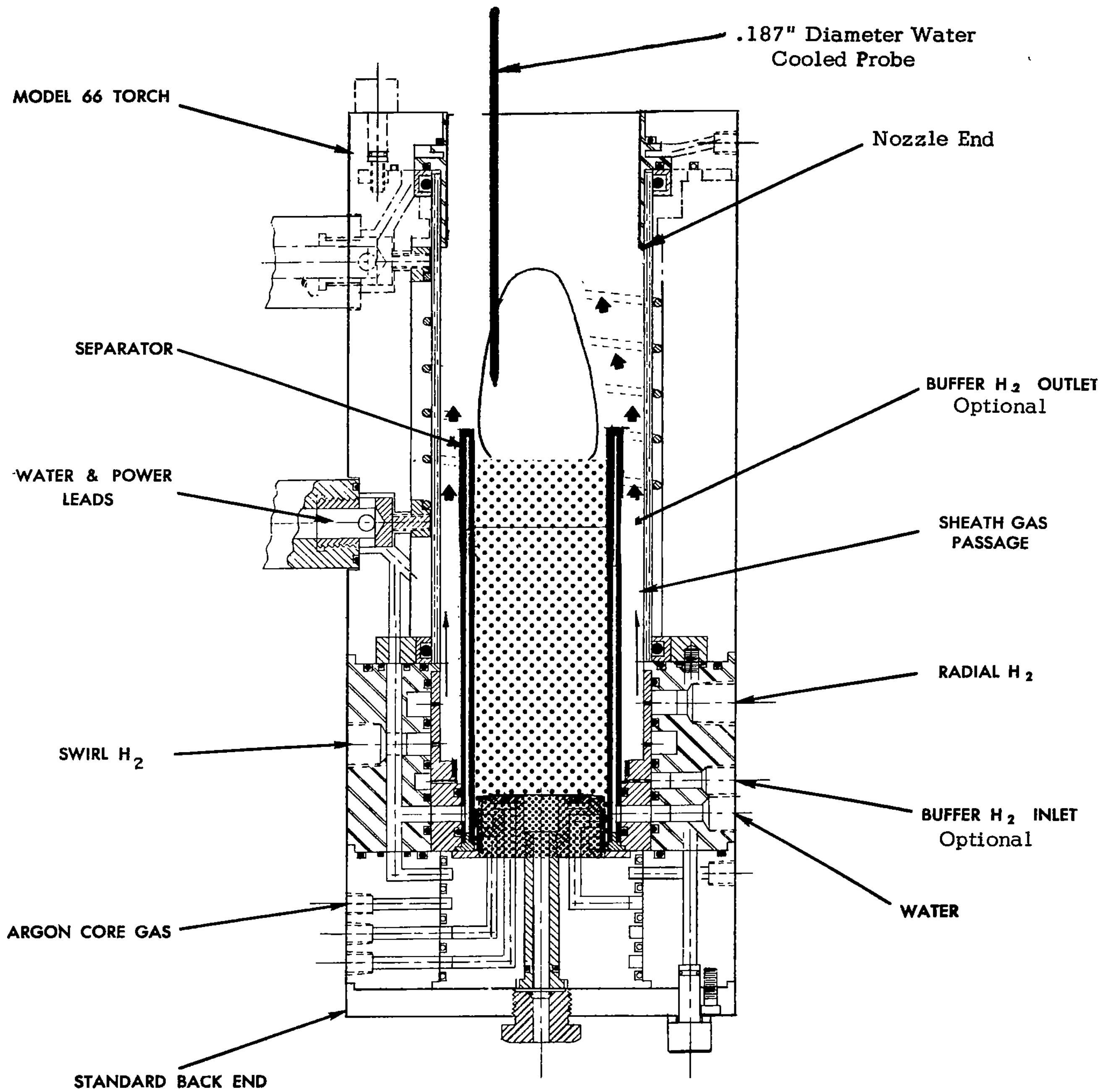
CALORIMETRIC DATA

Sheath gas	Air	Air	Air	Hydrogen
Flow rate (SCFH)	111	1035	1035	3800
Core gas	Argon	Argon	Argon	Argon
Flow rate (SCFH)	135	135	38	115
Sheath/core mass ratio	0.60	5.55	19.7	1.67
Tangential flow in core gas (%)	60	60	60	60
Plate voltage (kV)	8.4	9.1	9.6	9.1
Plate amperage (Amp)	4.0	4.0	4.0	4.0
Plate power (kW)	33.6	36.4	38.4	36.4
Oscillator tube loss (kW)	15.6	16.1	16.7	
Tank circuit loss (kW)	1.2	1.4	1.8	
rf coil and coaxial lead loss (kW)	3.4	3.8	4.1	
Metal separator loss (kW)	2.2	1.7	1.2	
Torch wall loss (kW)	2.5	1.9	1.9	
Power in gas leaving torch(kW)	8.7	11.5	12.7	
Power induction in plasma (kW)	13.4	15.1	15.8	

TABLE II

STAGNATION HEAD DATA

Position (inches from centerline)	Without plasma (inches of water)	With plasma (inches of water)
0	- .0358	+ .0658
.267	- .0339	+ .0938
.534	----	+ .0866
.801	- .0276	+ .0331
1.068	----	- .0232
1.335	- .0142	+ .0024
1.602	- .0020	+ .0473
1.737	+ .0099	+ .0796
1.872	+ .0189	+ .0879



THREE INCH SHEATH GENERATOR
(with sample probe shown schematically)

ARGON CORE GAS

FIG. 1

PROBE MOVEMENT MECHANICS

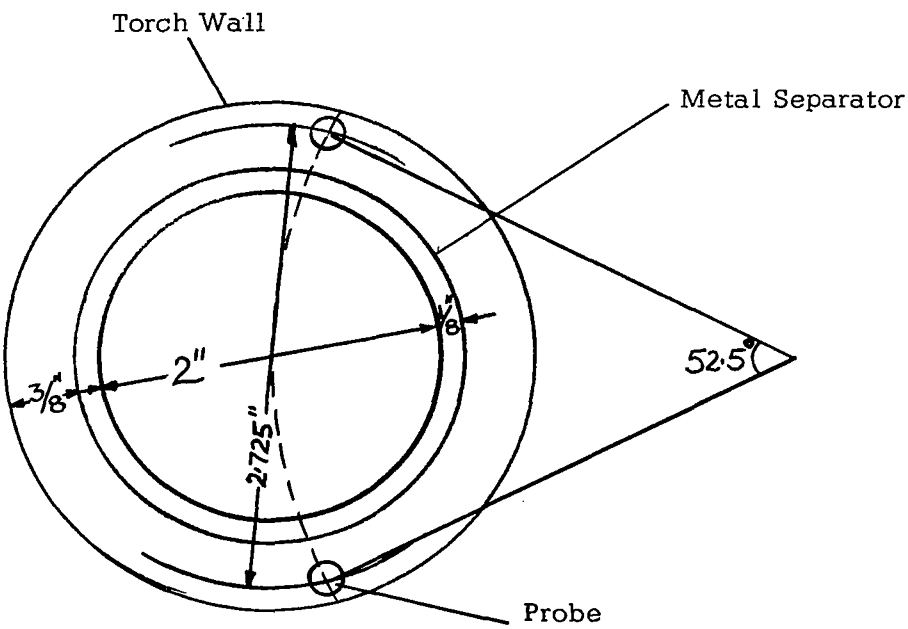


FIG. 2

GAS FLOW ARRANGEMENT WITHIN SHEATH TORCH

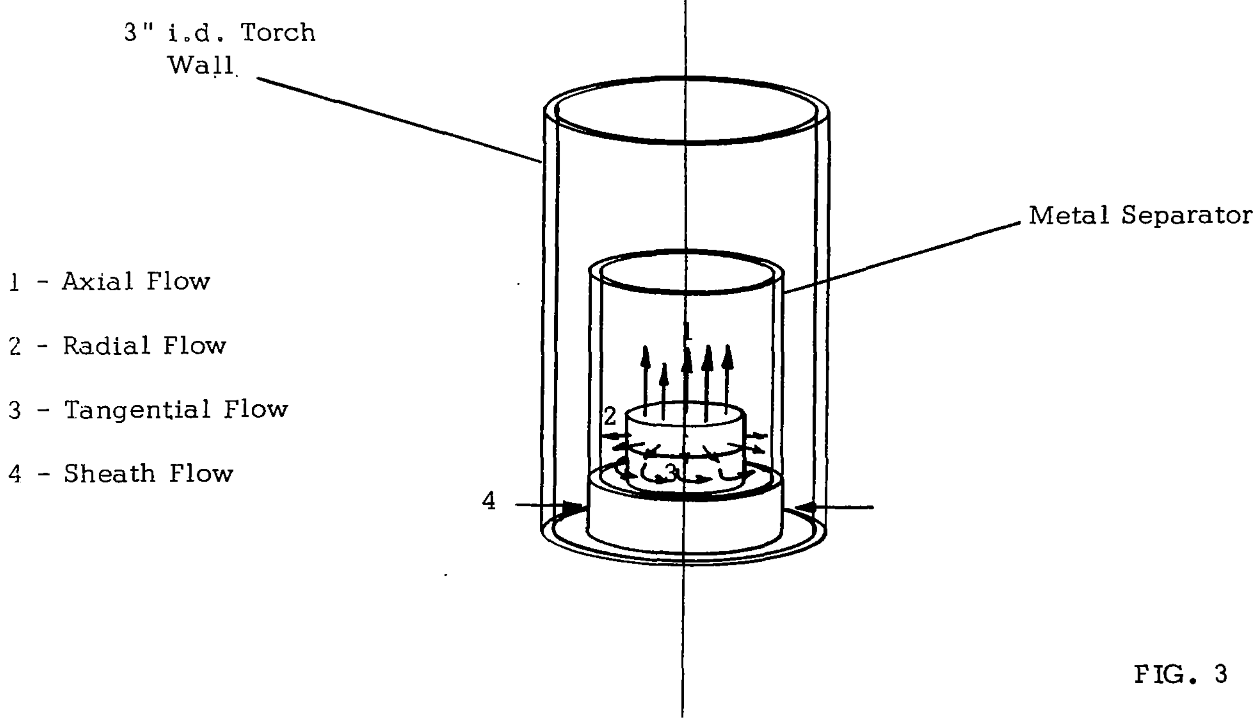
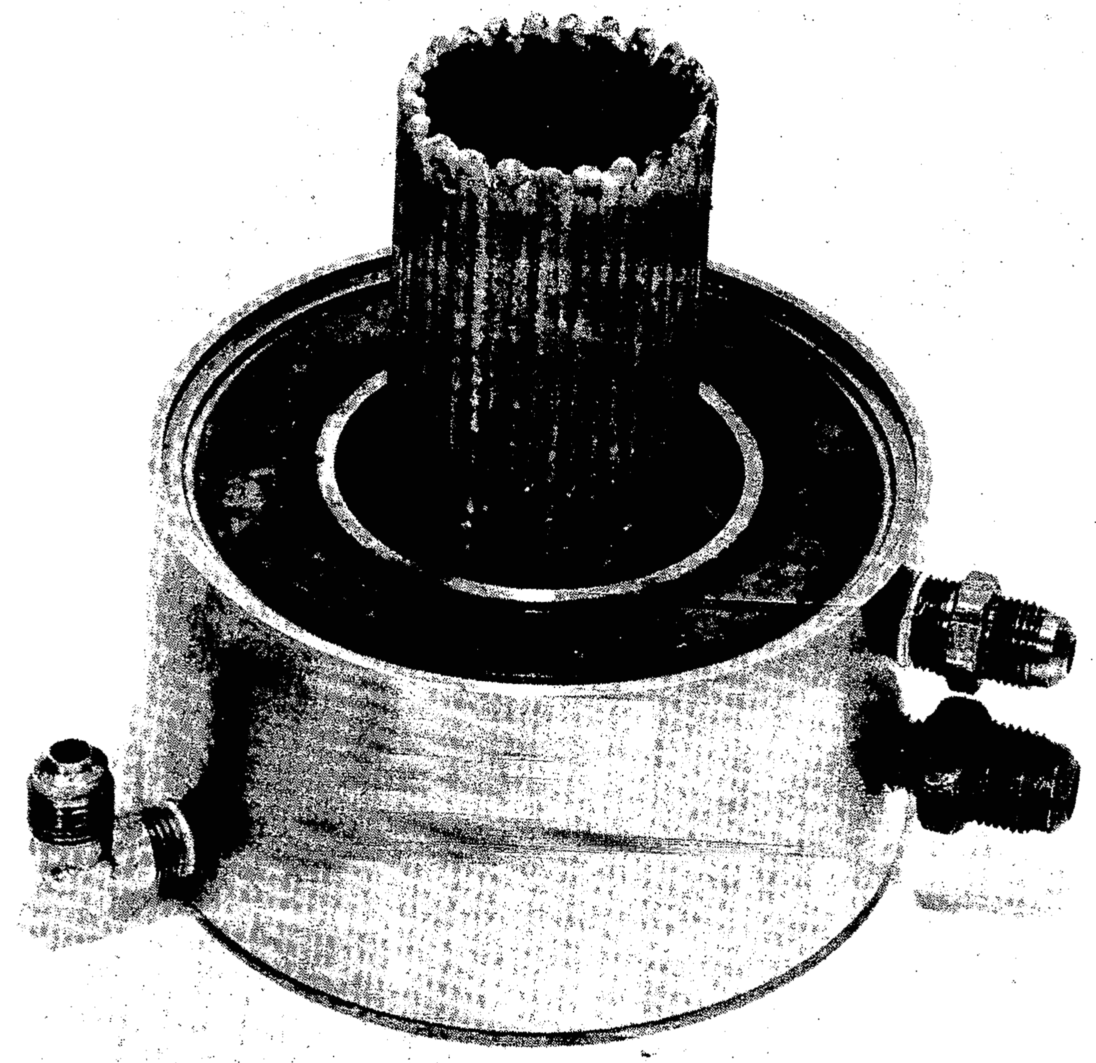
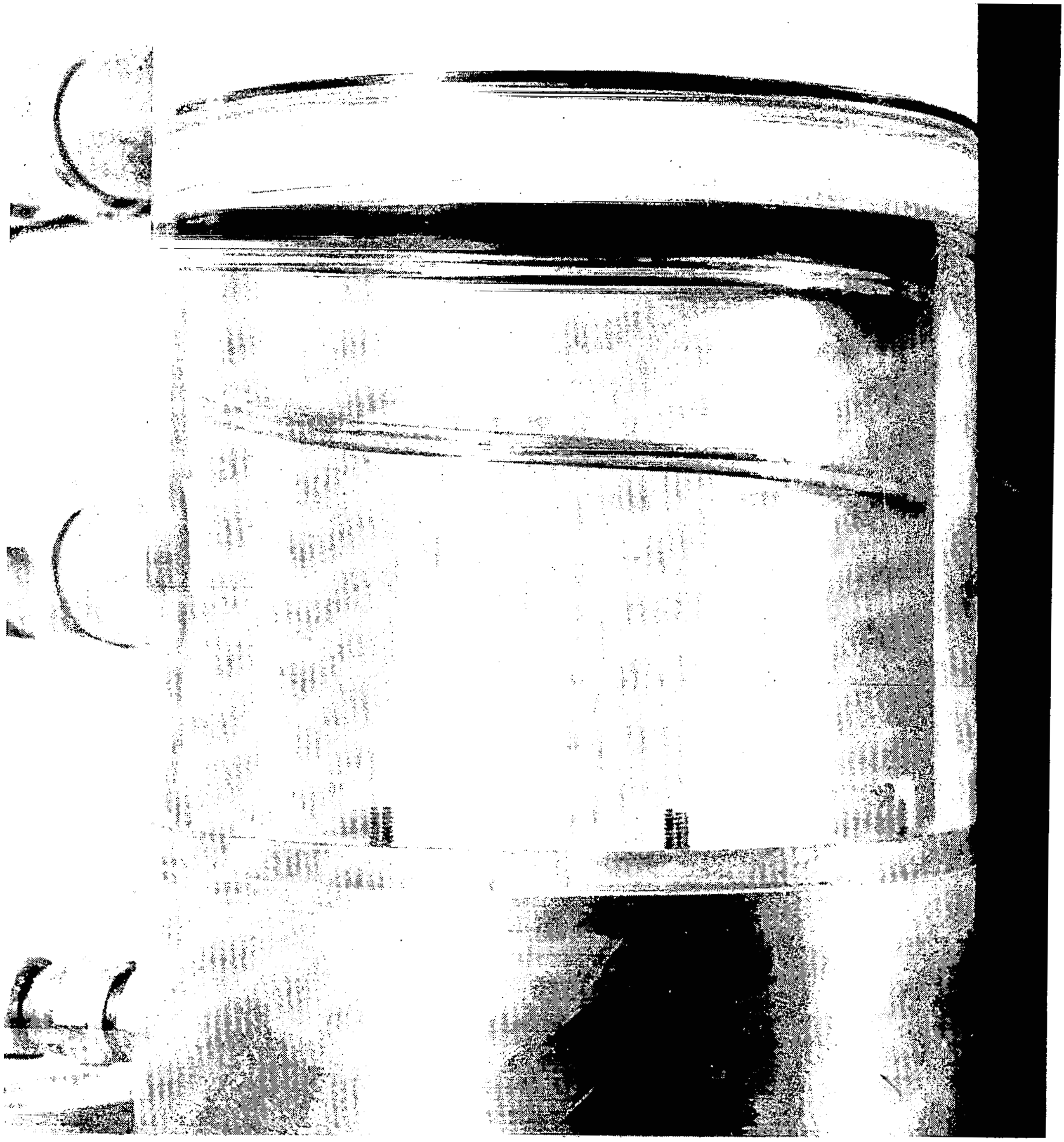


