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NASA CR-657

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PRODUCTION OF SUPERHEATED HYDROGEN PLASMA USING INDUCTION HEATING OF COLD PLASMA AND DC PLASMA ENHANCEMENT

by Merle L. Thorpe

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

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1966

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Prepared under Lewis Work Order C-69512A by
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

The research related to advance nuclear rocket propulsion that is described herein was conducted by the Humphreys Corporation, TAFA Division. The work was done under the technical management of Chester D. Lanzo of the NASA Lewis Research Center, Nuclear Reactor Division.

ABSTRACT

Preliminary experimental investigations were conducted to determine if pure hydrogen could be heated inductively with 25 KW 4 megacycle power. Results are presented which demonstrated that 70% hydrogen in argon can be heated, that direct current and RF plasmas can be operated in tandem with the RF energy added to the exit of a DC plasma gun. Other experiments are discussed with recommendations for apparatus necessary to heat pure hydrogen.

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PRODUCTION OF SUPERHEATED HYDROGEN PLASMA USING INDUCTION HEATING OF COLD PLASMA AND DC PLASMA ENHANCEMENT

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SUMMARY

1. It has been demonstrated that direct coupling of radio-frequency power to argon and oxygen exiting from a DC plasma torch is possible, however, further work and apparatus refinement is required to determine whether adequate enhancement of a hydrogen plasma is possible.

2. Direct coupling studies to a DC arc passed through the coil region of the induction torch indicates that direct coupling is possible and that an apparatus using this principle could be constructed.

3. With a well designed water cooled induction plasma torch it is possible to operate continuously without torch deterioration with a cold feed gas at 70 percent hydrogen in argon at 25 KW RF power. Results presented indicate that pure hydrogen operation at higher powers should be possible, however, experiments have not verified this fact to date.

INTRODUCTION

The objective of these investigations was to determine whether it was possible to obtain ultra-high hydrogen plasma temperatures either by coupling high frequency power inductively into the plasma gases exiting from a DC plasma generator operating on hydrogen or to heat cold hydrogen directly in an induction plasma generator.

The DC plasma generator is usually operated with a thoriated tungsten cathode and copper anode. The cathode is sharpened in conical fashion with the taper located in close proximity with a similar taper at the entrance of the copper anode. Gas is blown uniformly through the gap or annulus formed by the cathode and anode. The arc initiates at the tip of the tungsten cathode which runs molten to reduce the surface work function. From the cathode the arc is blown down into the nozzle by the coaxial stream of gas and terminates at the anode in a spot which oscillates axially and circumferentially over the anode surface. The nozzle diameter is made as small as possible so that most of the plasma forming gas passes in close proximity with the electric arc which is approximately 1/8 in. in diameter with nozzles 5/32 in. in diameter (at power levels of 50 KW).

Throughout this report the terms "plasma" and "arc" are used to mean different things. An "arc" is the area in the plasma generator where electric currents exist which are caused by the voltage impressed on the plasma generator by the power supply, for example, the current passed between the cathode and anode in the DC plasma generator is termed the arc. "Plasma" as used in this report refers to the hot gas outside the heating area and consists of gas in a variety of states varying widely in temperature and degree of ionization, i.e. the free jet leaving the torch is termed plasma regardless of its thermal and electrical state.

The method used to couple power into gas at radiofrequencies is entirely different than the DC counterpart. In its simplest form a quartz tube is surrounded by a conventional induction coil as shown in Fig. 1. A water cooled induction plasma system is shown operating in Fig. 2. The coil is connected to a Hartley type oscillator which will be described later. High currents (hundreds of amperes RF) are circulated through the coil at approximately 4 megacycles with 1500 volts RF impressed on the coil. If a steel bar were placed within the coil with a diameter close to the coil's inside diameter, approximately 65 percent of DC current entering the oscillator ends up in the steel bar. If the steel bar is removed and an easily ionized gas like argon is blown through the coil in the proper gas flow pattern (and a momentary ignition spark discharged within the coil) a cylindrical, tubular type arc is formed within the coil similar in shape to a steel tube of 2 mm. wall thickness. The tubular arc consists of gases which are at least 10 percent ionized to make them conductive and the resistance of this arc region approaches that of a steel bar. Conventional induction heating of this conductive region then occurs. In other words, eddy currents are produced by the impressed magnetic field and these heat the gas in the conductive region by I^2R heating. The gas flow in and out of the arc region is so regulated that a steady state thermal situation exists.

The induction plasma has some unusual characteristics which are desirable in the production of high temperature plasma. These include absence of electrodes which permits operation on any gas without electrode erosion. It is this electrode erosion which limits the enthalpy and pressure ranges of DC plasma generators, for example, as the arc pressure is increased arc spots get smaller and erosion rates increase, thus as the operating pressure goes up enthalpies must be reduced; this is not the case with the induction torch. A much larger RF arc is produced of tubular shape. A typical 25 KW DC arc operating in nitrogen would be solid and 3/4 in. long by 1/8 in. in diameter. In comparison, the induction plasma arc would be 1 in. in diameter and 3 in. long with a 1/16 radial thickness. Since both devices operate at approximately the same gas through-put, much lower plasma velocities can be produced with the induction device. A typical DC torch produces a plasma about 1/4 in. in diameter at 25 KW while the induction device produces a 1-1/2 - 3 in. diameter plasma, both operating at the same gas flow. It should be emphasized here again that the "plasma" as described here is the hot gas leaving the device as a free jet. This is to differentiate it from the electric arc which is the region where electric power enters the gas stream.

The arc region in the induction device shown in Fig. 3 is also much more accessible than the DC counterpart. This is also shown schematically in Fig. 4. Materials can be passed through and around the arc without affecting performance or electrode erosion. The large arc surface area makes the device unique for radiation studies and the like.

This report describes investigations oriented toward using existing apparatus and probing operating modes and operating areas which have been heretofore not investigated. The main objective here was to determine if hydrogen could be heated or superheated by direct induction heating of the gas with radiofrequency, 4 megacycle power. Since the time allotted for this project was limited, only short probing investigations could be conducted. Specifically, the program was oriented toward using existing induction plasma torches which operated well on gases like oxygen and nitrogen, to determine if with slight modifications they could be made to operate on pure hydrogen. In addition to this, various tests were run to determine if a radiofrequency 4 megacycle power could be coupled into the hydrogen plasma issuing from the exit of a DC plasma torch.

