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RADIATION MEASUREMENTS AND LOW FREQUENCY AND HIGH PRESSURE INVESTIGATIONS OF INDUCTION HEATED PLASMA

*by Charles E. Vogel, John W. Poole,
and Peter H. Dundas*

Prepared by
TAFE DIVISION
HUMPHREYS CORPORATION
Concord, N. H. 03301
for Lewis Research Center



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16. Abstract <p>A number of induction coupled plasma torches were operated under a variety of test conditions to simulate various requirements for the Gas Core Nuclear Rocket. Specifically, tests were operated at 4 MHz, 9,600 Hz, and 960 Hz. At 4 MHz, pressures up to 715 psia were obtained. Testing at 9,600 Hz and 960 Hz was performed up to 1 atmosphere and 300 mm respectively. In addition to obtaining radiation data, these tests provide operating techniques and design principles which will permit operating an induction coupled plasma torch at extremely high powers and pressures thereby more closely simulating the Gas Core Nuclear Rocket. Plots are presented showing the relationship of frequency, pressure, gas type, torch diameter, minimum operating power, and coupling efficiency.</p>					
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FOREWORD

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RADIATION MEASUREMENTS AND LOW FREQUENCY AND HIGH PRESSURE

INVESTIGATIONS OF INDUCTION HEATED PLASMA

By Charles E. Vogel, John W. Poole, and Peter H. Dundas

SUMMARY

A number of induction coupled plasma torches were tested to simulate various operating conditions of the Gas Core Nuclear Rocket. In addition to the testing of these torches, measurements of the radiation emitted from the plasma were made. All prior experience with induction coupled plasma torches had been conducted with rf power supplies. During this study MG sets were used for the first time as the power source in producing these plasmas. Successful operation at 9,600 Hz and 960 Hz was obtained. The 9,600 Hz torch was approximately 5 1/2" in diameter and operated at pressures up to 1 atmosphere at 145 kW coil power. The 960 Hz torch was approximately 12" in diameter and operated at pressures up to 300 mm at 700 kW coil power. The successful operation at these low frequencies permits scale-up to considerably larger torches and higher powers which in turn will more closely simulate the Gas Core Nuclear Rocket. In addition 4 MHz operation was extended to pressures up to 715 psia. Using the data obtained during these various tests and theoretical calculations it is now possible to make reasonable predictions as to the power required and obtainable for various torch sizes, frequencies, and pressures.

INTRODUCTION

The successful operation of the Gas Core Nuclear Rocket (GCNR) depends on the radiant transfer of heat from a gaseous uranium plasma to a hydrogen propellant. Both high pressure and high power are required to obtain satisfactory engine performance. An induction coupled plasma torch has been used to simulate various aspects of the GCNR¹⁻⁵ and was used in this study to obtain high pressures and evaluate techniques for operation at high power. Previous technology with induction plasma torches was limited to pressures up to 16 atmospheres⁶ and frequencies from 200 KHz

to 6 MHz. Typically, because of cost, equipment size, and operating efficiency, induction heating at high power is performed at low frequencies and therefore the first step to higher power operation was to demonstrate low frequency plasma heating. This report describes the theoretical calculations and experimental work performed using an induction coupled plasma torch operating at pressures up to 715 psia and at frequencies down to 960 Hz.

APPARATUS & PROCEDURE

This program involved using existing and modified high frequency (rf) generating systems located in the TAFE laboratories.⁷ The specific system used for the high pressure work was a conventional TAFE 190 kW dc plate power 4 MHz induction plasma system (12,700 volts, 15 amps dc). In addition arrangements were made to use two different facilities outside of the TAFE laboratories where large MG set installations were available. One was a 9,600 Hz, 450 kW system and the other was a 960 Hz, 1,250 kW system. All systems used were instrumented so that system energy balance measurements could be made and performance monitored. The controls used on all systems consisted of plasma forming gas flow meters, pressure gauges, power supply controls and meters. All torches tested were manufactured by TAFE.

The experimental procedures and calculations used relative to heat balance techniques and estimation of plasma enthalpies by calorimetry were similar to those previously reported.

LOW FREQUENCY EXPERIMENTS

Low Frequency Design Considerations

The design of an induction coupled plasma torch intended to operate at low frequency involves a number of electrical and design problems. As frequencies are reduced, the effective depth of electrical current penetration into the load increases and demands larger diameter work loads for efficient operation. In a plasma torch these larger diameters increase the radiation, convective and conductive losses thereby increasing the minimum power requirements. These considerations have led to a number of calculations which are relatively standard in the field of induction heating of metals but had to be applied to plasmas. Appendix A presents these calculations and the assumptions made while applying them to plasma operation. These calculations have assisted in choosing adequate power supplies and proper torch sizes, particularly in the low frequency experiments. As experimental data has been obtained, the calculations have been improved to incorporate the observed results.

9,600 Hz Operation

The initial step toward operating at lower frequencies was a test series conducted at 9,600 Hz. This represented a major departure from previous induction plasma technology inasmuch as a motor generator set rather than an rf induction power supply was used for the first time. Arrangements were made to use two 9,600 Hz MG sets connected in parallel to yield a total of approximately 450 kW of coil power.

Several experiments with various configurations were conducted to determine the loading characteristics of the system. Initially a water cooled metal calorimeter was inserted in a torch as shown in Figure 1 to conduct heat balance measurements. This torch contained both a segmented metal wall and a segmented metal separator.^{7,8} Additional metal calorimeter experiments were conducted without the segmented metal wall. A heat balance was also obtained with a torch in which both the segmented metal

wall and separator were removed and a 20% sulfuric acid solution inserted as the load to bracket anticipated plasma conductivities. A photograph of this experimental setup is shown in Figure 2. The heat balance data obtained for these various configurations are presented in Table I. The coupling efficiency to the acid was 9% as compared with plasma and steel efficiencies of 71-84% because of the high resistivity of the load and the lack of laminations to provide an adequate flux density for efficient heating.

A number of attempts were made to ignite a torch at one atmosphere containing a segmented metal wall as shown in Figure 3. At 40 kW dc, 160 volt open circuit power supply was used to provide a starting arc between two carbon electrodes inserted into the torch; however, it was impossible with this configuration to obtain any observable 9,600 Hz coupling to the dc arc. Because of the calorimetric results, it was assumed that the starting difficulties were caused by the large amount of power being absorbed by the metal wall. The torch configuration was therefore changed to omit the metal parts within the coil and once again the dc system was used in an attempt to ignite the torch. Additionally, modifications were made to the torch so that the pressure could be reduced in an effort to enlarge the starting arc. A photograph of this torch is shown in Figure 4. Unfortunately, this technique did not provide a sufficiently large conductive column to permit coupling to the 9,600 Hz supply. While the visual appearance of the arc was quite large, photographs verified that the actual arc column was only about 3/4" in diameter. This would give a load to coil ratio of 0.1 yielding a coupling efficiency of <1% or a maximum of 4.5 kW enhancement superimposed on the 40 kW starting arc.

As a result of these experiments, it became apparent that in order to successfully ignite a plasma torch operating at 9,600 Hz some other starting technique would have to be employed which would present a larger load to the 9,600 Hz field. A low pressure glow discharge technique was used to fulfill this function. In order to verify the proposed technique, a 6" diameter pyrex flask was inserted inside of the 9,600 Hz coil and electrodes placed outside each end of the flask. The flask was then evacuated to approximately 45 microns and a glow discharge generated throughout the flask by applying from 0.1 to 0.5 kW at 20 MHz across the electrodes. The 9,600 Hz coil was then energized and an obvious enhancement to the glow was produced. Figure 5 shows this experimental setup. It was impossible to sustain the glow entirely with 9,600 Hz even at powers as high as 350 kW without the

addition of laminations on the outside of the coil to increase the flux density within the coil. Figure 6 shows the flask and coil with the laminations located around the outside of the coil. With these laminations in place, it was possible to sustain a 9,600 Hz glow with 50 kW. Sustained operation was achieved and the brightness of the discharge could be varied as the power on the coil was varied.

Once successful operation of the 9,600 Hz glow inside the flask was demonstrated, the pressure was raised to approximately 800 microns to produce a thermal arc. The switchover from the glow condition to the thermal arc was readily observed by a dramatic change in brightness. The duration of this thermal arc was only about three seconds because the intense heat of the arc melted the flask which in turn imploded. During this experiment approximately 180 kW was being delivered to the work coil.

Subsequent to the confirmation of the ability to couple to a glow discharge and then convert to a thermal arc at 9,600 Hz, a torch configuration as shown in Figure 7 was assembled. This torch consisted of a 6" i.d. quartz wall placed inside the 9,600 Hz coil. A standard TAFA gas injection system was located at the bottom of the torch and an evacuation fitting and window located at the exit end of the torch. The quartz torch body could be evacuated to about 50 microns and electrodes were attached around the o.d. of the quartz tube near each end to produce a high frequency glow discharge. While this configuration ultimately led to successful operation at 9,600 Hz, the initial experiments were discouraging inasmuch as the thermal arc could not be sustained for more than a few seconds. It was discovered that the two MG sets did not share the load equally, producing a synchronization problem. Because the frequency of the one MG set would lag the other one, a low frequency oscillation of approximately 6 cps would develop shortly after torch ignition and cause arc extinguishment. Some circuitry modifications were installed and synchronization performed by observing the output of the coupled MG sets on an oscilloscope. It was also learned during these series of experiments that a small amount of contamination of hydrogen, carbon, or water inside of the torch seriously impaired the ability to obtain successful operation. With these problems resolved, repeated successful ignition and operation of the torch at pressures up to 1 atmosphere was achieved. Figure 8 is a photograph of the overall test area showing the torch, gas control panel, capacitors, MG control station and other auxiliary equipment.

The ignition of the 9,600 Hz plasma torch, as noted above, was performed at pressures of 1.0 to 1.5 mm in argon. Once a thermal arc was obtained it was possible to raise the pressure in the torch to 1 atmosphere. Figure 9 is a photograph of the torch operating at 1 atmosphere in argon. Several runs at 1 atmosphere were performed during which the power was turned down to determine the minimum sustaining power for this particular configuration. It was found that with approximately 700 SCFH of argon being passed through the torch the minimum sustaining power was 145 kW.

960 Hz Operation

The highly successful operation of a torch at 9,600 Hz led to the design of an experiment at 960 Hz. This frequency was chosen since it is a standard frequency of MG sets commonly used in large induction furnaces. Using the information presented in Figure 36, it was estimated that a torch 10-12" in diameter would require 1 megawatt of power to sustain a 1 atmosphere plasma at 960 Hz. The torch design employed for this work was essentially a scale-up from that torch successfully operated at 9,600 Hz. The main torch body was a cylinder of quartz, 12" i.d. by 60" long. At the base of the torch a gas injector was constructed which was a direct scale-up from that used in a standard TAFE Model 56⁹ torch. At the exit end of the torch a glass view port and evacuation tube were provided. The induction coil around the torch body consisted of a six turn coil constructed of 2" diameter heavy walled copper pipe. On the basis of calculations seven stacks of 7 mill thick laminations (1 1/2" x 6" x 22") were positioned around the o.d. of the coil to increase the flux density within the coil. A photograph of the completed and assembled torch is shown in Figure 10. Figure 11 is another photograph of the torch with the laminations removed to show more detail of the coil. Figure 12 is a photograph taken through a mirror mounted over the torch and provides a view down the inside of the torch body. This setup allowed visual observation and photographing of the plasma through the mirror during operation.

Actual testing with this torch was conducted on a 1,250 kW, 960 Hz power supply. This equipment was selected since it had been estimated that approximately 1 megawatt would be required for operation at 1 atmosphere and this facility was rated at 1,250 kW with capabilities of being run for

short periods of time at 30-50% overload. In addition it was calculated that from 20,000 to 25,000 KVAR would be required. This capacitance was required to cause the work coil circuit to resonate in phase with the MG output and produce the required high circulating currents utilizing the entire output of the generator. This particular installation had some 25,000-30,000 KVAR already wired into the circuit with capability of obtaining more from other induction systems nearby. Another attractive feature of this facility was that a number of capacitors could be added to the circuit after the power was turned on. Even though none could be removed from the circuit once the unit was operating, this capability of adding capacitance permitted some tuning of the circuit during operation. Figure 13 shows the motor generator set used as the power supply in this facility and Figure 14 shows a partial view of the capacitor bank.

Based on the experience obtained with the 9,600 Hz torch, it was anticipated that one of the problems in operating this 960 Hz torch would be ignition. An extrapolation of the power requirements utilized during the 9,600 Hz experiments predicted that as much as 1,200 kW would be required to ignite the 960 Hz torch. Since the ignition power required is directly related to the initial load presented to the low frequency coil, a higher powered rf ignition source was incorporated for use in this 960 Hz torch. This consisted of a 4 MHz power supply rated at an output of 25 kW. This is in contrast to the 20 MHz 200-500 watt ignition source used to ignite the 9,600 Hz torch. The ignition technique consisted of producing a glow discharge with the rf power supply in the torch at a pressure of approximately 350 microns and subsequent electrical coupling to the load with the 960 Hz power supply. Using this technique it was possible to ignite the torch at powers as low as 475 kW. This power is significantly lower than the value of 1,200 kW extrapolated from the 9,600 Hz experience and is very encouraging in terms of designing future tests with either large and/or lower frequency torches.

Repeated successful operation at 960 Hz was obtained. Figure 15 shows this torch operating at 300 mm. Unfortunately, it was impossible to operate the torch above about 300 mm due to the failure of the power supply to produce its rated capacity. Even though, as previously noted, the power supply was rated at 1,250 kW and it was expected that it could be overpowered by perhaps as much as 50%, it was possible to obtain only about 700 kW out of the machine. This limitation did not seem to be due to any mismatch in

the load circuit but rather to some basic difficulty with the power supply itself. It was impossible to draw either full voltage or full amperage from the machine even with the field current turned up well beyond its rating. It was learned later, in talking to operating personnel, that this machine had been recently rebuilt and had not been operating properly since that time. Unfortunately, the extent of the difficulties with the equipment had not been fully recognized until these tests were conducted.

The primary goal of this test series--demonstrating operation of a plasma torch at 960 Hz-- was successfully accomplished. Repeated and controlled runs were conducted and a significant amount of data obtained. The minimum sustaining power at a number of pressures up to 300 mm was obtained and extrapolation of this data shows that operation at 1 atmosphere should be accomplished at approximately 1 megawatt as originally predicted (Figure 16). There is little doubt that if the power supply had been able to deliver its rated capacity, successful operation at 1 atmosphere would have been obtained.

One of the early concerns of a noise problem during the operation of these torches at low frequency was found to be unwarranted. Both during the 9,600 Hz and the 960 Hz tests no noise was generated by the torch. The characteristic whine of the motor generator set operating at its rated frequency was apparent but did not create a sound intensity any more severe than it would during standard furnace heating operations. Exact sound level measurements were not made, however, there did seem to be agreement among those personnel who witnessed the tests that the sound level was less than that associated with typical 450 KHz rf induction plasma torch operation at the same power level.

Table II summarizes experimental data and projections made for operation of torches at various frequencies.

HIGH PRESSURE OPERATION

On the basis of the current state of the art with low pressure induction plasma systems and high pressure dc plasma systems, it was concluded that the optimum approach to operating a high pressure rf system would be to

build a rather simple device capable of operating at some modest pressure before designing and building a high pressure system. Figure 17 illustrates the system designed and built to perform these initial tests. This consisted of a 12" diameter pipe cross and extension with appropriate observation windows which could be operated at pressures up to 265 psia. Several torches were actually tested in this chamber and provided the information required to determine the operating conditions that could be expected at even higher pressures. A major portion of the testing was conducted with a standard TAFE Model 56 torch shown in Figure 23 (1.5" tube with 1.25" nozzle). Figure 18 presents the results obtained with this torch at various pressures in the chamber.

A heat balance was obtained on the system at various pressures. This consisted of measuring the losses in the power supply, the losses to the pressure chamber walls (which absorbed all the energy in the gas exiting from the torch), and the losses in the torch body mounted inside the chamber. Figure 19 shows these measured losses as a function of chamber pressure. It can be noted that the losses stabilized in the power supply at about 30% of the plate input power, in the chamber at about 15%, and in the torch at about 55% for the tests performed. In addition it was noted that the diameter of the plasma decreased up to about 45 psia and then remained relatively constant throughout the remainder of the pressure range up to the limit of 265 psia. No particular difficulties were encountered in operating the torch inside of the chamber over the entire range of pressures tested. As noted in Figure 18, operation with argon was extended to the pressure limit of the chamber, however, air operation was limited to 55 psia. This limitation was due to the increased heating that took place in the exit plumbing of the pressure chamber during air operation and was not due to any basic operational problem with the torch.

The results of these preliminary tests indicated that it was reasonable to expect to operate up to 1,000 psia on argon with the power supplies available at TAFE. It was also apparent that the construction of a pressure vessel such as had been used in these tests to withstand 1,000 psia was a formidable problem which did not represent a simulation of the GCNR. Consequently, a torch capable of operating at high pressure was designed to prove the concept of operating a high pressure torch. Initially a nozzle was attached to the exit end of a standard torch; however, reliable operation much above 40 psia could not be obtained with this configuration. It was

believed that the problems encountered were related to the proximity of the nozzle to the coil so a double length torch was assembled from standard Model 56 torch parts and tested. A photograph of this torch in operation is shown in Figure 20. It was possible, with the operating data obtained from the pressure chamber work, to successfully operate this torch on air at pressures up to 115 psia. The limitation of pressure on this particular torch was that standard components were used which were not capable of withstanding any greater pressure. These tests demonstrated the principles required for successful operation of a high pressure torch and the design work was initiated on a 1,000 psia unit. Figure 21 is a schematic of the design and Figure 22 is a photograph of the components of this torch. Figure 23 shows the assembled torch compared to a standard TAFE Model 56 torch.

In addition to the torch, it was necessary to design and construct a completely new gas metering system and water cooling circuit which could operate at the high pressures anticipated. The torch included a quartz plasma containing tube with a pressure rating of 500 psia. The water cooling passage outside the tube was therefore pressurized to keep the differential pressure across the quartz to less than 500 psia. An exit calorimeter allowed accurate measurements of the gas enthalpy leaving the torch.

The initial tests of this high pressure torch included a segmented metal separator as seen in Figures 22 and 23. Unfortunately, this device consumes some of the power from the coil and restricts the amount of power available to the plasma during operation. On the basis of the initial experiments with this torch, it was deemed imperative that all of the rf power available be utilized in the plasma if pressures up to 1,000 psia were to be achieved. Since the purpose of the metal separator was to reduce the radiant heat load on the acrylic body of the torch, some alternate technique had to be utilized to reduce this loading. This was accomplished by adding nigrosine*, a water soluble dye, to the cooling water which absorbed the radiant energy emitting from the plasma. This procedure increased the thermal load on the cooling system and also prevented a visual observation of the plasma during operation, however, with this particular operating configuration

*Nigrosine crystals, No. 12525, supplied by Howe & French, Inc.
Boston, Massachusetts

pressures as high as 715 psia were successfully obtained and it is believed that sufficient knowledge has been obtained to design a torch which could successfully operate at nearly any pressure within the limitation of the materials utilized and the power available. Figure 24 presents the data obtained with the high pressure torch using a 2" i.d. quartz tube, Figure 25 presents the data obtained with this torch using a 1 1/2" i.d. quartz tube, and Table III presents the heat balance data obtained. A maximum pressure of 715 psia was obtained during these tests. Higher pressures were not achieved due to a crack failure of the acrylic plastic torch body after repeated cycling to operating pressure.

It can be noted that the power requirements observed exceeded those predicted earlier in the program from operation of the standard TAF A Model 56 torch in the pressure chamber. (Data reported in Figure 17) It is believed that the primary cause of this was a design difference which resulted in significantly higher radiation losses in the high pressure torch. The standard Model 56 torch used in the chamber incorporated a gold plating on the inside of the quartz tube to aid in ignition; the high pressure torch did not contain this feature. It is believed that this coating was responsible for reflecting much of the radiation back into the plasma in the chamber tests resulting in lower power requirements. In addition to not having the reflecting surface on the tube, the water behind the clear quartz tube in the high pressure torch contained nigrosine dye to absorb the radiation. This dye was used to protect the outer torch body from heating due to the plasma radiation.

No basic difficulties were encountered during this testing which would suggest that plasmas could not be operated at extremely high pressures. Repeated reliable operation up to the maximum pressure of 715 psia was achieved. The only limitations experienced during this work was the fatigue failure of the torch pressure body and the limitation of available power. It should be noted that while the power requirements of the high pressure torch exceeded those predicted from experience in the pressure chamber, (200 kW vs. 50 kW at a pressure of 1,000 psia) neither set of results indicates excessive power requirements.

