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INDUCTION PLASMA HEATING:

High Power, Low Frequency Operation and Pure Hydrogen Heating

by M. L. Thorpe and L. W. Scammon

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

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ABSTRACT

Induction plasma heating systems have been developed and tested to powers up to 1000 kW. Operation on diatomic gases such as air at frequencies as low as 220 KHz has been achieved with continuous operation at exit gas enthalpies over 40,000 Btu/lb. Pure hydrogen heating has been demonstrated at 4 MHz and 100 kW producing exit gas enthalpies over one million Btu/lb. High power sheath mode operation has also been achieved.

FOREWORD

The work described herein was done at the TAFA Division of the Humphreys Corporation under NASA Contract NAS 3-9375. Mr. Chester D. Lanzo of the NASA Lewis Research Center, Nuclear Systems Division, was the Technical Manager for NASA.

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SUMMARY

The objectives of this experimental program were to demonstrate operation of an induction heating device with pure hydrogen and also to scale up existing induction plasma experimental work to power levels of 1000 kW.

The hydrogen heating was needed to assess the feasibility of producing high temperature hydrogen streams for absorption studies associated with the nuclear gaseous core rocket development.

Pure hydrogen operation has been achieved at 4 MHz at power levels in the range of 60-185 kW and gas flow rates of 1-16 SCFH. Unusually high exit gas enthalpies over one million Btu/lb. have been achieved.

All objectives of the program have been achieved. Reliable operation at 1000 kW has been demonstrated using a 450 KHz power unit and metal wall torches in the range of 3-6 inches in diameter. High coupling efficiencies have been demonstrated and exit gas enthalpies with air and nitrogen over 40,000 Btu/lb. have been run continuously, which is a fourfold increase over that previously obtainable with quartz walls.

INTRODUCTION

The work reported here is a continuation and expansion of that reported in Reference 1 which was limited to 88 kW. The induction plasma sheath system described in that reference which was developed to simulate the heat addition, mixing and stabilization mechanisms of the gas core reactor has been studied further and scaled up to 1000 kW plate power. The standard induction plasma operating mode (without sheath gas) has also been studied experimentally at frequencies as low as 200 KHz and plate powers to approximately 1000 kW. One of the original objectives of this program, operation of the induction plasma torch on pure hydrogen, has been achieved. Some studies of the performance of the induction plasma system with argon have also been made. These include radiation and brightness temperature measurements.

APPARATUS AND PROCEDURE

This program involved using existing and modified high frequency generating systems[1]. All systems used were calorimetrically instrumented in order that a baseline of performance could be established and so that performance of each system operated and modification thereof could be completely monitored and compared. The system used for most of this work consisted of a conventional 190 kW dc plate power TAFA induction plasma system (12,700 volts, 15 amperes dc). The control unit used to operate this system consisted of plasma forming gas flowmeters, power supply controls and meters. All torches tested were manufactured by TAFA.

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

SHEATH GAS OPERATION

Previous work has shown that a high velocity coaxial sheath of hydrogen can be blown by an rf heated arc using proper stabilization techniques. The performance of this unit has been improved and its power capability greatly extended by substituting a segmented metal separator for the quartz separator shown in Fig. 1 and 2. This metal wall has permitted over a tenfold increase in power density within this region of the torch without overheating of containment walls.

To achieve a high performance gas core reactor the volume of the heat addition region compared with the total reactor cavity volume must be large.[2] In addition, the ratio of hydrogen propellant-coolant flow versus the fuel flow rate must also be high. To estimate the performance of the sheath simulator relative to that desired for high performance in the final reactor engine, photographic experiments were performed to determine the volume of the induction arc relative to the total volume enclosed by the plasma generator walls. Photographs taken resembled those shown in Fig. 3. In making estimates it was assumed that the dimensions of the arc were given by the sharp intensity variations shown in the photograph, that chamber volume was prescribed by the containing plasma wall and was one diameter long commencing at the top of the metal separator. In all cases the same 3 in. sheath system was used. The cavity dimension volumes were therefore 3 in. diameter by 3 in. long. Different diameter metal separators were used in an attempt to increase the arc diameter in the same cavity. This data is shown in Fig. 4 and 5. Investigations were made to determine the effect of hydrogen sheath flow on the volume of the visible arc at a constant argon plasma forming gas flow of 120 SCFH. The phenomenon of thermal pinch is evident since when hydrogen sheath gas is added the arc volume shrinks. This shrinkage appears to be a function of the quantity of hydrogen added. The data indicates the arc volume falls progressively as hydrogen is added until the ratio of hydrogen to argon reaches 10:1. Beyond this point further addition of hydrogen has little effect. It can also be seen that an increase in metal separator diameter resulted in an expected increase in arc diameter, i.e. the arc expands to fill the separator.

Due to physical limitations of the apparatus the metal separator diameter cannot be expanded indefinitely. Figure 6 is an attempt to indicate the maximum fluid mechanic limits of this device. It will be shown that plate powers up to approximately 1000 kW can be sustained in tube diameters as small as 3.25 in. Tests will be reported on units in the range of 3.25 in. to 6 in. at this power level. Since it is desirable to maintain the highest possible power density within the arc region to more accurately simulate the gas core reactor, the operating ranges of Fig. 6 were limited to the areas of experimentation and the maximum arc power densities the present state of the art would appear to allow.

The operating limits of the apparatus constructed and investigated during this program will fall within the cross hatch region of Fig. 6. The various borders to this region are numbered and the reason for them follows.

Line 1 - Operation on this line assumes a cylindrical arc in a 6 in. i.d. torch with a 5 in. i.d. metal separator. The large (0.5 in.) annular sheath space was assumed because buffer gas or some other mixing reducing mechanism would be required to obtain the cylindrical (rather than conical) arc assumed in this area.

Line 2 - As the argon core flow is turned down at constant hydrogen sheath flow the arc gets smaller and smaller and is finally extinguished. Run 26, Table I, was such an extinguishment point. If hydrogen were substituted for the air used in this test the flow volume would be 32,800 SCFH or a hydrogen-argon <u>weight</u> ratio of 31:1. Our experimental and apparatus judgment leads us to believe this is probably the maximum ratio which could be achieved.

Line 3 - This limit is indicative of the smallest sustainable arc. It assumes a 2 in. arc in a 6 in. tube, i.e. a core to arc cavity volume ratio near .01.

Line 4 - This line is the predicted performance of a 5.5 in. metal separator in a 6 in. torch based on experimental results with the 3 in. torch (simple scale up). All experiments to date have shown a conical arc shape, thus all operating points above this line assume that a cylindrical arc region can be achieved by reducing mixing between the argon and hydrogen beyond that achieved experimentally to date.

Line 5 - This line is the absolute upper limit of conical arc performance and assumes an arc diameter equal to the cavity diameter at its base (an impractical design criteria).

The experimental data with the 3 in. sheath system measured by photographs is plotted and the estimated ratios achieved with the 6 in. torch when operating at 1000 kW (not measured) are given by Line 4.

LOW-FREQUENCY INVESTIGATIONS

From a practical standpoint, coil arcing and torch design problems increase as the power and frequency are raised. Since one of the objectives of the program was operation at power levels in the range of 1000 kW it seemed logical to use existing well engineered power supplies rather than become involved in additional development problems with regard to a special 1000 kW high frequency unit which had never been made or operated under the conditions desired. A standard high power unit was located and arrangements were made to test on the unit at the manufacturer's production plant before the unit was shipped to a customer's plant. The availability of a reliable, flexible, 1000 kW plate power machine at the 450 KHz range therefore dominated experimental thinking and necessitated experiments at this frequency at the 88 kW power range available in the TAFA laboratory to develop design information and permit testing of low frequency torches constructed.

Extrapolation of previous experimental work indicated that approximately 230 kW of 450 KHz power would be required to sustain 100 percent air operation. This is obviously much higher than the demonstrated 100 percent air operation at 15 kW and 4 MHz. Familiarity experiments similar to those described in Reference 1 to obtain an experimental feel for the effect of low frequency were then undertaken.

The 88 kW Lepel plate power unit described in detail in Reference 1 had a dual circuit, one for operation at 450 KHz, and the second at 4 MHz. In the KHz range the tank circuit contains four capacitors (totaling 5400 picofarads). The plasma torch offers an additional restriction in selection of circuit components. For a practical torch design the number of turns must not be more than 10 to minimize the surface area of the torch and thus heat loss. Tests run with a 3.3 in. i.d. coil which simulates the sheath generator and a 1.9 in. steel calorimeter which simulates the arc load were run with a variety of load coil turns. These results are shown in Fig. 7. From previous work done at 4 MHz the maximum efficiency of such a Class "C" oscillator appeared to be in the range of 70 percent, i.e. 70 percent of the plate power into the load. It can be seen from Fig. 7 that such efficiencies are achieved at the lower frequency with the machine used at great numbers of load coil turns. These high efficiencies would not be obtainable with a plasma torch because of the load coil turn restrictions. One can see from Fig. 7 that the expected best efficiency with four capacitors and 10 turns is in the range of 50 percent. A conventional step-down transformer was tried; however, this did not improve the efficiency.

Induction heating theory[3] shows that maximum circuit efficiency is achieved when the load impedence equals the equivalent oscillator tube impedence under Class "C" operation. In this instance oscillator tube impedence is 800 ohms and it can be seen that the efficiency curves in Fig. 7 peak when components are selected such that the tank circuit impedence reaches this value.

If the efficiency data presented in Fig. 7 is plotted versus impedence it yields the characteristic curve shown in Fig. 8 showing that at 800 ohms maximum efficiency is achieved. Note plasma operation is also shown.

Tests were then made with the 3 in. sheath system using argon and mixtures of air and argon. It was determined that a maximum of 25 percent air could be added before extinguishment of the plasma using a 10 turn coil. Comparison of this test point with data collected at 150 kW and 450 KHz some years ago gave a linear extrapolation of 100 percent air operation at 230 kW. Later tests with a larger power supply showed that nitrogen (which has a higher minimum sustaining power than air) could be sustained at this frequency at 192 kW (Run 8, Table I) in a tube as large as 6 in. This was not the minimum sustaining power (MSP) for nitrogen but was the lowest level which the power supply could be operated.

It should be expected that the minimum sustaining power with a given gas will rise as the frequency is lowered.

It has been theoretically predicted and experimentally confirmed by Eckert[4] that there is an energy threshhold below which an induction plasma cannot be formed. This threshhold is a function of the particular gas in question and is inversely proportional to the square root of the operating frequency. Thus, lowering the frequency increases this threshhold.

Table II presents experimental data recorded by TAFA with a variety of power supplies, torches and gases. Preliminary theoretical predictions by Dundas in Appendix A are based on a simplified model using a constant conductivity plasma and the experimental data of vonEngel[5] for the positive column of a dc arc. They show the relationship between the minimum sustaining power for various gases. This minimum sustaining power is a direct function of the Eckert threshhold referred to above.

It can be seen that these predictions follow the experimental trends shown in Table II, i.e. 276 kW for hydrogen.

The expected affect of skin depth as a function of frequency is demonstrated by the photos shown in Fig. 9 which were taken in the same 6 in. torch at similar powers. Variation in exposure caused the brightness differences. The coöler center of the arc similar to that measured by Johnston[6] can easily be seen.