FIG. 3



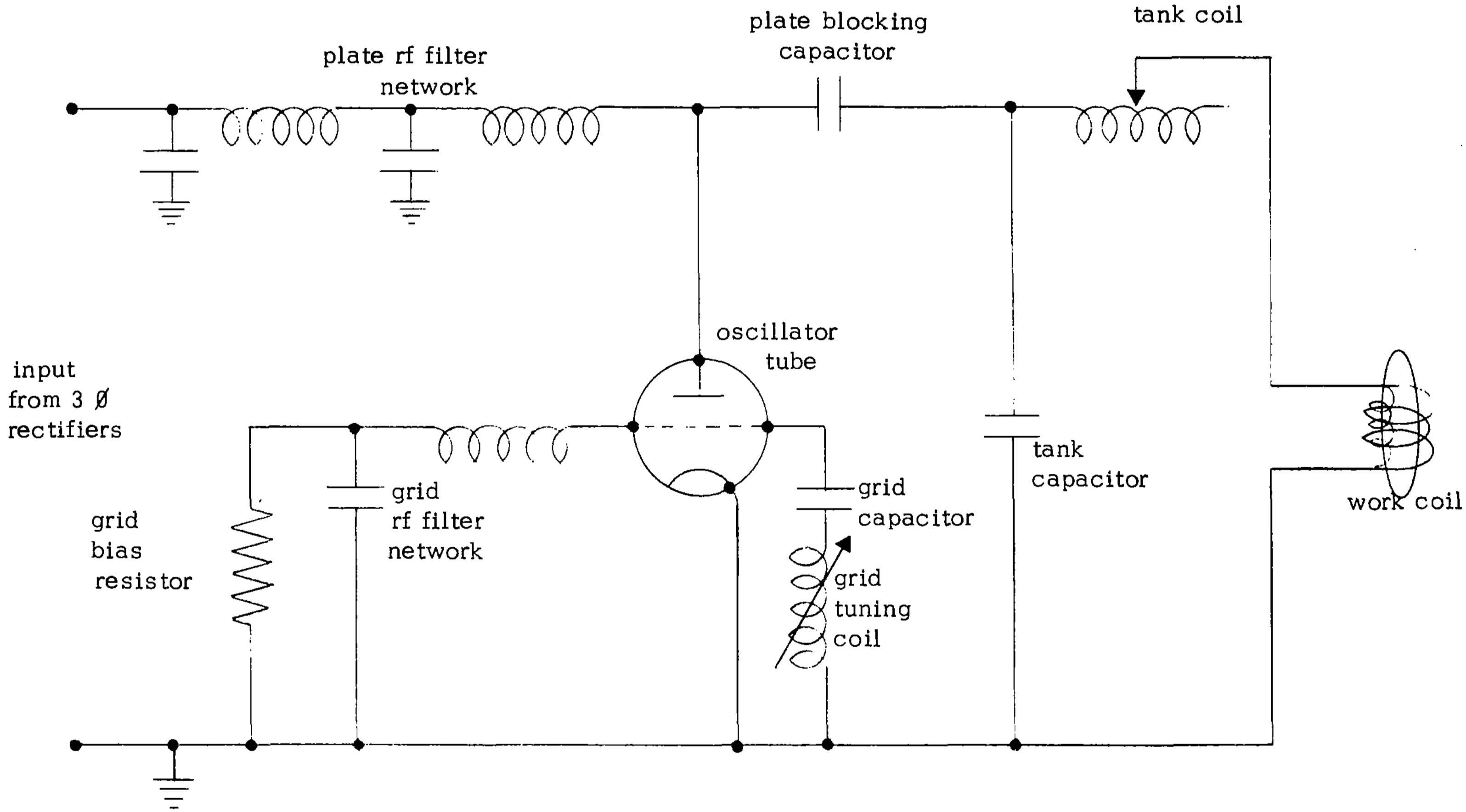
METAL SEPARATOR

FIG. 4



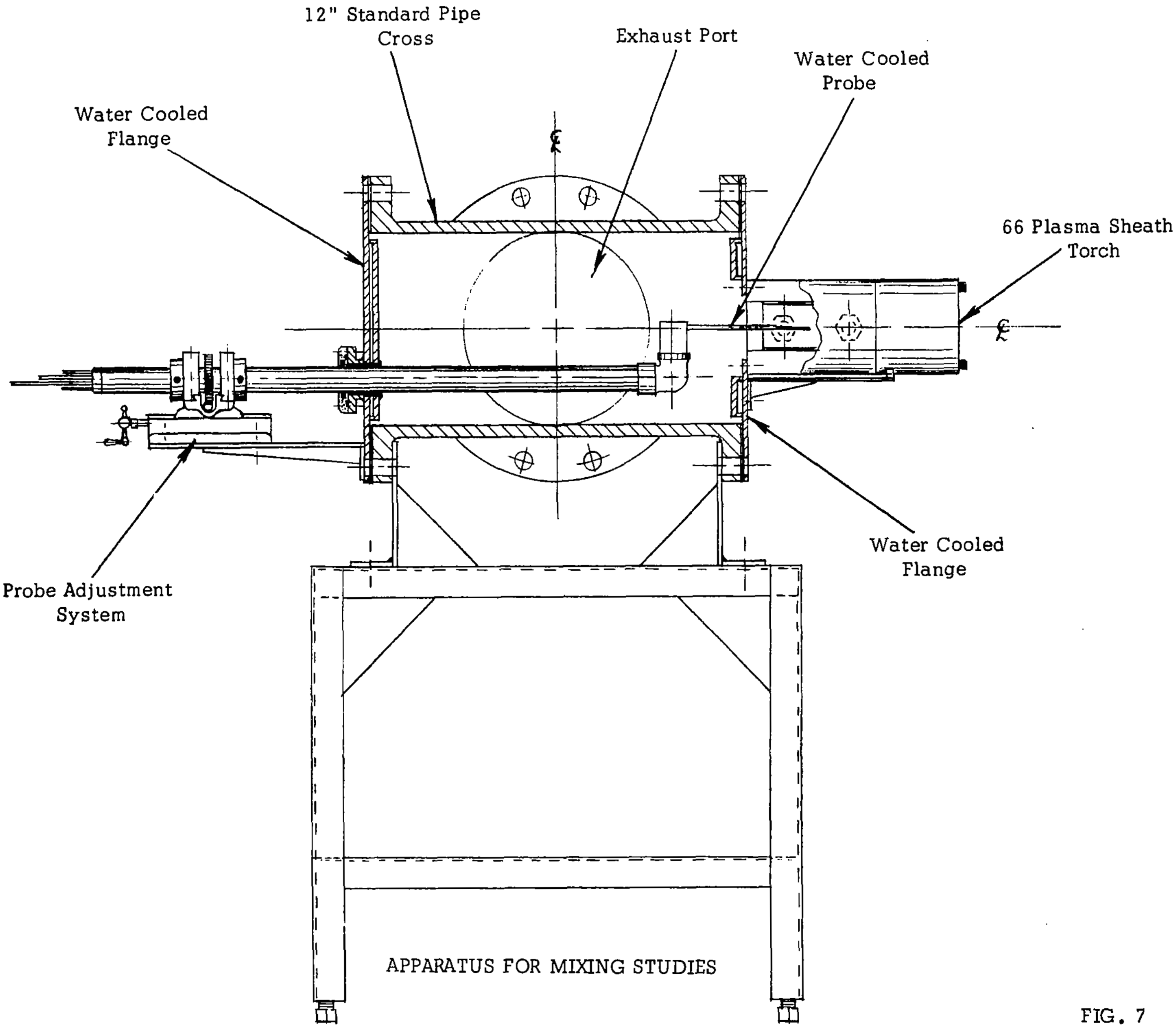
METAL SEPARATOR SEEN WITHIN ACRYLIC TORCH BODY

FIG. 5



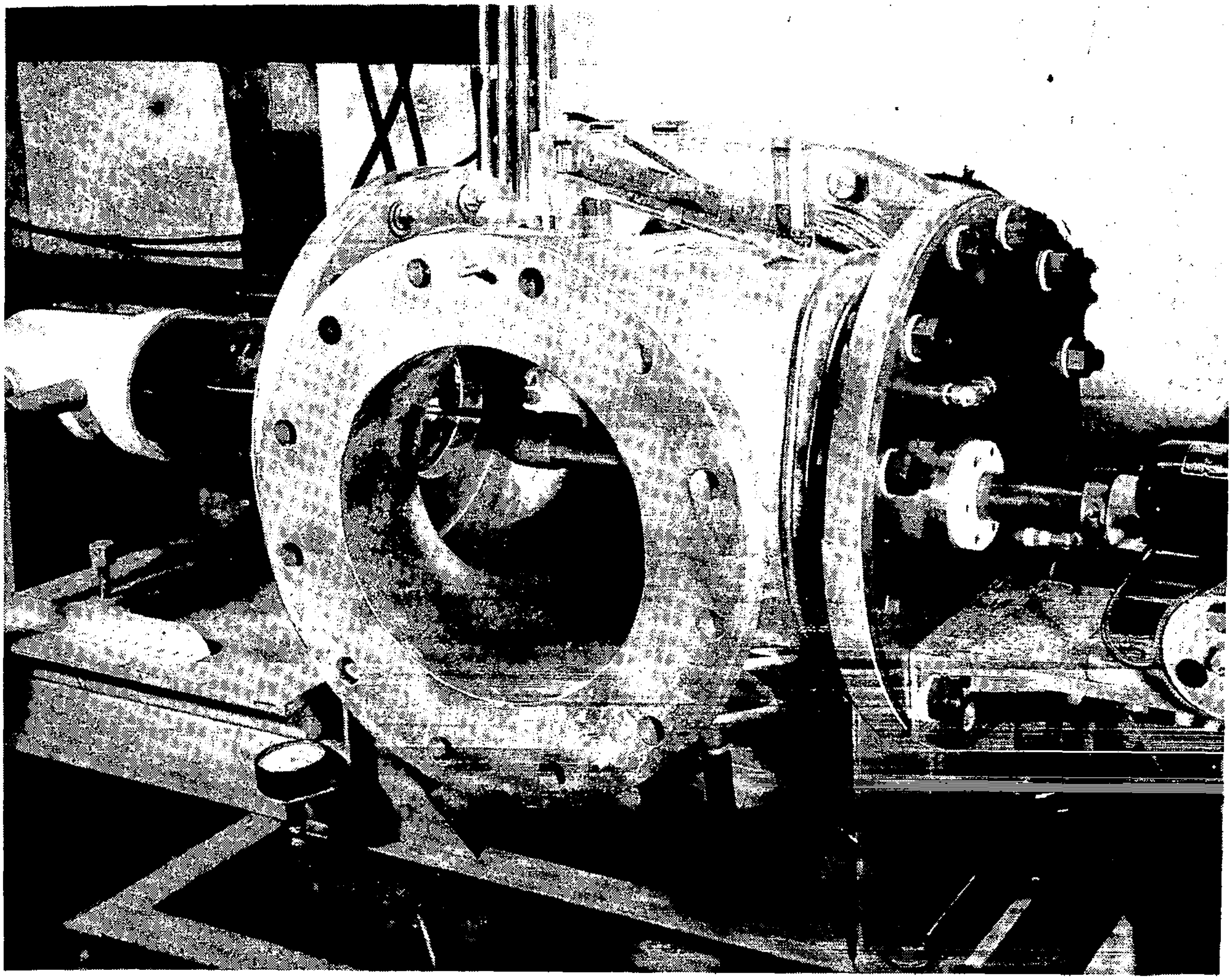
SIMPLIFIED OSCILLATOR CIRCUIT

FIG. 6



APPARATUS FOR MIXING STUDIES

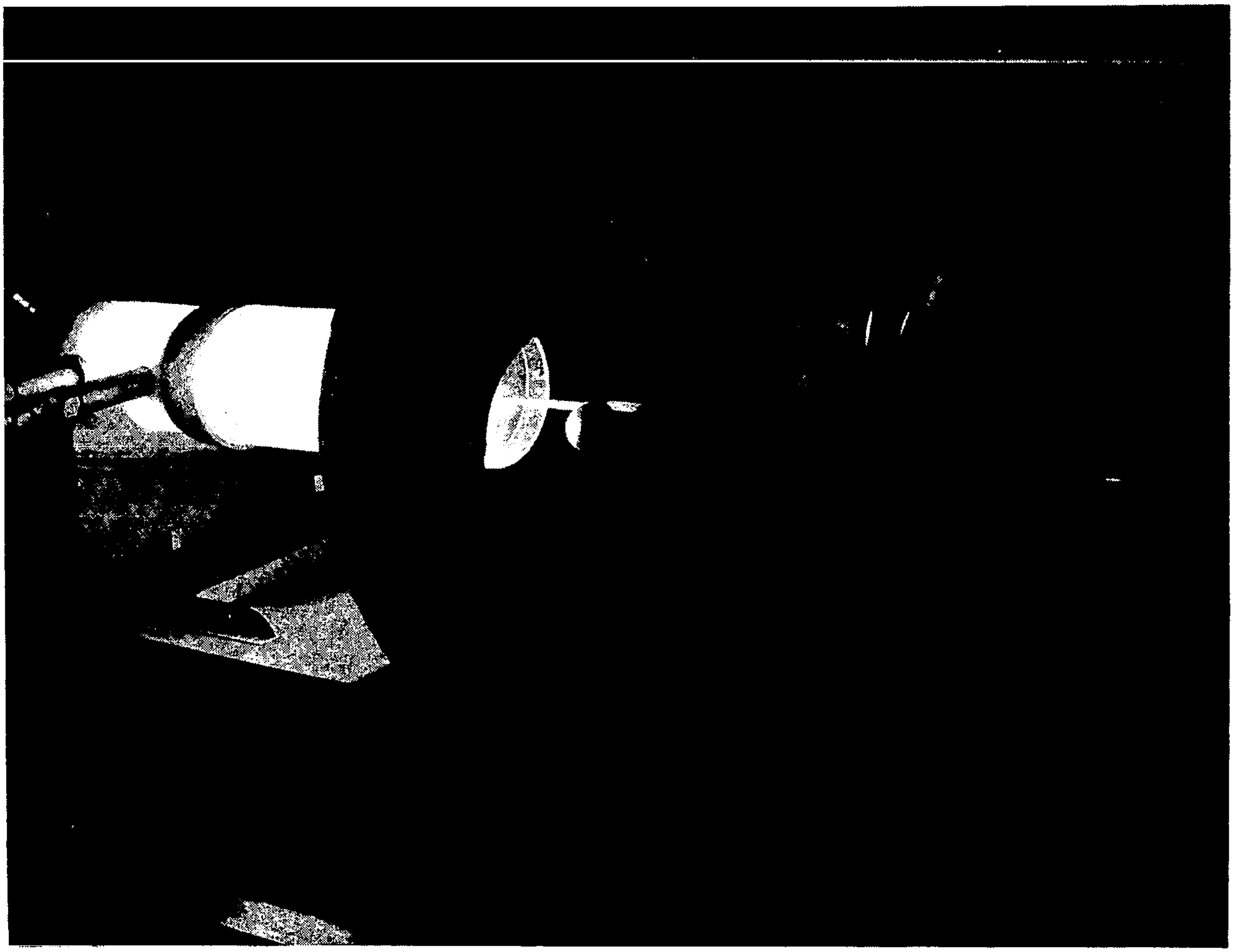
FIG. 7



PROBE AND MOVEMENT ASSEMBLY WITH

PROBE INSERTED IN MODEL 66 TORCH

FIG. 8