EQUIPMENT USED

The power supply electrode circuit relationship of the DC torch is quite well known and will not be discussed here, however, in the case of the induction torch, little has been published. Fig. 5 shows schematically the method by which the RF power is generated and transmitted to the plasma. This figure also shows losses in various parts of the circuit.

The induction circuit as indicated in Fig. 5 works as follows. A.C. line voltage is raised to approximately 10,000 volts by means of a transformer and then rectified and filtered to obtain DC power with 2 percent or less ripple. The capacitance and torch work coil at the right of the figure make up the Hartley type oscillator circuit. Inductance and capacitance are selected so that this circuit has a natural frequency in the range of 4 megacycles. A continuously variable grid drive is necessary to carefully tune the circuit for maximum efficiency. With a properly designed and tuned circuit approximately 22 percent of the DC power is lost in the oscillator tube with up to 68 percent entering the load inside the output coil. The 10 percent of remaining DC power is lost in the I^2R heating of the work coil capacitor and power supply leads. Typical operating conditions of the torch coil show approximately 1800 RF volts at 400 RF amperes when operating in the 25 KW range.

Equipment used in these tests included standard DC and induction plasma generator systems including torches and power supply. Twenty-five KW of 4 megacycle RF power and 50 KW of DC power were available. Both the DC and RF machines were flexible in nature relative to open circuit voltage and matching capabilities respectively. See Figs. 2, 6, and 7.

DISCUSSION OF RESULTS

During most of the direct induction heating tests RF power available was limited to 25 KW. A series of tests were run and various gas mixers used to optimize flow pattern to obtain most stable operation on high concentrations of hydrogen. These results are shown in Fig. 8 which is a plot of plate power vs. percent hydrogen in argon. These tests indicate that higher powers should permit pure hydrogen operation. Typical operation at 70 percent hydrogen yielded the following results.

Heating of Cold H_2-Argon Mixtures with H F Alone

58 CFH Argon, 158 CFH H_2, (73% H_2) 9300 plate volts 120 RF amps., 5.6 plate amps, 58,500 Btu/lb. in arc heating region, 23,400 Btu/lb. leaving torch. This was the maximum percentage of H_2 which could be used in argon, higher concentrations extinguished the plasma.

Other experience indicated that larger tube diameters permit higher power operation. This data is shown in Fig. 9. In this figure the heat flux failure point of a well cooled quartz tube is plotted against plate power. Both these plots show the direction in which we must proceed to obtain pure hydrogen operation. Fig. 8 indicates that higher powers are required for pure hydrogen with estimates in the range of 80 KW plate. A larger plasma containing tube (2 in.) must be used to contain the higher powers (Fig. 9). Preliminary tests were attempted with uncooled tubes in this diameter range to obtain results rapidly, however, they were not satisfactory and only confirmed previous experience that the torch must be well constructed and designed to withstand the high heat fluxes and to center the plasma properly. As of the date of this report tests with a larger diameter induction plasma torch were begun. This torch has the following features:

1. Ability to use either 2 or 3 in. diameter well cooled quartz tubes.

2. Ability to change the gas mixer.

3. The ability to restrict the exit orifice.

This larger torch has been tested extensively at 30 KW and limited tests at 50 KW indicate that the unit functions well on air, oxygen and nitrogen, however, hydrogen operation has not been attempted, therefore, at this point we are unable to verify the extrapolation in Fig. 8. Operation at 50 KW on nitrogen was extremely dramatic. A 30 in. long 2 in. diameter radiant plasma was produced which gave nearby observers a severe sunburn in less than a minute. Approximately 58 percent of the DC plate power (Fig. 5) ended up in the arc region of the torch with 25 percent of the plate power in the plasma leaving the torch. Further tests of this device using various gases, including hydrogen, will be conducted in the near future. Pure hydrogen operation still seems feasible, however, further testing is required to demonstrate this point. This higher power unit with large torch is shown in Fig. 6.

The approach here has been one of producing a useable high enthalpy jet of hydrogen rather than merely sustaining operation on the gas regardless of gas through-put, for example, we have momentarily (30 seconds) operated on pure hydrogen by limiting the gas flow through the torch to less than 2 scfh. A brilliant arc within the device is sustained, however, a negligible amount of energy leaves the device. We were not concerned with demonstrating this type of operation here.

Induction Coupling to Exit of DC Torch

Downstream coupling to the exit of the DC plasma was accomplished with the apparatus shown schematically in Fig. 10. All this work was conducted using a 30 KW RF machine. Operation was attempted with argon, helium, nitrogen and argon-hydrogen mixtures. The resistivity of ionized gases in the RF arc region is shown in the following table.

Comparable Resistivities - Plasmas & Solids

Argon	0.01	to	0.05 ohm-cm
Nitrogen	0.05	to	0.25
Hydrogen	0.25	to	1.00
Iron (20°C)	0.001	to	0.0035
Carbon	0.0009	to	0.0035
Copper	0.0000005	to	0.000009

From the table one can see that hydrogen is the most difficult to heat while argon being closer to iron is easier. Hence, all coupling tests were first tried with argon and then diluting the argon with the higher resistivity gas of interest.

The following sequence of operations was used during these downstream coupling tests:

1. The DC torch was mounted so that the plasma exited vertically upward.

2. An adapter was placed on the front of the torch as shown in Fig. 10 to receive the quartz tube under study. This tube diameter was varied from 1-1/2 to 4 in. I.D.

3. A 1/4 in. copper tube coil was fabricated as shown in Fig. 10 and wrapped closely around the quartz tube to insure the best coupling. The distance from the tip of the torch to the first coil was approximately 1 in.

4. Without the unit running the RF machine was adjusted to match the coil.

5. The DC torch was ignited and turned up to approximately 40 KW with the gas mixture being studied.

6. The flow through the torch was turned down as low as possible to produce the maximum enthalpy condition.

7. Compressed air jets located around the outside of the quartz tube were turned on to give some cooling and to extend running time to approximately two minutes.