The previous tests reported at the 88 kW level (450 KHz) with air-argon mixtures gave little hope that much hydrogen sheath gas could be added to the argon system since hydrogen's thermal pinch properties are even more drastic than air. We were pleasantly surprised; however, when the hydrogen sheath system was run. A 15:1 volume ratio with hydrogen was achieved at 70 kW plate power with extremely smooth operation and a very stable arc. In conclusion, these preliminary tests with low power 450 KHz showed that:

1) Conventional impedence matching calculations apply to the induction plasma system. It should therefore be possible to accurately calculate the coil and circuit requirements for the forthcoming high power tests on a different power unit.

2) The minimum sustaining power increases as the frequency is lowered; however, at 450 KHz these minimum sustaining powers are low enough to achieve meaningful results during the high power tests with most gases and torch designs of interest at 1000 kW.

PRELIMINARY GAS CONCENTRATION INSTRUMENTATION ANALYSIS

The following section discusses some preliminary tests conducted to demonstrate the feasibility of measuring mixing within the sheath system. The objective here was not to obtain concentration profiles within the torch. Based on previous work, it appeared feasible to introduce a small diameter probe into the plasma in order to withdraw gas samples from specific locations. It remained; however, to devise a simple method for determining the composition of these gas mixtures. Ideally, the method should be capable of both continuous and batch analysis. This would permit the use of a scanning probe to sample the gases across the diameter of a cylindrical plasma column while continuously recording some analytical signal which depends on the composition of the binary mixture of hydrogen and argon. For batch sampling, it would still be possible to measure the composition of these discrete samples.

A secondary aspect of the problem was the need for a method to check for the presence of other gases which might enter the system through leaks or by other means.

Proposed Method of Analysis

From data in the literature, it seemed likely that a thermal conductivity detector would provide a useful response for binary mixtures of hydrogen and argon. Since a gas chromatograph with thermal conductivity detectors was available, this instrument was used to check the feasibility of the proposed method. It is important to recognize that the gas chromatograph was not used to achieve any gas separation but rather the thermal conductivity detectors were employed as a measuring system. However, the potential to separate gases on molecular sieve columns as a means of checking for the presence of air in the hydrogen-argon mixtures made the selection of this instrument particularly attractive.

Apparatus and Conditions Used

1) Gas Chromatograph - A Varian Aerograph Model 1520, dual column, dual detector instrument was used. Since no gas separation was sought, no packing was present in the 4 ft. by .125 in. columns used. At the end of each column there were thermal conductivity detectors with matched and balanced pairs of nominal 30 ohm tungsten-rhenium (Wx) filaments. These were operated at 35 milliamps (dc) and an attenuation of 32 was employed. Temperatures were 75°C at the injector, 50°C for the column, and 80°C for the detectors. These conditions were not specifically optimized for this analysis since they provided ample sensitivity and precision without optimization.

2) <u>Recorder</u> - A Leeds and Northrup Speedomax W recorder with a linear 0.0-1.0 millivolt response was used.

<u>Experimental</u>.-The gas chromatograph was first set up with pure argon flowing through both the reference and the analytical detectors at a flow rate of approximately 10/ml/min. (measured at the tube exit with a soap bubble flowmeter). The response was set at zero. Since a probe for continuous sampling of gas mixtures would be expected to show some flow rate variations, the flow rate through the analytical detector was deliberately varied from 5 to 15 ml/min. while holding the reference flow constant at 10 ml/min. No significant change in detector response was noted.

The next step was to pass 5 ml/min. of pure hydrogen through the analytical detector while a constant flow of 5 ml/min. of argon was maintained through the reference detector. For the conditions specified earlier, a response of approximately 93 percent of full scale was obtained. The hydrogen flow rate was varied from 5 to 10 ml/min. with no significant change in detector response.

In changing back and forth from 100 percent hydrogen to 100 percent argon flowing through the analytical detector it was observed that full response for hydrogen was obtained in less than one minute after switching from argon to hydrogen. In contrast, when switching from hydrogen to argon, several minutes were required for the response to return to the baseline signal. This effect could be caused by adsorption of hydrogen on the detector filaments and very slow desorption when the flow is changed to argon. Several inquiries and considerable literature searching relative to this point has failed to provide a conclusive answer. Another possible explanation is that the low flow rates used provide an inefficient removal of hydrogen (which is a very light gas) from the area of the detector. To test this hypothesis, higher argon flow rates were tried and this did reduce the time required to return to the baseline signal. However, higher argon flow rates would also increase the rate of hydrogen desorption. Thus, this question will have to be considered further when flow rates for the sampling system to be used with the torch are known. If a very low flow rate has to be used, it appears that the response may be sluggish when going from a hydrogen rich region to an argon rich region. Distortion of concentration profiles would result. Of course, batch sampling would be free from this difficulty.

In order to obtain a calibration curve for detector response versus volume percent hydrogen in argon, a tank of hydrogen and argon was used to continuously supply mixtures of the two gases in known volume proportions. With the equipment available it was not possible to obtain sufficient reproducibility of flow rates to provide data with the desired precision. The solution to this problem would be the use of hydrogen-argon mixtures of known concentrations, one tank for each mixture. As an alternative method of calibrary, a batch sampling system was used. This was accomplished by filling a calibrated 2.5 ml gas syringe with appropriate proportions of hydrogen and argon. Care was necessary to insure that the dead volume of the syringe needle was filled with argon which gives no response above baseline. Binary mixtures containing 20, 40, 60 and 80 volume percent hydrogen were prepared. Four replicate 2.5 ml volumes of each mixture were injected into the chromatograph in random order. Since no separation occurred, the peak height of the detector response should approximate the response expected for a continuous flow of the same composition. In Fig. 10 recorder output for duplicate sample measurements of each mixture are presented. Agreement of replicates is excellent. Figure 11 is a plot of average argon. A smooth calibration curve for the whole range of composition was obtained. Sensitivity of measurement is better in the region between 0-40 percent hydrogen than it is for higher concentrations but the precision of the measurements appears adequate to make the whole curve useful.

Small amounts of air were added to pure hydrogen and pure argon. The hydrogen response was decreased and the argon response was increased, indicating that the thermal conductivity of air lies between the values for hydrogen and argon. Clearly the presence of air would cause some error in analysis of a mixture assumed to contain only hydrogen and argon.

As a final check to determine the effect of hot gas, a water cooled sampling probe (.25 in. o.d., .0625 in. i.d.) was used and samples were removed from a 5-10 percent premixed hydrogen in argon plasma operating in the Model 58 torch at 20 MHz and 2 kW. All tests involved premixed gases and samples withdrawn from various parts of the torch interior including the arc region showed no concentration gradients. Thus, it was concluded that heat addition will not complicate this concentration analysis system.

HIGH POWER TESTS

The following section will describe the 1000 kW tests conducted during this program. The data will be discussed in detail; however, a summary is presented here to orient the reader. A variety of torch sizes were successfully operated on diatomic as well as monatomic gases at 450 KHz. Enthalpies with diatomic gases such as air over 40,000 Btu/lb. were run continuously. Documented performance over a wide variety of operating conditions including sheath and plasma heating modes is presented. Typical data for normal operation is given in Table III and for sheath modes in Table IV.

High power tests were conducted with a variety of induction plasma torch designs and over 75 fully documented runs under a variety of conditions were recorded. The power unit used had a plate power rating of approximately 1000 kW with continuous rated rf output (into a 12 in. steel load) of 560 kW at 450 KHz. The power supply was extremely well regulated with ripple factor less than two percent and line voltage regulation of ± 1 percent within a range of line voltage variation of ± 10 percent.

The 450 KHz rf power unit used was for the continuous production of welded pipe. It is shown in Fig. 12 and has a continuous rating of 60 dc plate amperes at 16 kilovolts.

A variety of torch sizes and design modifications were fabricated ahead of time to be sure that adequate apparatus would be available during the test periods. As the experimental program unfolded successful operation was achieved with all apparatus used due to careful pre-testing of apparatus at 100 kW.

A gas metering system permitted mixing of two gases such as argon and air to each inlet port of the torch. The core gas at the center of the torch was injected through a standard TAFA injector with three inlet ports, one for radial gas, one for center gas and one for swirl gas. Additional ports were used for buffer and sheath gas flow, making a total of five inlets.

Bottle manifolds were used for all gases except shop air which was available at 120 p.s.i.g. The rotometers used had an accuracy of ± 2 percent.

All torch components were water cooled and adequate flows of 160 p.s.i.g. water were available. The high pressure water was used to assure adequate cooling of all torch designs with high wall heat fluxes. The smallest 3.25 in. i.d. torch tested when operating at the full power of the machine had a cooling water temperature rise of about 60°F. Using this temperature rise and calculating the heat flux to the wall indicated that this unit was approaching the heat flux burn out failure limit of one and a half million Btu. per square foot second at the maximum power levels tested. However, no failures occurred.

Data Collection

The test procedure and collection of data was straightforward. All water flow rates were metered through rotometers and the water temperature rise through each system component was measured with ± 2 percent dial thermometers. In the case of the power supply the total water flow through the unit was measured. This included heat losses to the plasma torch coil, transmission leads and oscillator tube. Power unit data developed with steel calorimeters showed that the loss to the power unit remained relatively constant over wide ranges of circuit parameters and power levels; this provided a quick check to determine whether system equilibrium had been reached during any test run. In all runs reported an attempt was made to allow the system to come to equilibrium by observing the temperature rise. Because of the small mass of torch components equilibrium was reached relatively quickly, usually in less than 30 seconds, while the power unit required approximately two minutes because of its larger thermal inertia.

Procedure for each run was always the same. The unit was ignited with an auxiliary dc arc at minimum power and argon flow only in the center core arc region. Once the plasma was established the dc electrodes were removed and disconnected. Power and gas flows were adjusted to desired levels and the unit allowed to run until thermal equilibrium was reached; all data was then recorded. While the unit was operating, high speed and 24 fps photographs were taken. A polished stainless steel mirror located over the torch permitted end on viewing of the arc region throughout the tests.

When radiation measurements were to be made the radiation head was located 60° to the horizontal looking down into the torch approximately eight inches from the arc and the output of this unit fed to a millivolt potentiometer.

Previous heat balance work with induction plasma systems[1] has shown that the energy leaving the torch can be accurately determined by subtracting all cooling water losses (torch and power unit) from dc input to power unit (plate power). Exit gas enthalpies reported were determined by this technique. They do not distinguish radiative component and sensible heat in the gas. More recent measurements with a calibrated total radiation head (reported later in this paper) indicate the radiative component to be small (5-15%).

All high power tests were made with metal wall devices. Initially the torch was connected close to the power supply inside the building with five foot lead lengths. All sheath gas operation inside was conducted with air rather than hydrogen because of the fire hazard. The hydrogen sheath tests reported used long rf extension leads to permit the torch to be operated completely outside the building. When hydrogen sheath testing was conducted, however, matching problems primarily associated with the inductance of the 35 foot lead extensions limited operation to 480 kW.

As a generalized observation, all high power testing went extremely well; only minor problems were encountered which permitted 76 data runs to be recorded during the eight day period. The data collected has given an excellent insight into the operating limits of this apparatus. It would appear that scale up of apparatus to power levels many times that tested would be straightforward.