RADIATION MEASUREMENTS

Spectral radiation measurements were made of plasmas operating under a variety of conditions during the course of this study. The instrument

used for this work was a Beckman DK1A spectrophotometer. The entrance slit of the instrument was adjusted to 0.01 mm which gave resolutions of 0.01 millimicrons to the ultra-violet, 0.1 millimicrons to the visible, and 1.0 millimicrons to the infra-red. This spectrophotometer used two types of detectors, a photo multiplier from 200 to 700 millimicrons and a lead sulfide cell from 600 to 3,500 millimicrons.

A number of traces were obtained while operating a plasma inside of the pressure chamber previously discussed. For these measurements the spectrophotometer had to be placed with the entrance slit approximately four feet away from the plasma and aimed at the plasma through a quartz window which had a low absorption coefficient.* During all of these tests when spectral radiation measurements were being made, nitrogen was introduced around the plasma torch as the pressurizing gas as argon was being passed through the torch as the plasma gas. This reduced the amount of absorption that would have been experienced in the high pressure chamber between the plasma and the measuring instrument if air had been used. The large effect of air versus nitrogen on the absorption is clearly seen in Figure 26.

Figure 27 is a combined presentation of the traces obtained at 1 and 14.6 atmospheres of an argon plasma in the visible spectrum. No change was made in the instrument sensitivity between the two runs so that the areas under the curves represent a true comparison of radiation. It appears that at 14.6 atmospheres there is approximately five times the radiation of the torch operating at 1 atmosphere. The ratio of the operating power levels for the two runs was 2.1:1. Results reported by others¹⁰ indicate that the radiation from an argon plasma at 14.6 atmospheres is 83% of the power in the plasma, whereas the radiation at 1 atmosphere extrapolates to be about 30%. These percentages applied to the runs above yield a radiant intensity increase of 5.8 times which indicates that some absorption was taking place in the chamber even with nitrogen as the pressurizing gas.

Figures 28 and 29 show the visible spectra of hydrogen-argon plasmas operating at the maximum reliable operating pressure with 7.8 and 45.0

*Quartz window was a piece of Spectrosil "A" from the Thermal American Fused Quartz Company

volume percent hydrogen. These tests were run with the dual Model 56 torch setup shown in Figure 20. The radiation path was through the quartz tube, about 3/16" of water, and the acrylic body of the torch.

A number of scans were made of the visible spectrum of argon measured through a Spectrosil "A" window (see sight port, Figure 21) looking directly into the pressure cavity of the high pressure torch. The radiation was reflected off a good quality front surface aluminized mirror and then projected through the spectrophotometer slit about 52" from the plasma. This arrangement, with the radiation coming primarily from the center and along the axis of the plasma, worked well for pressures up to 28 atmospheres. Above that, a combination of the turbulent nature of the plasma producing rapid variations in radiation intensity hitting the spectrometer slit plus a moderately high level of rf pickup, made it impossible to generate meaningful scans. Figure 30 shows the spectrum of the torch operating at 1 atmosphere and 12.5 kW, Figure 31 is at 14.6 atmospheres and 59.0 kW, and Figure 32 at 28.2 atmospheres and 108.8 kW. If these traces are adjusted for sensitivity changes in the spectrometer, the height of the continuum is about 1 for 1 atmosphere, 67 at 14.6 atmospheres, and 99 at 28.2 atmospheres.

During the testing of the 9,600 Hz torch at 1 atmosphere, total radiation measurements were taken with a Hy-Cal Pyrheliometer*. Figure 33 shows two total radiation profiles obtained. These runs represent two different starting techniques and demonstrate that the amount of total radiation is directly related to the power in the plasma, the plasma pressure, and the plasma temperature. It can be noted that immediately upon ignition of the thermal arc there is a large spike in radiant energy which drops off rapidly once the thermal arc is established. It can be postulated that for the ignition from a 9,600 Hz induced glow, at roughly 500 μ Hg pressure, the large spike is generated from a very hot plasma which forms when the glow

*A Hy-Cal Pyrheliometer Model P-8400-B-01-120 was used to obtain these values.

shifts over into an arc. This occurs because the tank circuit is being driven at roughly 200 kW and the convective and conductive heat losses are very small since the pressure and gas flows are also very small. The data indicates that a plasma temperature in the range of 15,000-16,000^oK is formed for a few seconds and then cools down very rapidly as the pressure rises with the introduction of high gas flow.

A tabulation of total radiation measurements of argon gas plasmas from various torch configurations is shown in Table IV. Values are given for the 9,600 Hz operation, the 960 Hz operation, the 3.7 MHz torch (TAF Model 56) operating at four different pressures in the chamber, and the high pressure torch operating at 7.8 atmospheres. Attention is drawn to the peak in the percent of power radiated from the 3.7 MHz torch at about 5 atmospheres, the same phenomena mentioned earlier relative to the spectral scans made during operation of the high pressure torch. A qualitative explanation for these observations is that at pressures up to about 5 atmospheres, significantly more power was available, and used, than that required to just sustain the plasma. This resulted in a higher than minimum temperature plasma, increased conductivity, resultant increased electrical coupling efficiency and a highly radiative plasma. As pressures were increased above 5 atmospheres, however, the amount of excess power was reduced, since the conductivity of the plasma reduces the increased pressure, resulting in a lower temperature, less conductive plasma with reduced coupling efficiency and a less radiative plasma. These observations indicate that careful analysis must be made of radiant measurements taken of an induction coupled plasma before they are used, because of these multiplying effects of conductivity, temperature, pressure, and electrical coupling efficiency.

CONCLUSIONS

The primary goals of this program to demonstrate low frequency and high pressure induction plasma operation were achieved. Radiation measurements of these plasmas were made at a variety of operating conditions. While equipment failures prevented operation at as high a pressure as desired with 960 Hz and 4 MHz, sufficient data was obtained to provide adequate input to subsequent advanced testing. Specific conclusions are as follows:

1. Successful operation of an argon induction plasma can be achieved using MG sets as the source of power at 9,600 Hz and 960 Hz.
2. A combination of theoretical and experimental results indicate that approximately 15 MW would be required to operate a 60 Hz argon plasma at 1 atmosphere.
3. The amount of power required to operate a 4 MHz argon induction plasma at pressures in the range of 2-50 atmospheres is not excessive in relation to commercially available power supplies at this frequency.
4. No unusual behavior was observed in the total radiation or spectral measurements made under the variety of plasma operating conditions studied.

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APPENDIX A

LOW FREQUENCY DESIGN CONSIDERATIONS

I. Plasma Generator Efficiency

It is important in designing an induction plasma torch to consider the coupling efficiency between the coil and the load to provide optimum design of the torch diameter and coil configuration. As applied to the induction heating of gases, the power induced in the load is represented as follows:

$$W_L = (nI)^2 2\pi^2 dh \sqrt{\rho f} \Phi^* \quad (1)$$

where

W_L = induced power, watts

n = turns per unit length of inductor, turns/cm

I = coil current, amperes

d = plasma diameter, cm

h = plasma height, cm

ρ = plasma resistivity, abohm-cm

f = frequency of applied electromagnetic field, Hz

Φ = Bessel function factor represented by

$$\Phi = \sqrt{2} \frac{\text{ber } \phi \text{ ber}' \phi + \text{bei } \phi \text{ bei}' \phi}{(\text{ber } \phi)^2 + (\text{bei } \phi)^2}$$

$$\text{and } \phi = \sqrt{2} \pi d \sqrt{\frac{f}{\rho}} \quad (2)$$

"ber" and "bei" are the real and imaginary parts of the zero order Bessel functions of the first kind with complex arguments and are known also as the Kelvin functions.

*Mensing, A.E., and Boedeker, L.R.: Theoretical Investigations of R-F Induction Heated Plasmas. NASA Contractor Report NASA CR-1312, April '69.

The power lost in the copper work coil is

$$W_C = (nI)^2 2\pi^2 DH \sqrt{\rho_C f} \quad (3)$$

where

W_C = power lost to coil, watts

D = coil diameter, cm

H = coil height, cm

ρ_C = resistivity of copper, abohm-cm

The coupling efficiency η is

$$\eta = \frac{W_L}{W_L + W_C} = \frac{1}{1 + \frac{W_C}{W_L}} \quad (4)$$

From equations (1) and (3)

$$\eta = \frac{1}{1 + \frac{DH}{dh} \left(\frac{\rho_C}{\rho}\right)^{\frac{1}{2}} \frac{1}{\Phi}}$$

If we assume a practical geometry where $h=D=H=1.5d$ and

$$\rho_C = 2 \times 10^{-6} \Omega\text{cm} = 2 \times 10^3 \text{ abohm-cm}$$

$$\eta = \frac{1}{1 + \frac{1.5 \times 44.7}{\rho^{\frac{1}{2}} \Phi}} \quad (5)$$

$$\eta = 1 / (1 + [67.1 / \rho^{\frac{1}{2}} \Phi]) \quad (6)$$

The relationship between Φ and ϕ is shown in Figure 34.

For $\phi < 1$, which applied for practical low frequency geometries,

$$\Phi \approx 8.87 \times 10^{-2} \phi^3 \quad (7)$$

or $\Phi \approx 7.8 d^3 \left(\frac{f}{\rho}\right)^{3/2} \quad (8)$

So $\eta = \frac{1}{(1 + [8.6 \rho / d^3 f^{3/2}])} \quad (9)$

This equation has been used to construct Figure 35 which shows the coupling efficiency for various sized argon plasmas generated by various frequencies. The shaded areas allow for the change in plasma conductivity from 8,000^oK to 11,000^oK.

This calculation, coupled with experimental data, may be used to construct a composite curve (Figure 36) which relates minimum power required on the coil, plasma diameter, and operating frequency. The base line curve on the figure was extrapolated from well established operating points at 4 MHz. It was assumed for simplification that the radiation increased with the volume, convection with the cross sectional area, and conduction with the circumference of the plasma. The efficiency as calculated from Equation (9) was then applied at two plasma temperatures and three frequencies to yield the shaded areas shown. The actual minimum one atmosphere operating point at 9,600 Hz was then plotted and a line drawn through that data point parallel to the shaded area. Predicted one atmosphere operating lines for 960 Hz and 60 Hz were then drawn parallel to the shaded area displaced a similar amount as experienced with the 9,600 Hz operating data. It can be noted that the extrapolated one atmosphere operating point for 960 Hz as seen in Figure 16 falls essentially directly on the predicted operating line.

II. Number of Coil Turns

In order to properly design a coil for actual testing of a low frequency plasma it is necessary to determine the number of coil turns required to fulfill the conditions previously described.

Induction theory of metals yields the following equations.

$$R_L = 2\pi^2 n^2 dh \sqrt{\rho} f \Phi \quad (10)$$

$$R_C = 2\pi^2 n^2 DH \sqrt{\rho_c} f \quad (11)$$

where

R_L = resistance of load as reflected into the inductor circuit, ohms

R_C = resistance of inductor coil, ohms

n = number of turns per unit length of inductor coil, turns/cm

d = load diameter, cm

h = load height, cm

D = inductor coil diameter, cm

H = inductor coil height, cm

ρ = resistivity of load, abohm-cm

ρ_c = resistivity of inductor, abohm-cm

f = applied frequency, Hz

Φ = Bessel function parameter

When the induction theory is applied to heating a plasma, it can be assumed that the reactance of the loaded inductor coil is approximately the same as the unloaded coil since the plasma resistivity is so high. This assumption allows the reactance of the loaded inductor to be

$$X = 2\pi fL \quad \text{where } L = \text{inductance}$$

$$X = \frac{2.47 \times 10^{-6} N^2 D^2 f}{(18D + 40H)} \quad (12)$$

$$\text{and } N = nH \quad (13)$$

*Pender, H., and McIlwain, K.: Electrical Engineers' Handbook, Communications-Electronics. John Wiley & Sons, New York, 3rd Edition, Vol. V, pg. 4-14.

If we consider a practical geometry where $H=D=h=1.5d$ and $\rho = 4.5 \times 10^{-2} \Omega \text{cm}$

$\rho_C = 2 \times 10^{-6} \Omega \text{cm}$. Equations (10), (11), and (12) reduce to

$$R_L = 2.25 \times 10^{-15} N^2 d^3 f^2 \quad (14)$$

$$R_C = 8.8 \times 10^{-7} N^2 \sqrt{f} \quad (15)$$

$$X = 6.4 \times 10^{-8} N^2 df \quad (16)$$

The electrical efficiency

$$\eta_e = \frac{R_L}{R_L + R_C}$$

$$\text{So } \eta_e = \frac{1}{1 + R_C/R_L} \quad (17)$$

The power dissipated in the load ($R_L + R_C$) is P_L

$$\text{So } P_L = I_L^2 (R_L + R_C) \quad (18)$$

The coil current $I_L = \frac{E_L}{Z}$ where Z is the load impedance

$$Z = \sqrt{(R_L + R_C)^2 + X^2} \quad (19)$$

As $X^2 \gg (R_L + R_C)^2$, $Z \approx X$

$$\text{So } I_L = \frac{E_L}{X} \quad (20)$$

$$\text{So } P_L = \frac{E_L^2}{X^2} (R_L + R_C) \quad (21)$$

If equations (14), (15), and (16) are represented by

$$R_L = aN^2 \quad (22)$$

$$R_C = bN^2 \quad (23)$$

$$X = cN^2 \quad (24)$$

Then Equation (21) becomes

$$P_L = \frac{E_L^2}{c^2 N^4} N^2 (a+b) \quad (25)$$

Rearranged it becomes

$$N = \frac{E_L}{P_L^{\frac{1}{2}}} \frac{(a+b)^{\frac{1}{2}}}{c} \quad (26)$$

Thus, Equation (26) gives the required number of coil turns for the inductor as a function of the generator frequency, power, and voltage.

It can be seen that each one of these calculations depends on the assumptions and results of the other calculations and, therefore, some degree of judgement is involved in the utilization of these considerations.

TABLE I

HEAT BALANCE DATA FOR 9,600 Hz INDUCTION PLASMA

	Test Configuration			
	1 Steel	2 Steel	3 Acid	4 Plasma
9,600 Hz Coil Power kW	130	134	134	143
Power to Load Percent	71	84	9	75
Power to Torch Wall Percent	13	0	No Wall	*
Power to Coil, Capacitors, and Bus Percent	16	16	91	25
Resistivity of Load Ohm-cm	2×10^{-5}	2×10^{-5}	1.3	4×10^{-2}

*No power was coupled directly into the wall, but wall was heated by radiation from the plasma.

Test Configurations:

1. Complete torch with 6" i.d. metal wall and metal separator. Three turn 800 volt coil. 4 1/2" steel calorimeter.
2. Torch with metal separator only. Five turn 1,600 volt coil. 4 1/2" steel calorimeter.
3. Load is 1 gal. flask of 20% sulfuric acid solution. Five turn 1,600 volt coil.
4. Torch operation at 1 atmosphere-uncooled quartz wall configuration, five turn 1,600 volt coil with laminations.

TABLE II

POWER REQUIREMENTS FOR ARGON INDUCTION
PLASMA AT VARIOUS FREQUENCIES

Frequency Hz	Minimum Ignition* kW	MSP** at 30 mm kW	MSP at 1 atm. kW
9,600	180	27	145
960	475	200	950***
50	(6,800)****	(2,900)	(13,600)

* Ignition using an auxiliary rf glow discharge

** MSP = Minimum Sustaining Power

*** Extrapolated from experimental data up to 300 mm (See Figure 16)

**** Number in parenthesis indicates predicted values

TABLE III

HIGH PRESSURE 4 MHz INDUCTION TORCH
CALORIMETRIC DATA

DC Plate Power kW	Torch Gas SCFH Ar	Pressure psia	% Loss to Power Supply	% Loss to Separator	% Loss to Torch	% Loss to Exit Calorimeter
44.8	285	115	32.5	33.4	27.8	.5
43.5	372	120	37.0	31.7	32.6	1.0
52.7	234	115	39.1	28.4	34.0	.8
104.0	305	170	39.8	18.6	38.8	3.8
46.0	427	215	43.9	-	57.5	.4
52.2	277	215	44.5	-	54.9	.5
120.0	226	270	42.0	-	51.0	1.3
147.7	535	317	39.3	-	57.1	3.5
157.5	472	370	39.3	-	54.7	2.7
156.0	472	433	42.1	-	56.7	3.4

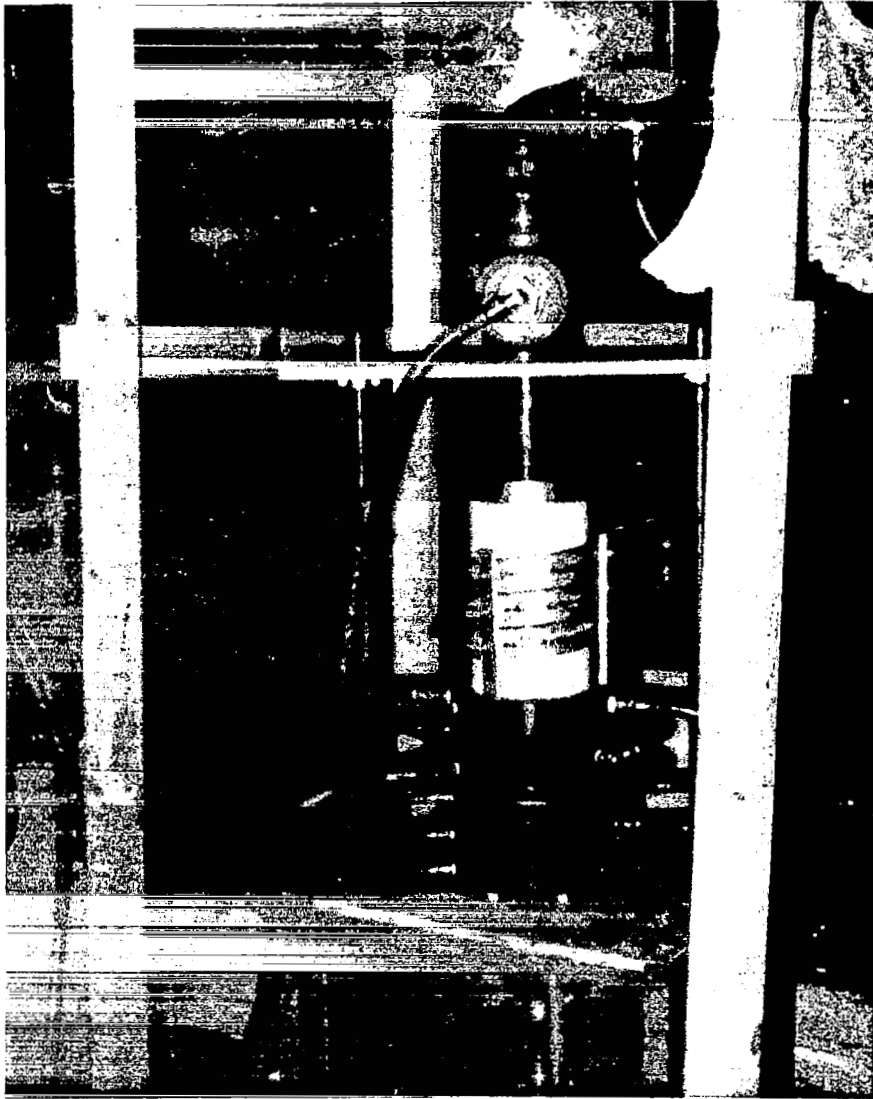
TABLE IV

TOTAL RADIATION MEASUREMENTS OF ARGON PLASMAS
IN VARIOUS TORCH CONFIGURATIONS*

	Plate Power (kW)	Radiated Power (kW)	Percent Power Radiated
9,600 Hz, 6" dia. torch at 1 atm.	325**	49	15
960 Hz, 12" dia. torch at 0.25 atm.	860**	57	7
3.7 MHz, 1.5" dia. torch			
1 atm.	7.9	1.27	16
5.1 atm.	8.7	2.32	27
7.8 atm.	10.6	2.32	22
14.7 atm.	16.0	3.07	19
High Pressure torch at 3.4 MHz and 7.8 atm.	45	14.4	32