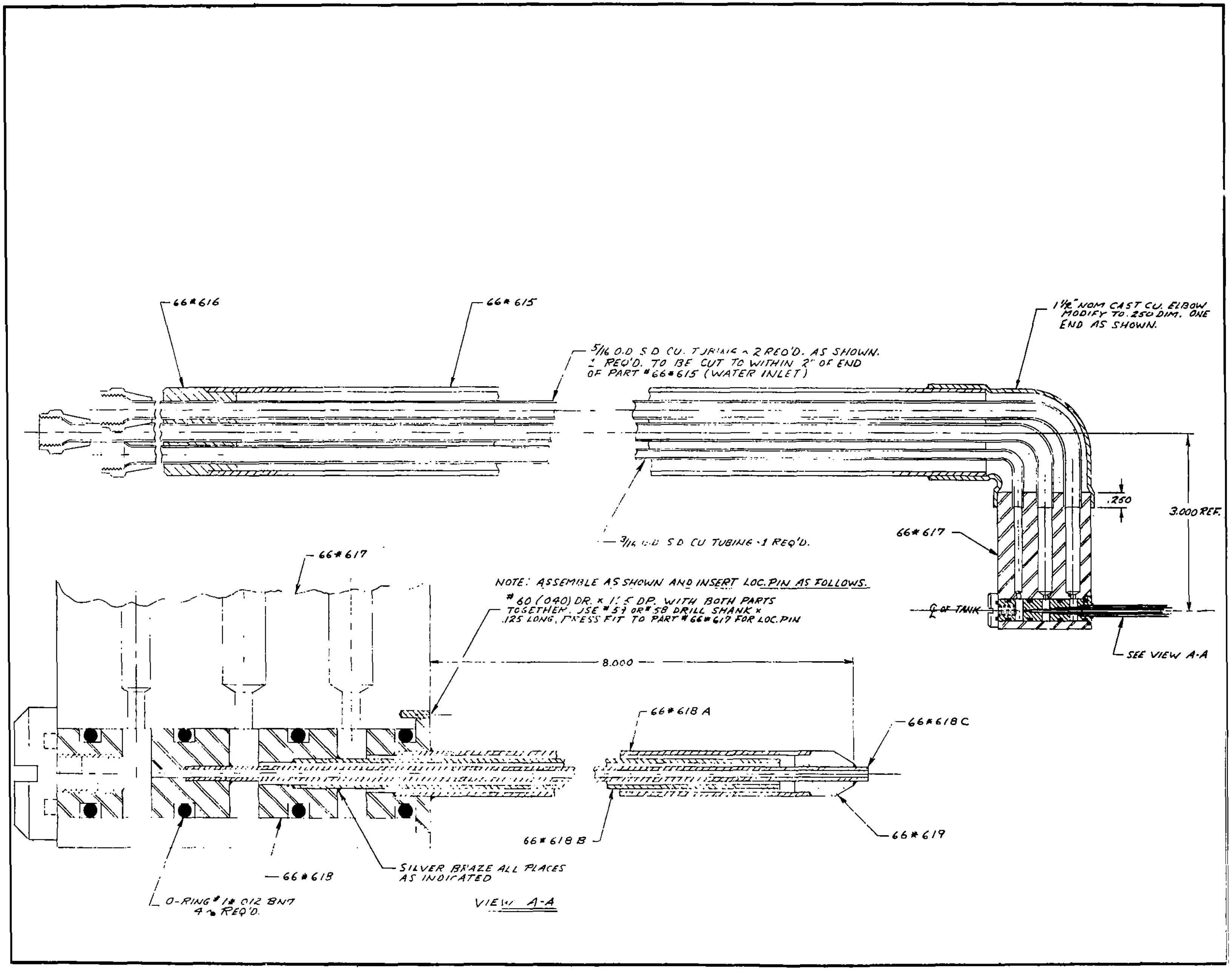


PROBE AND MOVEMENT ASSEMBLY WITH

PROBE INSERTED IN MODEL 66 TORCH

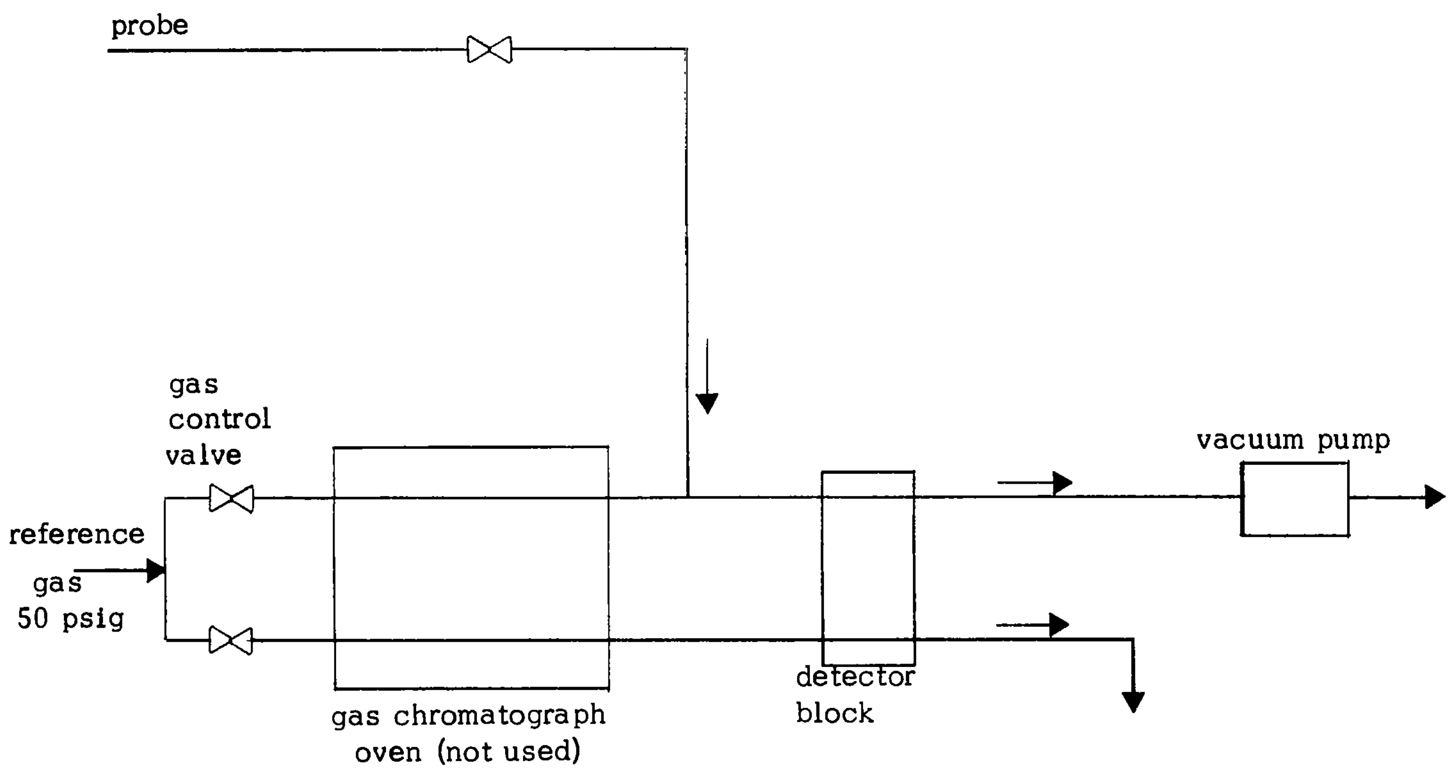
WITH TORCH IGNITED

FIG. 9



PROBE FOR DIAGNOSTIC STUDIES

FIG. 10



FLOW SYSTEM FOR SAMPLE ANALYSIS

FIG. 11

MIXING MAP WITHOUT PLASMA
AIR/ARGON MASS RATIO=0.67

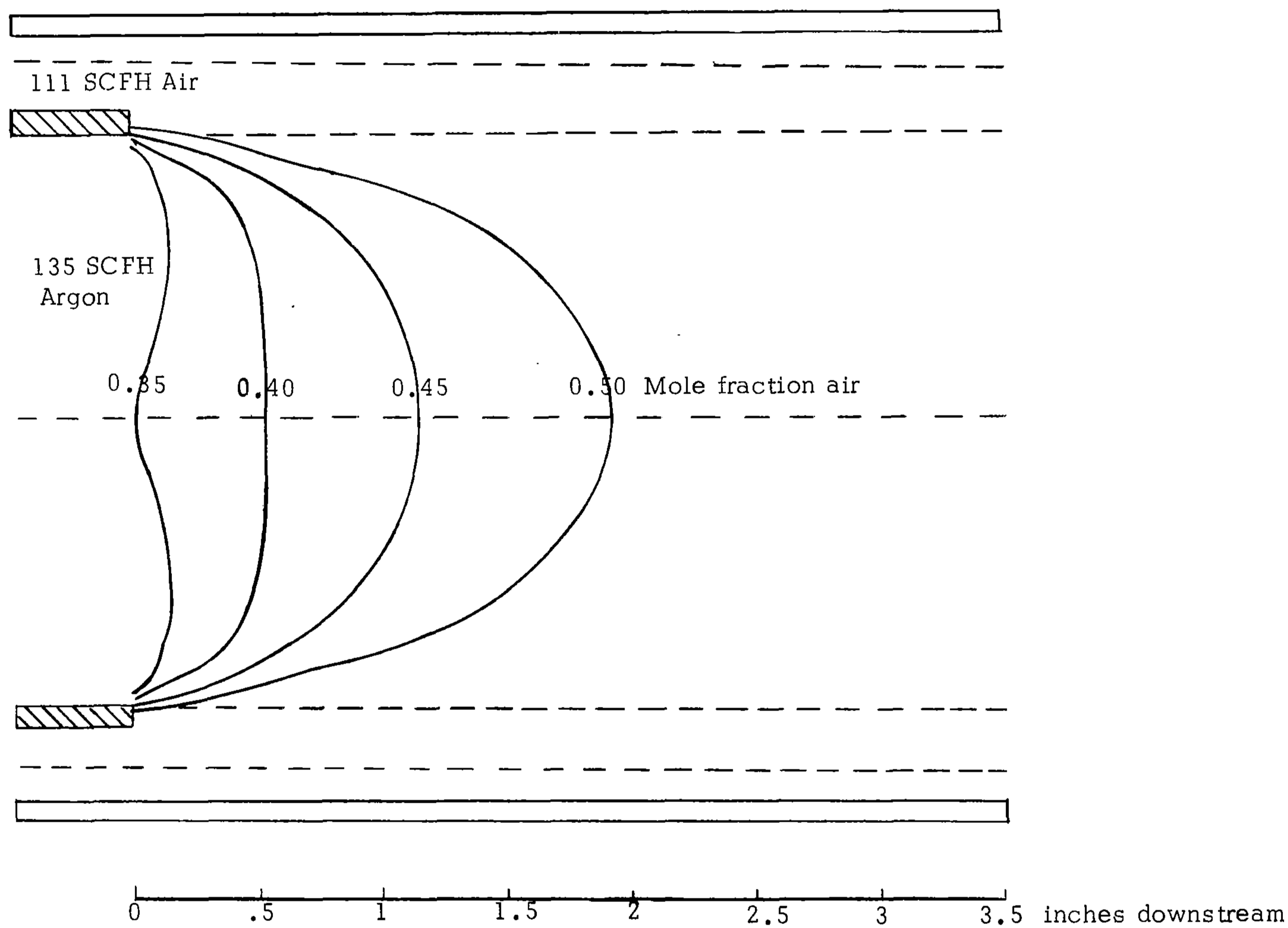


FIG. 12

MIXING MAP WITH PLASMA
AIR/ARGON MASS RATIO=0.67