Six Inch Metal Wall Operated in Air Sheath Mode

The 6 in. unit shown in Fig. 13 was set up close to the power unit (5 foot lead length). Before the tests began we had considerable concern relative to the detrimental effect of high power ignition on the torch. The power supply could be connected in either Y or delta. The minimum power with the high power Y connection was about 250 plate kW. It was felt that this might give problems and that lower power ignition should be studied to determine the best gas flows to prevent damage to the torch. The delta connection was therefore used first and this permitted turn down to 50 kW. Ignition at this power was no problem and the power was graudally increased in a series of tests until it was demonstrated that ignition at 250 kW presented no complications as compared with 50 kW ignition.

Once the ignition problem was understood the power unit was switched to Y connections which permitted maximum output of the machine. It was determined that ignition also occurred without difficulty with the air sheath on full (2200 SCFH) and normal argon core gas (780 SCFH). All subsequent sheath gas runs were then ignited with all flows preset. To minimize equipment problems a series of tests were run at increasing powers with the 6 in. metal wall torch. It was soon evident that this torch was under powered even at the maximum output of the machine with temperature rises of $47^{o}F$ in the most severely heated component. All components checked out well.

Runs 1-7, Table I, present typical data with the 6 in. system. It should be noted that the table presents frequency, number of torch turns, plate power input, percent of plate power distributed to the various components of the system, percent power in the arc, percent power in the gas stream leaving the torch and average exit gas enthalpy. In addition, radiation levels were recorded with a Brown Radiamatic head, Model RI3, looking down into the arc region at 45^{o} (Fig. 14) where appropriate. Run 1 is a minimum power run. This was the lowest power to which the unit could be operated in the Y connection. The torch operated at this power level, thus minimum sustaining power could not be recorded. Tests not listed demonstrated that the unit operated equally well at lower air sheath flows. Sheath flow for this series of tests was therefore maintained at the maximum available to give maximum mixing and disturbance to the argon core to best simulate the effect of hydrogen. It is obvious that hydrogen constricts the arc still further; however, it was felt that generation of this data would be helpful in later tests. The 2200 SCFH air sheath is approximately 164 lbs/hr. of air. On the basis of hydrogen flow, the same weight flow hydrogen would result in 31,300 SCFH or a sheath to core flow ratio of 39.7:1. It should be noted that in Run 7 that 967 kW of plate power was used. This is the maximum power test for the entire test period. The temperature rise in the metal separator for this run was $27.5^{o}F$ and the metal wall $47^{o}F$. Temperature rises over 60^{o} have been run with later experiments at the same water pressure which would indicate that this 6 in. metal wall could be run at 1200 kW plate power before this temperature rise was achieved. Power levels above this would require either higher water pressures or enlargement of existing passages to permit more water flow.

Some pertinent comments and observations relative to this series of tests are as follows.

With the sheath flow on, the arc performed and looked very similar to the lower power apparatus run at the TAFA laboratory. Most of the observations and data collected should be directly applicable to higher power equipment; for example, the arc diameter remained slightly smaller than the metal separator and the arc stabilized down inside the separator.

The arc to coil diameter ratio for the 6 in. metal wall, assuming a 5 in. arc, is .645 in., thus one would predict good coupling efficiencies. This turned out to be true. The percent plate power in the arc in all runs except at very low powers remained around 63.5 percent. This is exactly the same percent of power input that was measured with a 12 in. steel load. The matching problems previously discussed at the 88 kW level (450 KHz) in the TAFA laboratory were not present with the larger equipment and 4-8 coils were adequate. All data points to a relatively constant machine loss of 33.5 percent (this included the coil loss). If one assumes an eight percent coil loss, this means an oscillator loss of 25.5 percent which is quite comparable to the 20 percent loss achieved in the 4 MHz range at lower powers[1]. One can generalize then that high power tubes are available to operate with plasma at 450 KHz with efficiencies approaching that of low power 4 MHz operation. An important factor as scale up is considered, i.e. negligible sacrifice in efficiency will result.

The smallest load to coil ratio occurred with the 3.25 in. torch described in Runs 32-40. In this case a 2.75 in. arc was produced with a load to coil ratio of 0.44. Under these circumstances 63.5 percent of the power still appeared in the arc, indicating negligible effect of load to coil ratio in the range from 0.44 to 1.

It can be seen by comparing 4 MHz, 3 in. sheath system data[1] with the high power 6 in. torch, 450 KHz data here, that considerable similarity exists in performance which indicates that data collected with the small power unit is directly applicable to the estimation of high power performance.

The 33 percent power in the gas stream leaving the torch is low when compared with operation on other core gases such as nitrogen or air (See Run 11-14 and 18-20) where 40-45 percent of the plate power is accounted for in the exit plasma leaving the torch at about 20,000 Btu/lb. This 10 percent increase with diatomic gases, even though the sheath is omitted (resulting in higher convective wall losses) is attributed to the higher radiation level from the argon arc. Actual radiation measurements show a 10 percent drop in plate power radiated when the switch is made from argon to air at the same input power level. It should further be noted that these torches were not designed for minimum surface area and thus the efficiencies reported are not the maximum achievable. Other data with a shorter torch (some of which is reported in Run 31-42, Table I) indicates that 10 percent more plate power can be put into the exit gas by proper torch sizing.

The gas enthalpies listed are the average enthalpies of the exit gas based on the heat balance data, and, assume in the case of sheath operation, that they are characterized by the sheath gas alone.

Runs 8-10 give performance of the 6 in. metal wall operated with nitrogen core gas and no sheath. It can be seen that performance is almost identical to the 4.5 in. nitrogen data presented in Runs 11-14, and the percent heat in the plasma leaving the torch is considerably above that when operated in the argon core-sheath gas mode.

Runs 11-20 present data with the 4.5 in. torch operating with nitrogen, oxygen and air as the core gas without sheath flow.

It should be noted that nitrogen and air are almost identical in performance.

As can be seen in Runs 18-20, the percent heat in the plasma leaving the torch drops as the enthalpy of the exit gas stream is increased. This results from higher radiation losses due to higher fireball temperatures and greater convective losses to the torch walls from the hotter gases.

Run 20 demonstrated continuous air operation at 703 kW and 41,700 Btu/lb. leaving the torch. This was not the highest enthalpy possible but is the highest recorded in this test series.

From the trend in Runs 18-20 it would appear that higher gas flows would have yielded higher percentages of heat in the exit gas stream. This would undoubtedly level out at 45-55 percent, probably in the area of 50 percent.

The temperature rise of the cooling water to the metal wall at the 771 kW level in Run 18 was 27.5°F. Based on a maximum tolerable temperature rise of 60°F as described previously, the maximum power at which this 4.5 in. torch could be run with the existing water flow would be 1690 kW. A similar analysis of Run 10 with a 6 in. unit would indicate a power capability of 1860 kW without use of higher gas flows, higher pressure water or revised torch design.

Oxygen behaved differently than nitrogen or air. The measured minimum sustaining power (MSP) for oxygen was in the range of 360 kW plate (Run 15) and operation with this gas was more unstable than nitrogen or air. The 360 kW MSP is about twice that of nitrogen or air. This is logical since vonEngel[5] has shown experimentally that the electric field strength in the positive column of an oxygen arc is considerably greater than nitrogen or air and is more akin to hydrogen; for example, the field strength in an oxygen plasma is two and one-half times that of nitrogen or air for the same arc current where hydrogen is 10 times greater than nitrogen. The paradox still exists that in the TAFA 1.5 in. Model 56 torch oxygen has a MSP slightly less than air or nitrogen. This gives experimental verification that apparatus design or size may also have an influence on minimum sustaining power. Later work presented in this report also demonstrates the effect of gas flow on MSP.

It should also be noted that the loss to the metal wall is 10 percent higher with oxygen than nitrogen or argon at the same power. This resulted in approximately 10 percent less heat in the gas leaving the torch. The phenomenon is unexplained at the present time. It may perhaps be related to the fact that oxygen is a better radiator.

Runs 21-26 cover operation with an argon and air sheath while Runs 27-31 show operation with a hydrogen sheath.

Run 26 demonstrated that the argon core could be turned down to 48 SCFH without extinguishment. This point was not the lowest argon core gas which could be operated at the 2340 SCFH air sheath used. With the air sheath on full and the power settings remaining constant the argon core gas was turned down. As the flow was reduced from 200 SCFH to below 48 SCFH the arc became smaller and more stable (no visible movement) and looked the most stable of all tests when operated at the 48 SCFH level. An attempt was then made to turn the flow below 48 SCFH and the arc was extinguished somewhere between 48 and 0. It should be noted that the air to argon core ratio at this exceptionally stable point (Run 26) was 49:1, and that the percent heat in the gas leaving the torch increased to 36.2 percent and the metal wall loss dropped by 10 percent, while at the same time the metal separator loss increased by approximately five percent. This trend is probably caused by the fact that more of the argon arc remained within the metal separator, raising its loss, while radiation and convection to the walls was reduced by air dilution.

Attempts were made to run with hydrogen rather than air in the sheath of all torches tested. The 35 foot extension leads (required to feed the power to the torch located outside of the building) added so much inductance (coil = 7.2 microhenrys, 35 ft. lead = 30 microhenrys) to the circuit that matching was difficult and the maximum output limited to 480 kW. Since the machine was not designed for such large load inductance, very high frequency (100 MHz+) parasitics developed which caused frequent coil arc-over. The added inductance decreased the frequency of operation to 220 KHz (Run 27, Table I).

It should be noted that Run 27 was the only run in which much sheath hydrogen could be added. With this particular data point a heat balance could not be made before parasitic arc-over occurred destroying the work coil. This run gives a hydrogen-argon ratio of 5:1. It is interesting to note that in Run 31 where the power was reduced from 480 to 356 kW no hydrogen could be added without extinguishing the arc. It thus appears that we are in the critical transition range presented in Fig. 15 which indicates the operating limits for the 3 in. sheath system, i.e. up to the minimum sustaining power negligible amounts of hydrogen can be added, but once this point is reached one is able to add hydrogen rapidly with small increases in power. This data then indicates that one would expect to run with high hydrogen sheath flows at power levels of 600-800 kW at 220 KHz and probably at powers in the range of 200 kW at 450 KHz. It is possible that with the metal separator extended further into the coil, rather than the position shown in Fig. 1, hydrogen could have been run at 220 KHz, however, this was not tried.

Pure argon operation is described in Runs 32-41 and should be self explanatory. The metal separator alone was used in these tests without an intermediate metal wall as was used in the sheath generator.

Metal Separator Operated as a Torch

The metal separator has been operated as an individual unit with pure argon. Operated in this mode the unit is essentially a short, efficient torch. The following paragraphs present performance of this unit.

The first tests run with this design utilized the 5 in. i.d. metal separator in a setup similar to Fig. 16 and are covered in Runs 32-35. It can be seen that the less dense plasma at the same power level in the large unit produced considerably less radiation than the more dense one in the 3.5 in. metal separator (see radiation head millivolt readings). The plate power in the gas stream leaving the torch is slightly higher with the 3.5 in. as compared with the 5 in. unit. Both units performed the same when comparing heat loss to the various components of the torch. The larger unit was obviously under powered at the power levels run, hence, most available experimental time was devoted to the 3.5 in. unit. It can be seen when comparing Runs 35-41 that the performance of smaller torches at lower powers is very similar to the high power ones. Run 41 is a 2 in. metal separator operating at 54 kW in the TAFA laboratory at 4 MHz while the other runs referenced are all at the 600 KHz and 10 times the power. Note that the percent heat in the gas stream leaving the torch is almost identical. Since torch losses are close, this again indicates the simplicity of developing data at lower powers and applying it to high power operation.