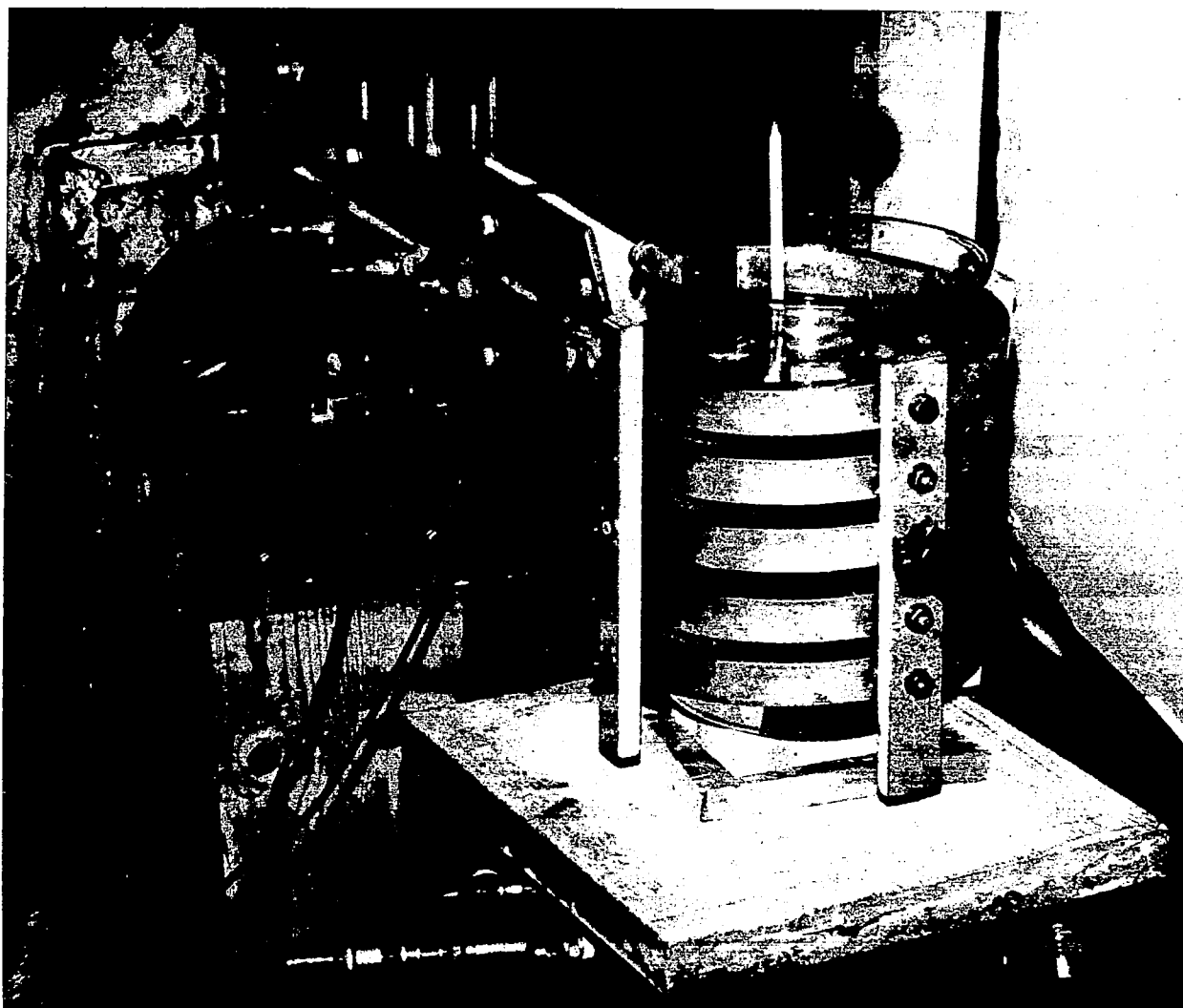
*Measuring instrument used was a Hy-Cal Engineering Pyrheliometer,
Model P-8400-B-01-120.

*Actual MG power readings (coil power) divided by 0.7 to yield numbers
for comparison with rf data which is reported as plate power.