8. The RF power was then turned on and set at various levels ranging from 2 to 30 KW RF power.

9. After a maximum of two minutes operation the quartz tube began to deform and the DC and RF power were shut off.

Using a four-turn work coil and 1-1/2 in. tube, coupling to argon and helium was possible and noticeable plasma enhancement was achieved. This was detected by eye through visual brightness of the plasma leaving the exit of the containing tube. The RF amps, plate volts and plate amps as well as grid of the RF power supply all indicated coupling was occurring. Representative data collected was as follows:

HF Coupling Downstream to DC Plasma

25 CFH Argon, 25 volts, 700 amps, 9,900 Btu/lb. leaving DC torch, 29 KW RF Power (4.0 DC plate current, 7,250

DC plate volts, 110 RF current in torch coil) 28,500 Btu/lb. in RF section, 17,560 Btu/lb. leaving RF section. This shows an enthalpy enhancement of 77.5%. Enthalpy values were calculated in the RF section using conservative figures from past experience, i.e. 50% plate power in arc region and 20% plate power in gas leaving torch.

The settings which were used to attempt to couple to pure Hydrogen were: 120 DC volts, 500 DC Amps., 300 SCFH, 96,000 Btu/lb. leaving DC gun.

An attempt was made to pass the exit gases through a calorimeter to determine the amount of heat added, however, run times were not long enough to reach equilibrium.

It appeared that the sharp velocity profile leaving the DC torch was detrimental with the diatomic gases, i.e. special nozzles should be fabricated to diffuse these gases and permit better coupling. In addition to this, the coil must be located closer to the torch so that the extremely high enthalpy region just in front of the DC torch is well within the coil region. During the reported tests this was not the case.

These tests suggest that a more systematic approach must be instituted if one is to optimize this system and obtain coupling to hydrogen. These tests will involve better diffusion of the jet as it leaves the DC torch and a water cooled RF section to permit continuous operation and use of tubes of 1 in. diameter.

Conducting part of the DC arc through the induction region and terminating it prior to stream exit should also be helpful since it will give additional conductivity in the RF region.

Direct Coupling to DC Arc

Tests were run conducting an arc from a carbon electrode at the rear of the induction torch to a second anode outside the front end of the torch. The RF power coupled well to the arc and a noticeable plasma brightness increase occurred. These tests were conducted with argon and nitrogen, however, adequate open circuit DC voltage was not available to run hydrogen tests. These tests did look promising enough to indicate that one can couple to arcs passing through the RF coil region.

CONCLUSIONS

In conclusion, it has been demonstrated that it is possible to heat diatomic gases like nitrogen and oxygen efficiently with a maximum of approximately 68 percent of the DC power supplied to the oscillator ending up in the plasma gas within the torch.

It has also been demonstrated that it is possible to couple directly to the plasma issuing from a DC torch with 4 megacycle RF power using the hot plasma gases as the induction load. Attempts to heat pure hydrogen by induction power alone were not successful, however, it was demonstrated that up to 70 percent hydrogen in argon could be run reliably with extrapolation of results indicating that it should be possible to run pure hydrogen at powers twice those available during these tests.

Experimental results developed show the relationship between hydrogen concentration in the plasma forming gas, power and torch diameter.

It is felt that with further work pure hydrogen operation will be possible either by direct coupling to DC hydrogen plasmas, higher power direct induction plasma heating of cold hydrogen or a hybrid system which would involve a DC arc superimposed on a more conventional RF plasma torch.

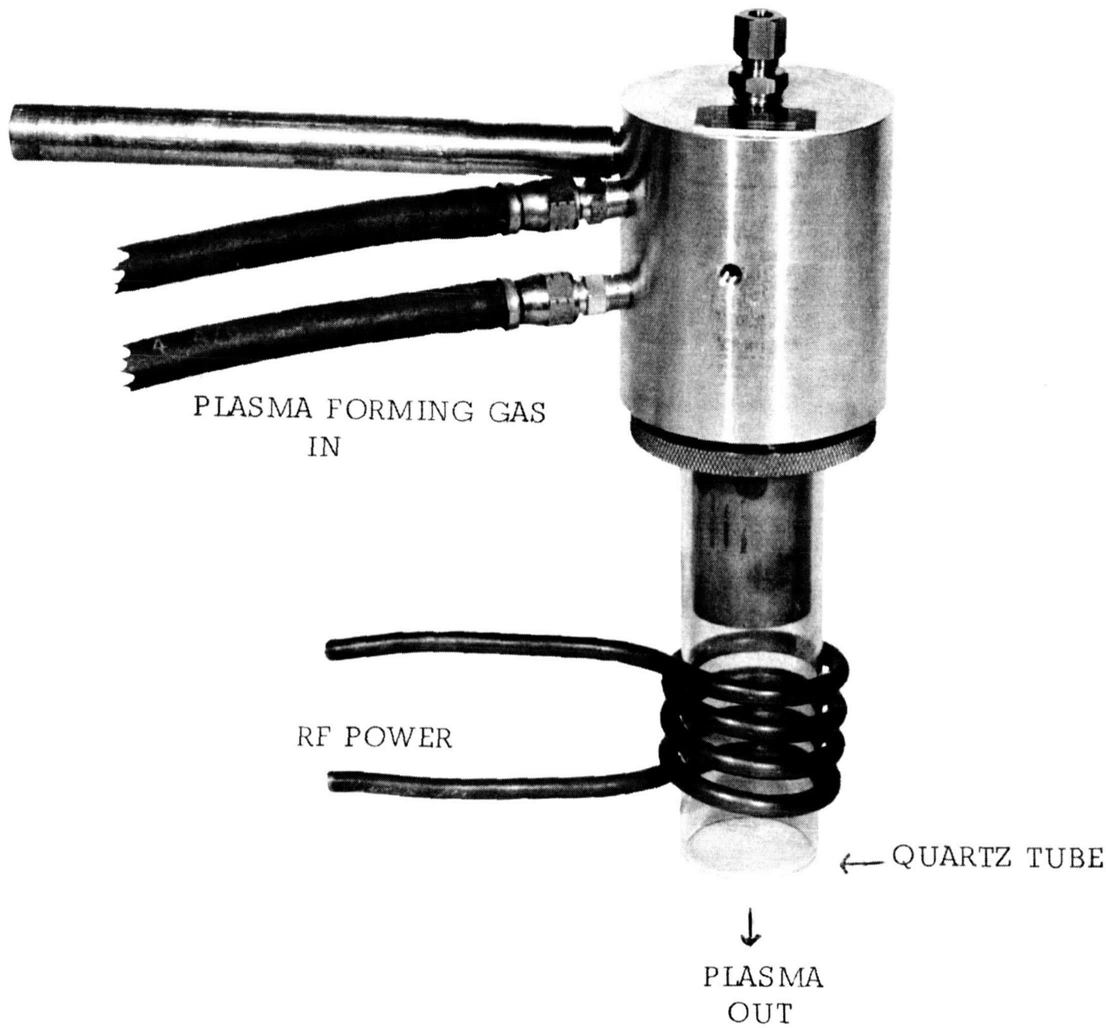


Figure 1. - Simplified uncooled induction plasma torch.