It should also be noted that extremely high enthalpies with argon have been achieved.

Run 40 was toward the end of the test sequence and power was continually turned up in this sequence to determine the maximum power capabilities of this size torch. At 880 kW this unit operated well.

PURE HYDROGEN HEATING

Induction heating of a pure hydrogen stream was one of the original objectives of this program. The work reported in Reference 1 showed that approximately 70 percent hydrogen in argon could be heated by a 4 MHz 88 kW plate power unit. Extrapolation indicated about 160 kW would be required to achieve pure hydrogen operation.

The power supply used permitted operation to plate powers to 190 kW.

Pure hydrogen operation has been achieved during this phase of the program utilizing the setup shown in Fig. 16 which consisted of a segmented metal wall and seven turn coil. The torch was coated on the outside with Sauereisen cement and then slipped into a 1.5 in. i.d. x 8 in. quartz tube, the outside of which was spaced .125 in. from the surrounding coil. Operation was always vertical and in open air.

The unit was ignited on pure argon and the power turned up to 100 kW. Six SCFH of hydrogen was then added to the 100 SCFH argon ignition flow and the argon turned off immediately, leaving only hydrogen. The power unit was especially developed for this purpose; however, the circuit was a conventional Class "C" oscillator with a capacitance of 1200 picofarads and total circuit inductance, including the work coil, of approximately one microhenry.

Operating limits of the device were determined and are presented in Fig. 17. On this figure the stable operating region is bounded on the left by a line of minimum powers below which the arc becomes first unstable and then is extinguished. Operation is stable within the area designated. As plate power is increased this is reflected in increased plate and coil voltage. At approximately 12,000 plate volts the power unit or coil arced over and extinguished the plasma. The same result can be achieved by raising the gas flow at powers above 130 kW. This region of the operating limit then is related to the specific power unit and coil design rather than the torch or plasma forming gas. If the machine could have been operated at the higher voltages, higher gas flows and power levels could have been achieved. The operating envelope presented in Fig. 17, except for the lefthand limit, is representative of the particular power unit used. The points labeled A, B and C on Fig. 17 were typical stable operating points and complete heat balances for these points are recorded in Table V. Air and helium operation using the identical setup are shown for comparison. One should note the relatively low exit gas efficiencies (12-14 percent). This low efficiency is undoubtedly due to the low gas flows and associated high convective and radiative losses within the torch. Because of power supply limitations we were unable to operate at high hydrogen flows; however, Table VI demonstrates that air acts similarly. Note that when the unchanged hydrogen plasma system was used with air that it actually had a lower efficiency than hydrogen (5.05 percent for air). Note also that as the air flow rate through the torch is increased to 230 SCFH this efficiency is raised to 40.2 percent. The torch design was not ideal for maximum efficiency with air, i.e. seven turns were used and this moved the arc far down into the torch as compared with the same torch operating with four turns. Figure 18 shows a comparable performance with hydrogen and air in the same torch. From the air trend and Table VI one can speculate that hydrogen at gas flows in the range of 200-500 SCFH would produce efficiencies in the range of 30-50 percent.

The relationship of hydrogen-argon mixtures to plate power and gas flow is shown in Fig. 19. This curve points out the increase and minimum sustaining power with gas flow rate in the torch as well as hydrogen concentration. It should be noted that at the 50 SCFH hydrogen rate through the torch the percent hydrogen in argon could not be increased above 75 percent before arc over occurred in the power supply similar to that associated with the righthand limit of Fig. 17.

Extremely high exit gas enthalpies have been produced with pure hydrogen as indicated in Table V. To determine the radiative component and the calorimetrically determined enthalpy, a calibrated High Cal Engineering (Santa Fe Springs) detector #C-7015 was used in a water cooled aperture mount giving a 3 in. diameter field of view at nine inches (See Fig. 16). This unit was calibrated and gave 0.257 millivolt/solar constant

(1 solar constant = 140 milliwatts/cm.^{2}). The measured radiative component was 10-20 percent, thus the exit gas enthalpies were truly of the magnitude indicated, which, to our knowledge, is an order of magnitude greater than those previously achieved by other arc heating devices. In addition, a laminar jet was produced approximately .75 in. in diameter (Fig. 20). Flow rates lower than 1.5 SCFH hydrogen were not run because of ambient air operation which did not permit maintenance of a pure hydrogen atmosphere within the coil. A few short tests in which the flow was turned off demonstrated that the arc was sustained at zero flow before air diffused in. Mitin and Pryadkin[7] have demonstrated that operation on other gases is possible without flow in a closed container, hence it would appear logical that continuous operation at zero flow on hydrogen is possible along the baseline of Fig. 17.

CONCLUSIONS

Specific conclusions are as follows:

1) The induction plasma torch has been operated at frequencies as low as 220 KHz at plate powers up to 1000 kW with efficiencies and performance almost identical to 50 kW, 4 MHz work reported previously.

2) A metal walled plasma torch has been operated at power densities 10 times those of water cooled quartz tubes and has permitted continuous operation on diatomic gases like air at exit gas enthalpies over 40,000 Btu/lb. Over 50 percent of the plate power has been measured in the exit gases leaving the torch with 64 percent in the arc region.

3) The sheath gas system developed for simulation of the nuclear gas core

reactor has been operated at 1000 kW with results similar to those reported previously at the 50 kW level, i.e. velocity ratio of sheath to core 50:1.

4) Pure hydrogen operation has been achieved at one atmosphere at power levels in the range of 60-160 kW in a 1.1 in. i.d. metal walled torch with hydrogen flow rates from 1 to 16 SCFH.

5) Unusually high hydrogen exit gas enthalpies in the range of 1.1 million Btu/lb. have been achieved. This is an order of magnitude above those previously obtained with any other arc heating device.

APPENDIX A

ANALYSIS OF THE THERMAL PINCH EFFECT

Peter H. Dundas

VonEngel in his book, Ionized Gases, states that "the purpose of setting up the energy balance in the positive column (of a dc arc) is to find relations between the electric field X, current i, radius R of the conducting cylinder--the seat of thermal ionization--the gas and its pressure."

He attempts this but soon shows that it is not as easy as it first appears. However, following his suggestions and assuming a degree of ionization less than 10 percent, it can be shown that the following relations hold.

$$x \propto N_e \quad \text{and} \quad N_e \propto j/X \tag{1}$$

So

$$x \propto j/X$$

where x = degree of ionization, N_e = electron concentration, j = current density, X = electric field strength. (2)

For a dc arc positive column

$$j = i/\pi R^2$$

where i = current, R = radius of plasma (3)

So

$$x \propto \frac{i}{\pi R^2 X} \tag{4}$$

Now, the voltage across the positive column $e = Xl$ where l is the length of the column

So

$$x \propto \frac{W}{\pi R^2 X^2 l}$$

where W = input power (5)

For an arc of constant length

$$x \propto \frac{W}{R^2 X^2} \qquad (6)$$

Now for the current range under investigation and applicable to our system ($10^2 < i < 10^4$ amps) the electric field strength is approximately constant for a particular gas.

For

Hydrogen	X = 20 v/cm		
Nitrogen	X = 2 v/cm		vonEngel, p. 262
Argon	X = 1.5 v/cm		

Therefore, for a constant power input the ratio of ionization for two gases can easily be expressed

$$\frac{x_{H_2}}{x_{N_2}} = .01 \left(\frac{R_{N_2}}{R_{H_2}}\right)^2 \qquad (7)$$

From this ratio the temperatures of the two plasmas may be found by applying the familiar Saha equation (vonEngel, p. 82).

Then a heat balance based on radiation and conduction to the wall of the containing vessel (In this case the plasma torch body) can be formulated.

Radiation:

$$Q_R = \epsilon \sigma \, 2\pi R l T^4$$

where ϵ = gas emissivity, σ = Stefan-Boltzmann constant, T = absolute temperature of plasma (8)

Conduction:

$$Q_c = k \, 2\pi l \, \Delta T / \ln \frac{R_T}{R}$$

where k = thermal conductivity of plasma, ΔT = temperature difference between plasma and containing wall, R_T = containing tube radius. (9)

Then the heat balance can be written

$$W = Q_R + Q_c \qquad (10)$$

Problem then becomes,

Given R_T, l, and a constant input power, what is R for hydrogen, nitrogen and argon.

The method is an iterative one. First choose R_{H_2}. Then from equation (7) find ratio of ionization. From this the plasma temperatures may be obtained. Equations (8) and (9) give the energy losses

where $\sigma = 5.71 \times 10^{-15}$ kW/cm^2 $^oK^4$

$k_{H_2} = 7 \times 10^{-5}$ kW/cm^2 ^oK/cm

$k_{N_2} = 2 \times 10^{-5}$ kW/cm^2 ^oK/cm

$k_{Ar} = 0.6 \times 10^{-5}$ kW/cm^2 ^oK/cm

This iterative process has been used to calculate the dimensions of hydrogen, nitrogen and argon plasma in a 6 in. diameter containing tube with a constant input power of 31.3 kW and a length of 4 in.

Plasma Gas	Radiation Loss	Conduction Loss	Plasma Diameter in a 6 in. tube
Hydrogen	7.1 kW	24.2 kW	.75 in.
Nitrogen	13.6 kW	17.7 kW	3 in.
Argon	21.5 kW	9.8 kW	4.75 in.

The thermal pinch effect in hydrogen is most evident.

This analysis, as stated before, is a development of vonEngel's suggestion for a dc arc. The effect of radio frequency heating is an interesting extension.

The one turn gas load model yields a current density

$$j = i/\ell\varepsilon$$

where ε = skin depth $= \frac{1}{2\pi}\sqrt{\frac{\rho}{f}}$ (11)

So $$x \propto i/\ell\varepsilon X \qquad (12)$$

Now $$e = 2\pi R X \qquad (13)$$

Therefore $$x \propto \frac{W}{\ell\varepsilon X^2 2\pi R} \qquad (14)$$

Also $$\varepsilon \propto \rho^{1/2} \propto 1/N_e^{1/2} \propto 1/x^{1/2} \qquad (15)$$

So $$x \propto \frac{W^2}{R^2 X^4} \qquad (16)$$

So

$$\frac{x_{H_2}}{x_{N_2}} = 10^{-4}\left(\frac{R_{N_2}}{R_{H_2}}\right)^2 \tag{17}$$

(compare with eq. 7)

Calculations using equation (17) reveal that the degree of ionization for a hydrogen plasma is extremely small for the same power to produce 10 percent ionization in nitrogen. No plasma can exist until the power is increased appreciably and will not be sustained until a specific value is reached. A conclusion which may be drawn is that thermal pinch which is evident in dc arcs is even more apparent in rf plasma systems. This again supports the experimental evidence that it is very difficult to sustain a pure hydrogen plasma with radio frequency energy.

SPECIAL REQUIREMENTS FOR A PLASMA LOAD

In order to sustain a discharge, a certain electric field strength has to be maintained within the plasma. The gas load takes the form of a one turn gas coil with a variable electric resistivity.