METAL CALORIMETER IN 9,600 Hz TORCH
FOR HEAT BALANCE MEASUREMENTS

FIG. 1

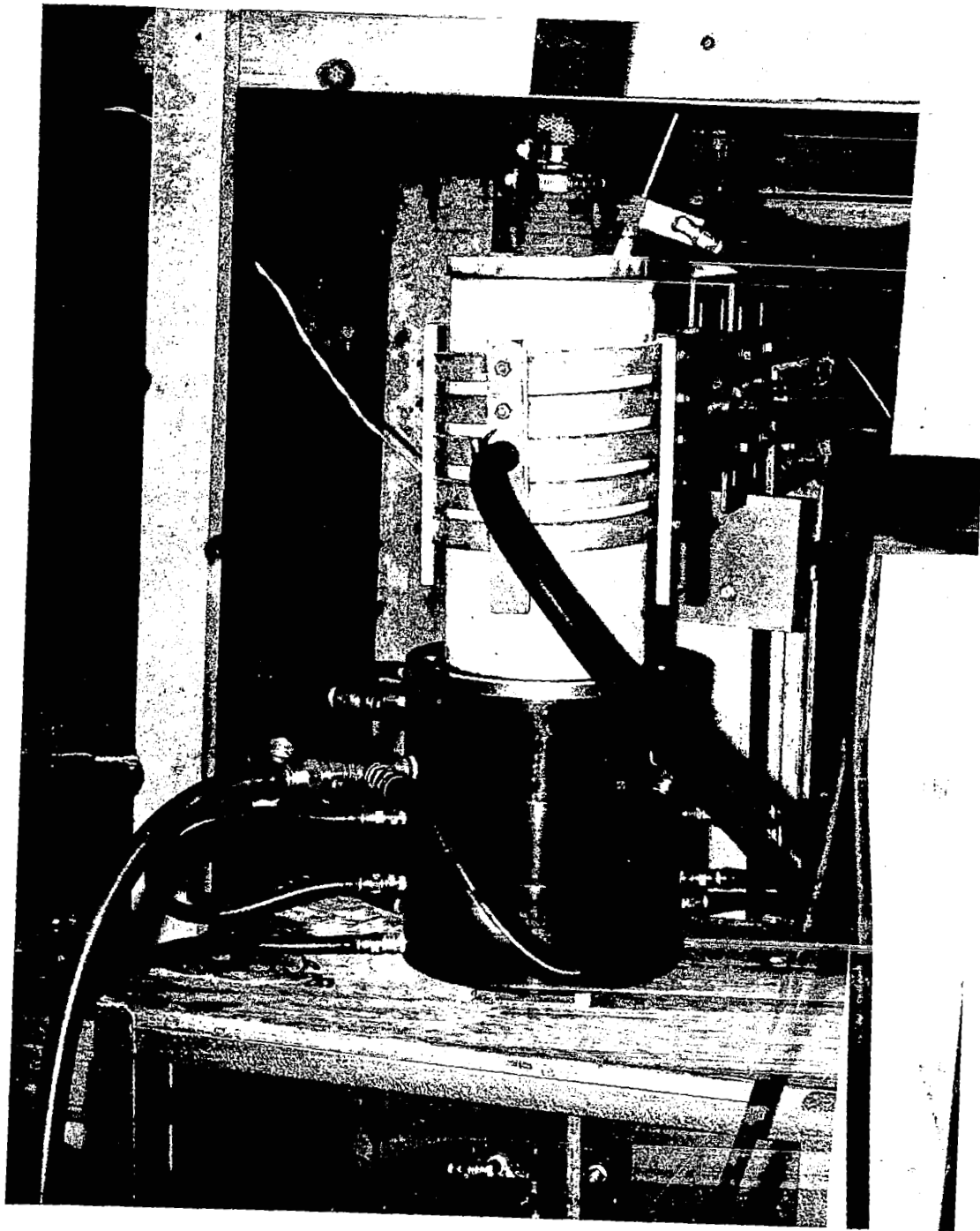


20% SULFURIC ACID SOLUTION IN 9,600 Hz COIL FOR
CALORIMETRY MEASUREMENTS

FIG. 2

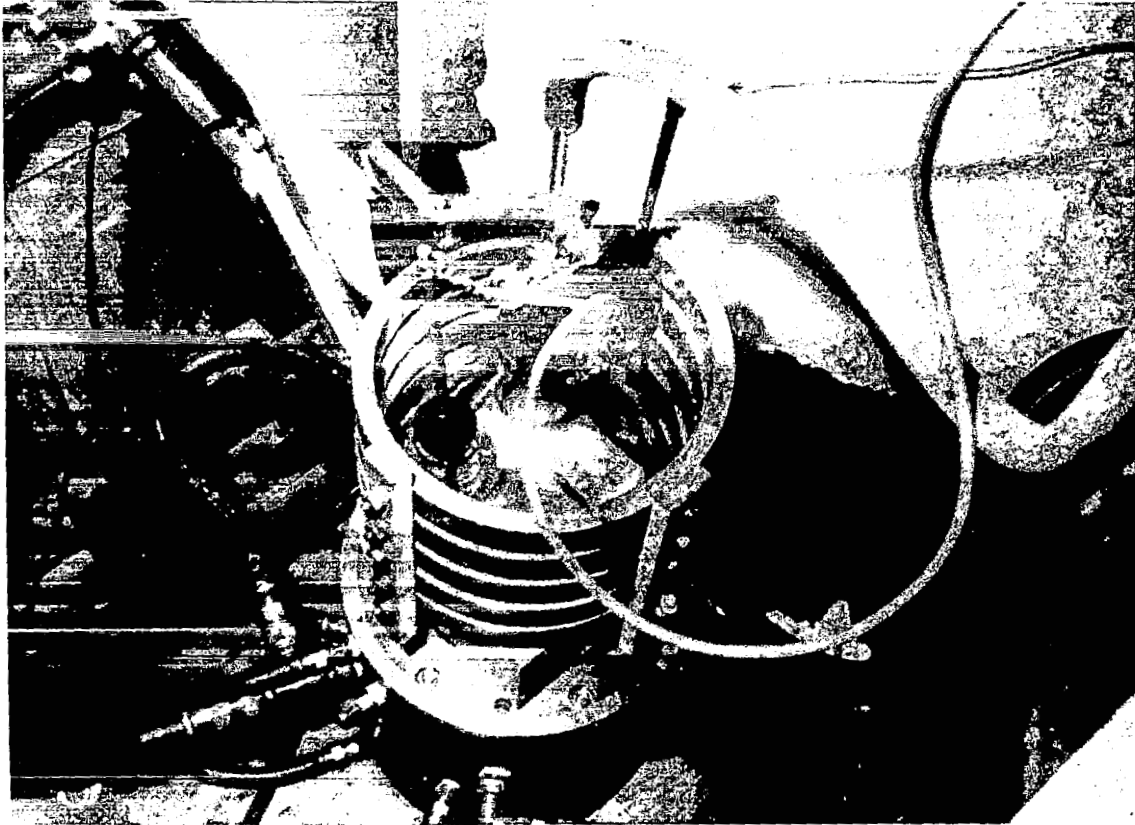


SEGMENTED METAL SEPARATOR IN
9,600 Hz TORCH
FIG. 3

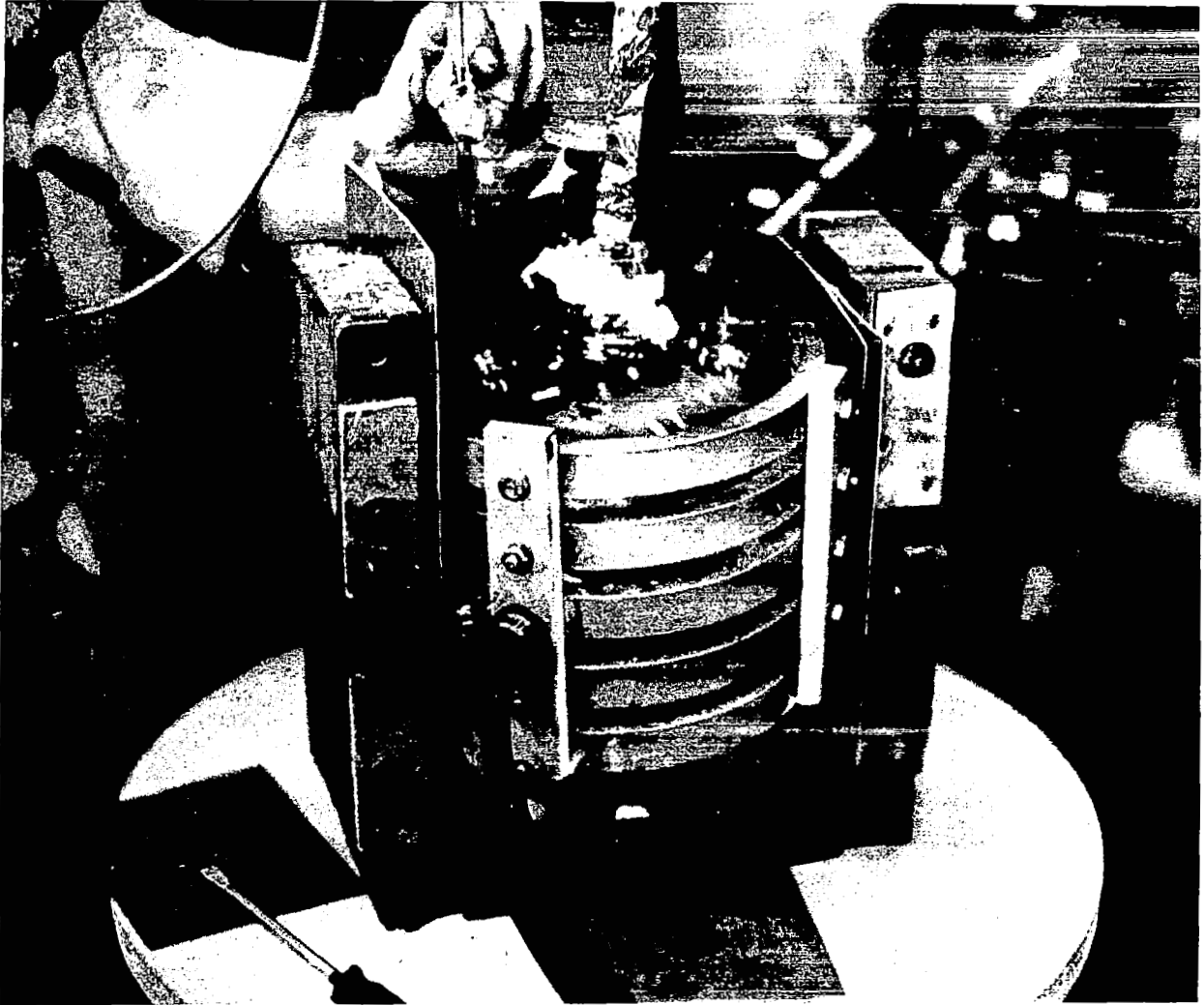


9,600Hz TORCH WITH VACUUM FITTINGS AND
CARBON STARTING ELECTRODES

FIG. 4

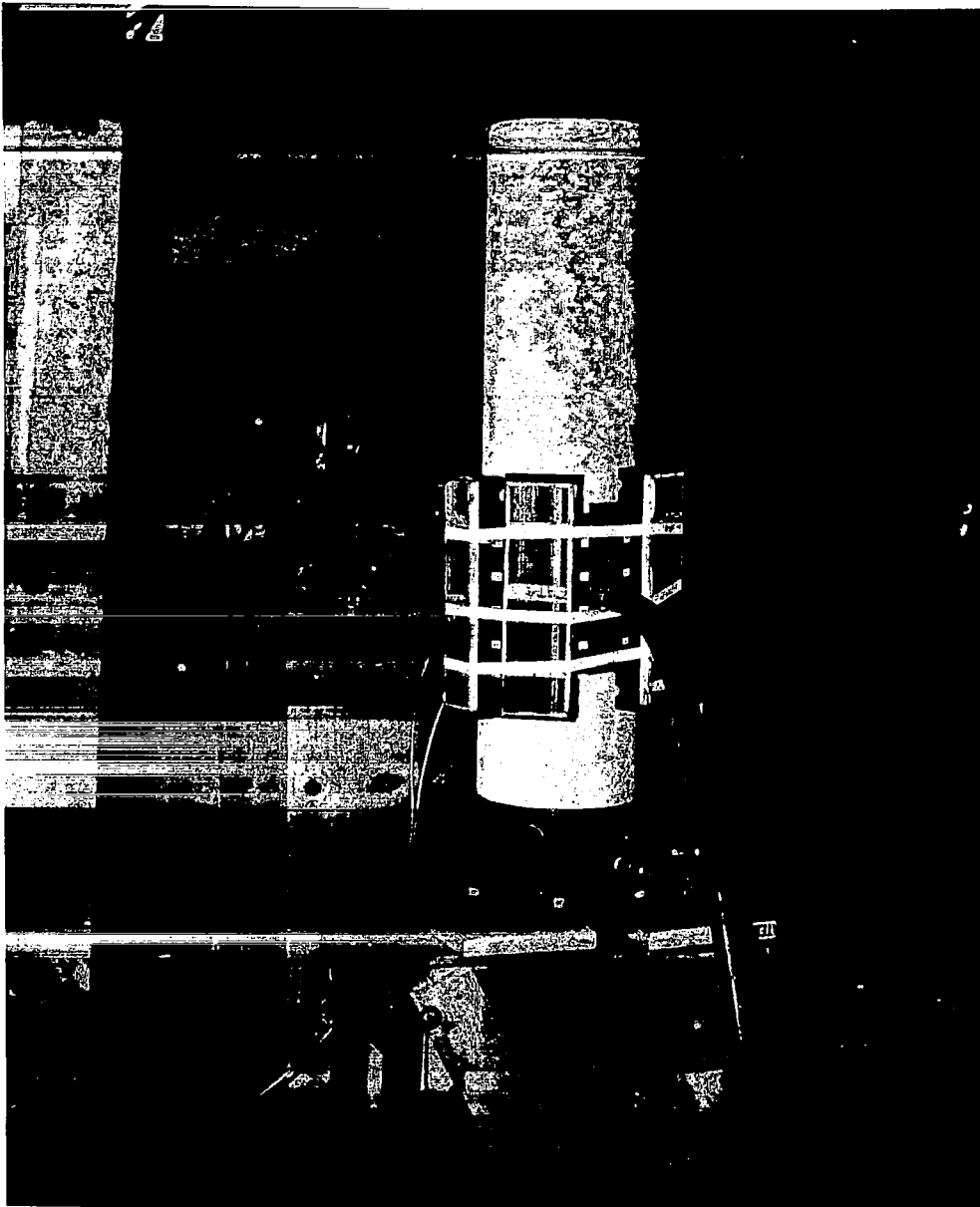


9,600Hz FLASK EXPERIMENT
SHOWING SET-UP WITHOUT LAMINATIONS
FIG. 5



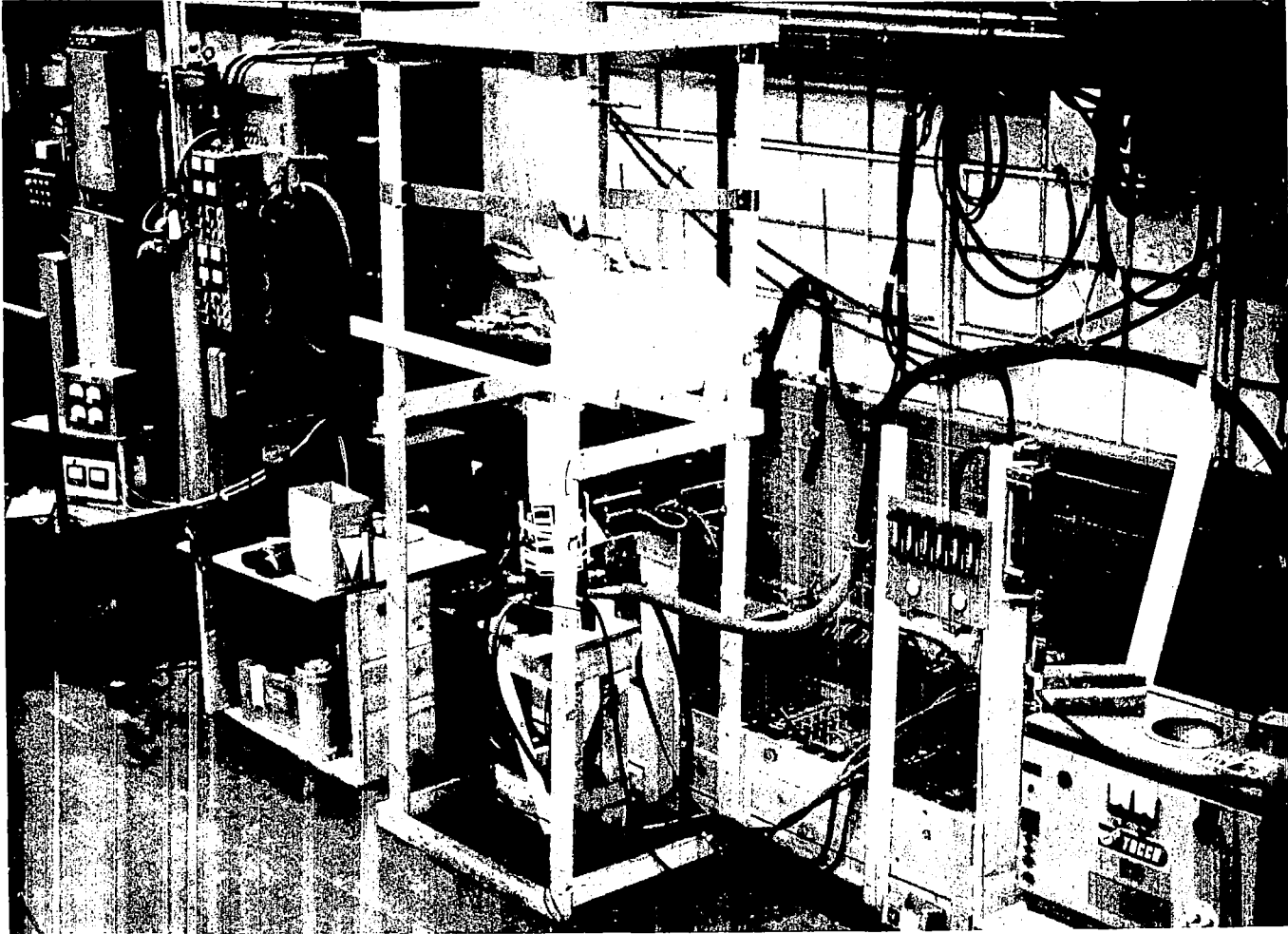
9,600 Hz FLASK EXPERIMENT SHOWING
SET-UP WITH LAMINATIONS

FIG. 6



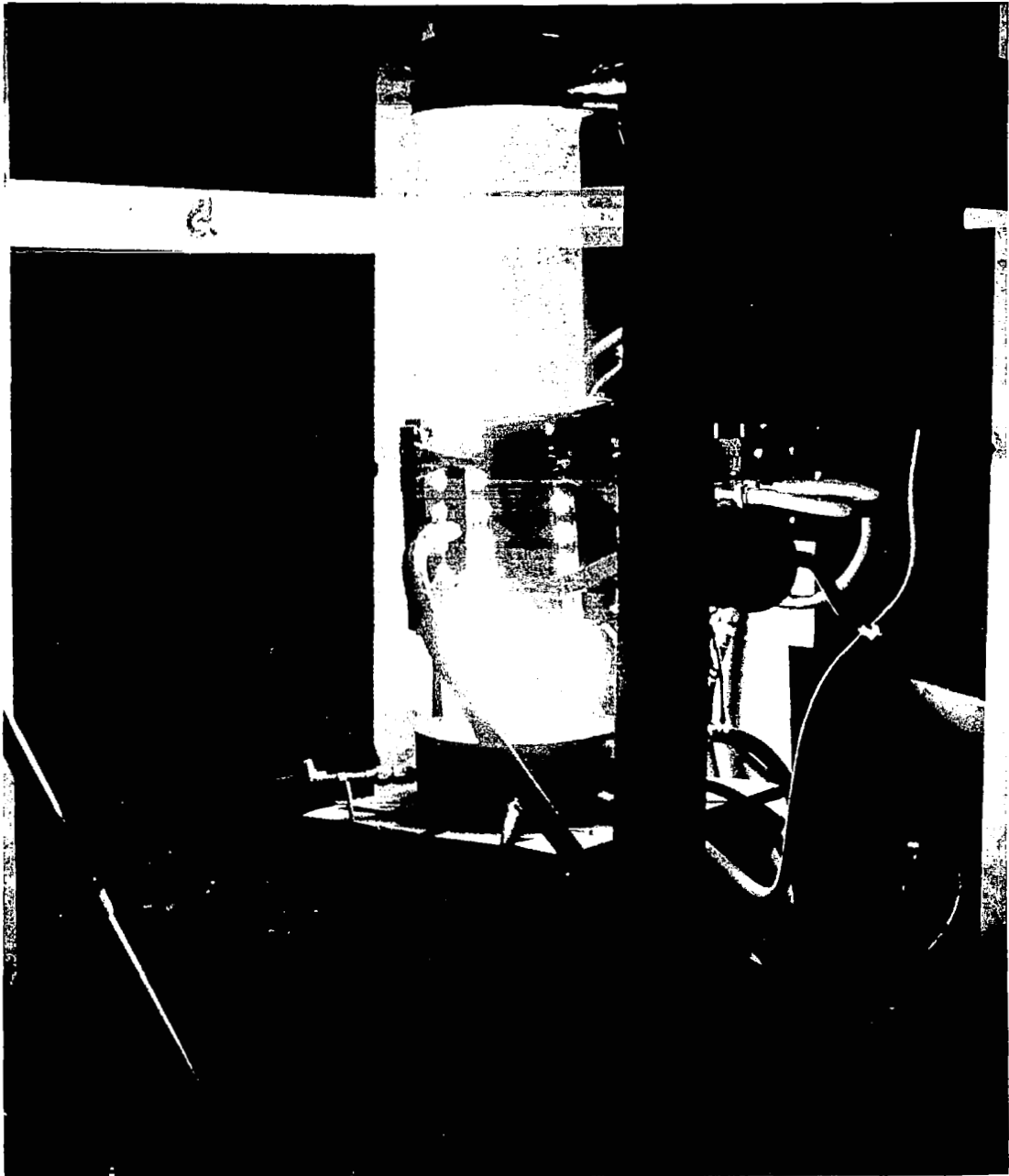
9,600Hz TORCH WITH LAMINATIONS

FIG.7



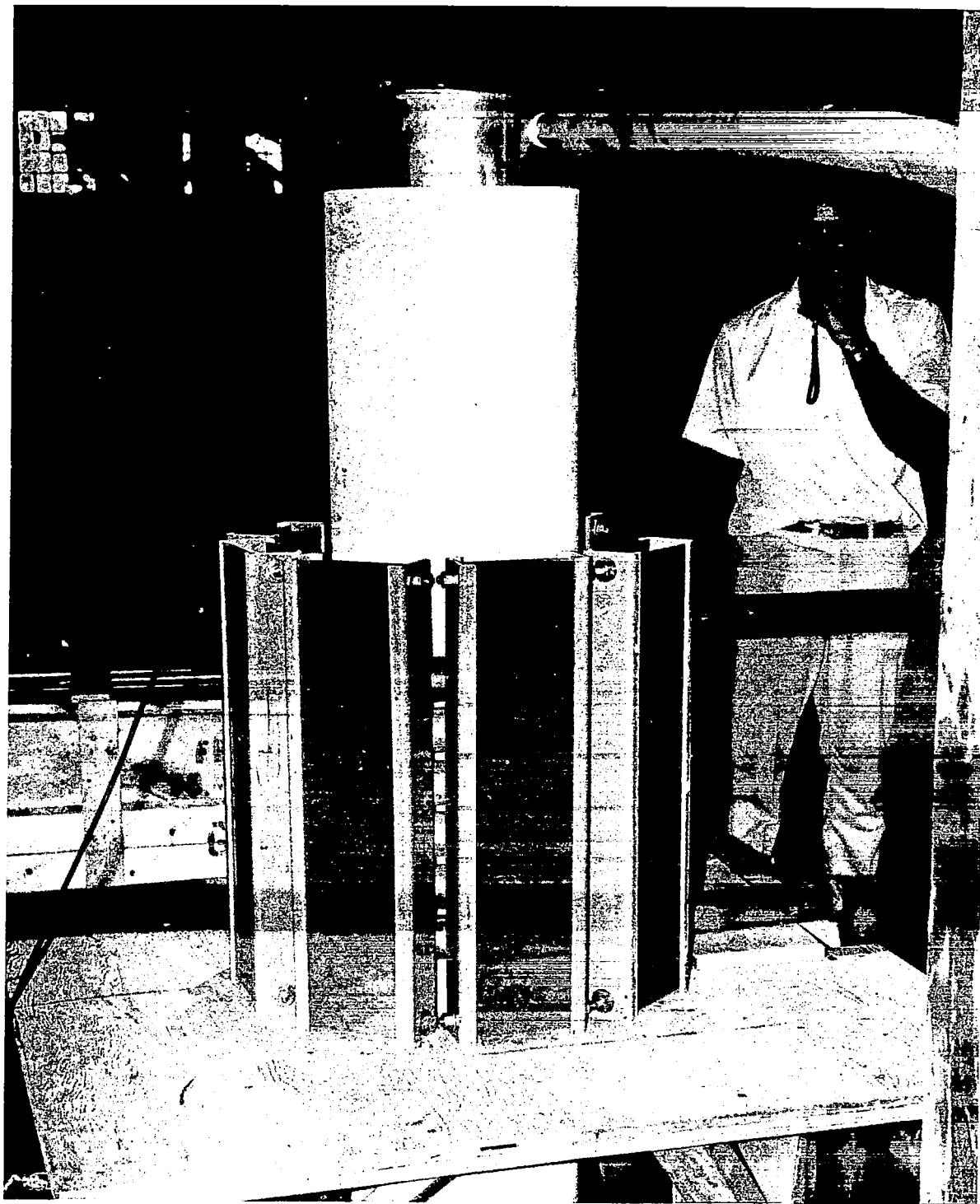
OVERALL VIEW OF 9,600 Hz TORCH TEST AREA