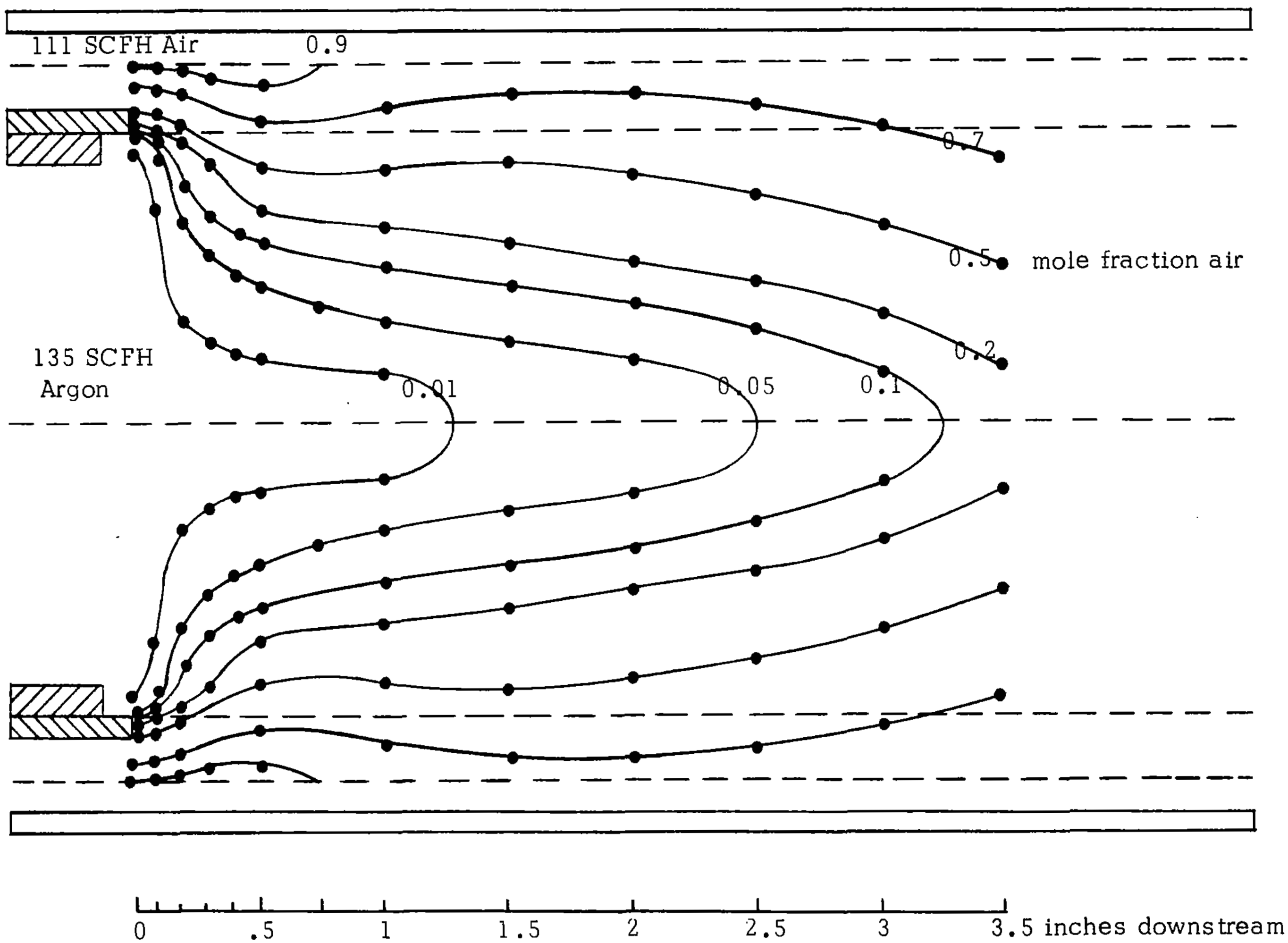


FIG. 13

MIXING MAP WITHOUT PLASMA
AIR/ARGON MASS RATIO=5.55

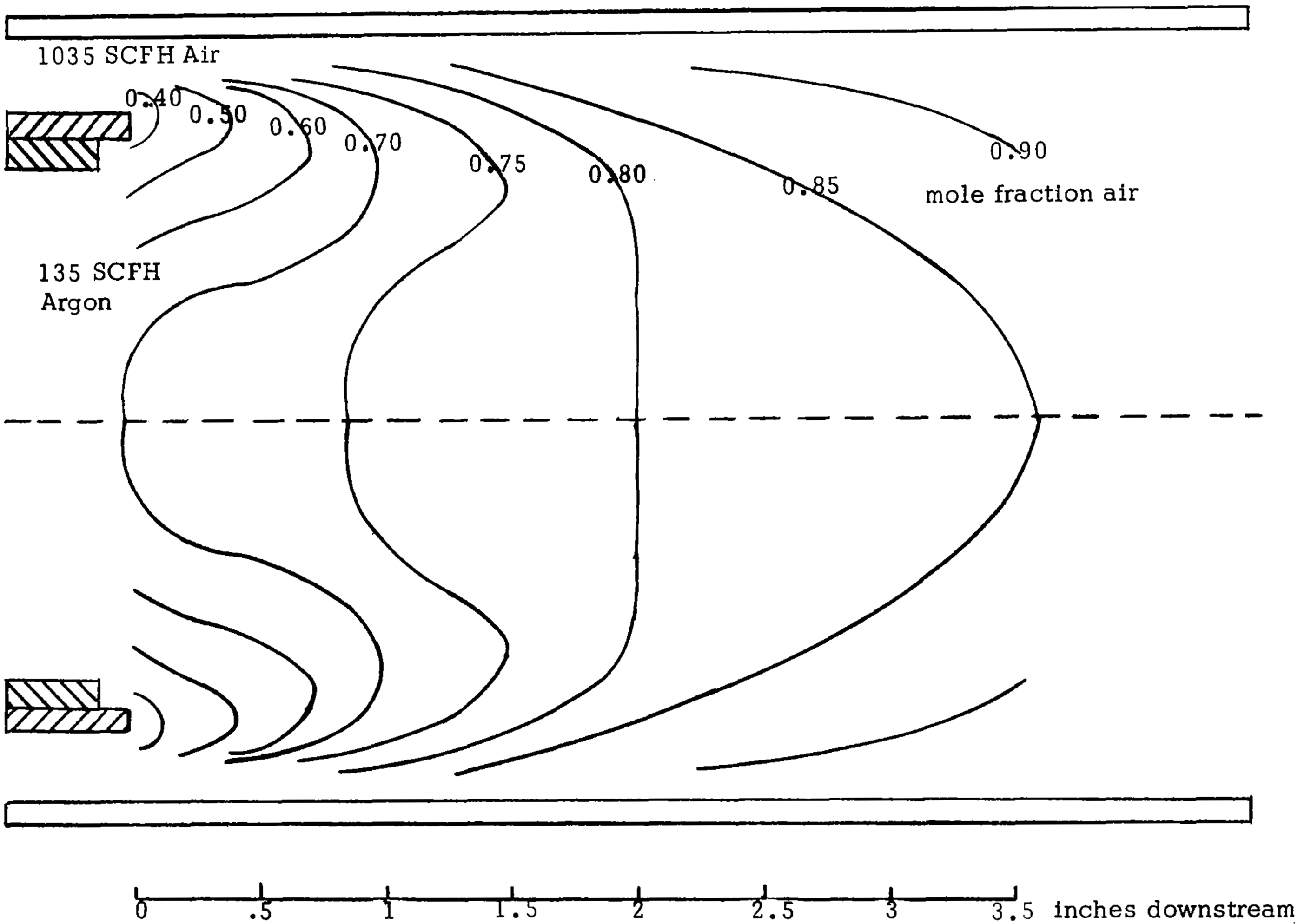


FIG. 14

MIXING MAP WITH PLASMA
AIR/ARGON MASS RATIO=5.55

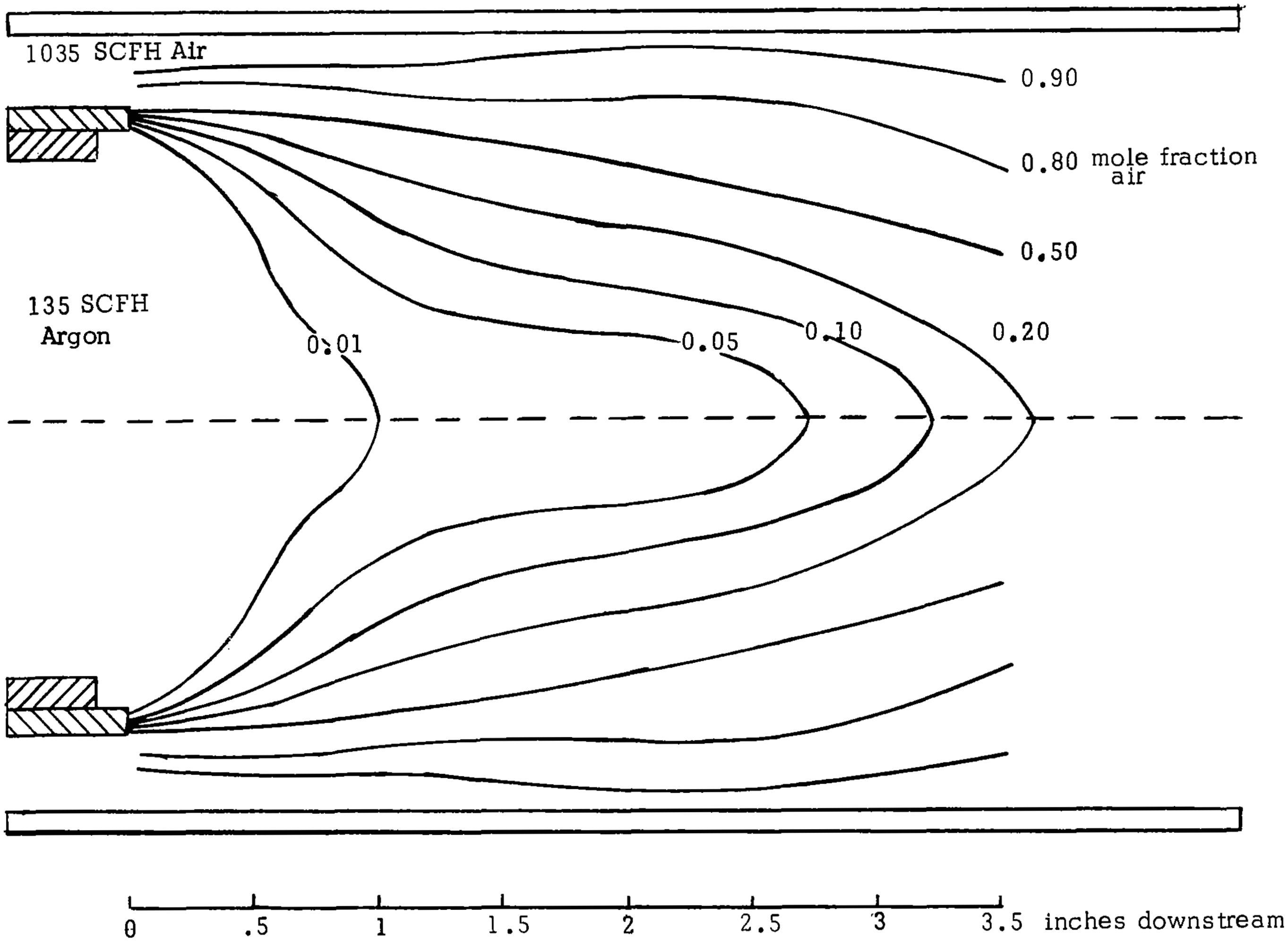


FIG. 15

MIXING MAP WITHOUT PLASMA
AIR/ARGON MASS RATIO=19.7

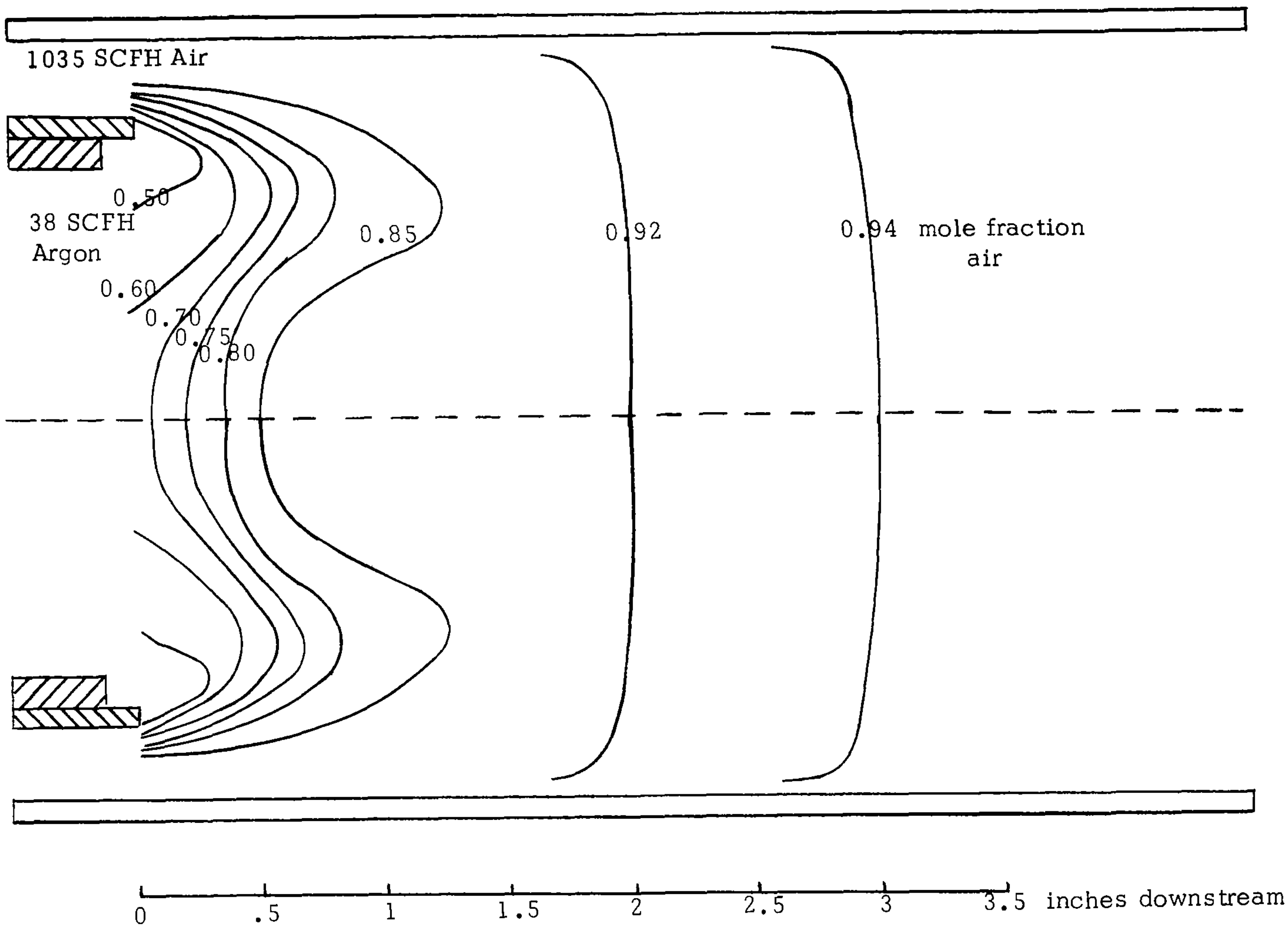


FIG. 16

MIXING MAP WITH PLASMA
AIR/ARGON MASS RATIO=19.7