Assume that a current i flows in this turn. The minimum voltage around the turn is e

where

$$e = E_s \pi d \tag{18}$$

and E_s is the required field strength for sustaining the plasma. This field strength is a function of the current i and over a certain range the following approximate relationship holds

$$i = J / E_s^4 \tag{19}$$

Ref. vonEngel, <u>Ionized Gases</u>, Oxford Univ. Press, 1965, p. 262

The resistance of the gas load is therefore

$$r = e/i = \frac{E_s^5 \pi d}{J} \tag{20}$$

but r can also be expressed in terms of the skin thickness

$$r = \frac{\pi d \rho}{l \varepsilon} = 2\pi^2 \frac{d}{l} \rho^{1/2} f^{1/2} \tag{21}$$

The resistivity of the gas load, ρ is a function of the sustaining voltage and the induced current (vonEngel).

$$\rho \approx \frac{10 E_s}{i} = \frac{10 E_s^5}{J} \tag{22}$$

Eliminating r from the above equations (20, 21 and 22)

$$r = 2\pi^2 \frac{d}{l} \sqrt{10} \frac{E_s^{5/2} f^{1/2}}{J^{1/2}} = \frac{E_s^5 \pi d}{J} \tag{23}$$

Required power to sustain the discharge

$$W_{REQ} = ei = \frac{E_s \pi d J}{E_s^4} \tag{24}$$

So

$$W_{REQ} = \frac{\pi d J}{E_s^3} \tag{25}$$

Therefore

$$W_{REQ} = \frac{\pi}{(2\pi)^{6/5}} \cdot \frac{J^{2/5}}{10^{3/5}} \cdot \frac{d\ell^{6/5}}{f^{3/5}} \tag{26}$$

So

$$W_{REQ} = 8{\cdot}7 \times 10^{-2} \, J^{2/5} \, \frac{d\ell^{6/5}}{f^{3/5}} \tag{27}$$

As this analysis involves physical and electrical parameters, units and dimensions are most important. Absolute cgs units are employed here unless otherwise stated.

For argon $\quad J = 6.25 \times 10^{35} \qquad J^{2/5} = 2.05 \times 10^{14}$ (28)

So

$$W_{req} = \frac{d\,\ell^{6/5}}{f^{3/5}} \times 1.78 \times 10^{13} \tag{29}$$

In absolute units for $d = 5$ cm, $l^{6/5} = 10$ and $f = 4 \times 10^6$

$$W_{req} = 9.75 \times 10^{10} \text{ erg/sec} = \underline{\underline{9.75 \text{ kW}}} \tag{30}$$

For hydrogen $J = 2.56 \times 10^{39}$ $J^{2/5} = 5.8 \times 10^{15}$ (31)

So $$W_{req} = 5.05 \times 10^{14} \frac{d\ell^{6/5}}{f^{3/5}}$$

$$W_{req} = 27.6 \times 10^{11} \text{ erg/sec} = \underline{\underline{276 \text{ kW}}} \quad (32)$$

Therefore it requies 28.3 times the power to sustain a hydrogen discharge

So $$W_{req} = \frac{d\ell^{6/5}}{f^{3/5}} \quad (33)$$

and as a function of frequency, this shows that 3.7 times more power is required at 450 KHz than at 4 MHz and 2.6 times less at 20 MHz. The minimum sustaining powers calculated above are not absolute values due to simplifying assumptions made in the theory. However, the ratio of the sustaining powers as a function of frequency can be relied upon with a degree of certainty since this ratio is independent of these assumptions.

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TABLE I

HIGH POWER INDUCTION PLASMA TESTS

(a) 6 IN. TORCH WITH SHEATH OPERATION

Table Run No.	1	2	3	4	5	6	7	8	9	10
Torch diameter - inches i.d.	6"	6"	6"	6"	6"	6"	6"	6"	6"	6"
Coil diameter - inches i.d.	7-3/4"	7-3/4"	7-3/4"	7-3/4"	7-3/4"	7-3/4"	7-3/4"	7-3/4"	7-3/4"	7-3/4"
No. coil turns	6	6	6	6	6	6	6	6	6	6
Frequency KHz	460	465	--	--	--	--	--	--	--	--
Core gas type	Ar.	Ar.-N_2	Ar.-N_2	Ar.-N_2	Ar.-N_2	Ar.	Ar.	N_2	N_2	N_2
Core gas flow SCFH	786	769 368N_2	787 381N_2	787 381N_2	787 381N_2	413	787	795	795	795
Sheath gas type	Air	Air	Air	Air	Air	Air	Air	--	--	--
Sheath gas flow SCFH	750	2200	2200	2200	2200	2200	2200	0	0	0
Plate power input - kW	159	293	425	533	699	721	967	192	664	856
Metal separator loss %	--	8.8	8.6	8.4	8.3	7.5	8.4	--	5.8	5.9
Metal wall loss %	--	24.9	24.5	27.3	25.2	20.7	26.2	--	19.5	17.0
Total torch loss %	38.6	33.7	33.1	35.7	34.1	27.8	34.6	26.1	25.2	23.4
[1]Power unit loss %	42.8	37.2	33.5	33.2	33.1	33.5	32.4	33.0	33.5	33.5
Total loss %	81.4	71.0	66.7	69.0	67.2	61.4	67.0	59.0	58.8	56.9
Power in plasma leaving torch %	18.6	29.0	33.4	31.2	33.0	38.5	33.0	41.1	41.4	43.2
[2]Power to arc %	54.2	59.7	63.5	63.9	64.1	63.3	64.6	64.2	63.6	63.6
Exit gas enthalpies Btu/lb. gas	--	1300	2160	2520	3500	4800	4880	4670	16,200	21,800
	1	6	7	8	9	10	15	19	16	17

[1]Includes oscillator tube, tank circuit and load coil

[2]Exit plasma % + torch loss % -3%, 3% allows for eddy heating of torch walls

TABLE I

HIGH POWER INDUCTION PLASMA TESTS - Continued

(b) $4\frac{1}{2}$ IN. TORCH WITH NO SHEATH OPERATION

Table Run No.	11	12	13	14	15	16	17	18	19	20
Torch diameter - inches i.d.	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"
Coil diameter - inches i.d.	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"
No. coil turns	8	8	8	8	8	8	8	8	8	8
Frequency KHz	460	475	--	545	460	455	460	545	545	545
Core gas type	N_2	N_2	N_2	N_2	Oxygen	Oxygen	Oxygen	Air	Air	Air
Core gas flow SCFH	783	556	556	361	708	729	708	902	359	226
Sheath gas type	--	--	--	--	--	--	--	--	--	--
Sheath gas flow SCFH	0	0	0	0	0	0	0	0	0	0
Plate power input - kW	847	786	763	700	360	515	730	771	715	703
Metal separator loss %	2.5	7.4	--	5.3		3.9	4.5	2.5	4.4	7.1
Metal wall loss %	23.3	17.8	--	19.4		28.4	27.8	18.9	19.3	18.8
Total torch loss %	25.8	21.4	21.9	26.1		32.3	32.2	23.0	24.4	29.9
1)Power unit loss %	33.8	33.5	34.0	42.8		33.5	33.5	33.5	40.0	40.7
Total loss %	59.6	54.9	55.8	67.5		65.8	65.8	55.9	64.4	70.7
Power in plasma leaving torch %	40.5	45.1	44.2	33.5		34.1	34.5	44.4	35.6	29.3
2)Power to arc %	63.3	63.5	63.1	56.6		63.4	63.7	64.4	57.0	56.2
Exit gas enthalpies Btu/lb. gas	20,600	30,000	28,400	29,700		9900	14,520	17,200	32,400	41,700
Run number (original)	29	60	61	62	33	30	31	63	64	65
Average enthalpy temperature of exit gases °K / °F				12,500°K / 22,000°F	Minimum sustaining power					

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1) Includes oscillator tube, tank circuit and load coil

2) Exit plasma % + torch loss % -3%, 3% allows for eddy heating of torch walls

TABLE I

HIGH POWER INDUCTION PLASMA TESTS - Continued

(c) $4\frac{1}{2}$ IN. TORCH WITH SHEATH OPERATION

Table Run No.	21	22	23	24	25	26	27	28	29	30	31
Torch diameter - inches i.d.	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	4-1/2"	6"	6"
Coil diameter - inches i.d.	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	7-3/4"	7-3/4"
No. coil turns	8	8	8	8	8	8		12	18	10	
Frequency KHz	--	--	--	--	--	--	--	--	220	255	--
Core gas type	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.
Core gas flow SCFH	768	749	614	730	749	48	750	749	749	769	769
Sheath gas type	Air	Air	Air	Air	Air	Air	H_2	Air	H_2	Air	H_2
Sheath gas flow SCFH	2200	2200	2520	2520	2200	2340	3750	2130	0	2900	0
Plate power input - kW	309	629	778	864	870	770	480	480	476	378	356
Metal separator loss %	5.1	5.2	5.1	4.8	4.9	11.2		10.4	7.9	11.2	
Metal wall loss %	28.0	28.0	25.7	26.9	28.1	19.2		32.1	42.4	27.2	
Total torch loss %	36.0	34.0	30.9	31.7	32.5	30.4		42.5*	50.4*	38.3*	
[1] Power unit loss %	35.3	33.5	36.4	36.3	34.6	33.5		22.7	25.6	25.2*	
Total loss %	71.3	66.4	66.4	67.9	67.0	64.0		65.3	76	63.4	
Power in plasma leaving torch %	28.9	33.8	33.6	32.2	33.2	36.2		34.8	23.9 .	36.6	
[2] Power to arc %	61.9	63.8	61.5	60.9	62.7	63.6		--	--	--	
Exit gas enthalpies Btu/lb. gas											
Run number (original)	24	25	53	52	26	59	43	42	47	48	50
						Core Gas Turn-down					

****

1) Includes oscillator tube, tank circuit and load coil

2) Exit plasma % + torch loss % -3%, 3% allows for eddy heating of torch walls

*Note coil water from these tests came from torch rather than power unit.