FIG. 8



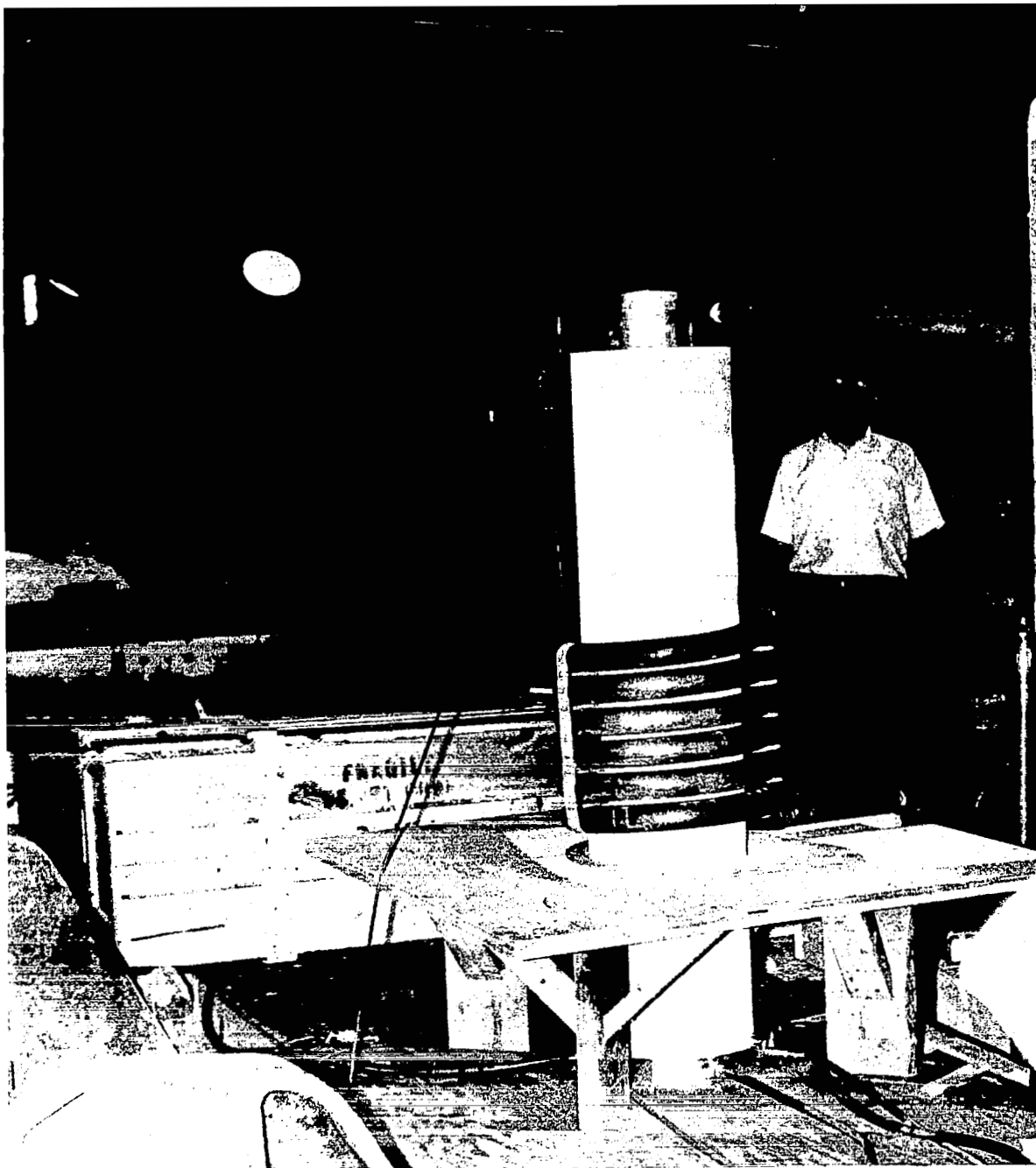
9,600Hz TORCH OPERATING ON ARGON
AT 1 ATMOSPHERE

FIG. 9



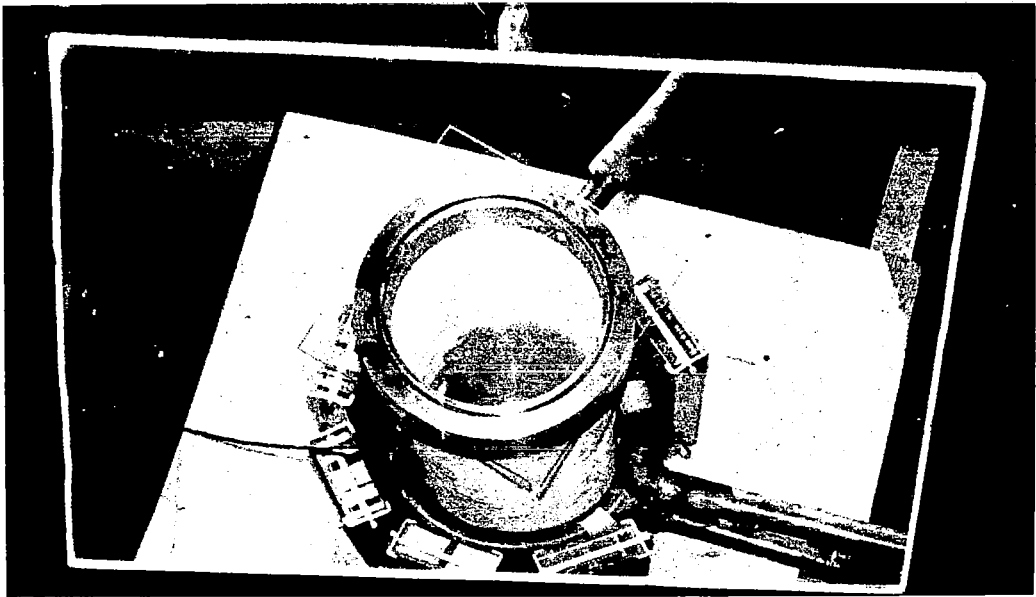
960 Hz TORCH WITH LAMINATIONS

FIG.10



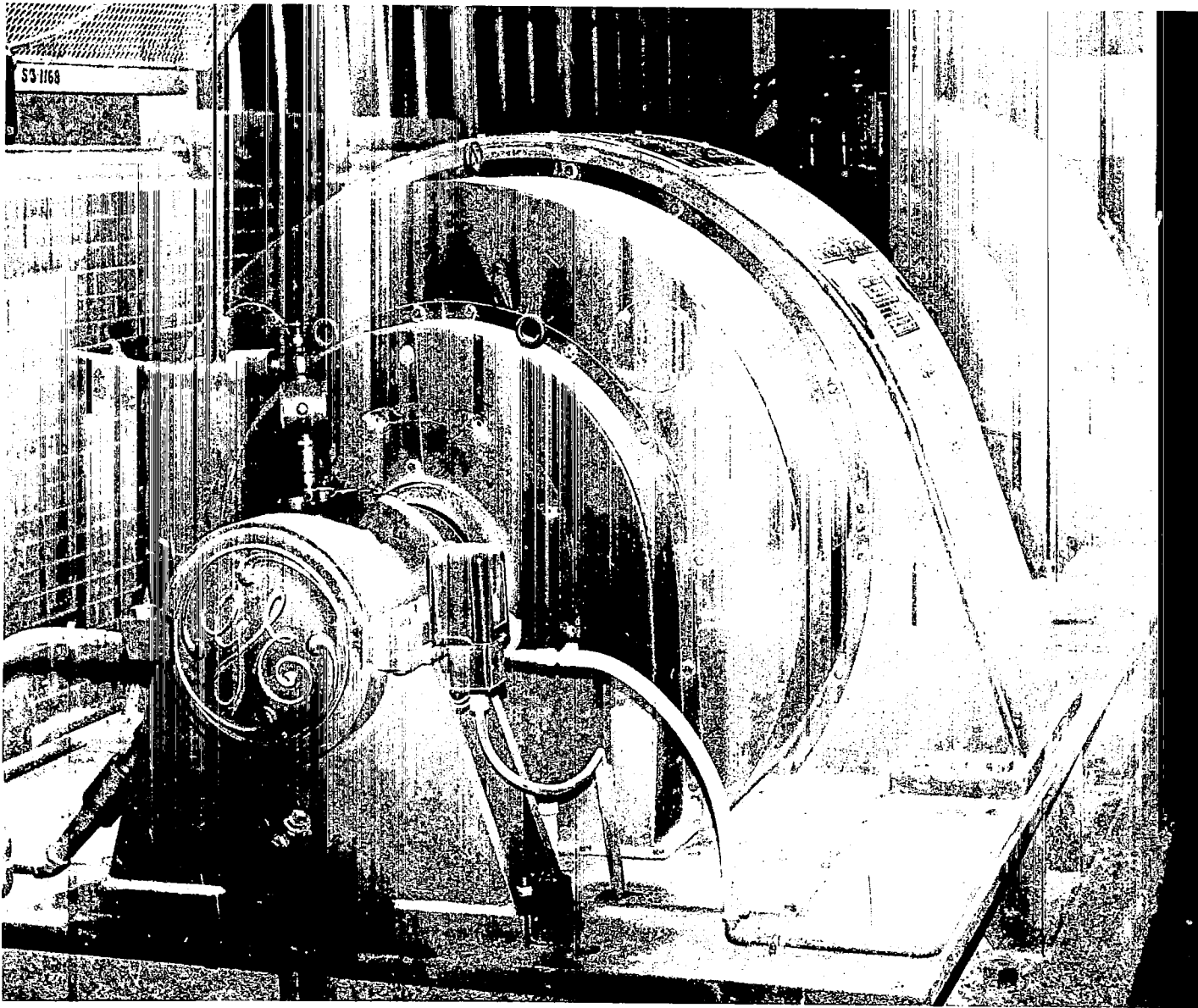
960 Hz TORCH WITH LAMINATIONS REMOVED
TO SHOW COIL

FIG. II



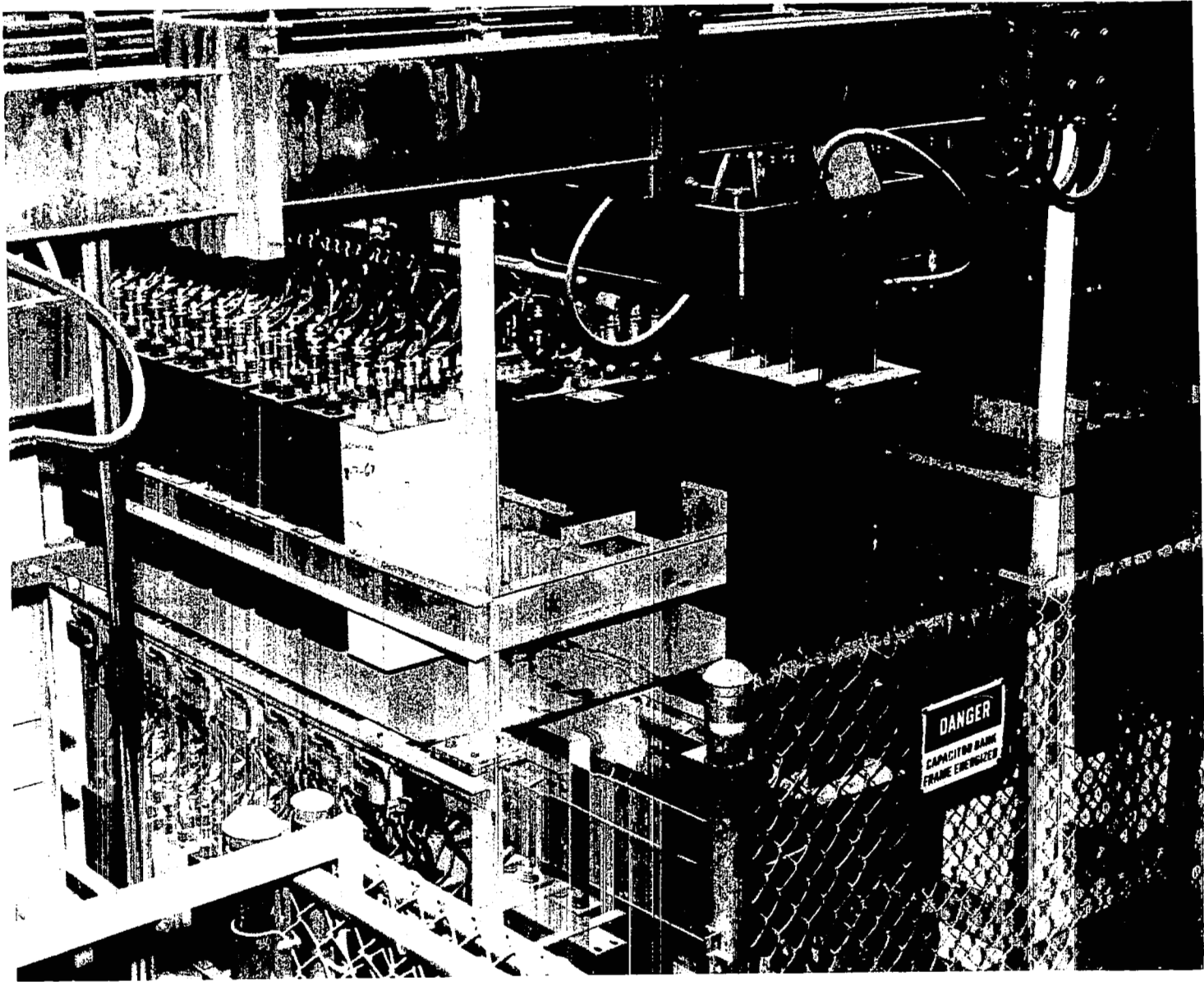
VIEW THROUGH MIRROR OF
INTERIOR OF 960Hz TORCH

FIG.12



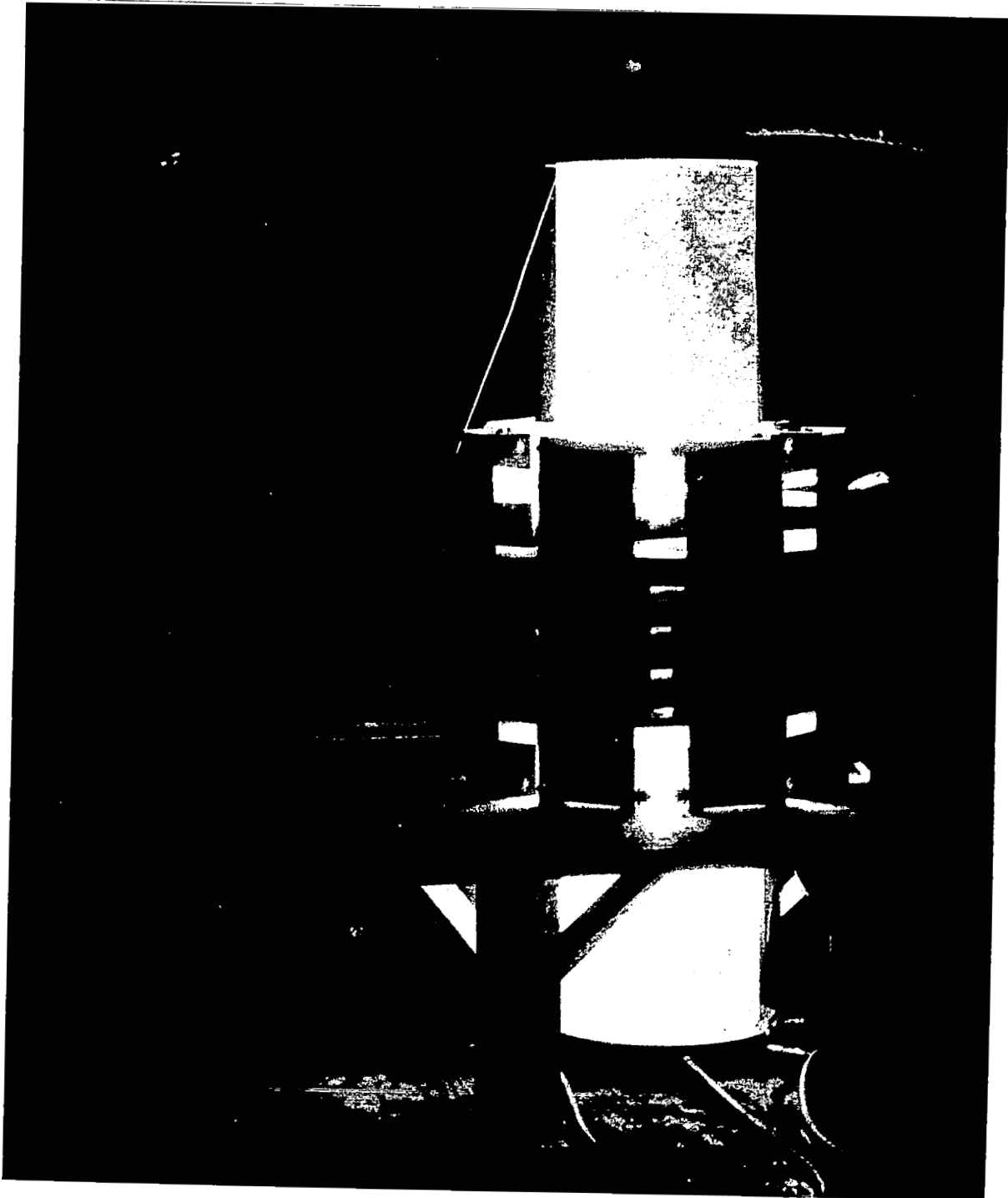
960Hz, 1250KW MG SET

FIG. 13



960 Hz CAPACITOR BANK

FIG.14



960 Hz TORCH OPERATING AT 300 MM

FIG. 15

MINIMUM SUSTAINING POWER REQUIREMENTS
AT 960 HERTZ FOR AN ARGON PLASMA

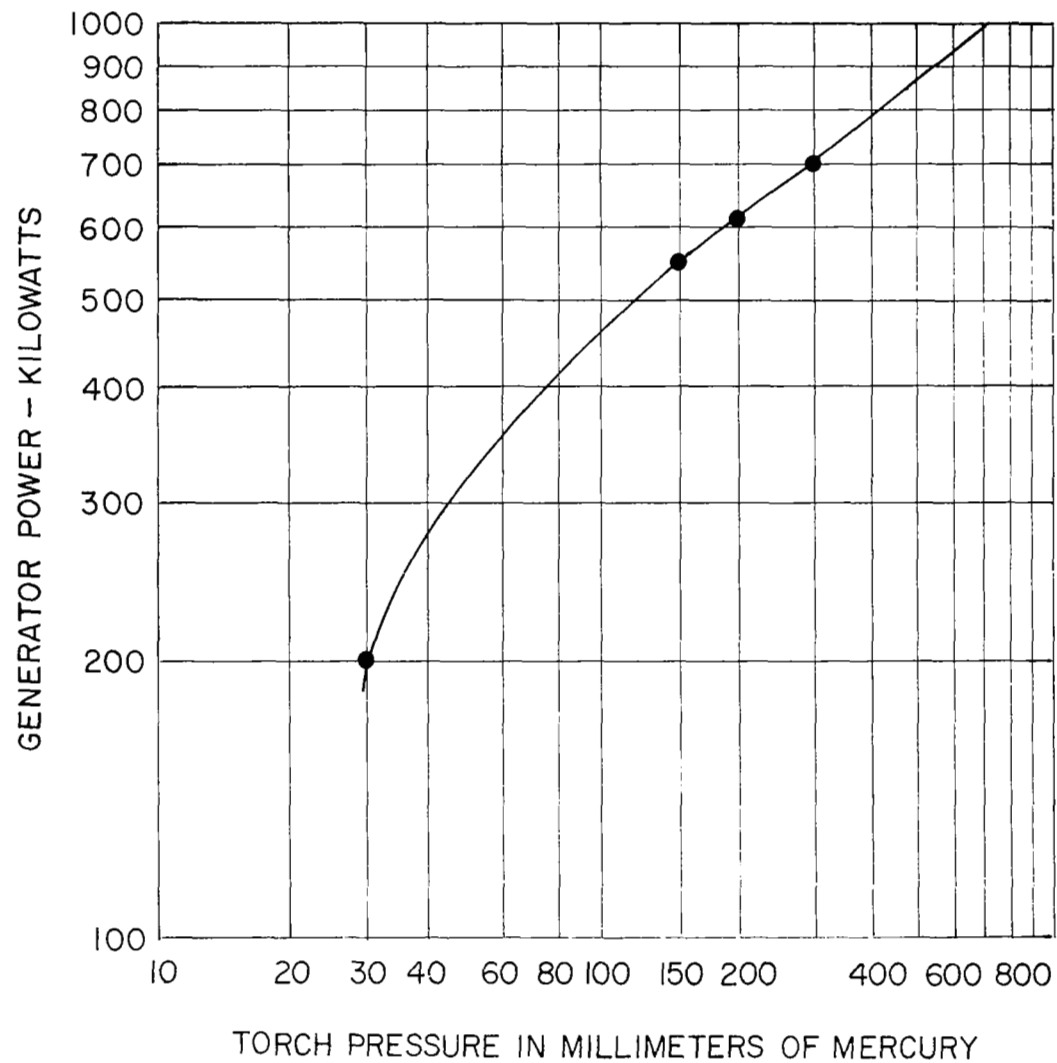


FIG. 16



265 psia PRESSURE CHAMBER

FIG.17

POWER vs PRESSURE
MODEL 56 PLASMA TORCH IN PRESSURE CHAMBER

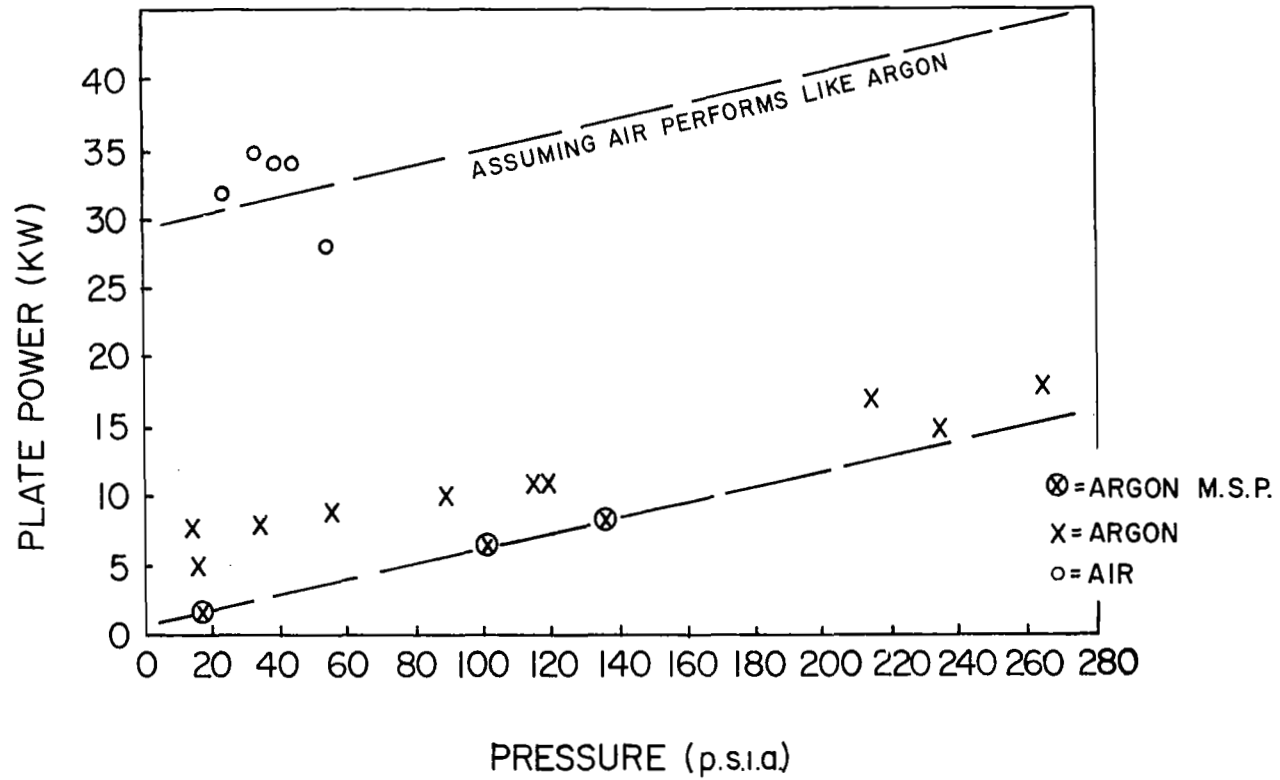


FIG. 18

**DISTRIBUTION OF COOLING LOSSES FOR MODEL 56 TORCH
OPERATING ON ARGON IN 250 P.S.I. CHAMBER TEST RUNS
R-1 THRU. R-18**

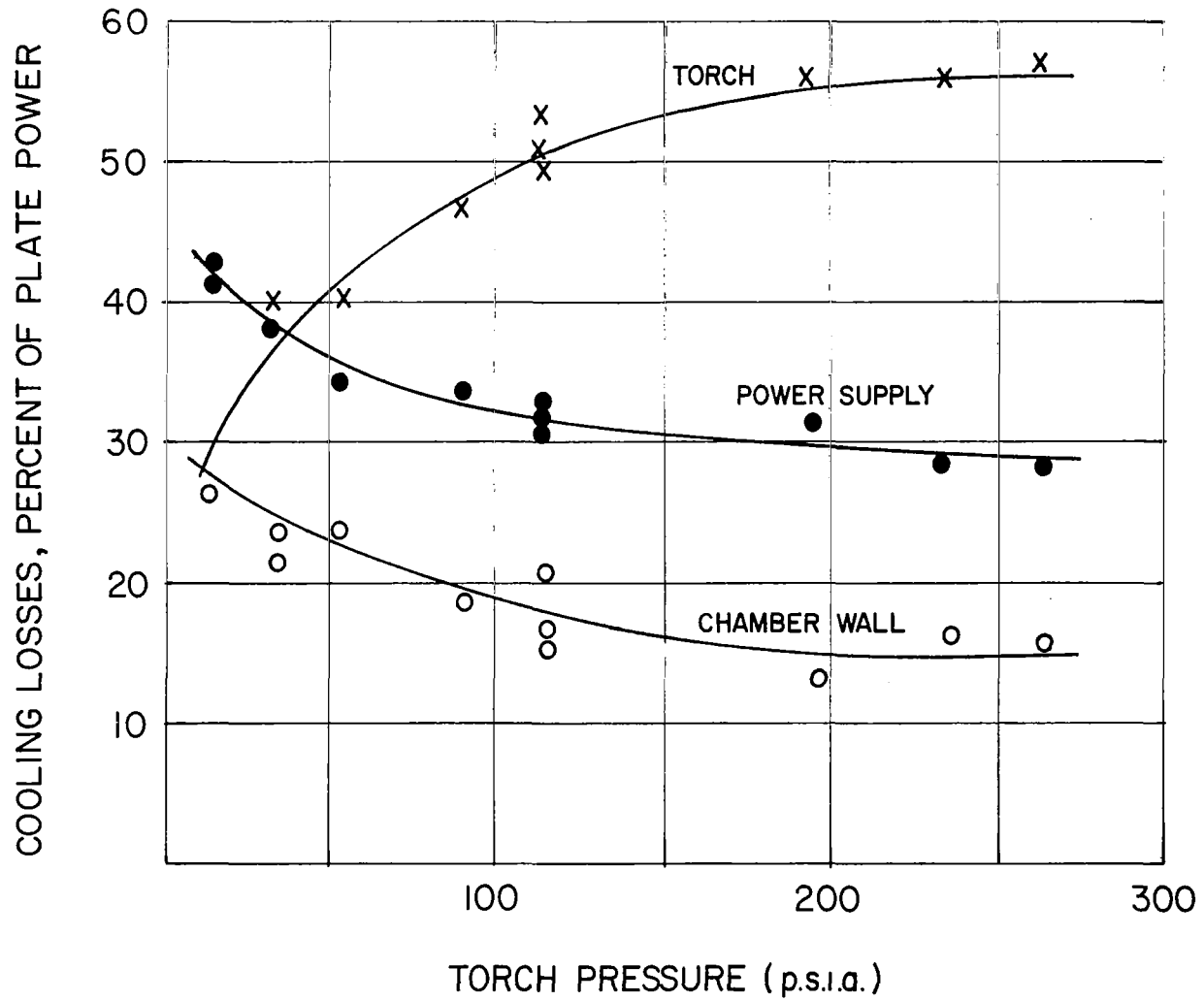
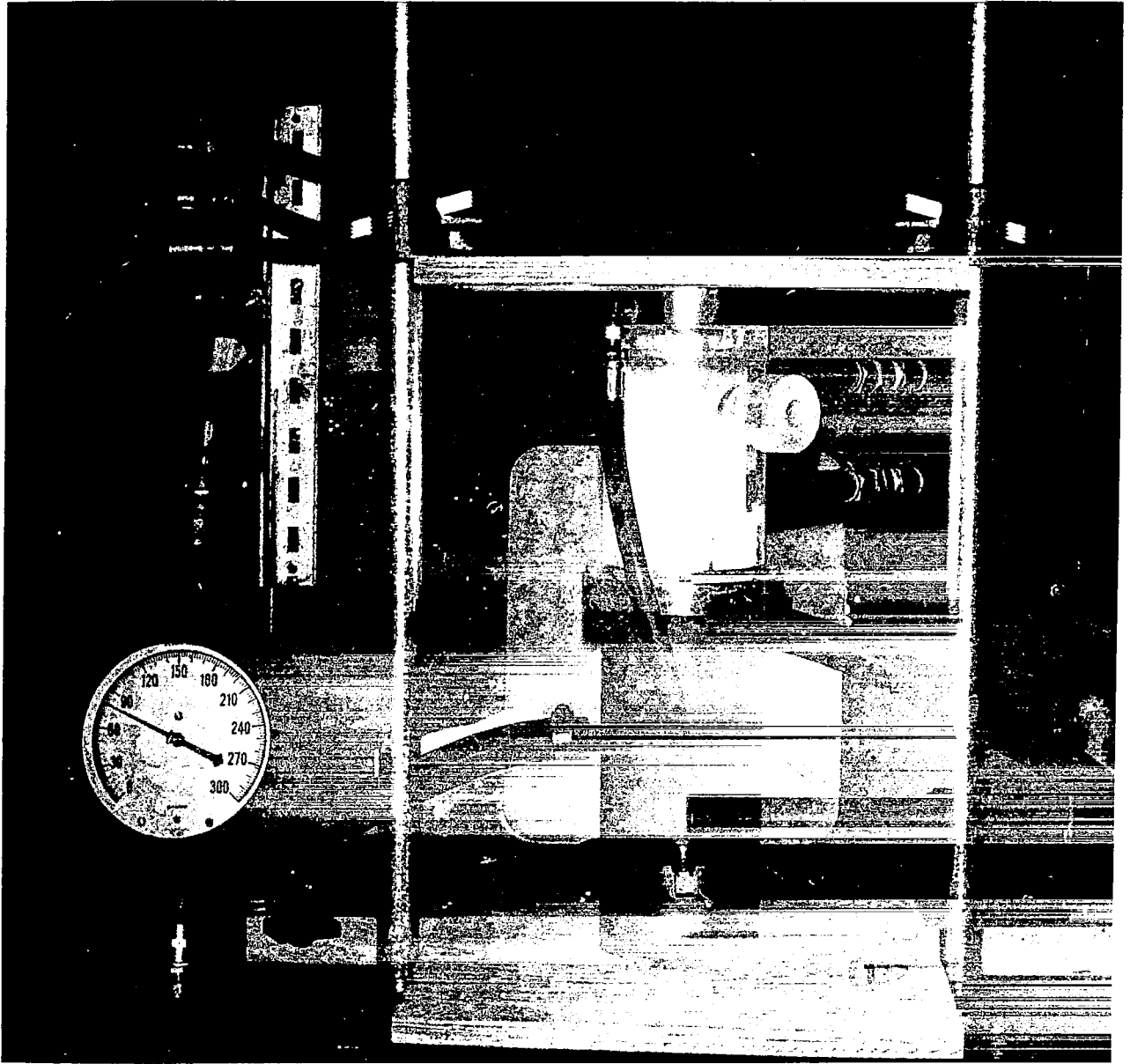
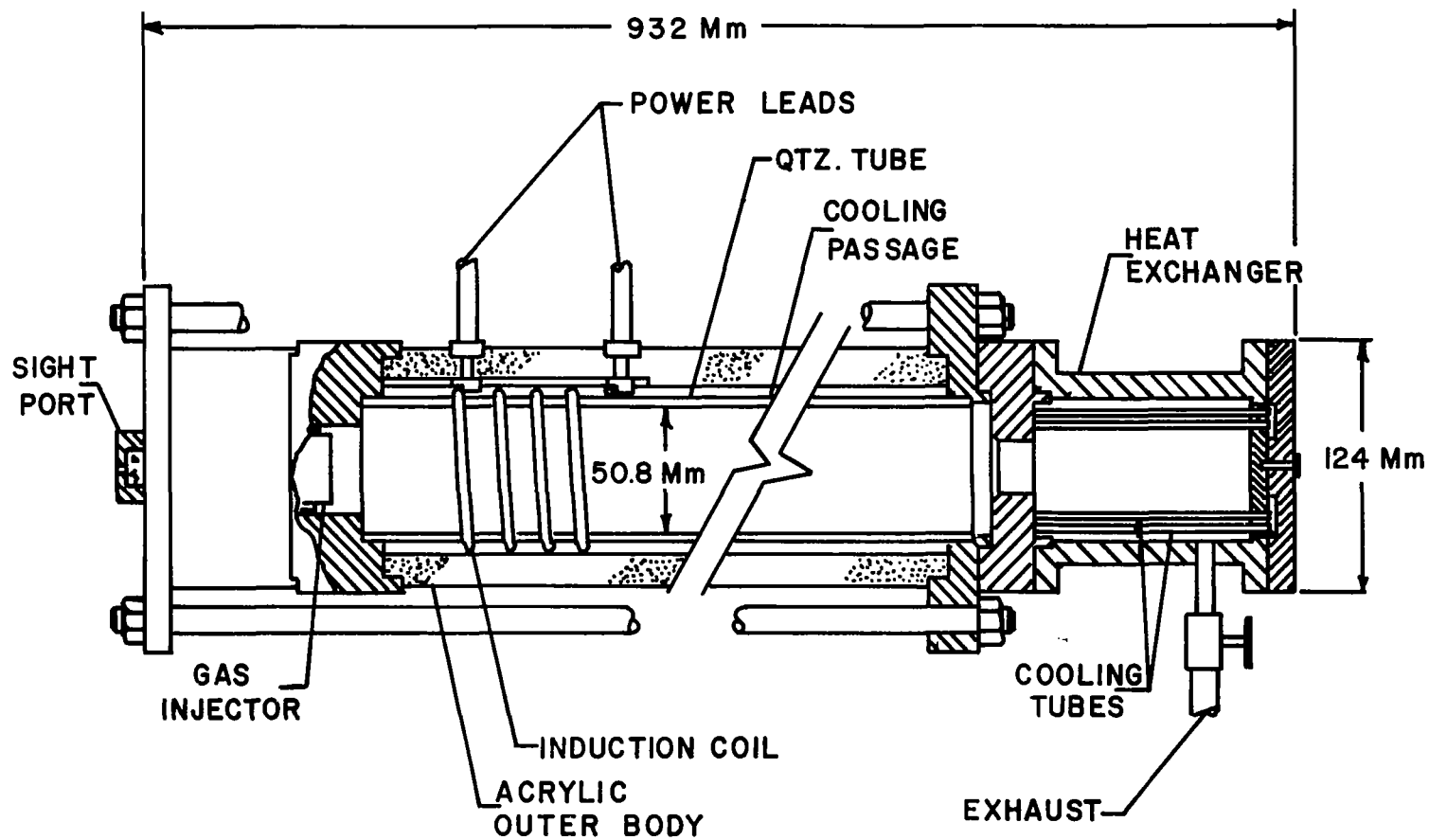