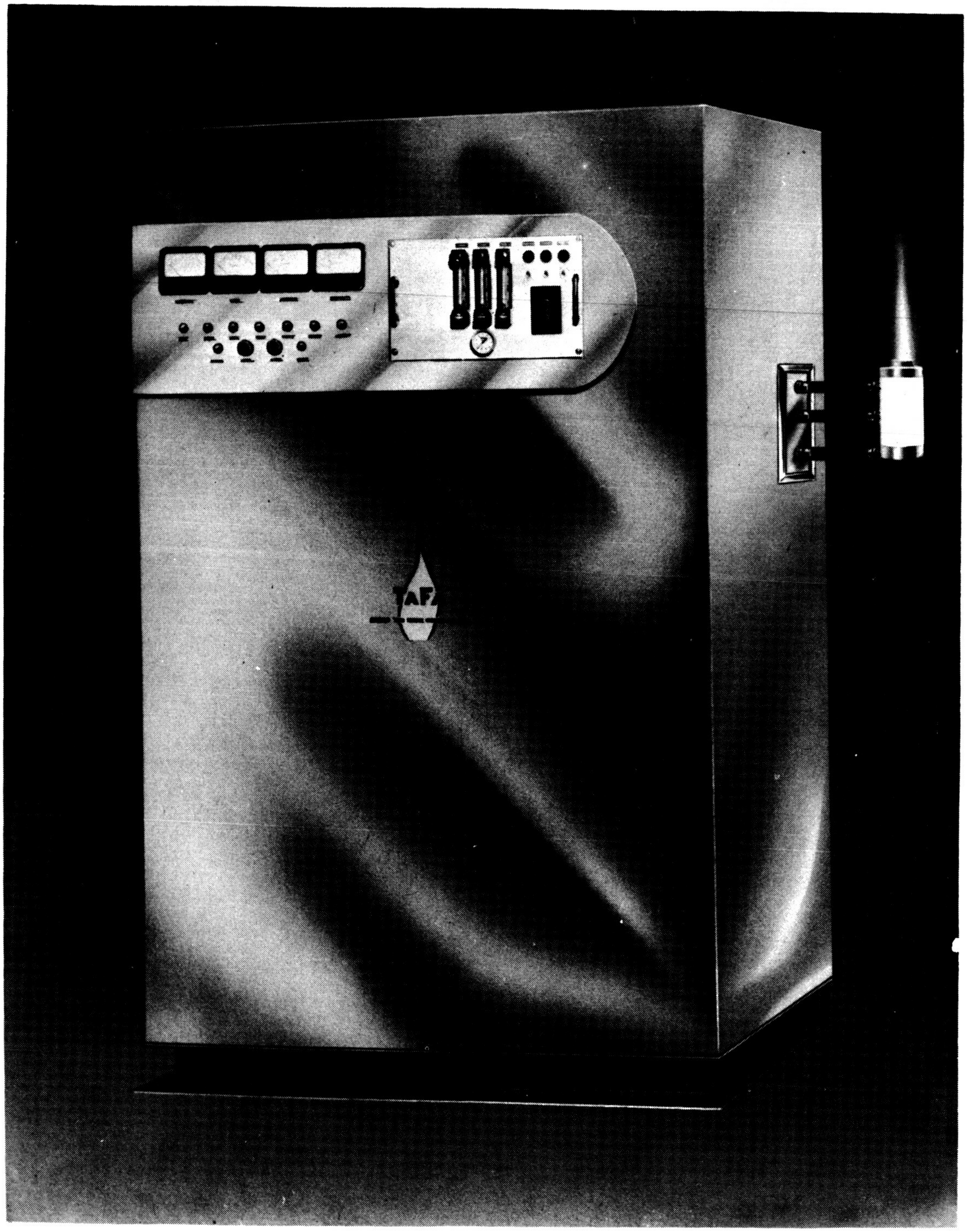


Figure 2. - Water cooled induction plasma system.

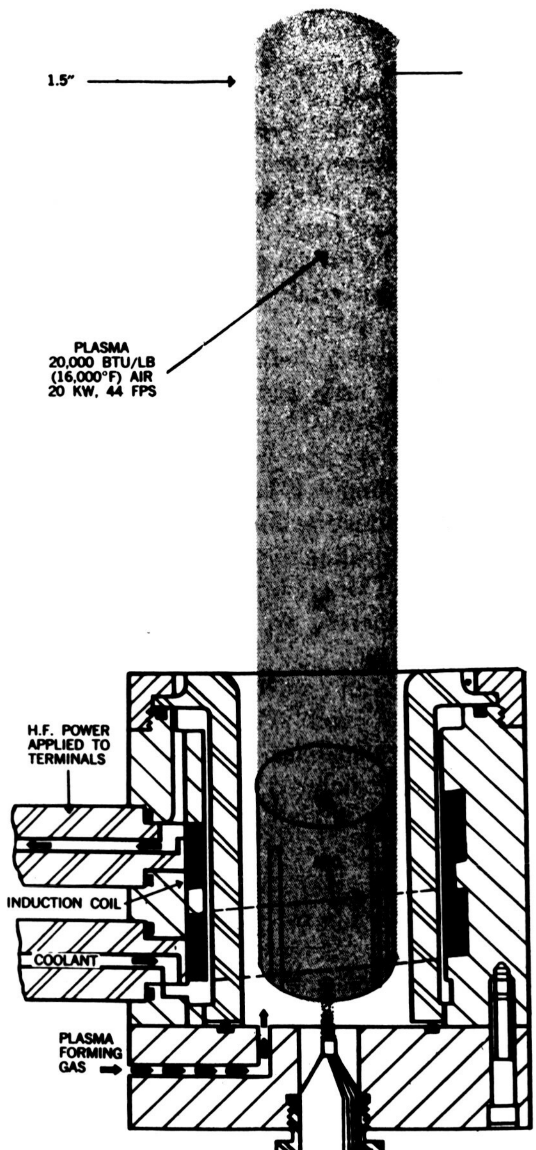


Figure 3. - Plasma torch.