TABLE I

HIGH POWER INDUCTION PLASMA TESTS - Concluded

(d) 2 TO 5 IN. TORCH WITH NO SHEATH OPERATION

Table Run No.	32	33	34	35	36	37	38	39	40	41
Torch diameter - inches i.d.	5"	5"	5"	5"	3-1/2"	3-1/2"	3-1/2"	3-1/2"	3-1/2"	2"
Coil diameter - inches i.d.	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	6-1/4"	3-1/4"
No. coil turns	4	4	4	4	4	4	4	4	4	4
Frequency KHz	--				600	600	605	--	--	--
Core gas type	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.	Ar.
Core gas flow SCFH	768	796	796	796	730	730	826	826	826	280
		$46N_2$	$46N_2$	$46N_2$						
Sheath gas type	--	--	--	--	--	--	--	--	--	--
Sheath gas flow SCFH	0	0	0	0	0	0	0	0	0	0
Plate power input - kW	405	500	485	485	324	624	605	790	850	54
Metal separator loss %	22.6	22.4	20.6	Same	21.8	20.8	21.3	21.9	--	24.6
Metal wall loss %	0	0	0	Settings	0	0	0	0		0
Total torch loss %	22.6	22.4	20.6	As	21.8	20.8	21.3	21.9	--	24.6
1)Power unit loss %	37.0	40.8	33.6	Previous	43.7	33.5	34.8	37.9	--	30.7
Total loss %	59.7	63.1	54.3	Run	55.5	54.2	56.0	59.8	--	55.4
				Changed						
Power in plasma leaving torch %	40.2	36.8	45.8	Angle of	44.4	46.0	44.0	40.2	--	44.6
2)Power to arc %	59.8	56.2	63.4	Radiation	63.2	63.8	62.3	59.1	--	72.3
				Head					40%	
Exit gas enthalpies Btu/lb. gas	7000	7640	9200		6500	12,920	11,650	12,700	13,600 Est.	
Run number (original)	20	21	22	23	34	36	66	68	67	DB9 P22
Millivolts Brown recorder	10.9	13.0	13.0	31.7	74.9	121	73	97	102	19.7
Average enthalpy temperature of exit gases °K						16,400°K				
°F						29,000°F				

****

1) Includes oscillator tube, tank circuit and load coil

2) Exit plasma % + torch loss % -3%, 3% allows for eddy heating of torch walls

TABLE II

EXPERIMENTAL MINIMUM SUSTAINING PLATE POWERS (MSP) FOR VARIOUS GASES

Gas	Frequency	Experimentally determined MSP (kW plate power)	
Gas velocity[a] fps		High gas flow 8.0	Low gas flow 0.5
Argon	4 MHz	1.5[b]	--
Argon	450 KHz	5[b]	--
Nitrogen	4 MHz	28[b]	5[b]
Nitrogen	450 KHz	120[b]	21[c]
Hydrogen	4 MHz	250[d]	60[b]

[a]Cold plasma forming gas velocity
[b]Experimentally determined
[c]Estimate
[d]Extrapolated from argon-hydrogen mixture data

TABLE III

PERFORMANCE OF INDUCTION PLASMA SYSTEM AT ONE ATMOSPHERE

Gas type & SCFH	Plate kW	% Plate kW to torch	% Plate kW leaving torch	Mean exit enthalpy Btu/lb.	Torch dia. inches
730 Ar.	624	20.8	46.0	12,920	3.5
730 ar.	324	21.8	44.4	6,500	3.5
280 Ar.	54	24.6	44.6	7,930	2.0
340 Ar.	80	23.1	50.1	3,890	1.0
226 Air	703	29.9	29.3	41,700	4.5
359 Air	715	24.4	35.6	32,400	4.5
902 Air	771	23.0	44.4	17,200	4.5
185 Air	73	16.0	56.0	10,000	2.0
120 Air	72	16.1	55.0	15,000	2.0
40 Air	75	31.9	37.8	31,900	1.0
120 Air	80	21.8	50.0	18,700	1.0
556 N_2	786	21.4	45.1	30,000	4.5
795 N_2	856	23.4	43.2	21,800	6.0

TABLE IV

SHEATH GAS SYSTEM PERFORMANCE
(3" at 4 MHz and 4.5 and 6" at 450 KHz)

Torch dia.	Plate kW	% Plate kW to torch	% Plate kW leaving torch	Argon core SCFH/dia. inches	Sheath type SCFH	Buffer gas type/ SCFH
3	87.5	28.6	45.7	120/2	H_2/3100	H_2/1000
3	84.2	28.6	43.0	120/2	H_2/3100	H_2/850
3	72.2	30.2	39.2	120/2	H_2/2800	0
6	159	38.6	18.6	787/5	Air/750	0
6	293	29.0	29.0	787/5	Air/2200	0
6	425	33.1	33.4	787/5	Air/2200	0
6	721	27.8	38.5	413/5	Air/2200	0
6	967	34.6	33.0	787/5	Air/2200	0
4.5	629	34.0	33.8	749/3.5	Air/2200	0
4.5	870	32.5	33.2	749/3.5	Air/2200	0
4.5	770	30.4	36.2	48/3.5	Air/2340	0

TABLE V

PERFORMANCE OF 1.1" I.D. METAL WALL TORCH ON HYDROGEN, AIR AND HELIUM

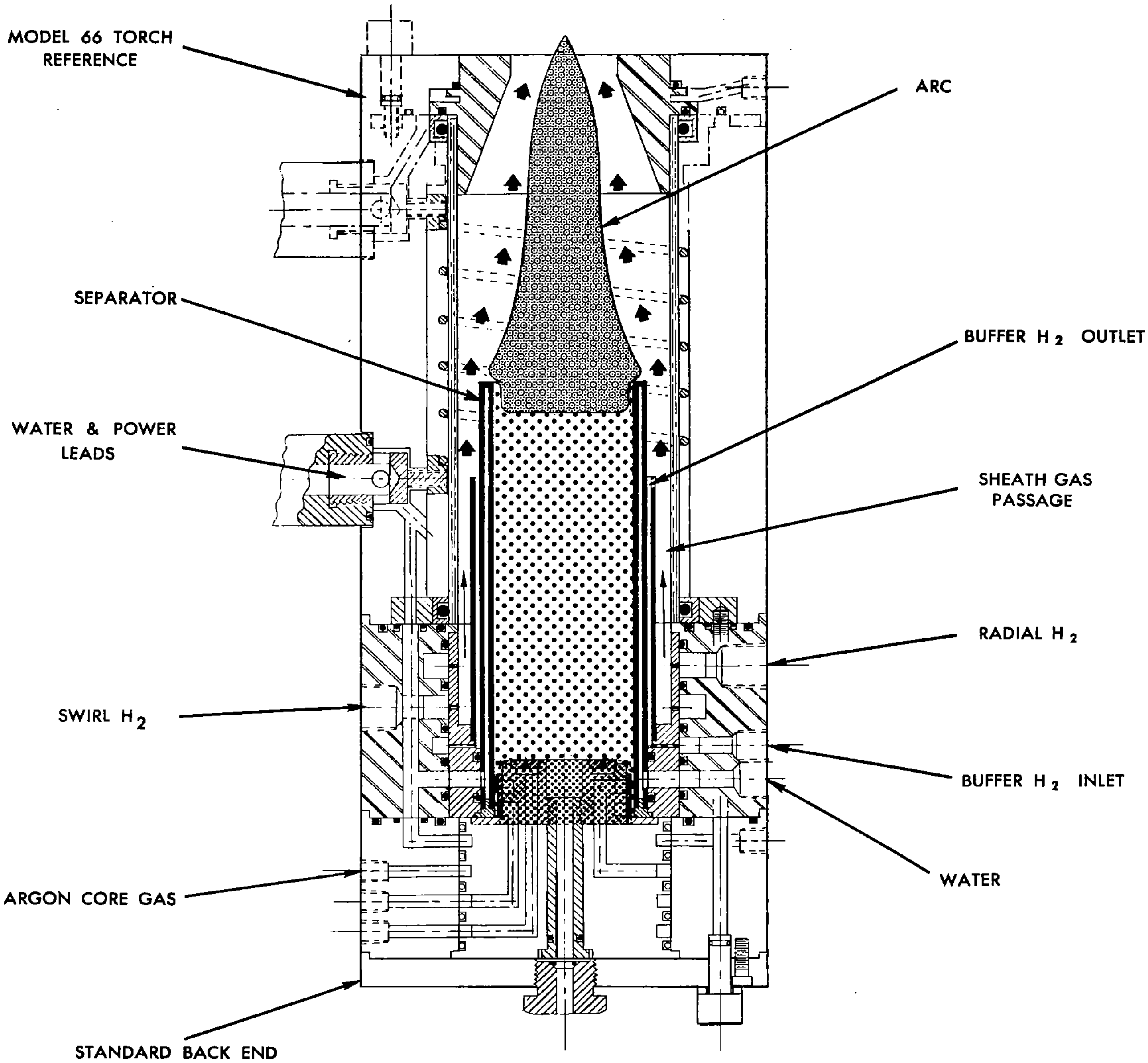
Operating point[a]	Hydrogen A	Typical air	Hydrogen B	Hydrogen C	Helium
kW plate power	110.1	95.0	114.1	103.7	57[b]
dc kilovolts	11.6	9.5	10.1	9.7	--
dc amperes	9.5	10	11.3	10.7	--
Work coil turns[c]	7	8	7	7	7
Torch i.d. inches	1.1	1.1	1.1	1.1	1.1
Gas flow SCFH	10.0	115	6.0	4.5	60
% to oscillator tube	38.2	38.0	38.6	38.6	45.7
% to metal wall	40.3	25.3	41.4	40.3	43.2
% to coil and gas injector	7.7	6.2	7.1	6.75	3.86
% to exit gas[d]	13.8	30.0	12.8	14.38	7.38 MSP[b]
Average exit gas enthalpy Btu/lb.	591,000	11,100	1,594,000	2,162,000	23,200

[a]Letters refer to operating point on Fig. 13
[b]Minimum sustaining power; plasma extinguished below this power level
[c]1.5 in. i.d.
[d]% of plate power in exit gas

TABLE VI

PERFORMANCE OF AIR IN TORCH USED FOR PURE HYDROGEN OPERATION, EFFECT OF GAS FLOW ON EXIT GAS EFFICIENCIES
(1.1" i.d. metal wall, 7 turn coil)

Air flow SCFH	10	23	46	90	230
kW plate power.......	75.0	74	81	92	99
% to oscillator........	48.0	51.4	44.5	43.5	34.4
% torch and coil......	47.0	42.3	38.7	29.0	25.8
% gas...............	5.05	6.4	16.9	27.0	40.2