FIG. 19



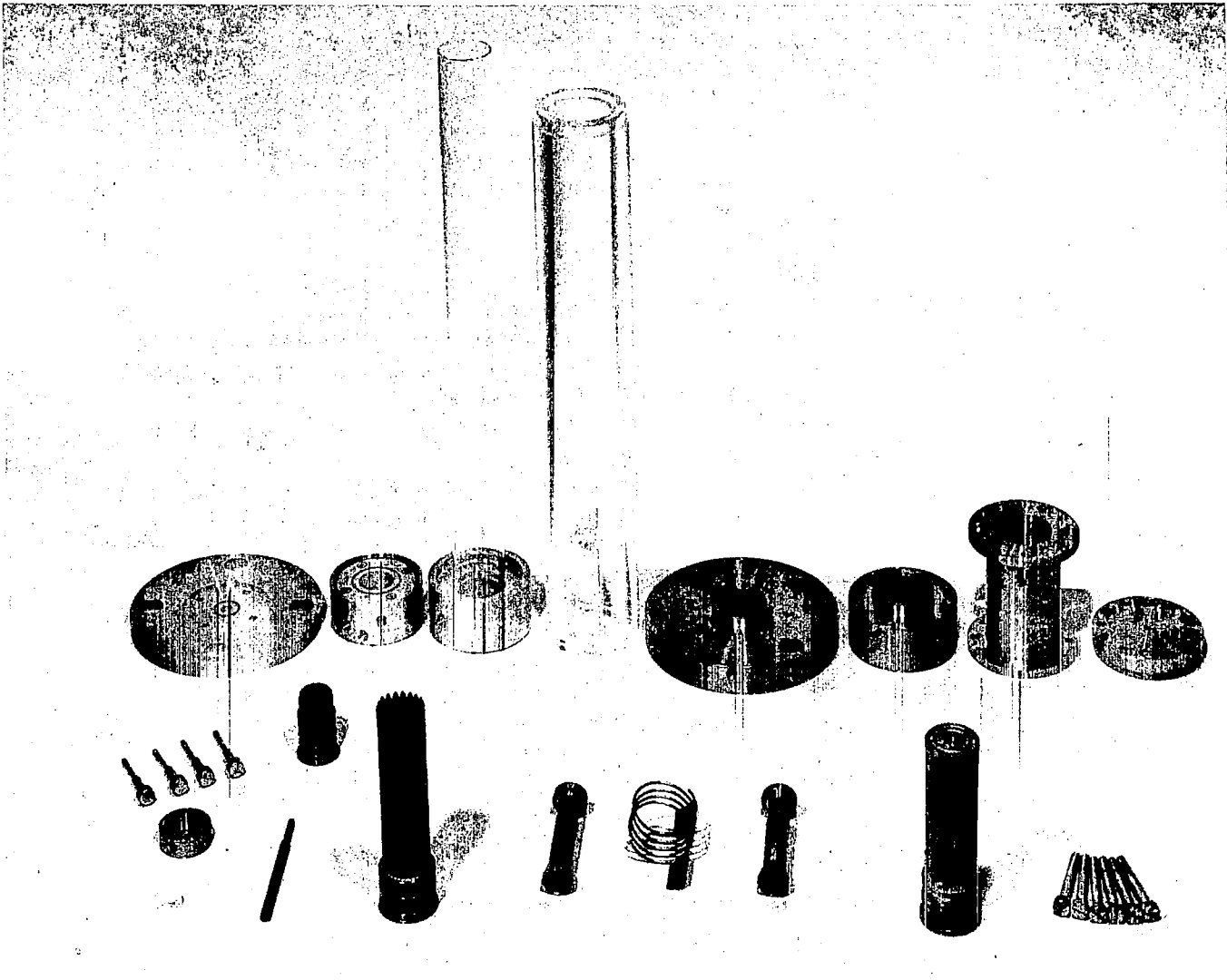
DOUBLE LENGTH Tafa MODEL 56 TORCH
OPERATING AT 80 psig