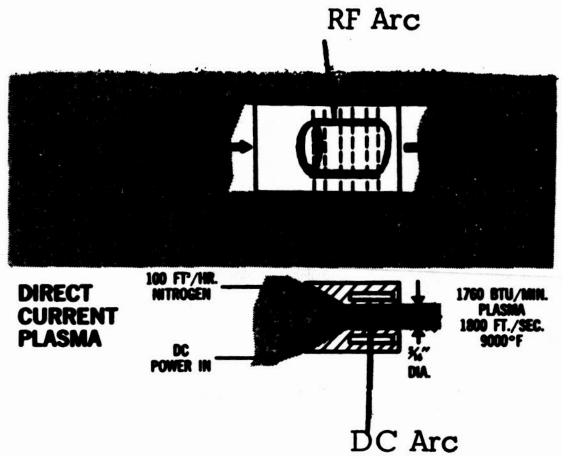


Figure 4. - Schematic of DC and induction plasmas.

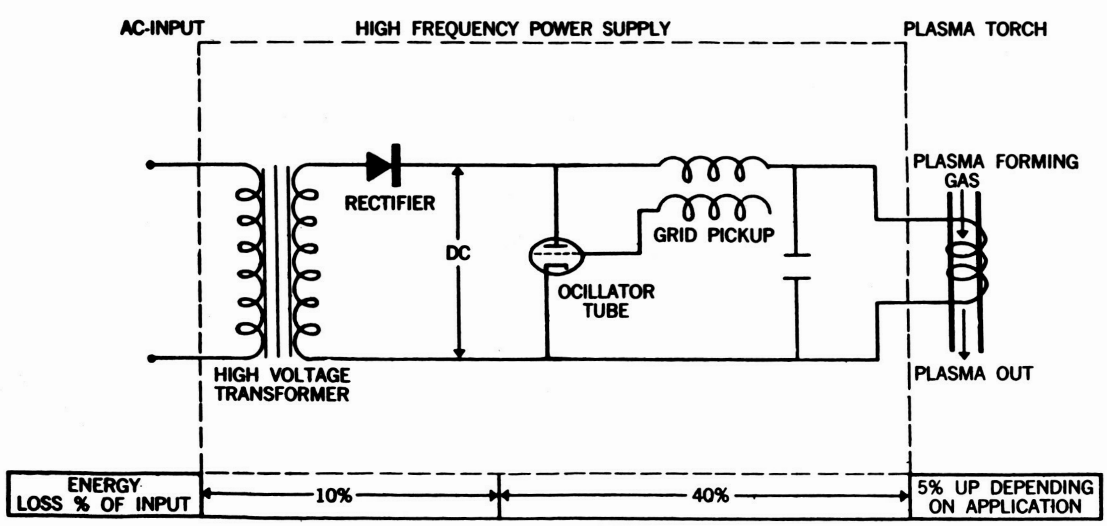


Figure 5. - Induction plasma torch electrical system.