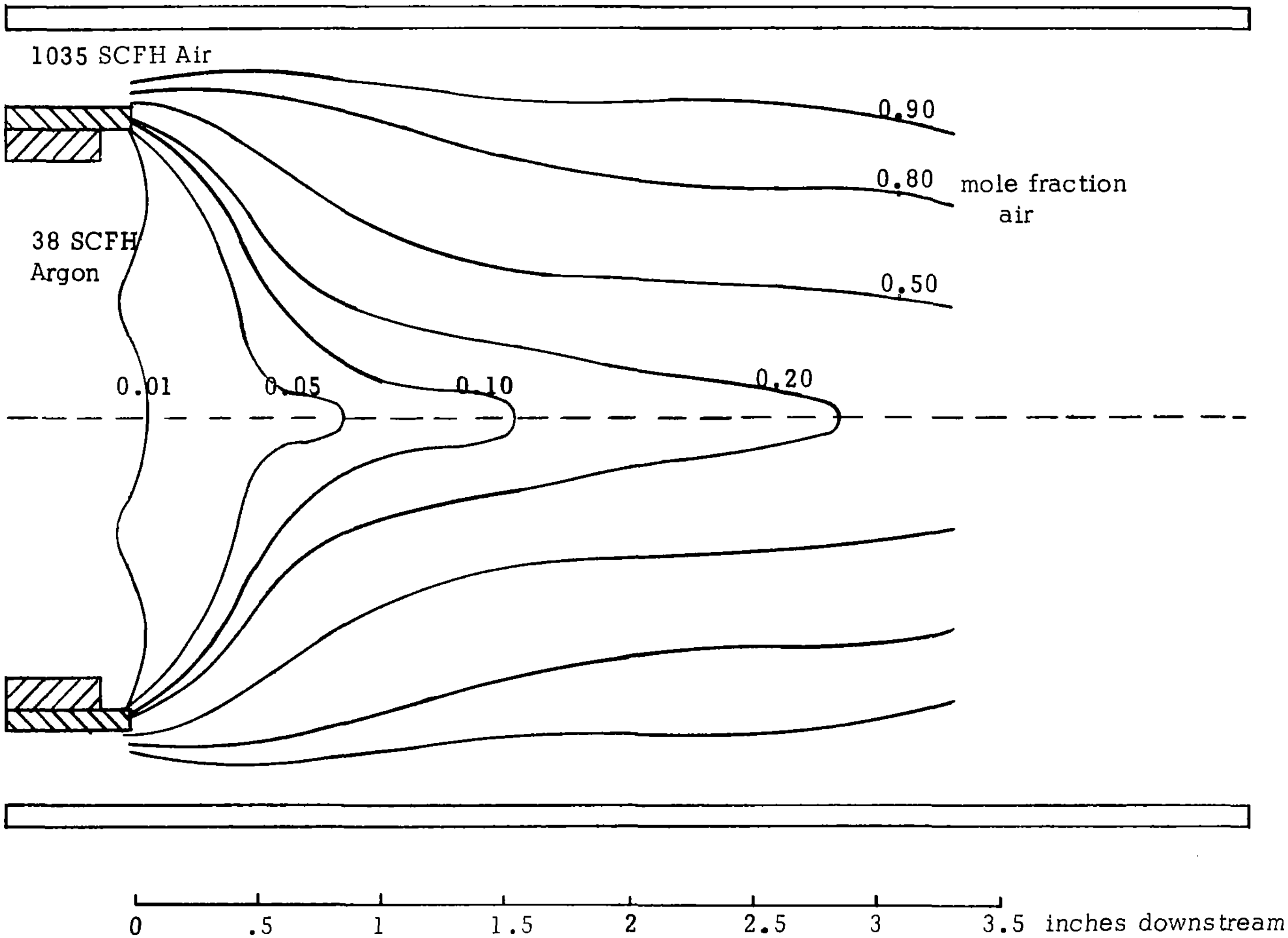


FIG. 17

MIXING MAP WITHOUT PLASMA
HYDROGEN/ARGON MASS RATIO=1.67

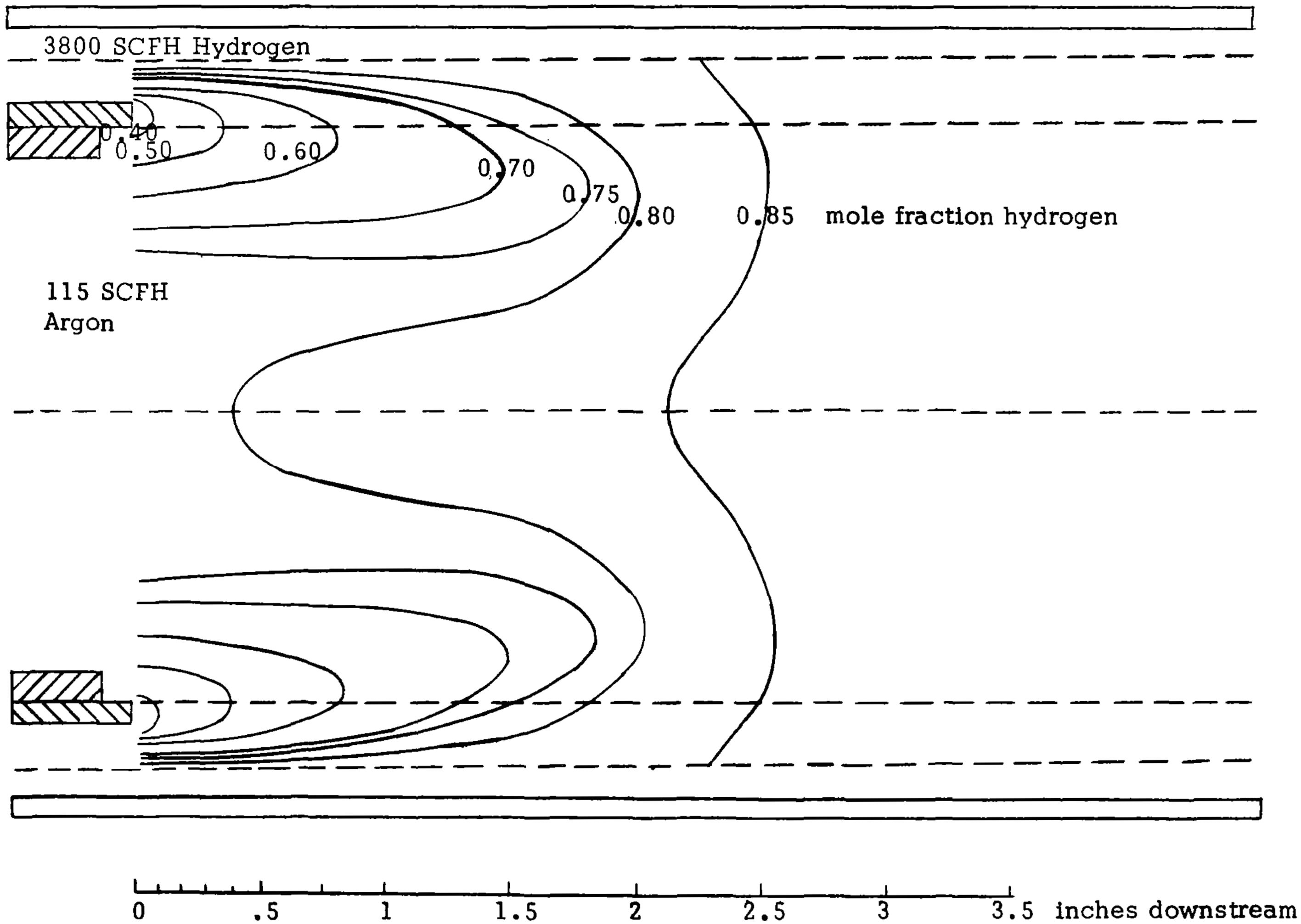


FIG. 18

MIXING MAP WITH PLASMA
HYDROGEN/ARGON MASS RATIO=1.67

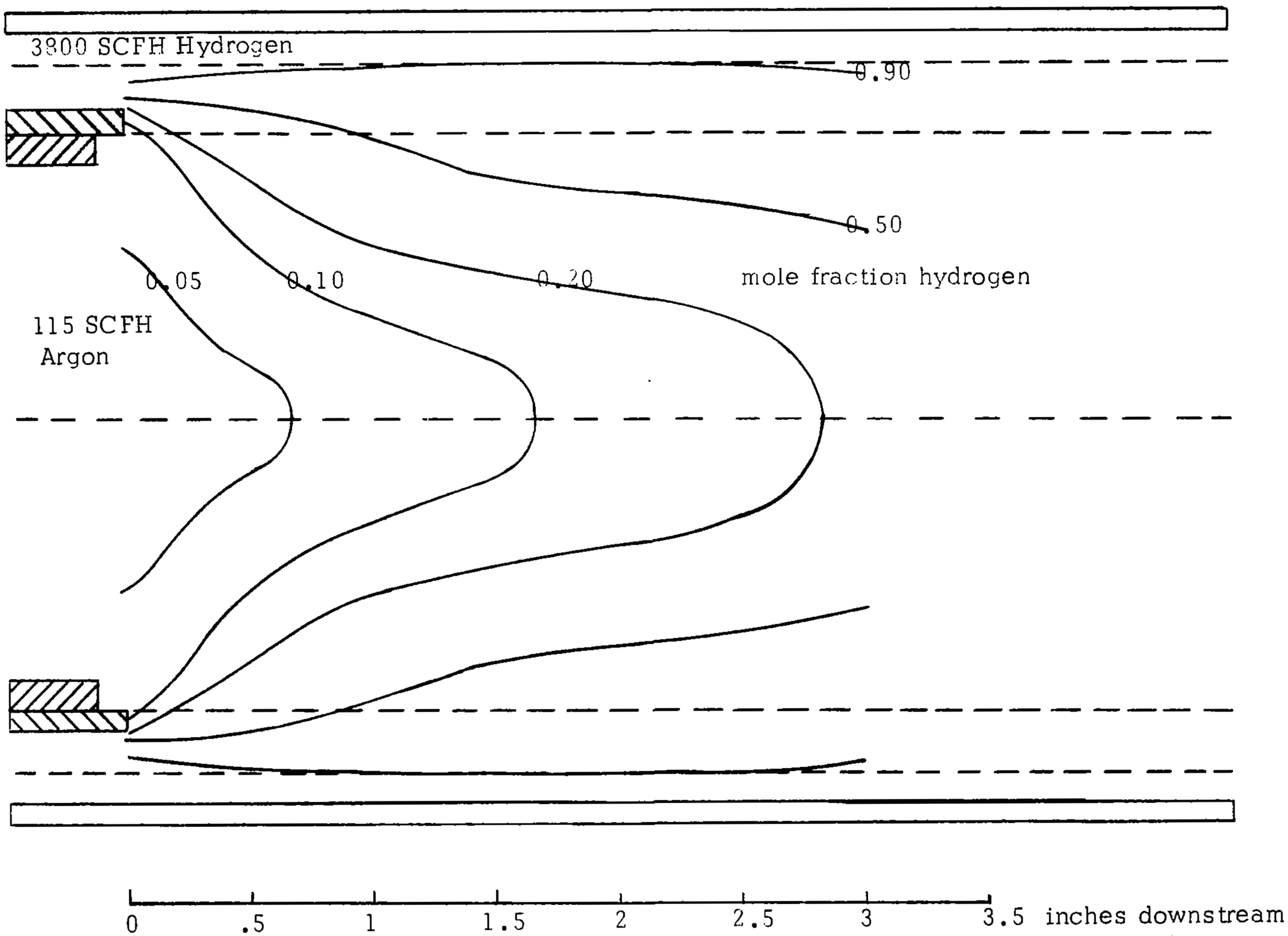


FIG. 19

LAMINAR MIXING PATTERN FOR ISOTHERMAL CONDITIONS

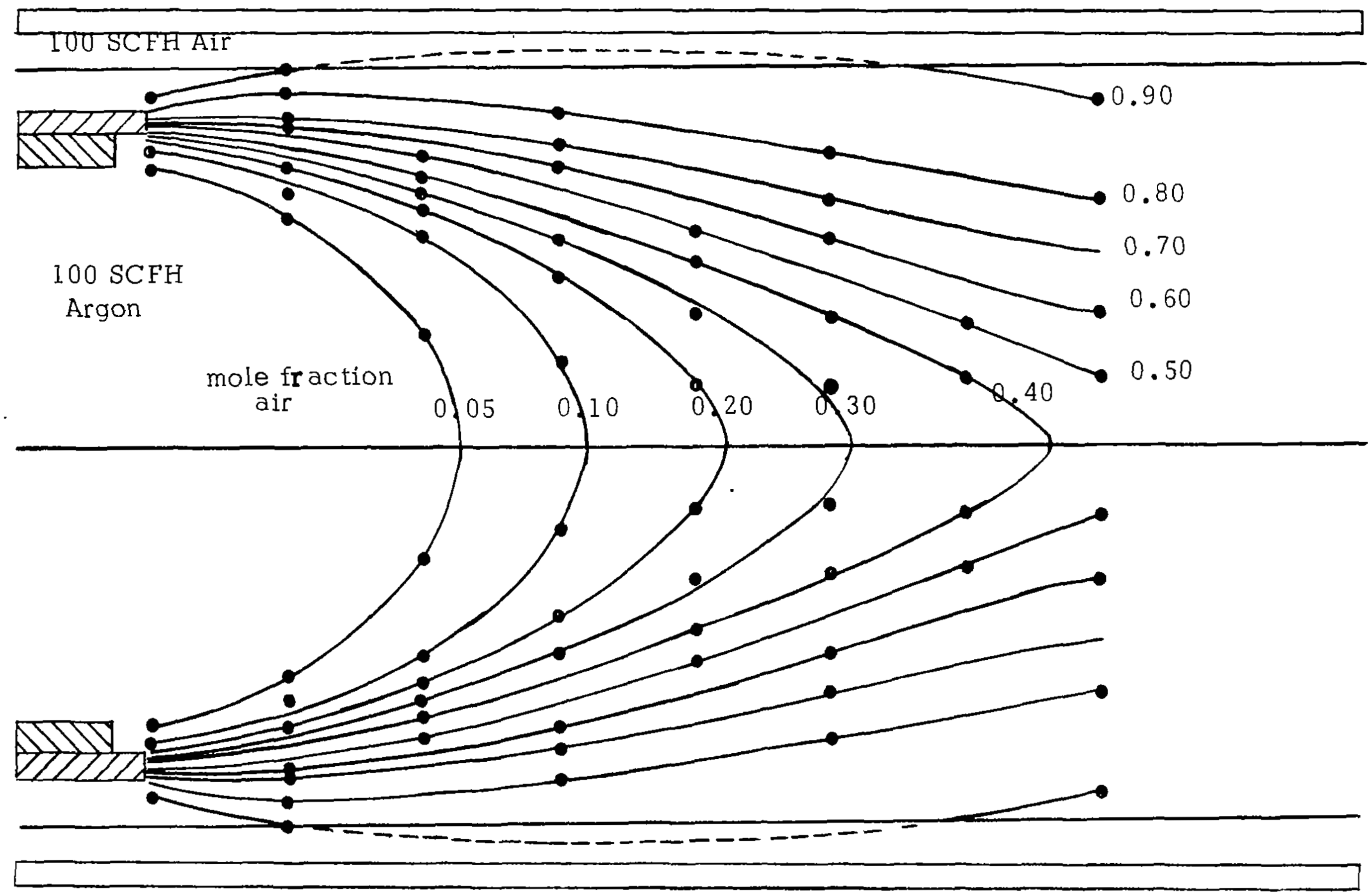
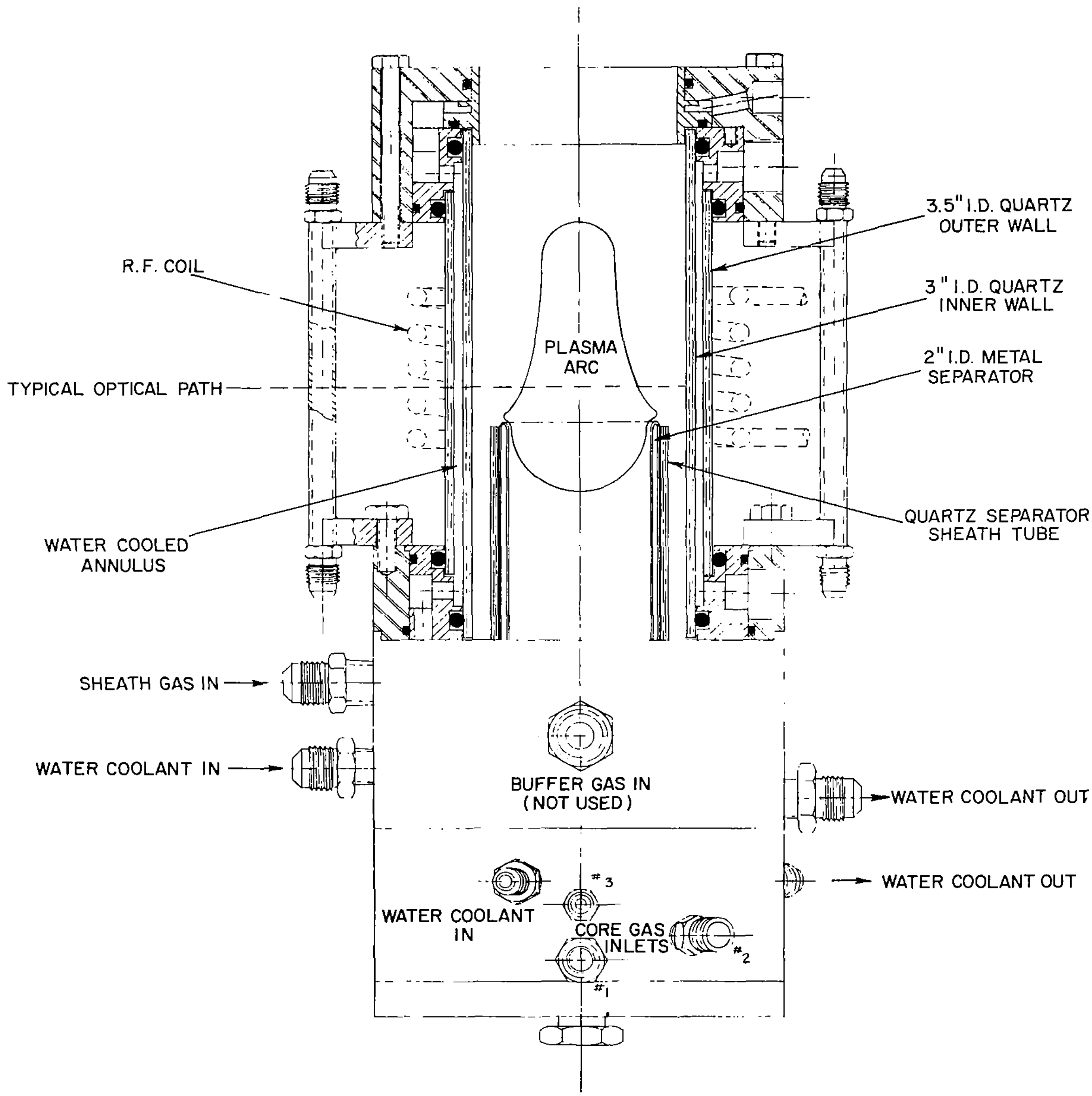
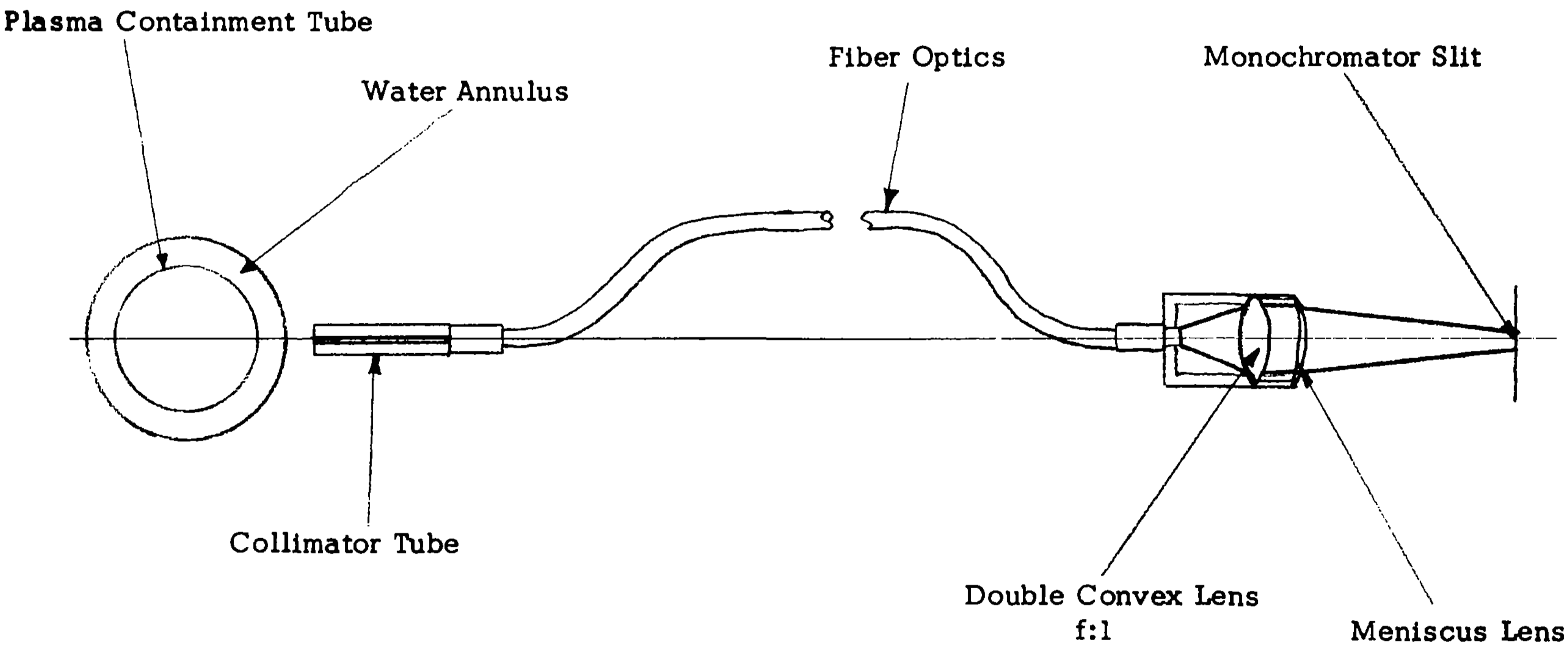