FIG. 20



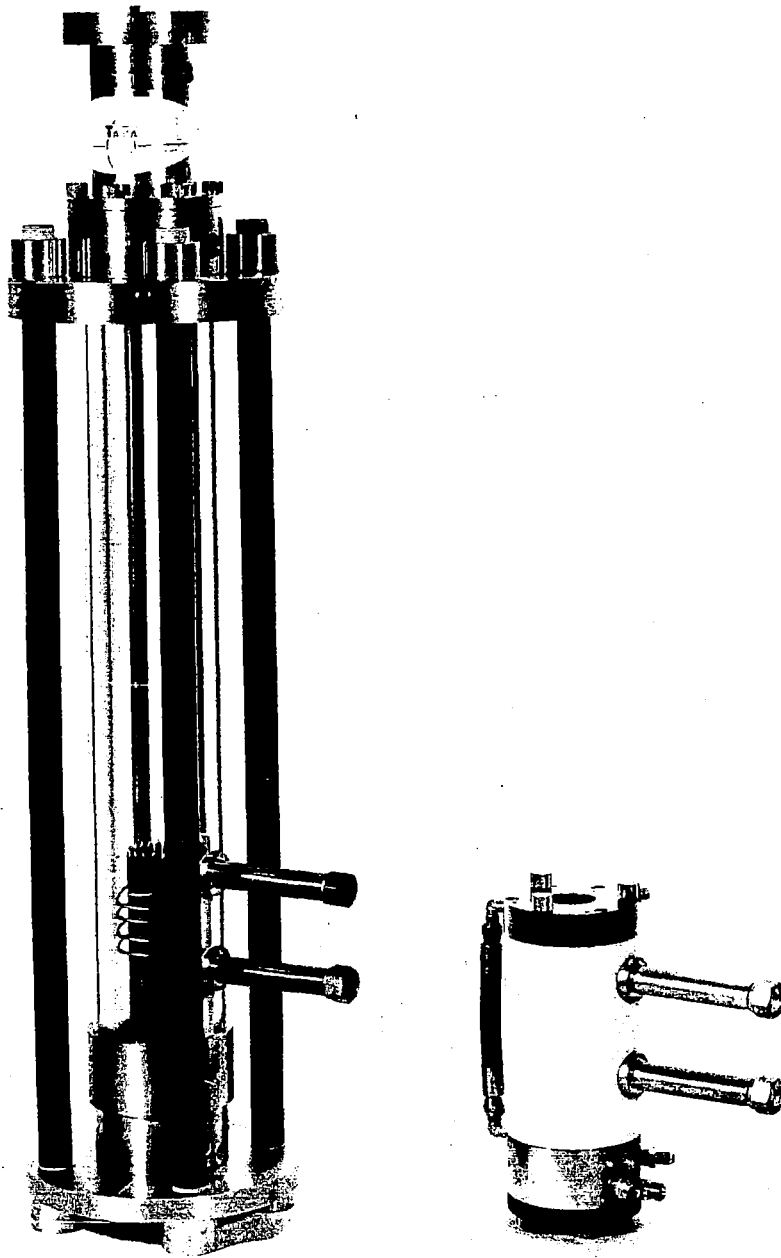
**SCHEMATIC REPRESENTATION OF
HIGH PRESSURE TORCH**

FIG. 21



HIGH PRESSURE 1000 PSI TORCH COMPONENTS

FIG.22



HIGH PRESSURE TORCH

Tafa Model 56 TORCH

COMPARISON OF HIGH PRESSURE AND
MODEL 56 TORCHES

FIG. 23

PLATE POWER vs TORCH PRESSURE
HIGH PRESSURE PLASMA TORCH
OPERATING ON ARGON AT 3.5 MHz
WITH A 50.8 MM I.D. QUARTZ TUBE

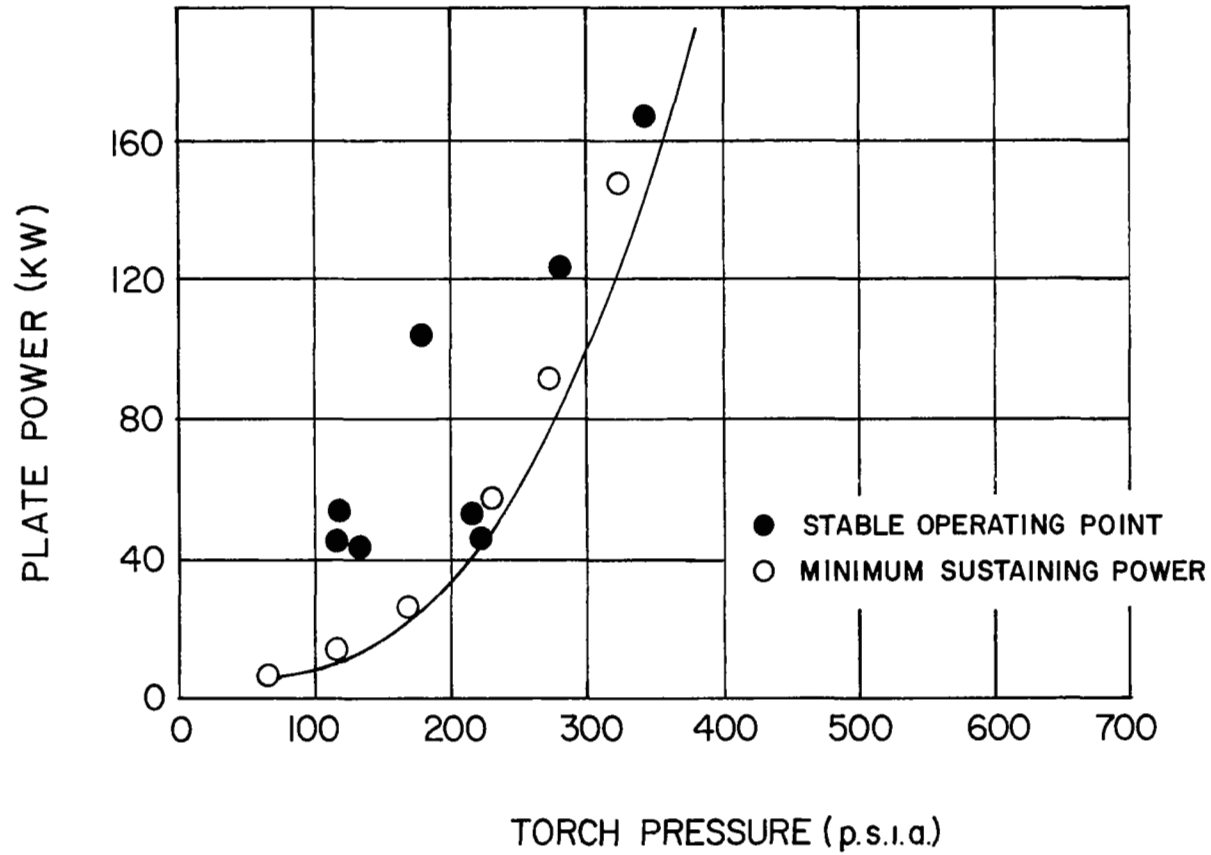


FIG. 24

PLATE POWER vs TORCH PRESSURE
HIGH PRESSURE PLASMA TORCH
OPERATING ON ARGON AT 3.5 MHz
WITH A 38.1 MM I.D. QUARTZ TUBE

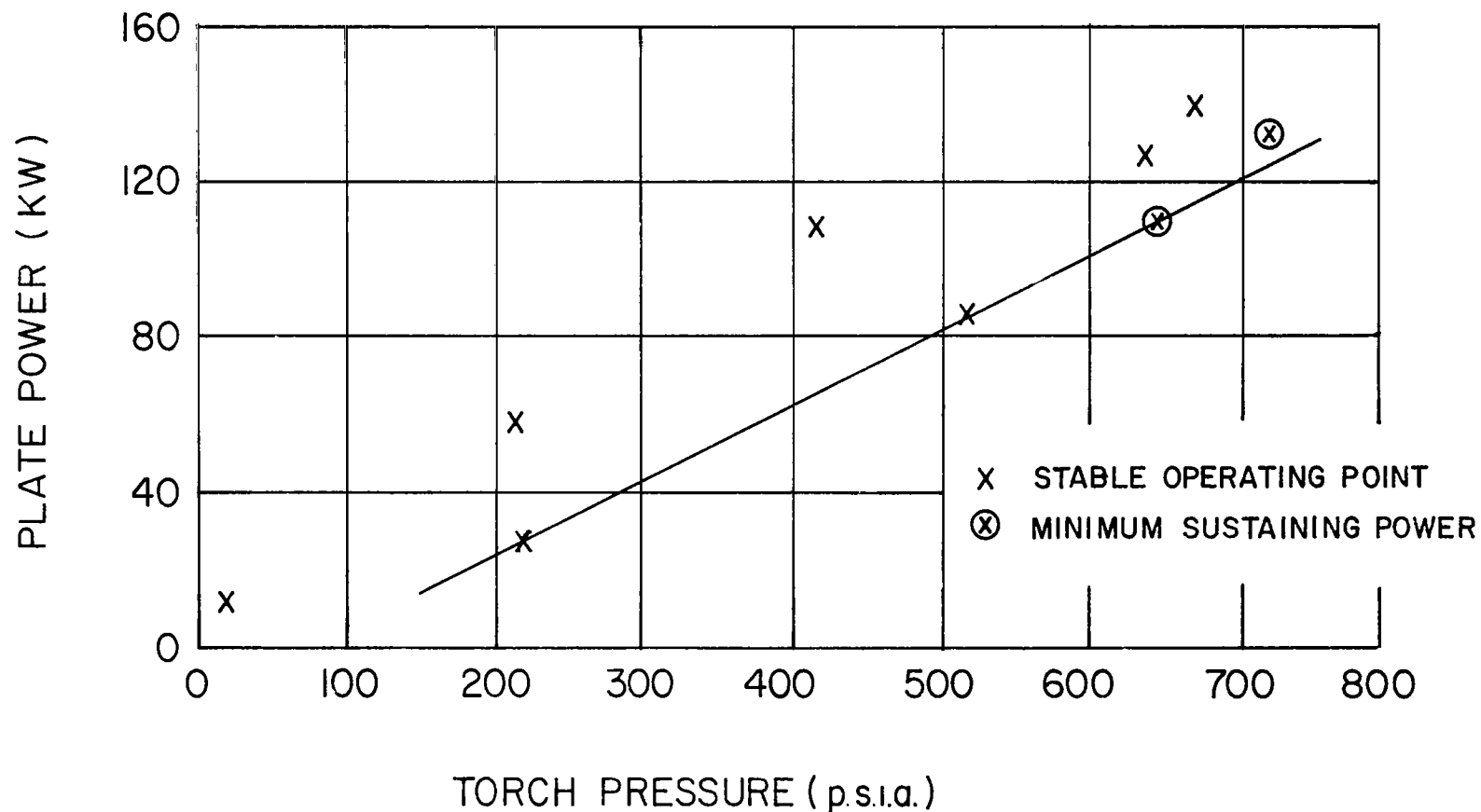
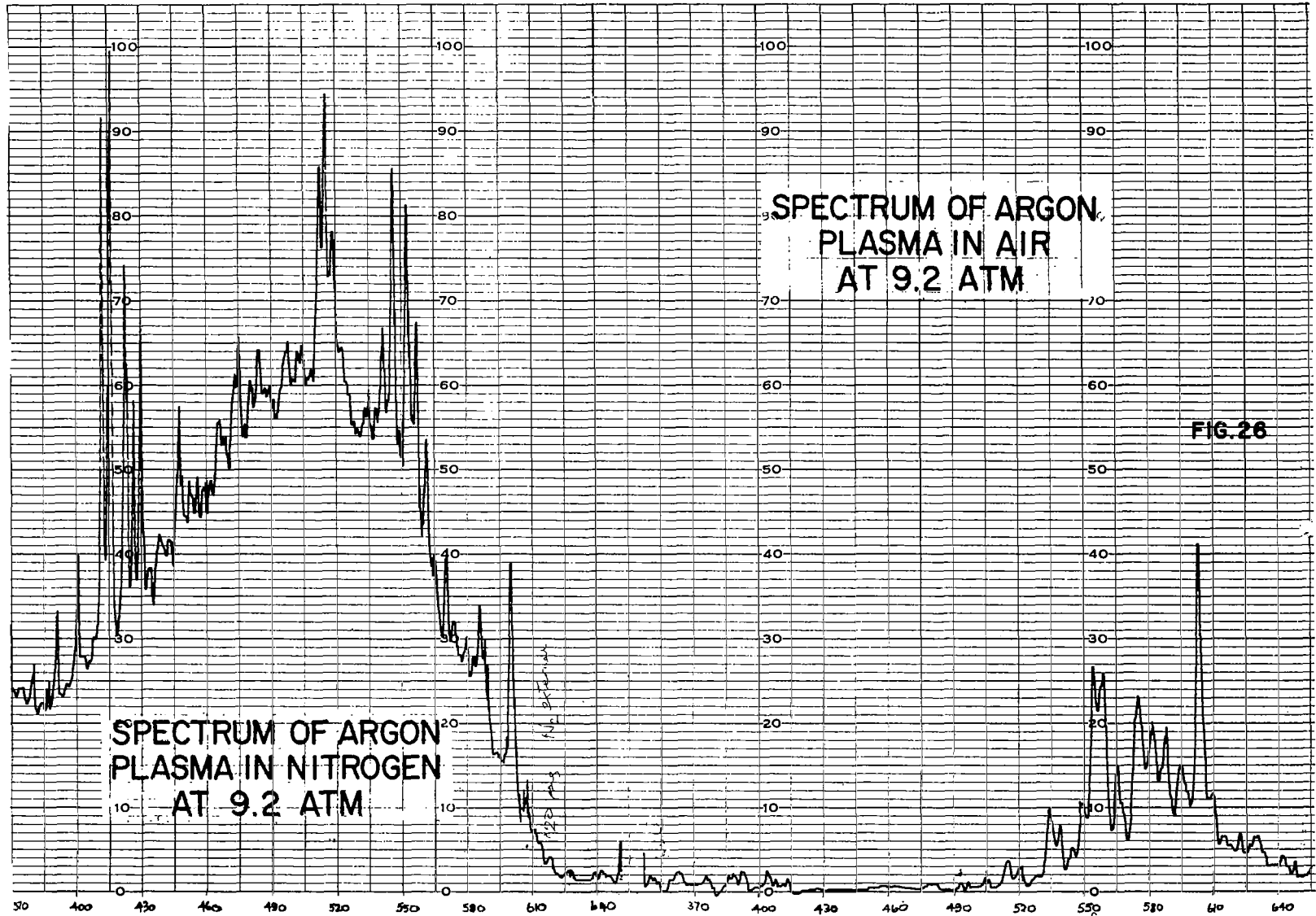
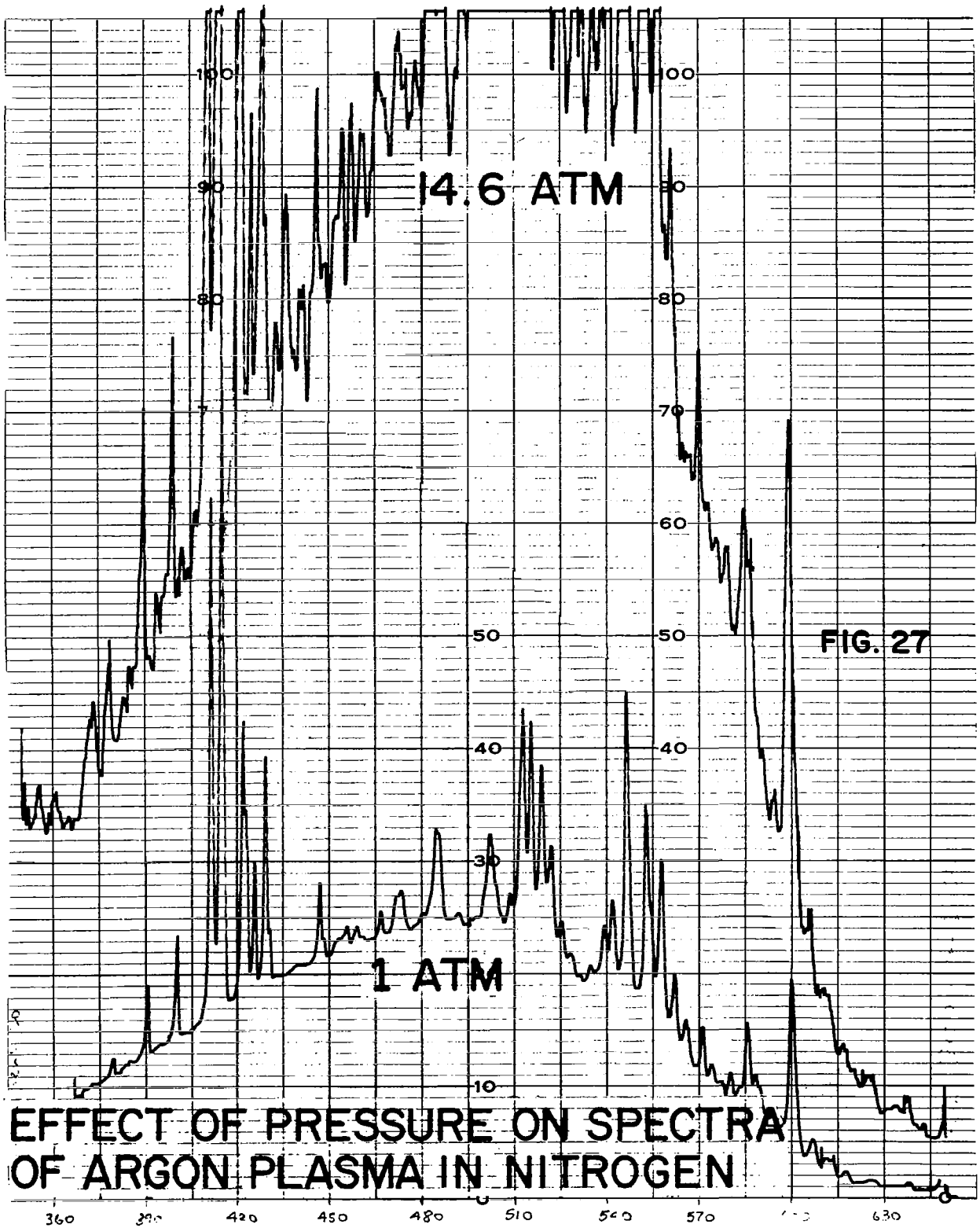


FIG. 25





EFFECT OF PRESSURE ON SPECTRA
OF ARGON PLASMA IN NITROGEN

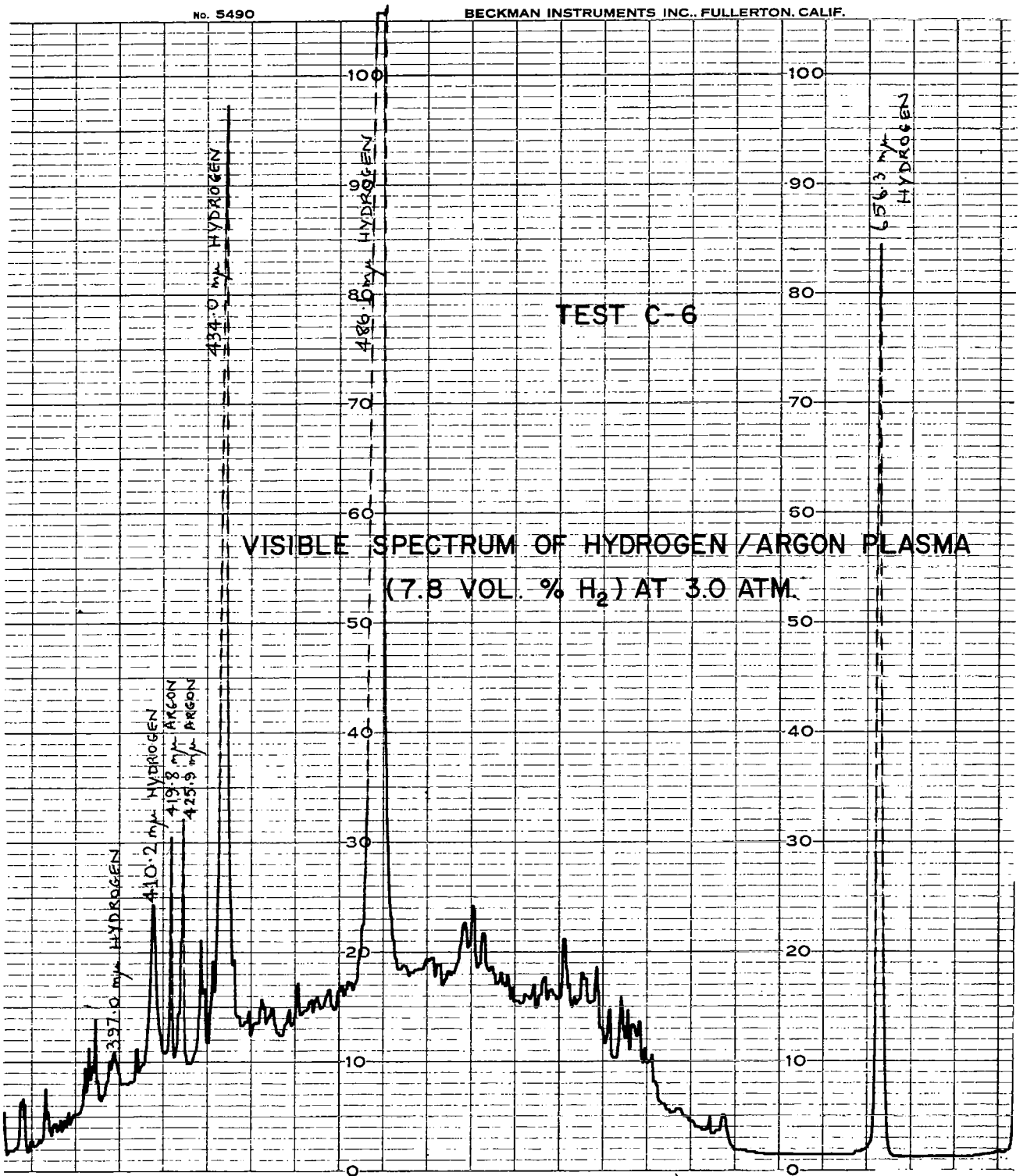


FIG. 28

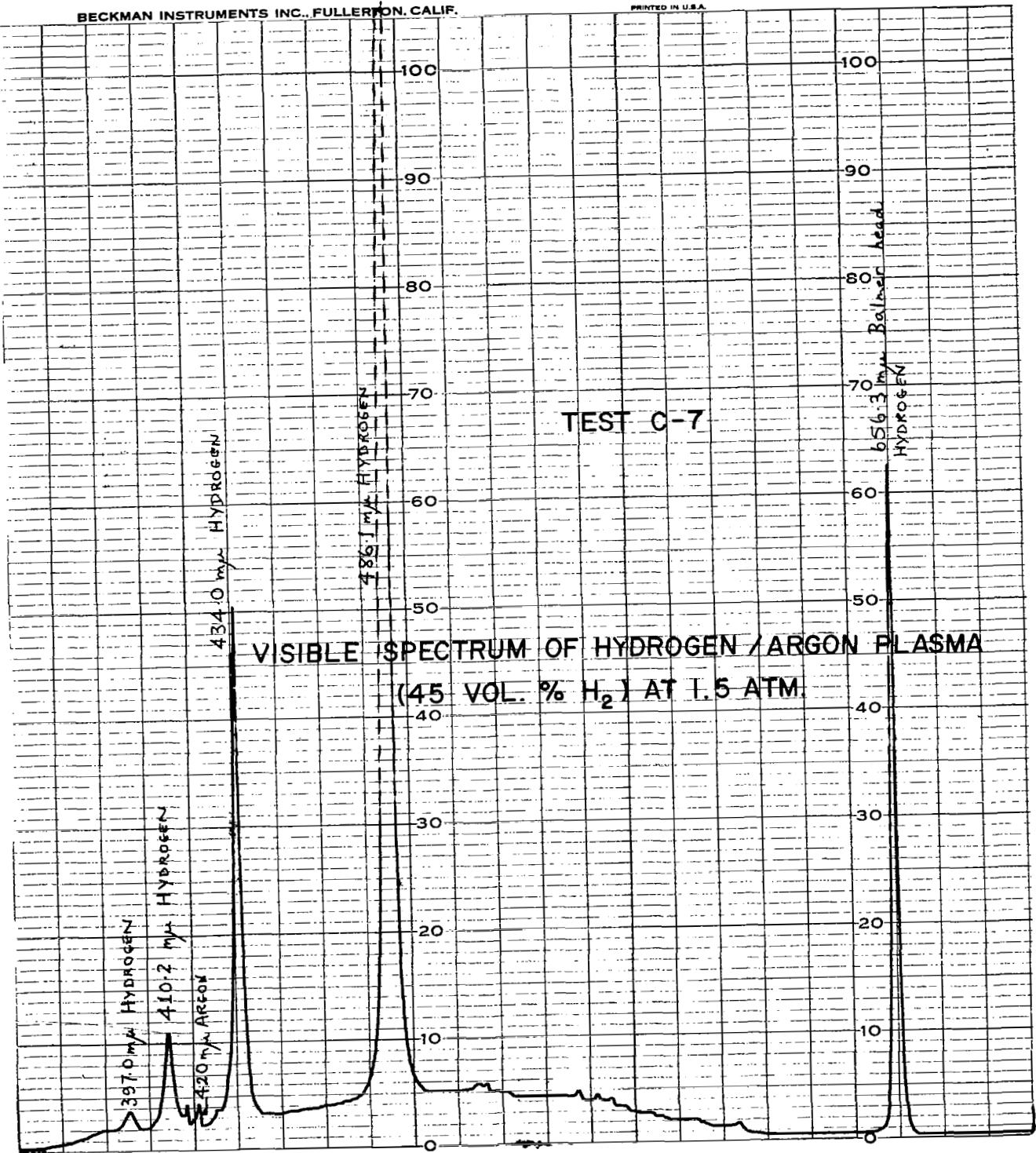


FIG. 29

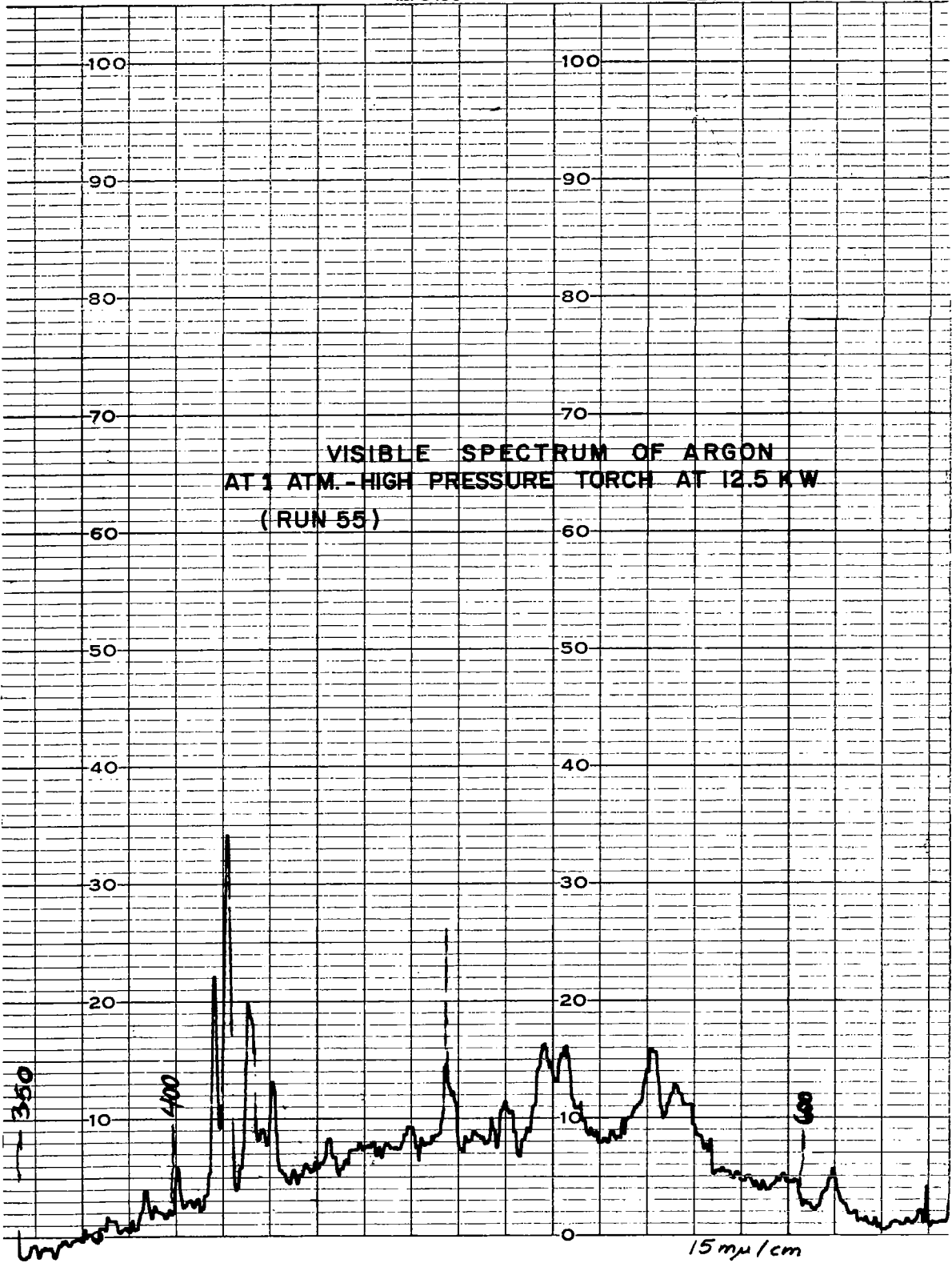
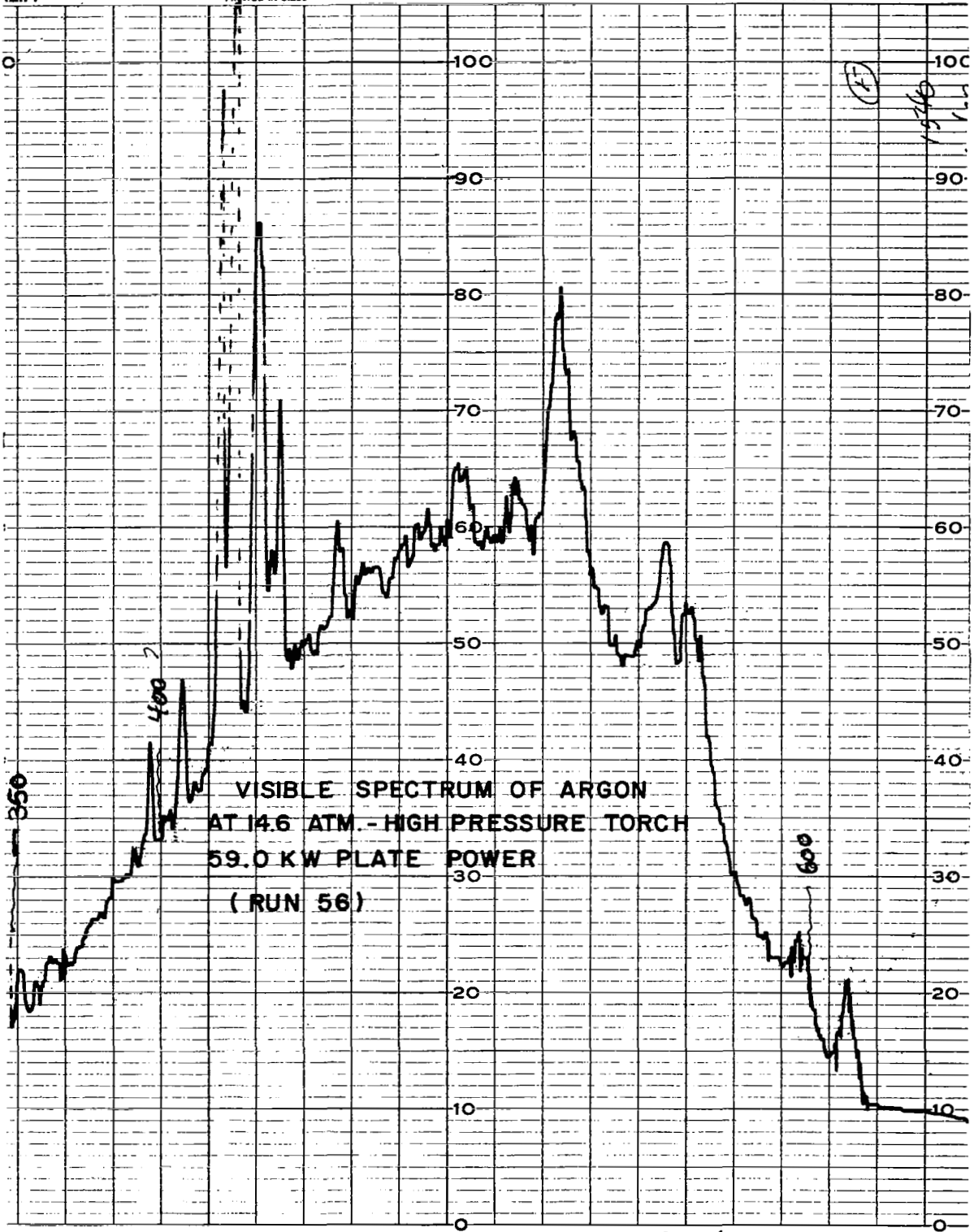