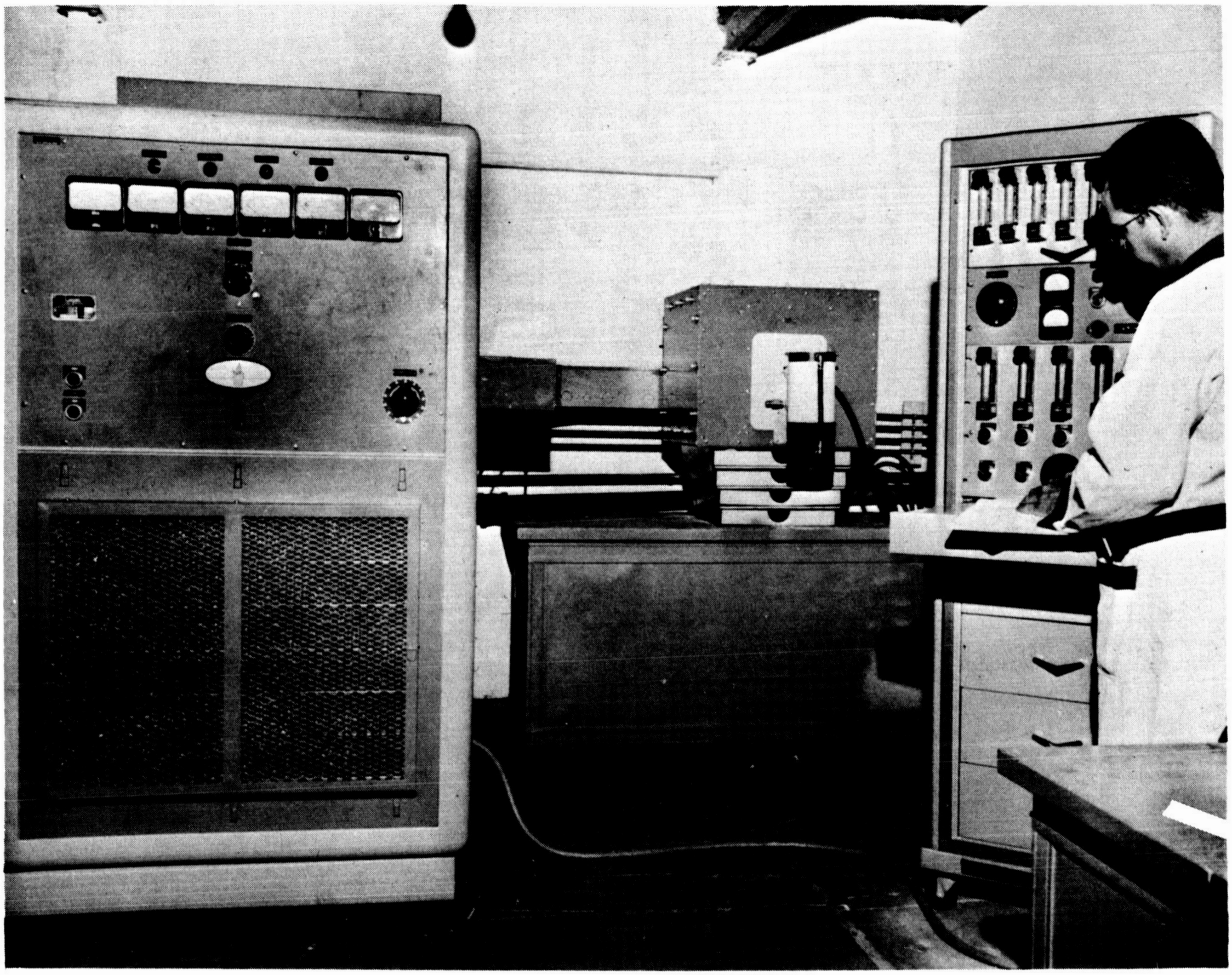
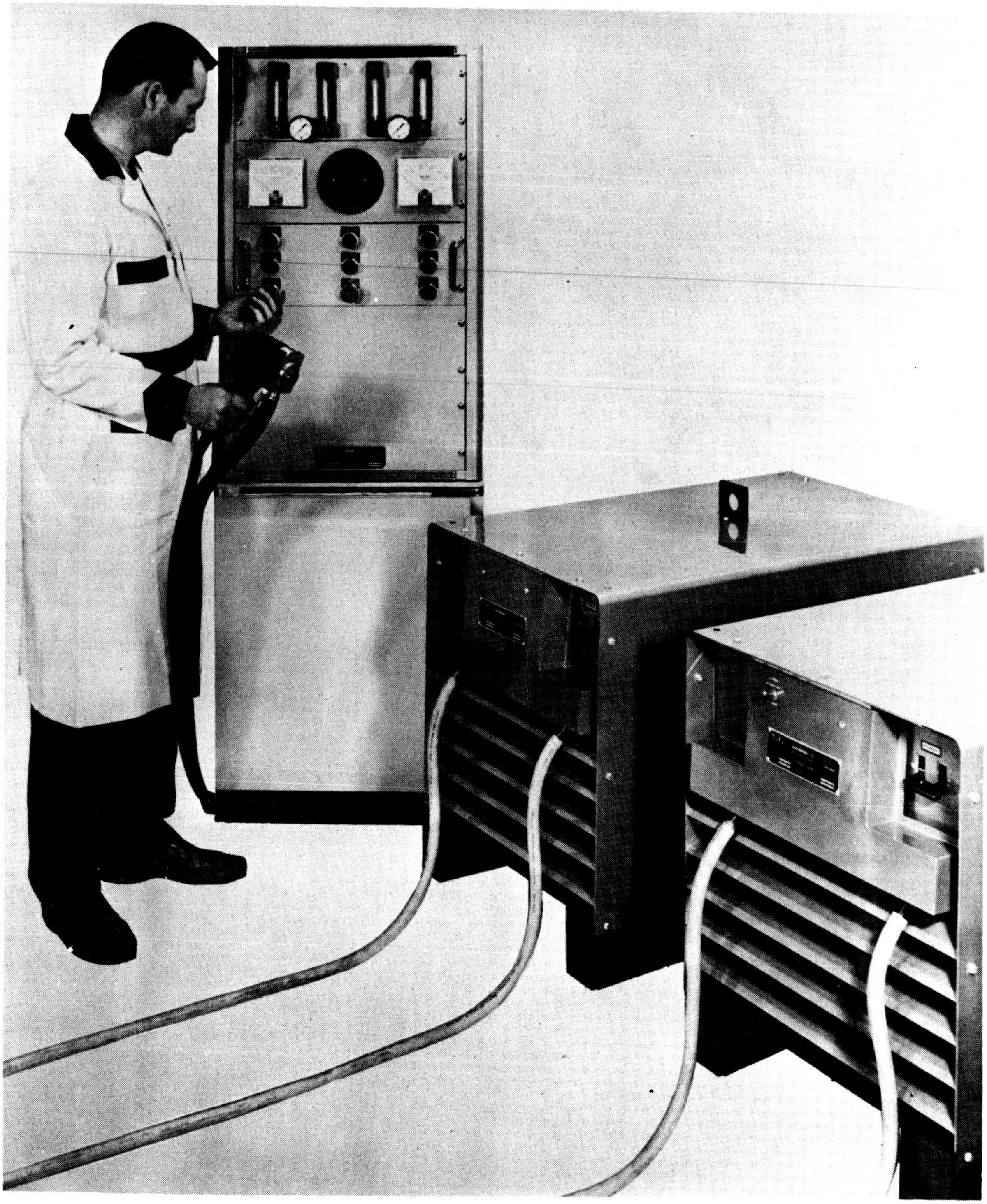
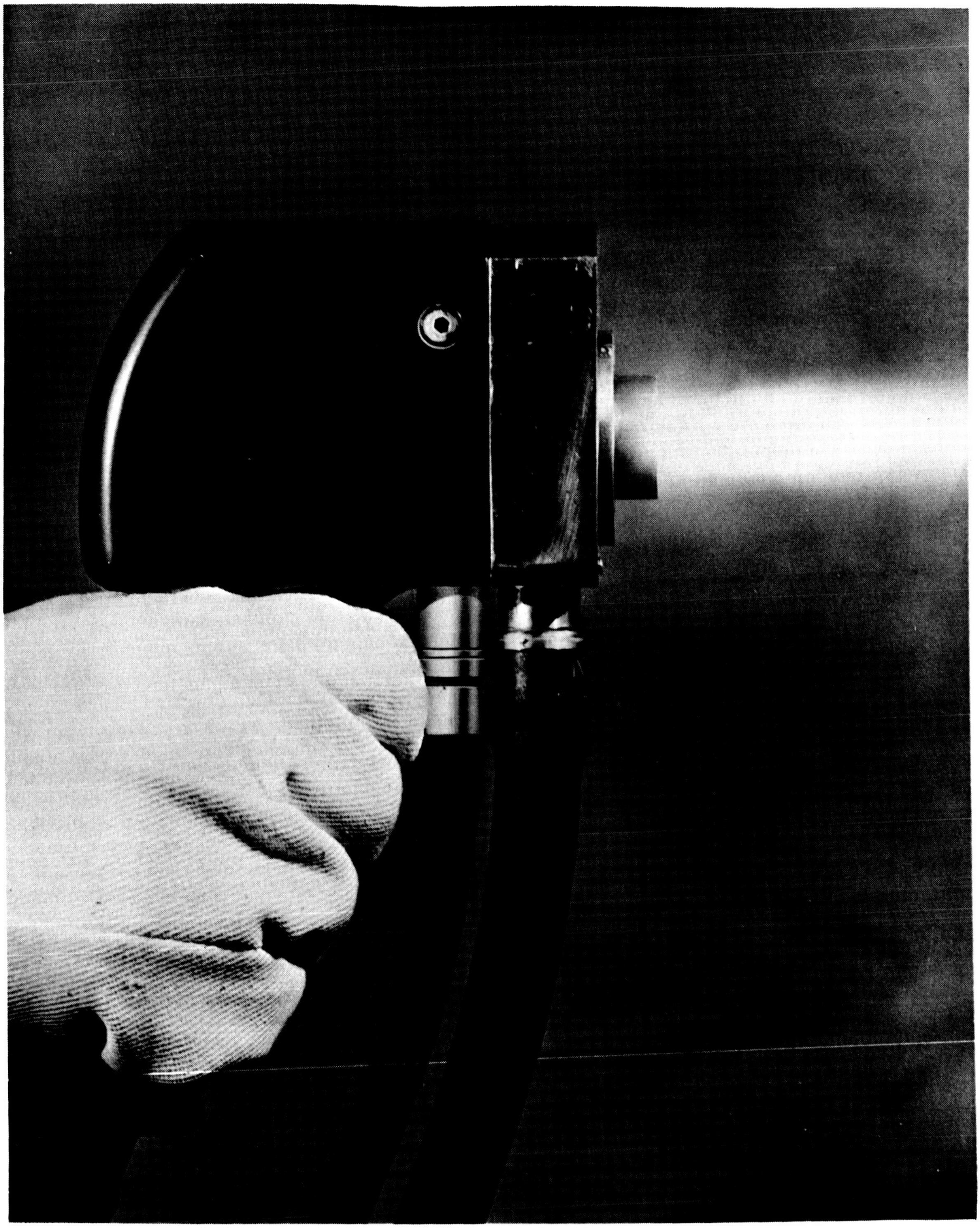