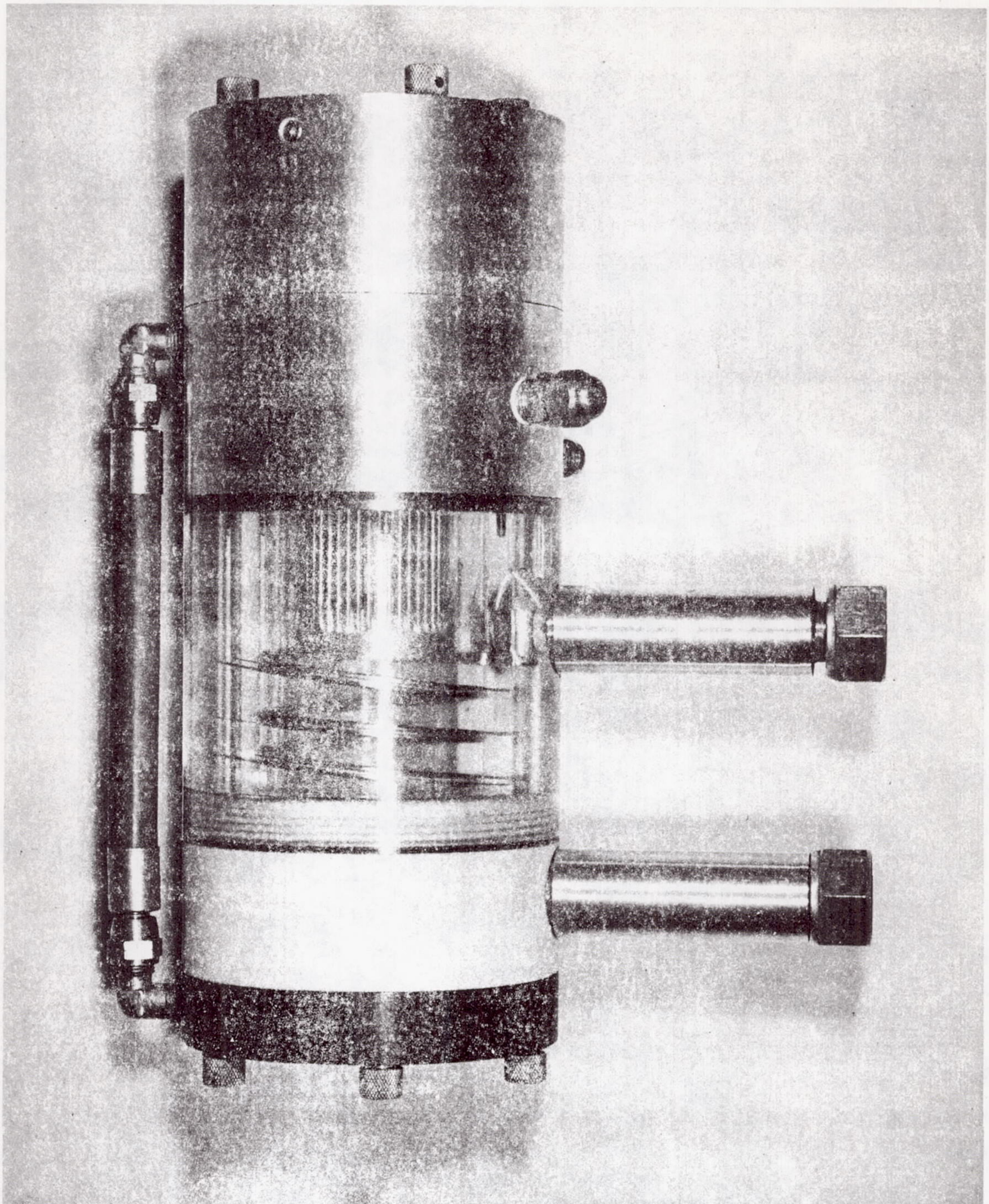
THREE INCH SHEATH GENERATOR

ARGON CORE GAS

PLASMA ARC

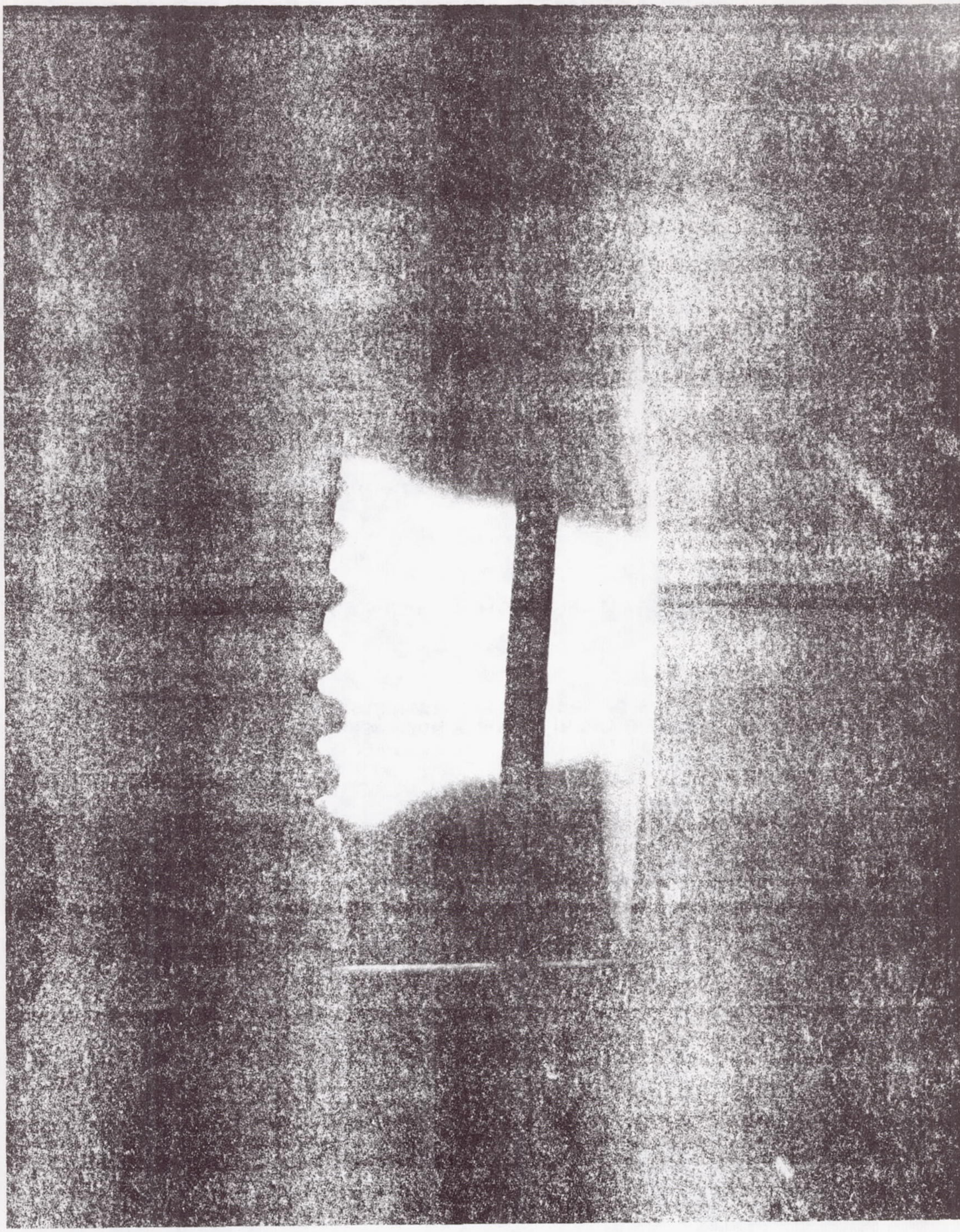
SHEATH GAS FLOW

FIG. 1



MODEL 66 TORCH WITH 2 IN. METAL SEPARATOR
(SEE FIG. I FOR CROSS SECTION)

FIG. 2



3 IN. SHEATH SYSTEM OPERATING
(120 SCFH ARGON, 5000 SCFH HYDROGEN)

FIG. 3

VARIATIONS OF ARC SIZE IN SHEATH SYSTEM WITH HYDROGEN-ARGON RATIOS IN MODEL 66 TORCH (3" TUBE)

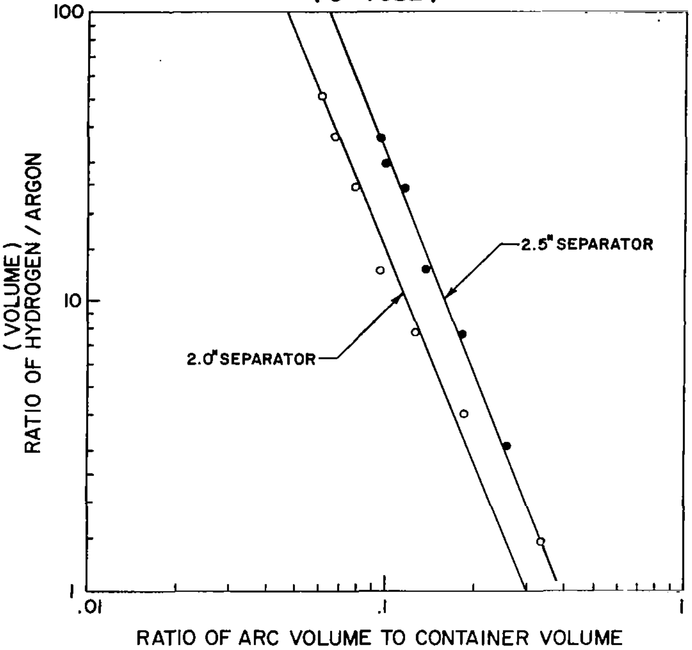


FIG. 4

VARIATIONS OF ARC SIZE IN SHEATH SYSTEM WITH HYDROGEN-ARGON RATIOS IN MODEL 66 TORCH (3" TUBE) USING 2" METAL WALL

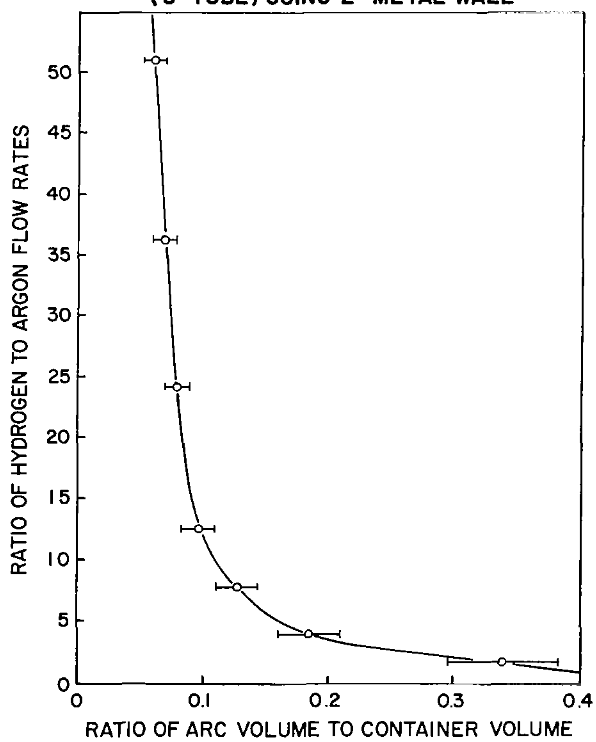


FIG. 5

FLUID MECHANIC LIMITS OF INDUCTION PLASMA SHEATH SIMULATOR

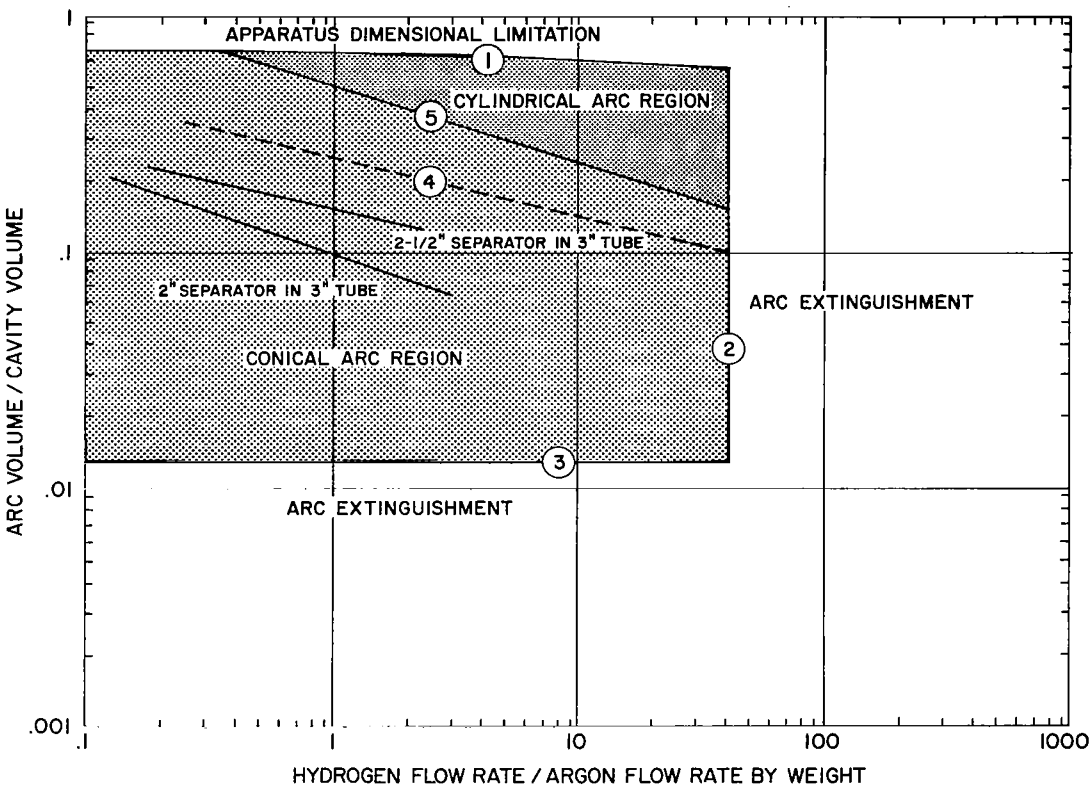


FIG. 6

PERCENT OF PLATE POWER COUPLED TO 1.9" O.D. STEEL LOAD VS. LOAD COIL TURNS (3.3" I.D.) USING LEPEL 90 KW PLATE POWER SUPPLY – EACH CAPACITOR 5400 X 10^{-12} FARADS
Z = TANK CIRCUIT IMPEDANCE