FIG.30



VISIBLE SPECTRUM OF ARGON
AT 14.6 ATM. - HIGH PRESSURE TORCH
59.0 KW PLATE POWER
(RUN 56)

FIG. 31

15 mμ/cm

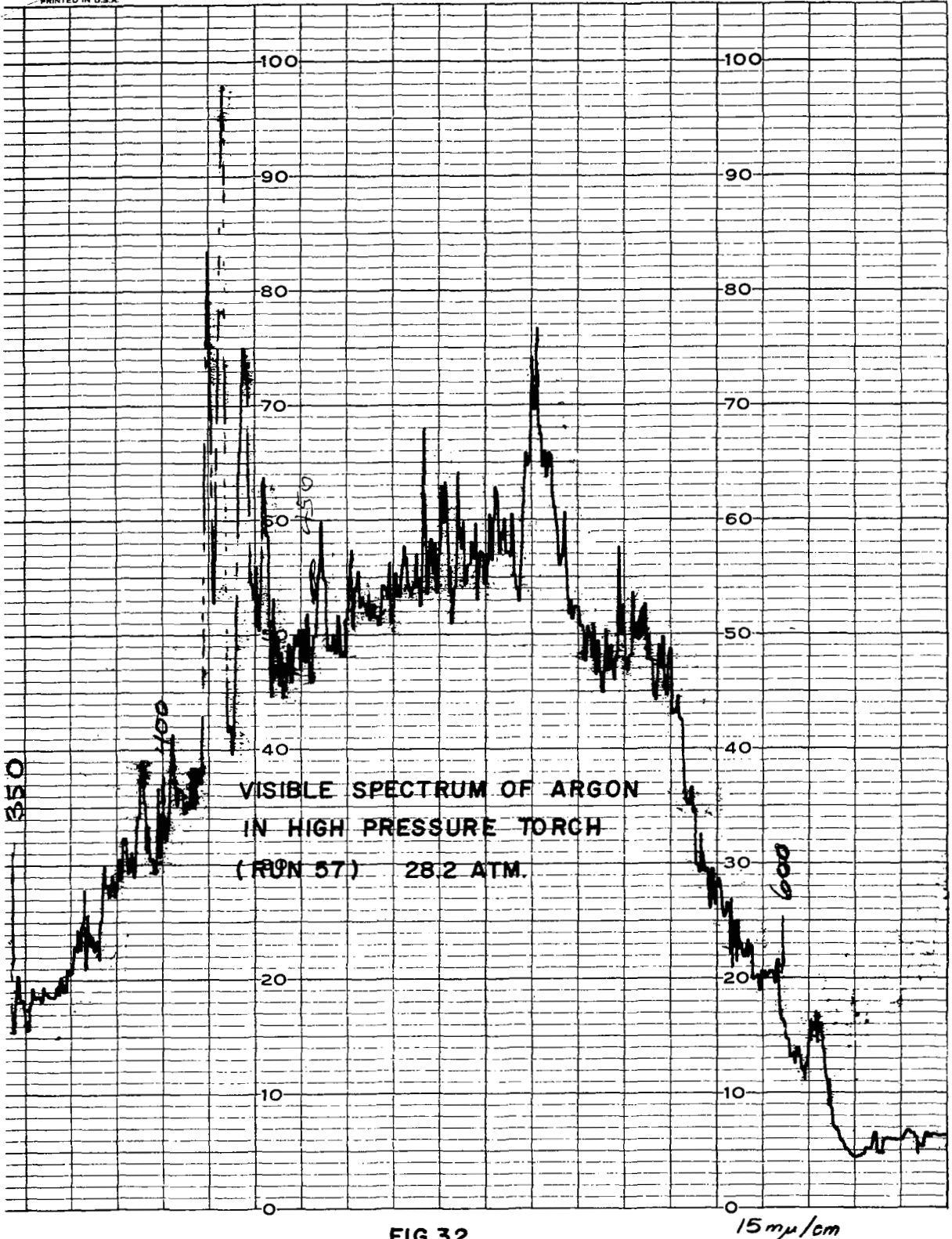
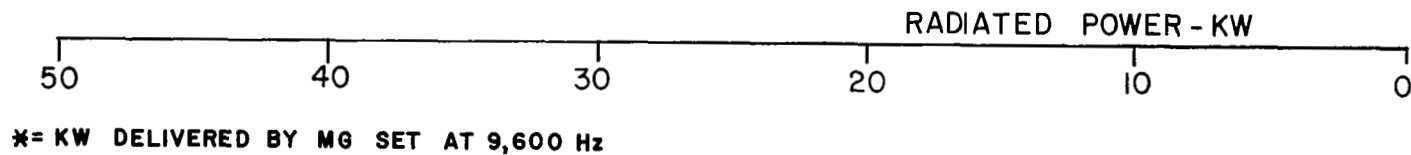
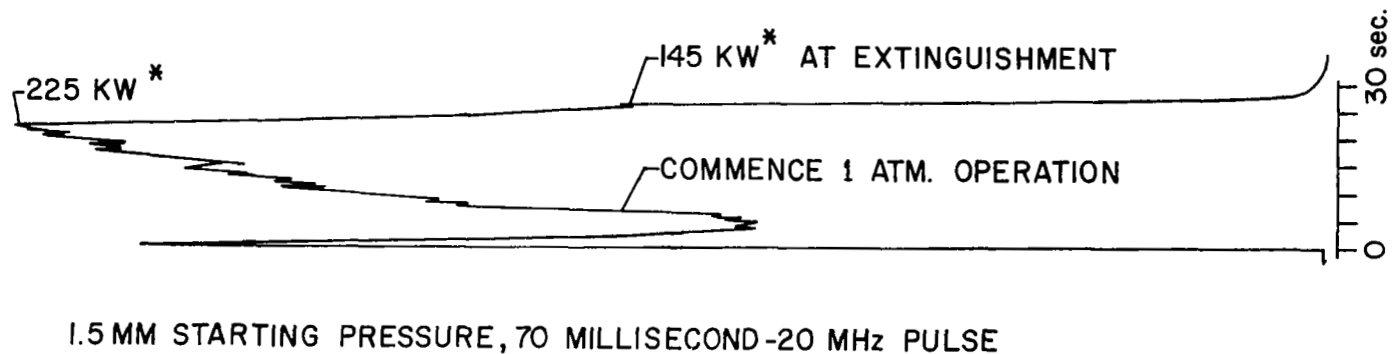
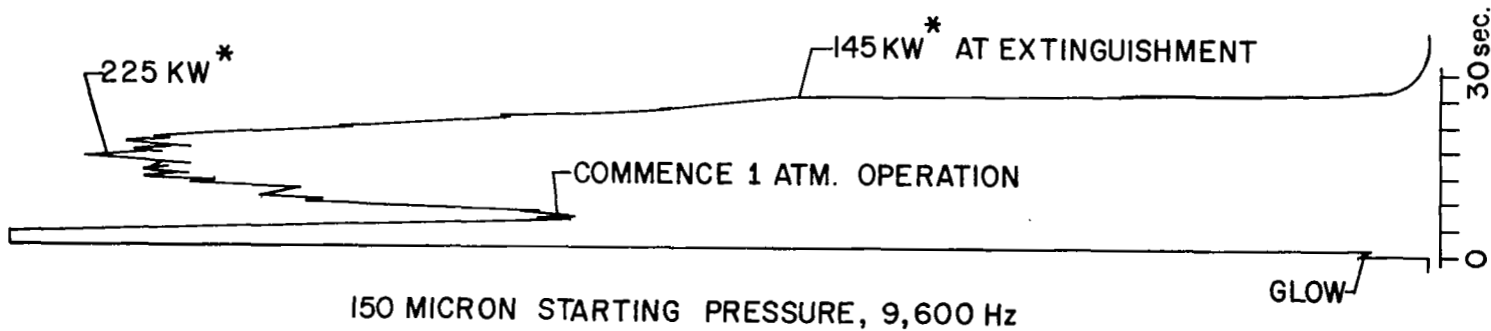
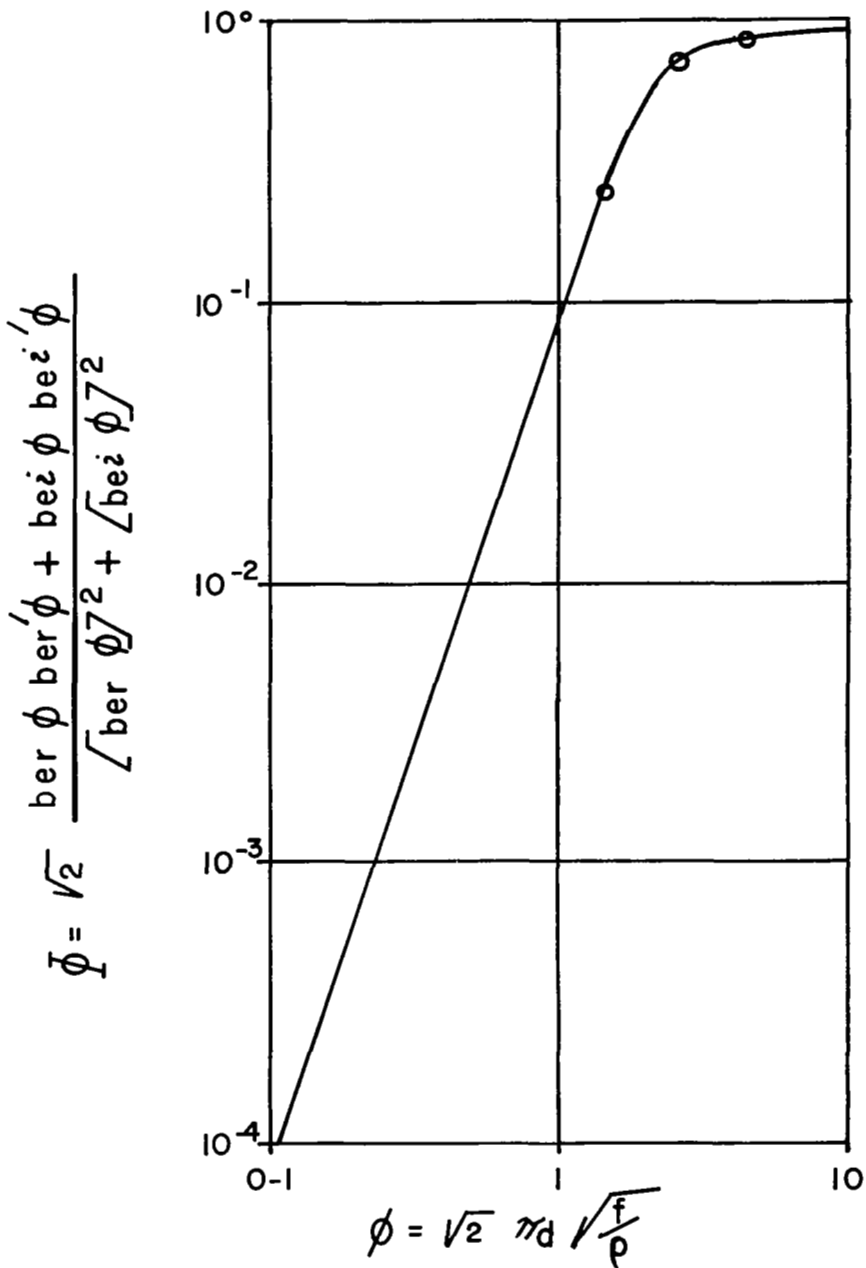


FIG.32



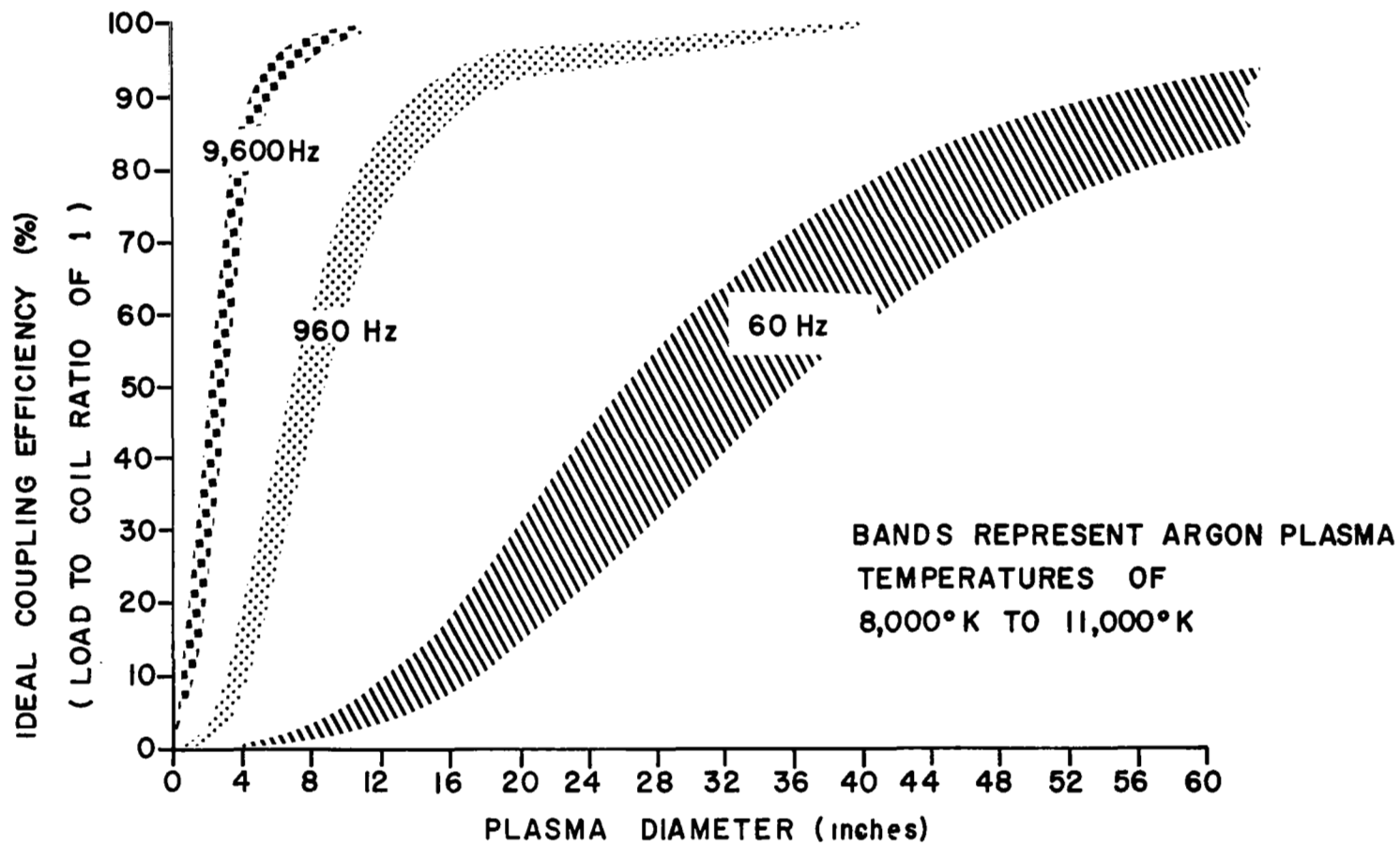
TOTAL RADIATION -9,600Hz TESTS AT 1 ATMOSPHERE

FIG.33



RELATIONSHIP BETWEEN THE BESSEL FUNCTION PARAMETERS MENTIONED IN TEXT

FIG. 34



IDEAL COUPLING EFFICIENCY AS A FUNCTION OF PLASMA DIAMETER

FIG.35

INDUCTION PLASMA POWER
REQUIREMENTS vs DIAMETER
AT VARIOUS FREQUENCIES

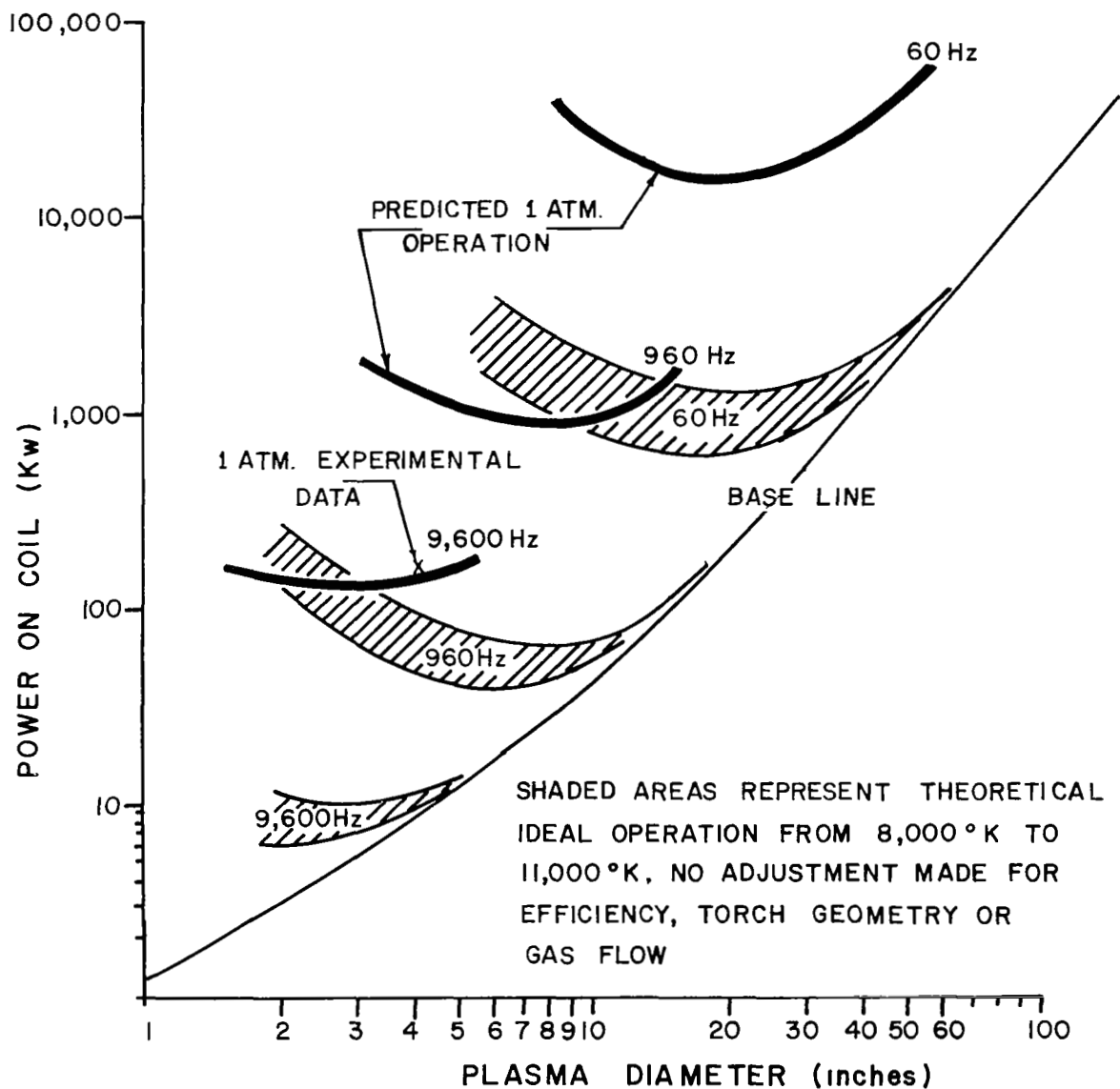


FIG. 36