Figure 6. - 50 Kilowatt output power supply with remote tank, model 66 torch and floor mounted control console with remote power supply controls.



(a) Overall system.

Figure 7. - 50 Kilowatt DC plasma torch.



(b) Torch in operation.

Figure 7. - Concluded.

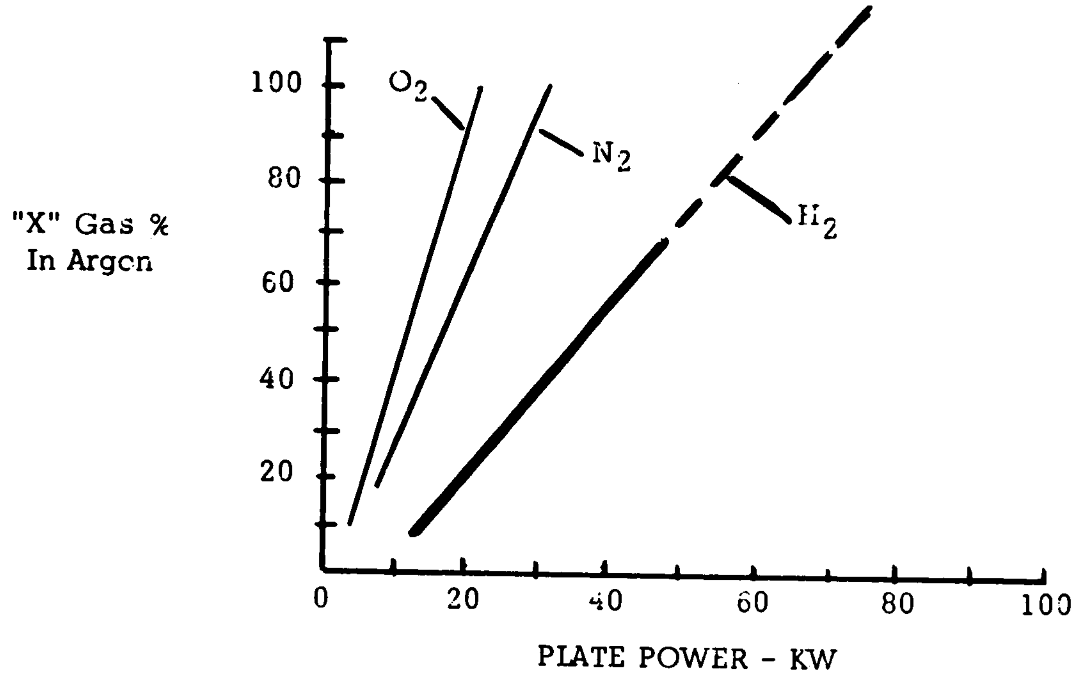


Figure 8. - Variation of gas capability with 5 MC power input to model 56 induction torch.