FIG. 20



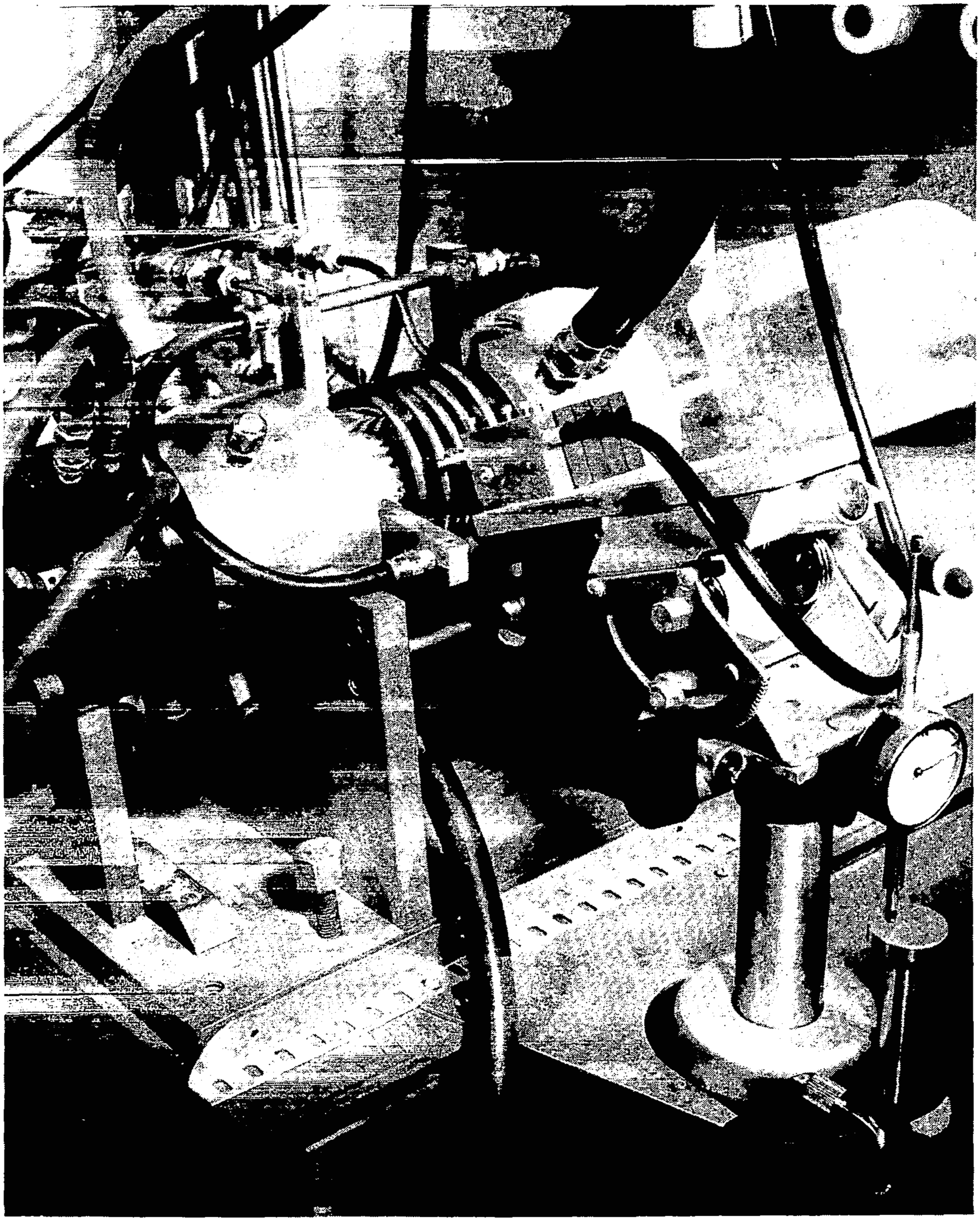
66 TORCH MODIFIED FOR USE IN TEMPERATURE MEASUREMENT EXPERIMENTS

FIG. 21



FIBER OPTICS ENERGY TRANSMISSION ARRANGEMENT

FIG. 22



FIBER OPTICS HEAD POSITIONED TO

DETECT PLASMA RADIATION

FIG. 23

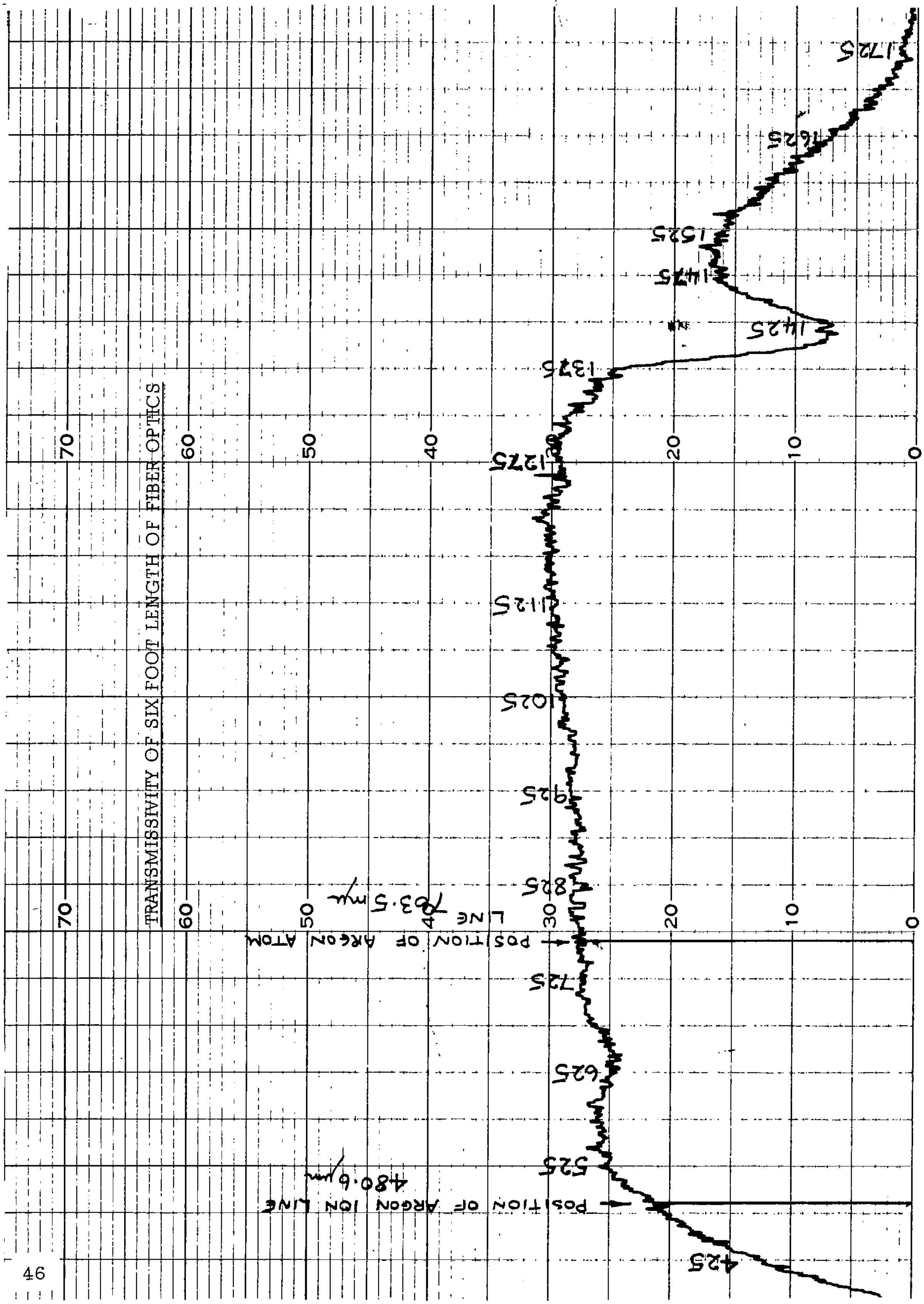
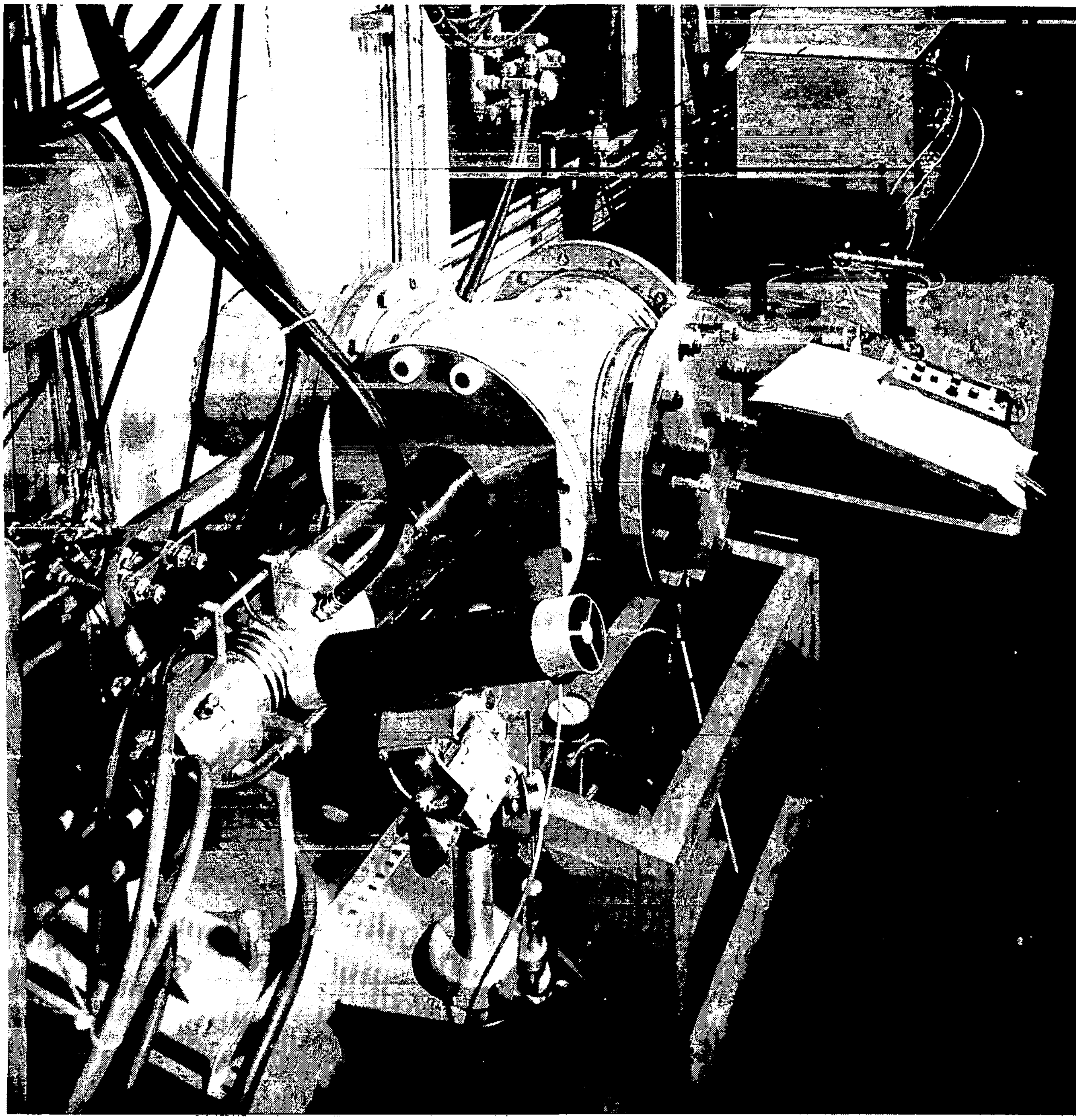

TRANSMISSIVITY OF SIX FOOT LENGTH OF FIBER OPTICS
POSITION OF ARGON ION LINE
480.6 mμ
POSITION OF ARGON ATOM LINE
703.5 mμ
0
10
20
30
40
50
60
70
425
525
625
725
825
925
1025
1125
1275
1375
1425
1475
1525
1625
1725
46

FIG. 24



PHOTOGRAPH SHOWING LASER BEAM

CALIBRATION ASSEMBLY

AND EXHAUST CHAMBER

FIG. 25

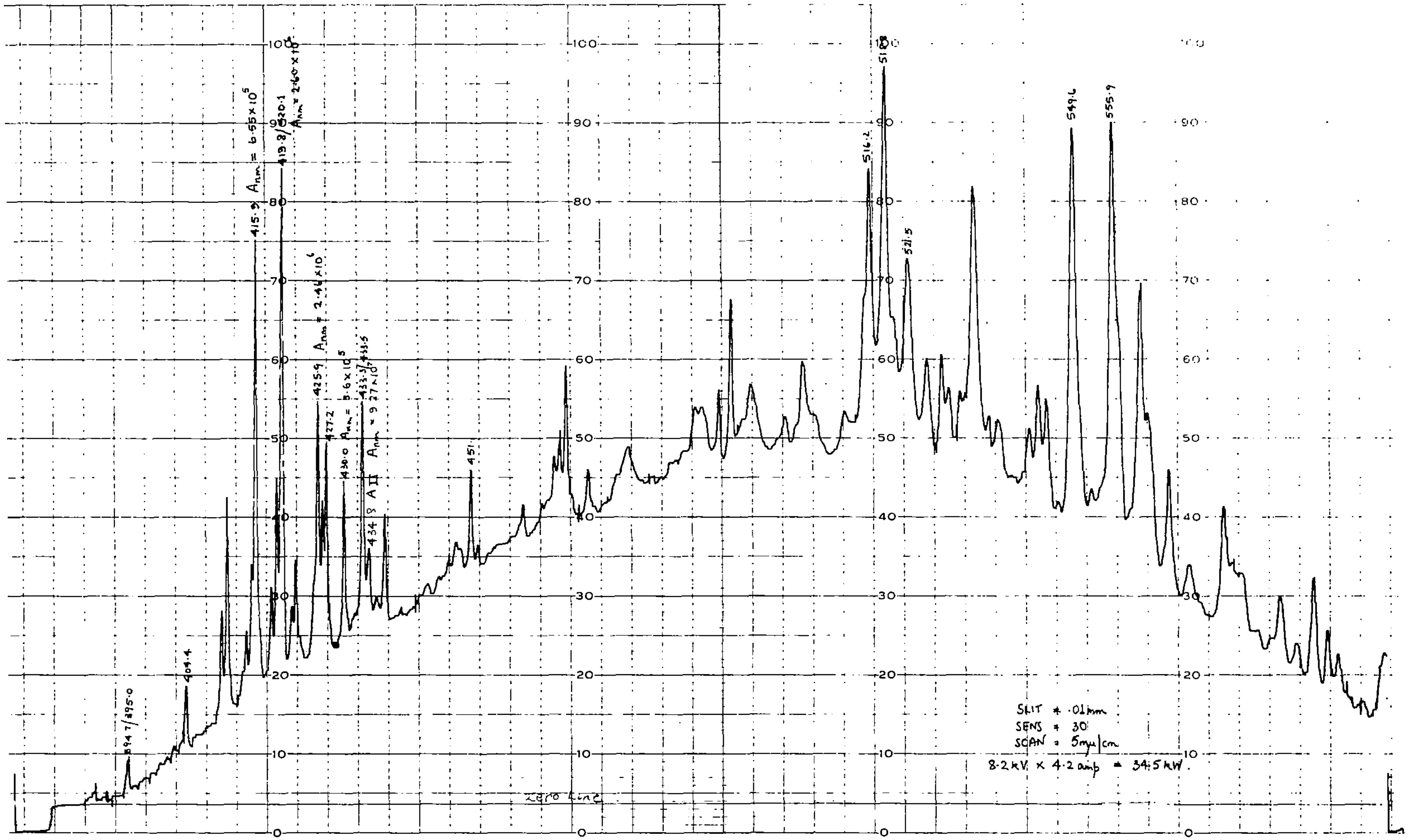
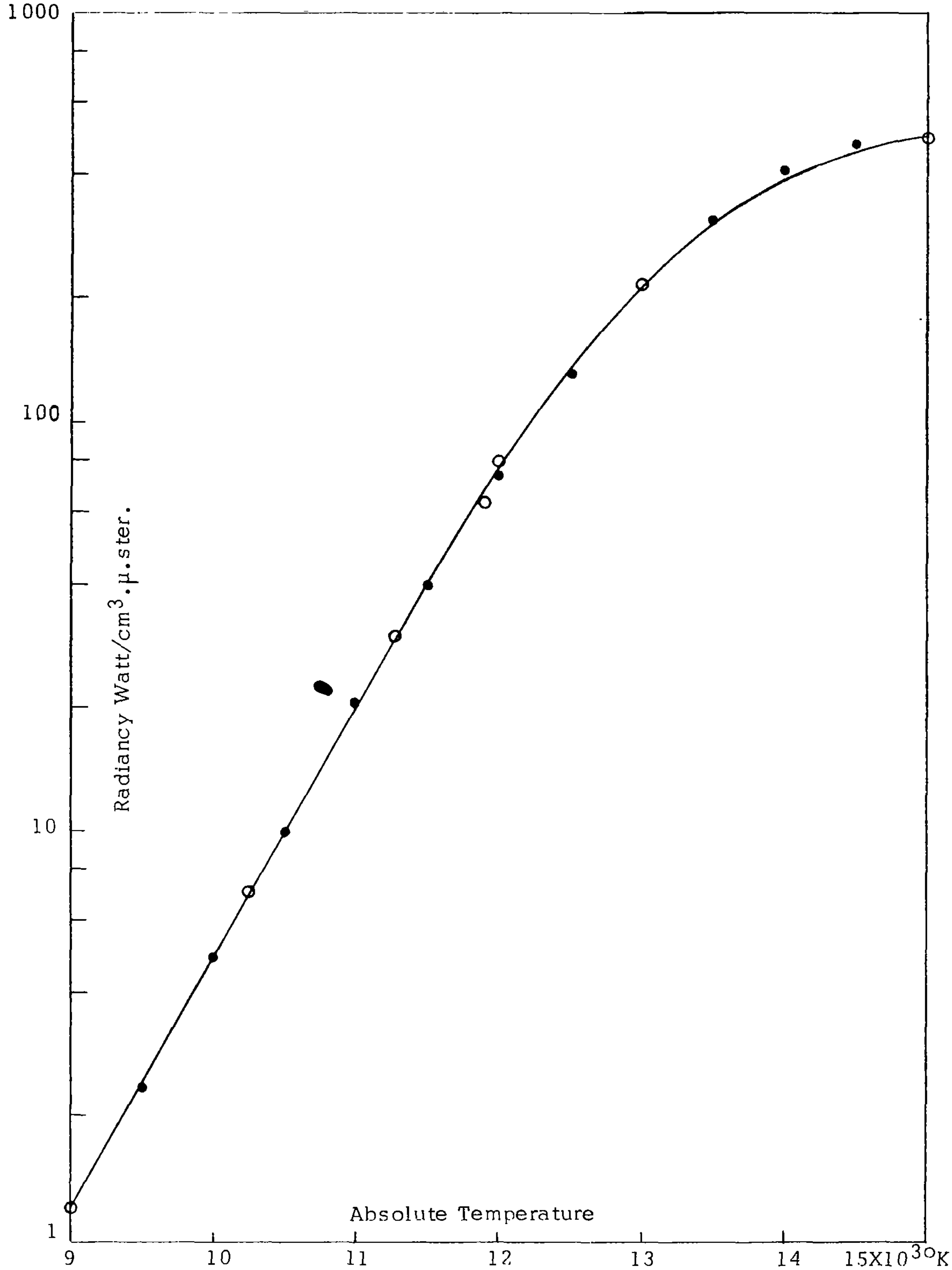

394.7/395.0
404.4
415.9
$A_{nm} = 6.55\times10^5$
425.9
$A_{nm} = 2.41\times10^6$
427.2
430.0
434.8 A II
451
516.2
521.5
549.6
555.9
Zero Line
SLIT = ·01mm
SENS = 30
SCAN = 5mμ/cm
8·2kV × 4·2amp = 34·5kW

FIG 26



CALIBRATION FOR AGRON CONTINUUM AT 428.5 mμ

FIG. 27

```
LIS 2770

TAFA1         10:44    05/12/69  MONDAY      NYC

2770 X=0
2780Y,Y1=0
2790 F1=1
2800 F2=2
2810 FOR I=1 TO N
2820Y=Y+B(I)*(R↑2-X*X)↑I
2830 G1=(2↑(2*I)/&PI)*(F1↑2/F2)
2840 Y1=Y1+B(I)*(R↑2-X*X)↑(I-.5)*G1
2850 H(I)=B(I)*G1
2860 F1=F1*(I+1)
2870 F2=F2*(2*I+2)*(2*I+1)
2880 NEXT I
2890 PRINT X,Y,Y1
2900 X=X+S
2910 IF X>R GOTO 2930
2920 GO TO 2780
2930 PRINT
2940 PRINT
2950 PRINT"      ABEL"
2960 PRINT
2970 FOR I=1 TO N
2980 PRINT H(I)
2990 NEXT I
3000 GO TO 2220
3010 IF Q9 = 0 GOT311
```

This section of the program takes the coefficients B(I), computed earlier, and performs an Abel inversion to yield new coefficients H(I). These are used to evaluate the chordal profile Y and the radial profile Y1.

PORTION OF PROGRAM TAFA1

FIG. 28

```
STOP.
READY.

1120 R=1.4
1 DATA 7
2 DATA 0,.2,.4,.6,.8,1,1.2
RUN
```

Sets radius R at 1.4 inches.
Sets number of simultaneous equations to be seven.
Sets the seven chord positions.

```
TAFA1        09:40    02/24/69   MONDAY      NYC


ENTER RIGHT HAND SIDE ... THE CHORDAL INTENSITIES
SPECIFY FIRST 5 VALUES? 1,.99,.96,.9,.68
NEXT  2    VALUES? .22,.04
```

The seven chordal intensities corresponding to the seven chord positions set above.