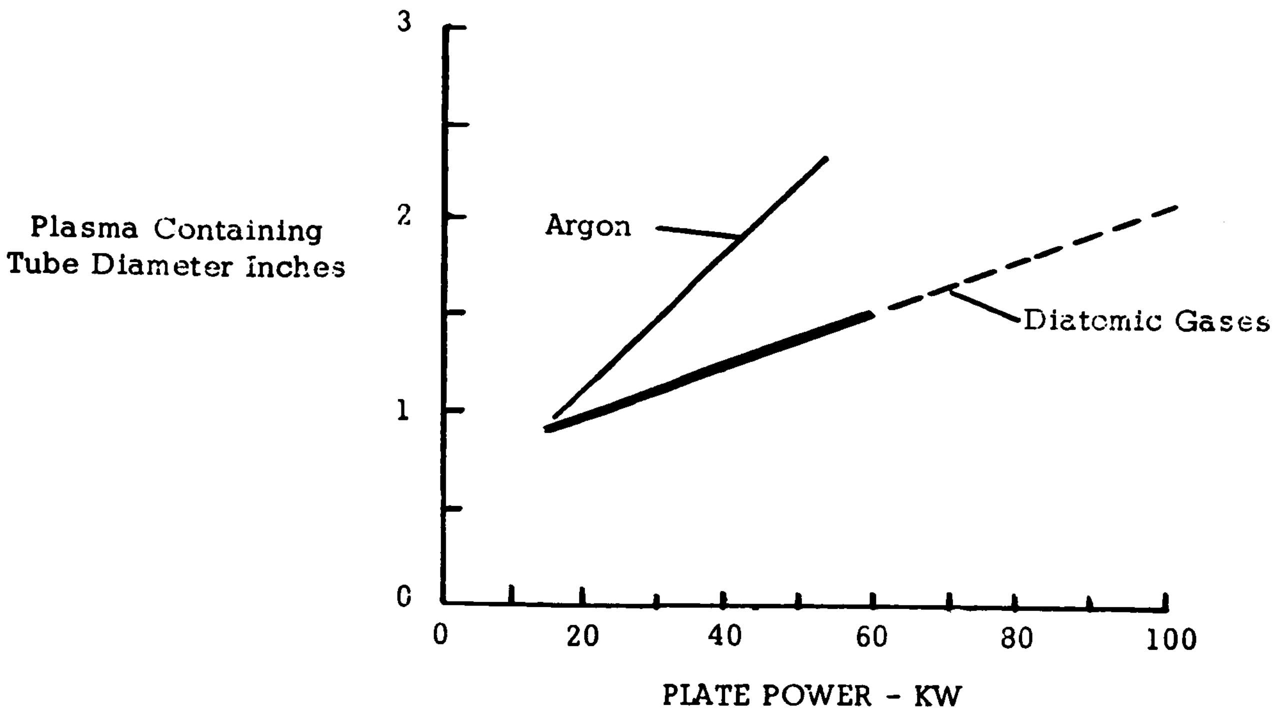


Figure 9. - Power rating various plasma tube diameter with various gases - 1 ATM.

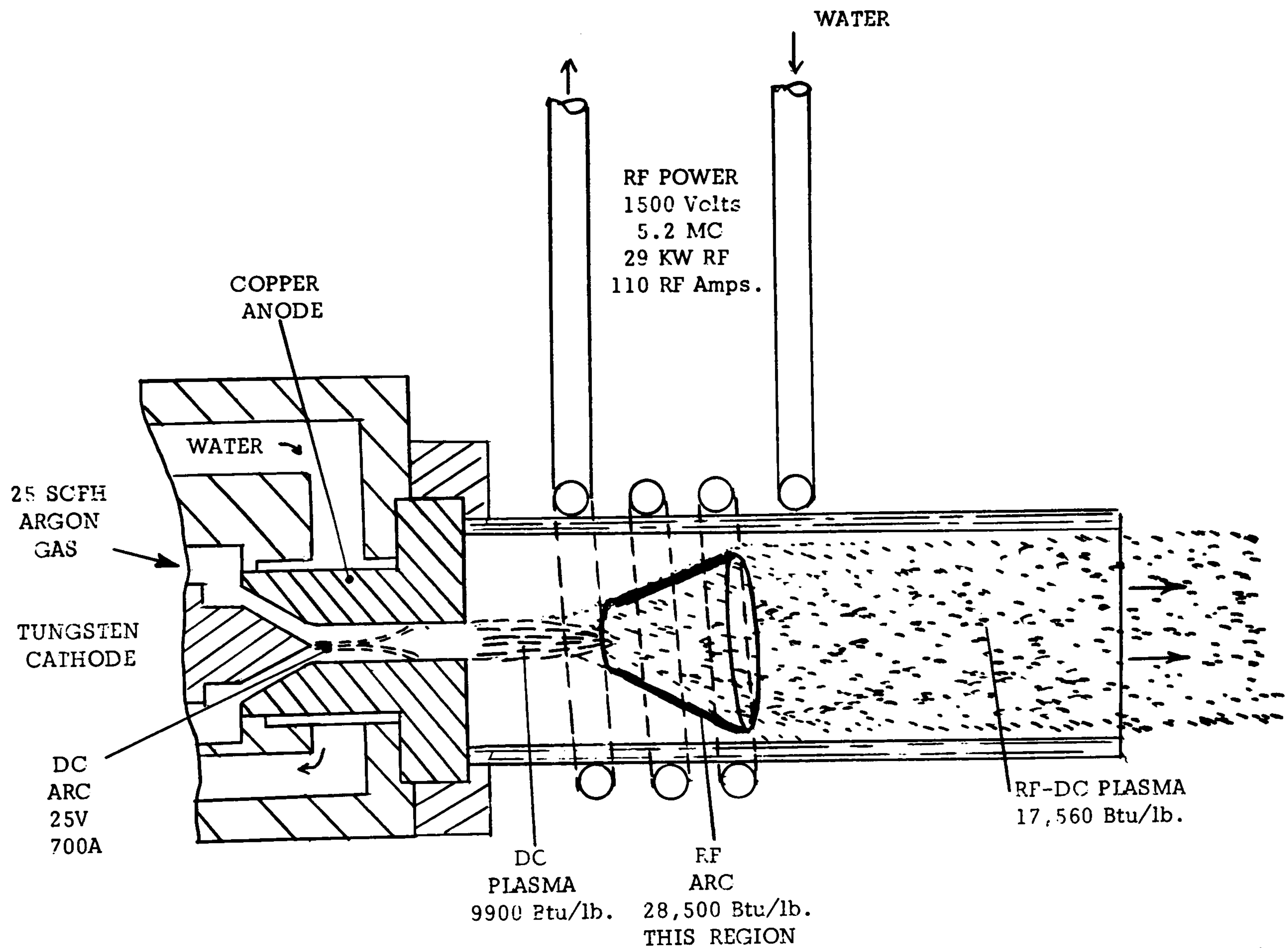


Figure 10. - Setup for coupling to DC plasma.

NASA-Langley, 1966 E-3451

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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