Computer calculates the polynomial coefficients.

```
     COEFFICIENTS                 CHORDAL  INTENSITIES

X( 1) = -5.0292966E-01         1.0000000E+00
X( 2) =  6.8794649E+00         9.9000000E-01
X( 3) = -2.3870486E+01         9.6000000E-01
X( 4) =  3.5521973E+01         9.0000000E-01
X( 5) = -2.5142974E+01         6.8000000E-01
X( 6) □  8.4858873E+00         2.2000000E-01
X( 7) = -1.1047874E+00         4.0000000E-02


      X,R              CHORDAL  PROFILE     RADIAL  PROFILE

 0                  9.999999999E-01    4.252796588E-01
 1.000000000E-01    9.975795489E-01    4.268733324E-01
 2.000000000E-01    9.899999999E-01    4.306770031E-01
 3.000000000E-01    9.771724778E-01    4.362265715E-01
 4.000000000E-01    9.600000000E-01    4.479949393E-01
 5.000000000E-01    9.375341016E-01    4.750741296E-01
 6.000000000E-01    9.000000000E-01    5.213966768E-01
 7.000000000E-01    8.238424903E-01    5.699782178E-01
 8.000000000E-01    6.800000000E-01    5.753477169E-01
 9.000000000E-01    4.619662505E-01    4.832060238E-01
 1.000000000E+00    2.200000000E-01    2.841394079E-01
 1.100000000E+00    5.780351460E-02    6.970850837E-02
 1.200000000E+00    4.000000000E-02    2.383147250E-04
```

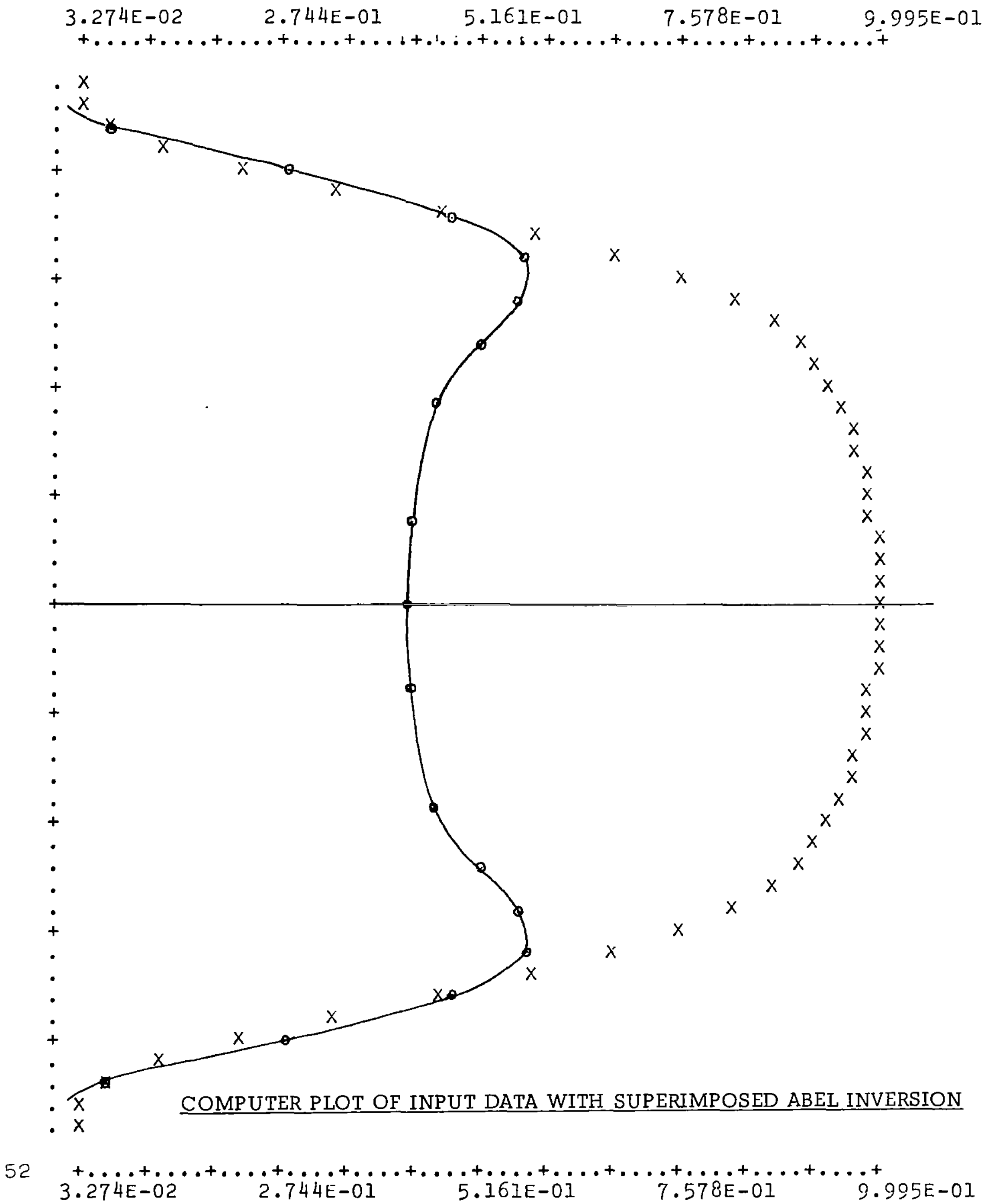
The CHORDAL PROFILE is the computer smoothed input data. The RADIAL PROFILE is the compute generated Abel transformation of the CHORDAL PROFILE.

```
DO YOU HAVE ANOTHER CHORDAL PROFILE (RHS)? 0


TIME    0 MINS.   2 SECS.
```

<u>TYPICAL COMPUTER OUTPUT</u>

FIG. 29

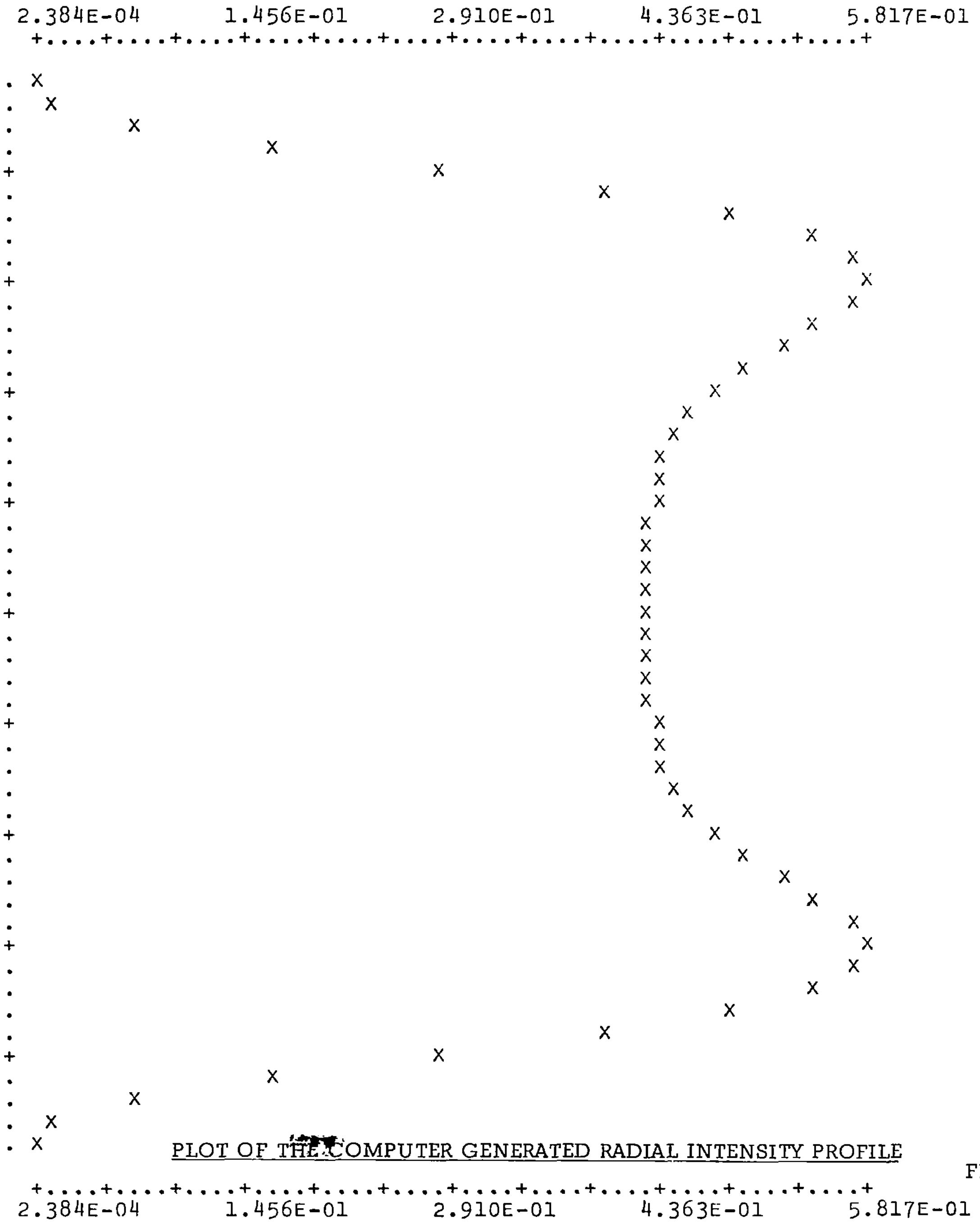
```
PLOT1       17:29   02/24/69  MONDAY      NYC

XMIN,XMAX? -1.2,1.2
NUMBER OF VALUES TO BE PLOTTED? 49


XMIN = -1.2000E+00, XMAX =  1.2000E+00, X INCREMENT =  5.0000E-02
YMIN =  3.2745E-02, YMAX =  9.9953E-01, Y INCREMENT =  1.6113E-02
```



COMPUTER PLOT OF INPUT DATA WITH SUPERIMPOSED ABEL INVERSION

FIG. 30

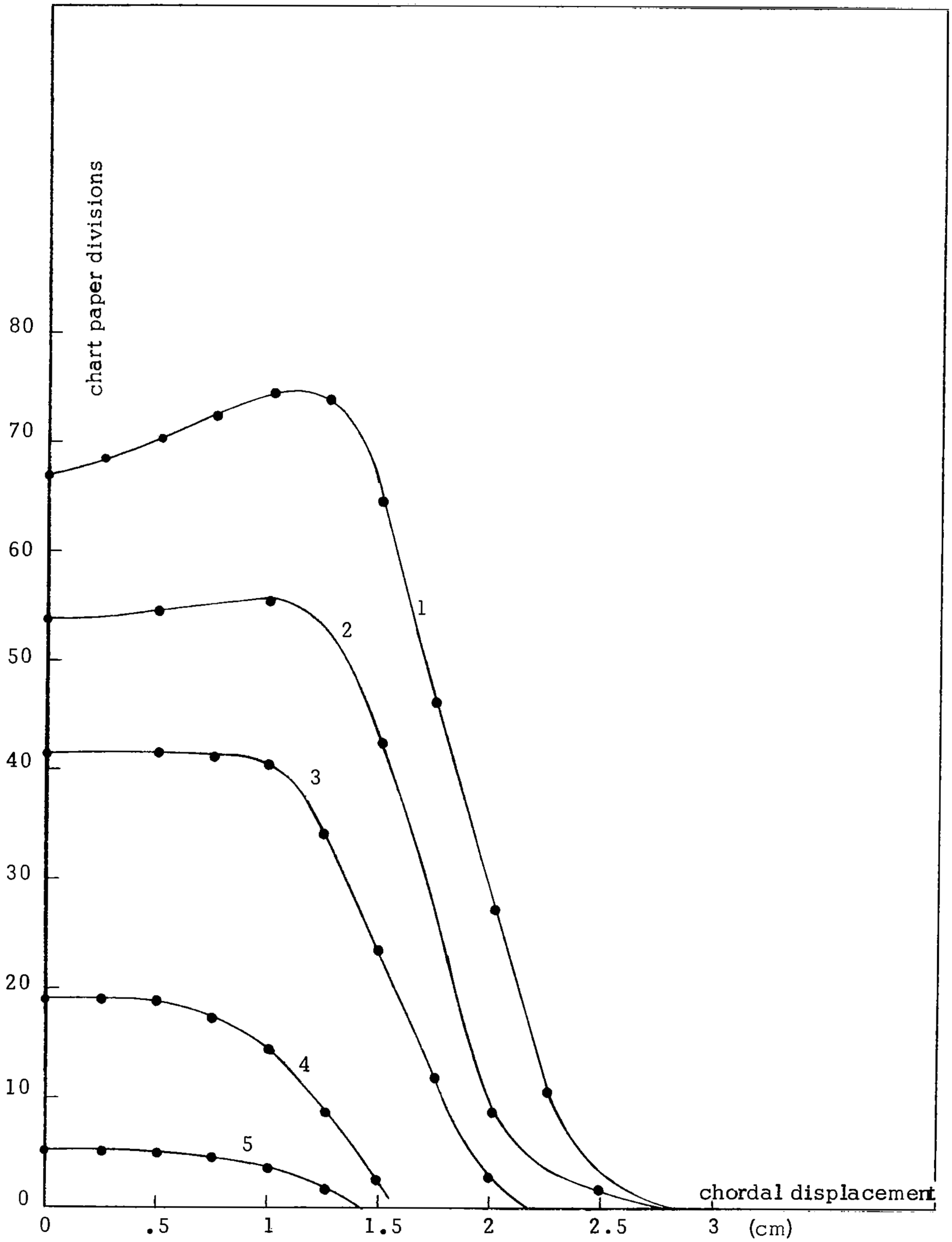
```
PLOT1        10:02    02/26/69  WEDNESDAY   NYC

XMIN,XMAX? -1.2,1.2
NUMBER OF VALUES TO BE PLOTTED? 49


XMIN = -1.2000E+00, XMAX =  1.2000E+00, X INCREMENT =  5.0000E-02
YMIN =  2.3841E-04, YMAX =  5.8171E-01, Y INCREMENT =  9.6913E-03
```



PLOT OF THE COMPUTER GENERATED RADIAL INTENSITY PROFILE

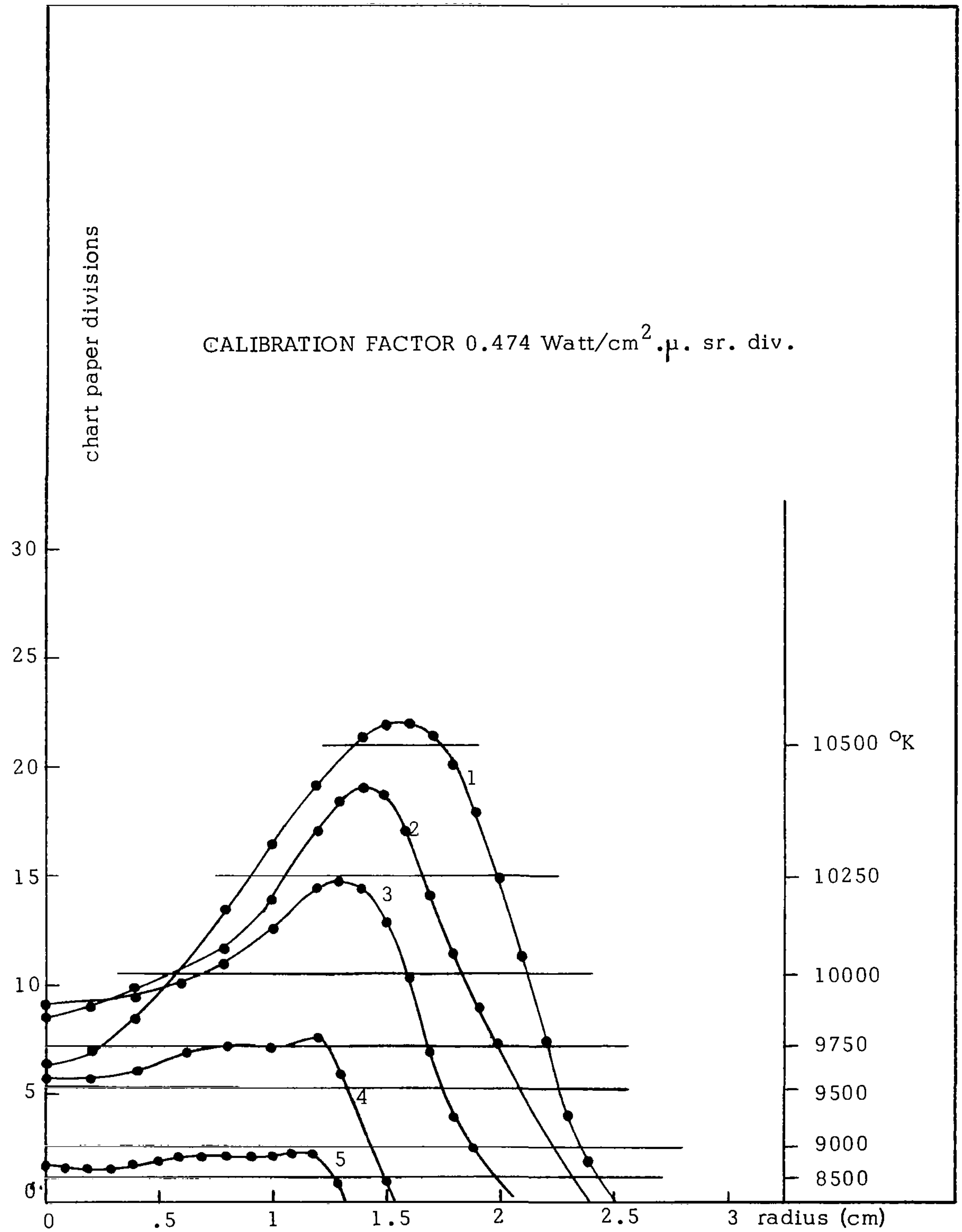
FIG. 31

53



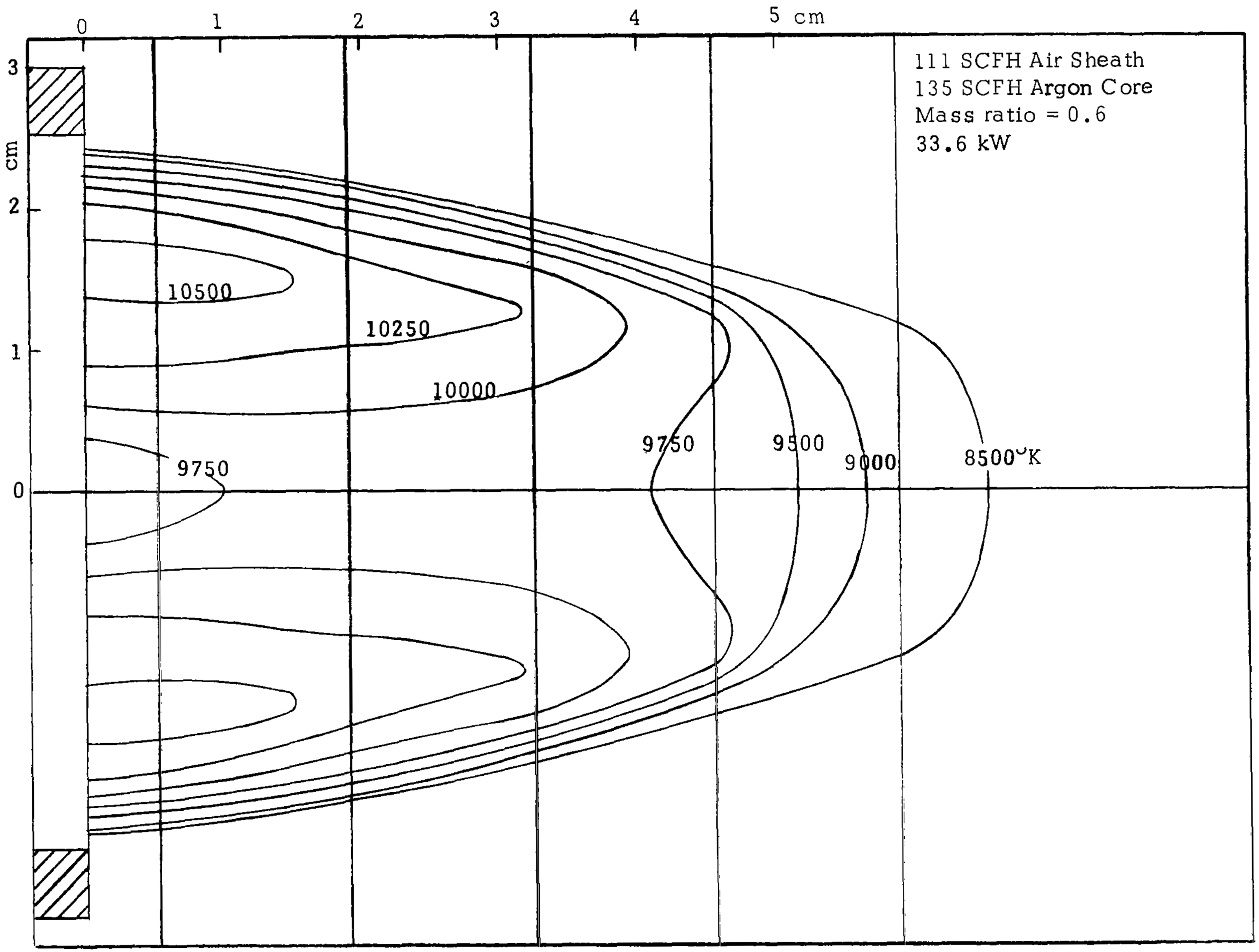
CHORDAL PROFILE INPUT DATA
AIR/ARGON MASS RATIO=0.67

FIG. 32



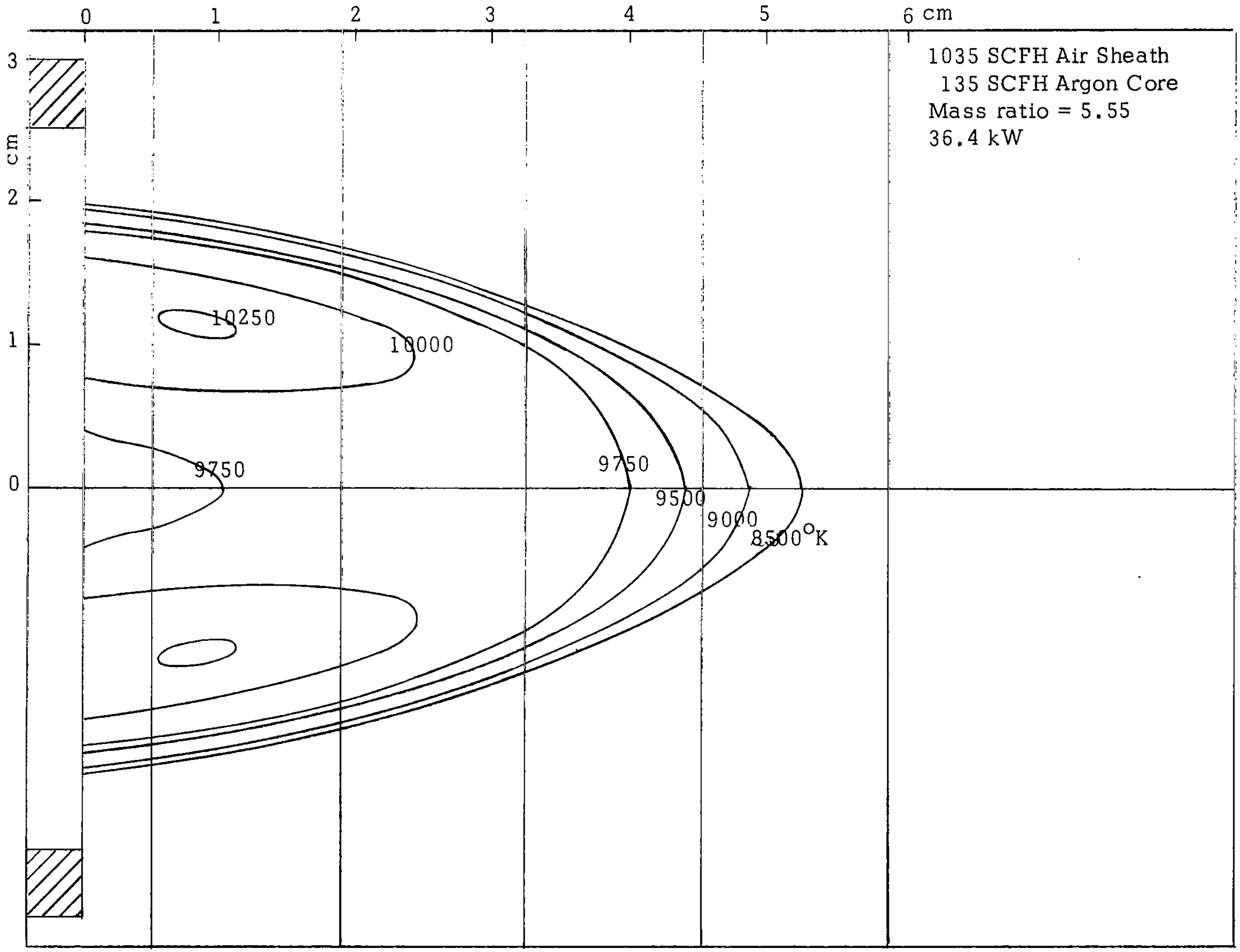
COMPUTED RADIAL PROFILE
AIR/ARGON MASS RATIO = 0.67

FIG. 33



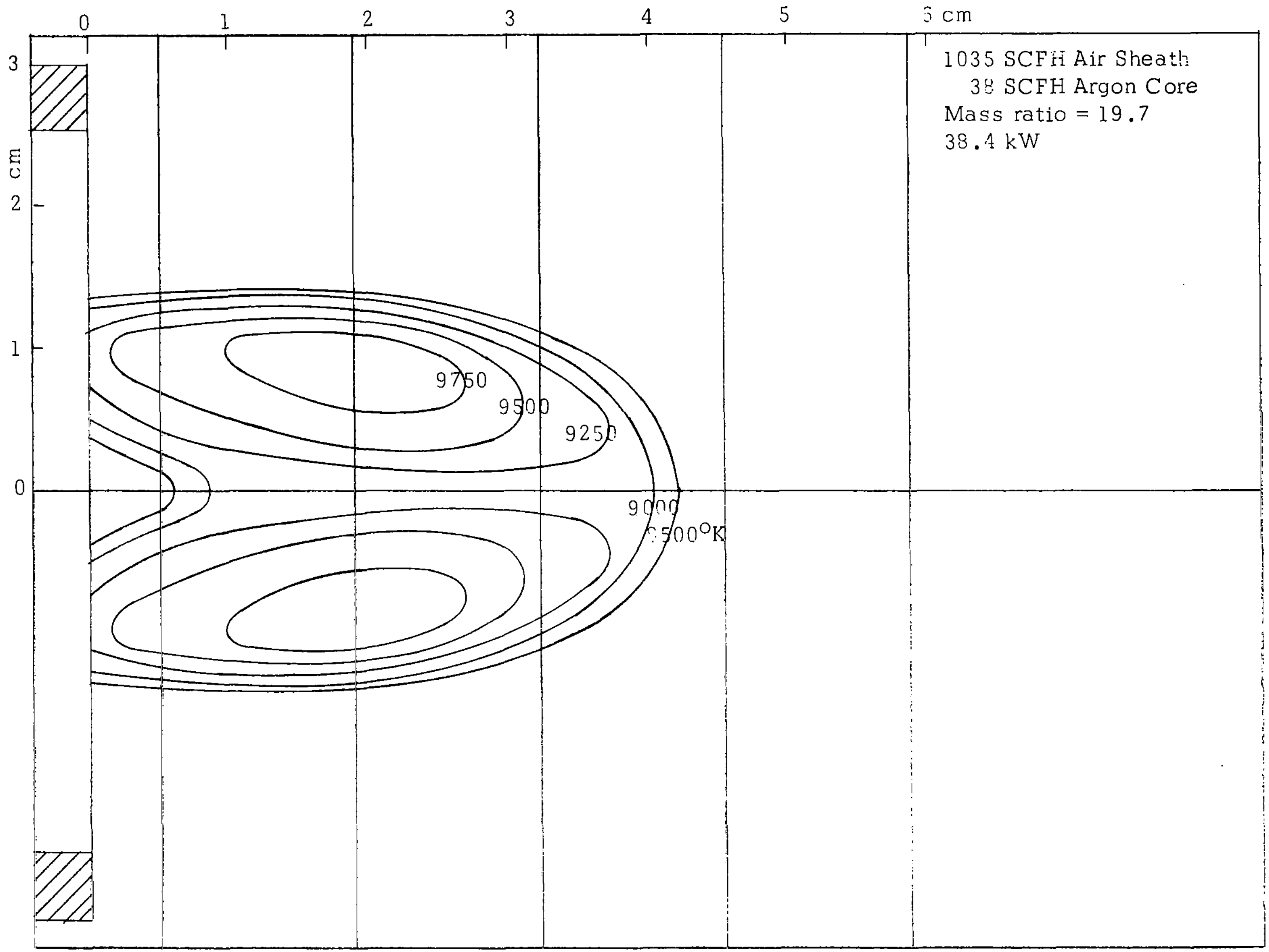
TEMPERATURE MAP
AIR/ARGON MASS RATIO=0.6

FIG. 34



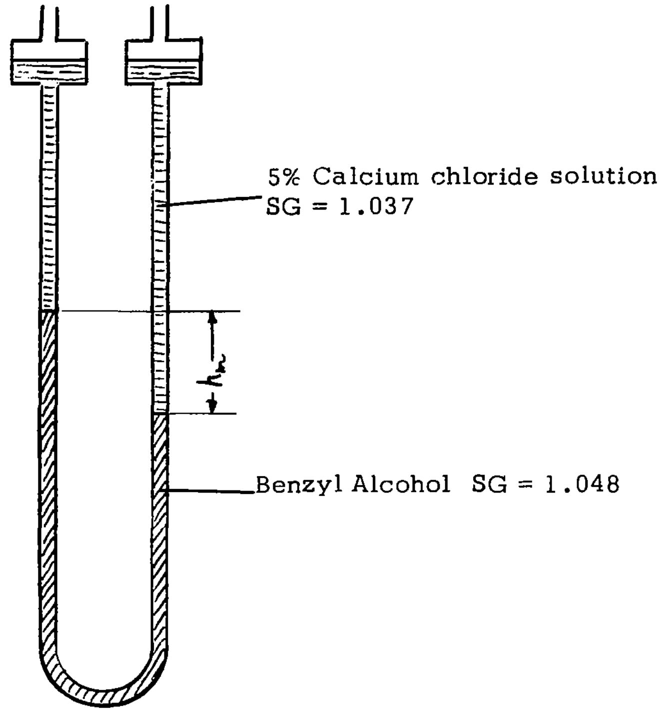
TEMPERATURE MAP
AIR/ARGON MASS RATIO=5.55

FIG. 35



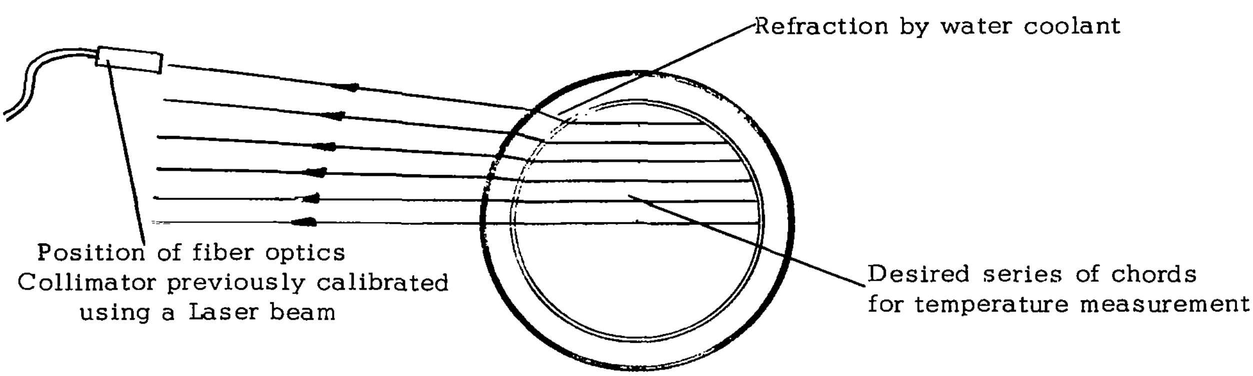
TEMPERATURE MAP
AIR/ARGON MASS RATIO=19.7

FIG. 36



TWO LIQUID MANOMETER

FIG. 37



REFRACTION EFFECTS PRODUCED BY THE DOUBLE WALL
TAFA SHEATH TORCH SYSTEM

FIG. 38

STAGNATION HEAD ACROSS THE TAFA AIR-ARGON TORCH SYSTEM

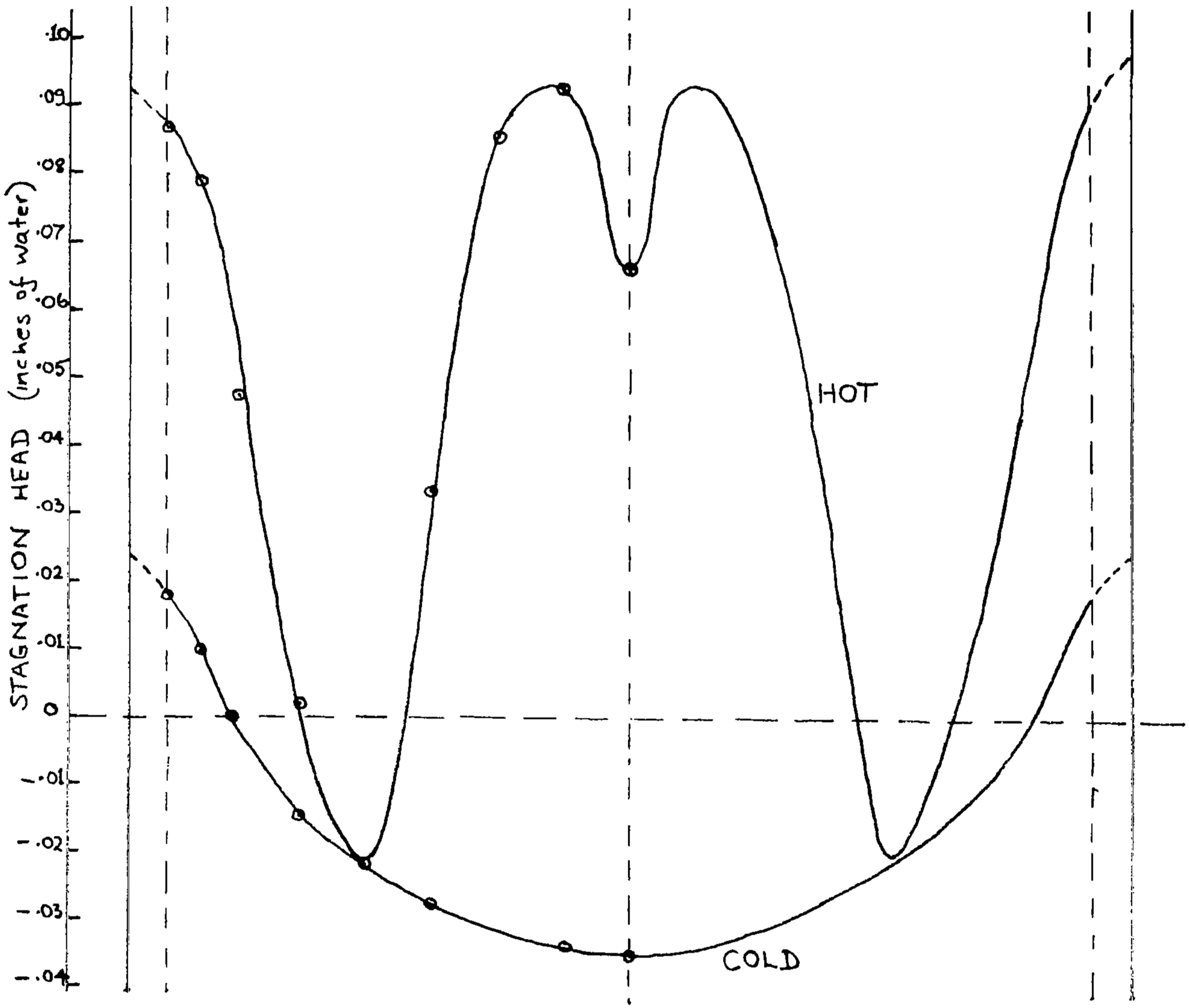


FIG. 39

NASA-Langley, 1970 —— 25 E 5353