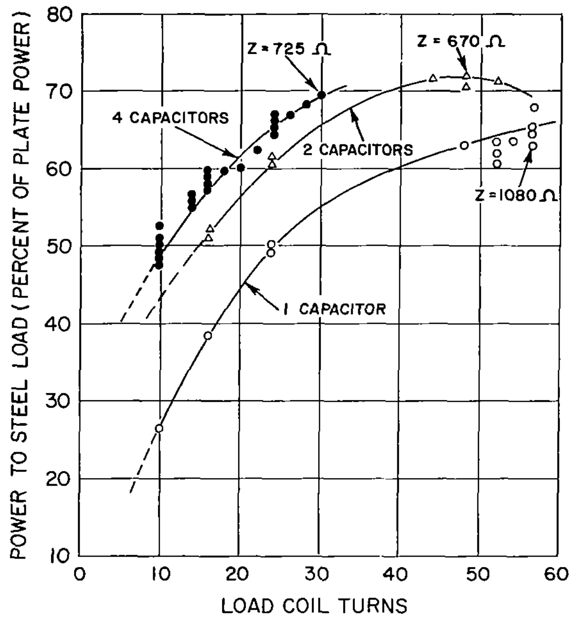


FIG. 7

VARIATION OF EFFICIENCY WITH OSCILLATOR CIRCUIT IMPEDANCE THEORETICAL AND EXPERIMENTAL FOR 90 KW PLATE POWER SUPPLY WITH 3.3" I.D. COIL AND 1.9" DIAMETER STEEL LOAD AT FREQUENCIES FROM 200 – 450 KHz.

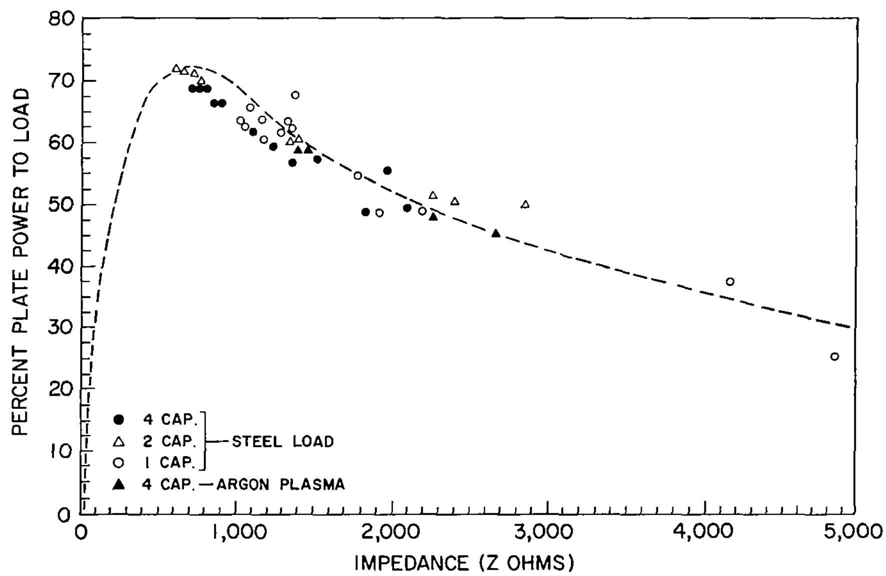
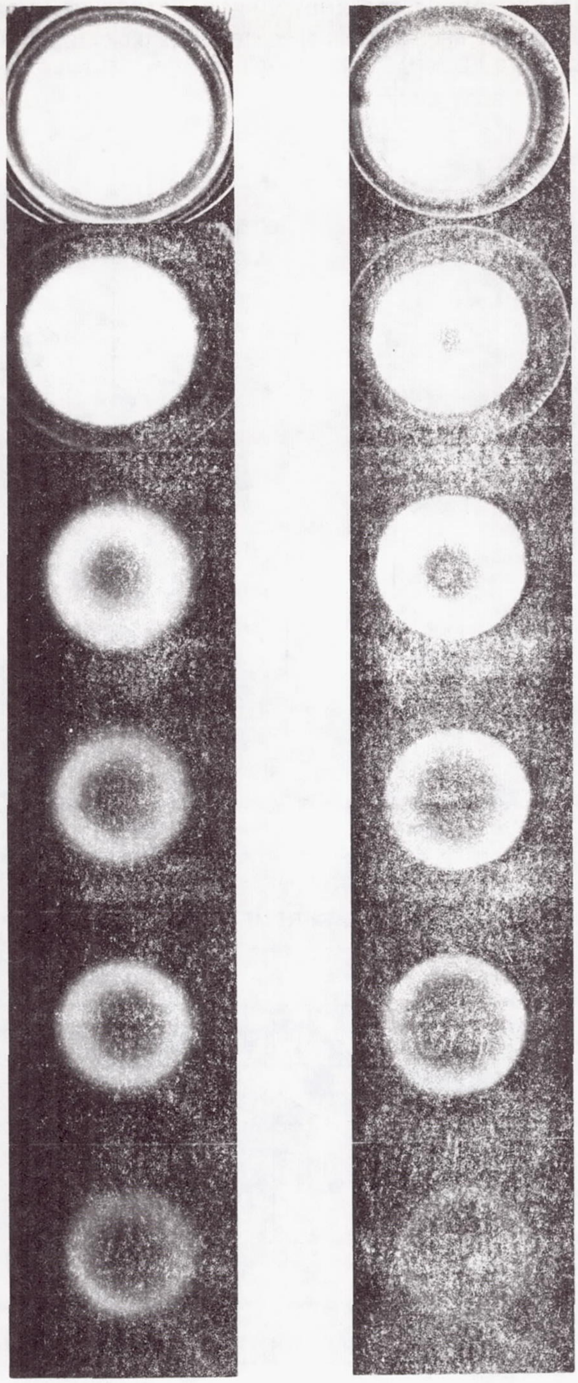


FIG. 8



END VIEW OF INDUCTION ARC, SHOWING EFFECT OF FREQUENCY ON SKIN DEPTH OPERATIONS AT 4 MH_Z (RIGHT COLUMN) AND 450 KH_Z (LEFT COLUMN)

FIG. 9

THERMAL CONDUCTIVITY RESPONSE FOR KNOWN PERCENTAGES OF HYDROGEN IN ARGON

TO BRIDGE OUTPUT FOR ARGON CARRIER, PERCENTAGES INDICATE H_2 IN ARGON, SAMPLE 2-1/2 ML., SMALL PEAKS INDICATE SAMPLE INJECTION

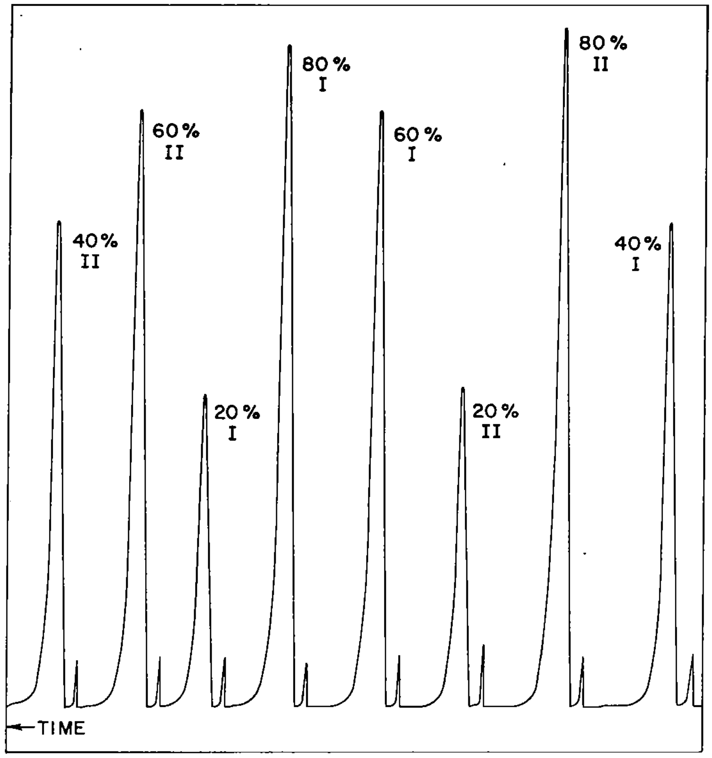


FIG. 10

CALIBRATION CURVE FOR MEASUREMENT OF HYDROGEN IN ARGON

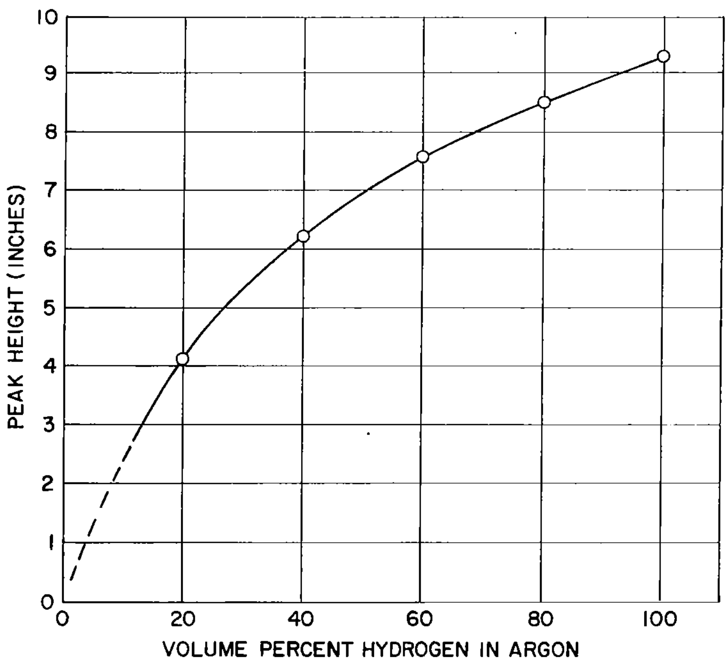


FIG. 11

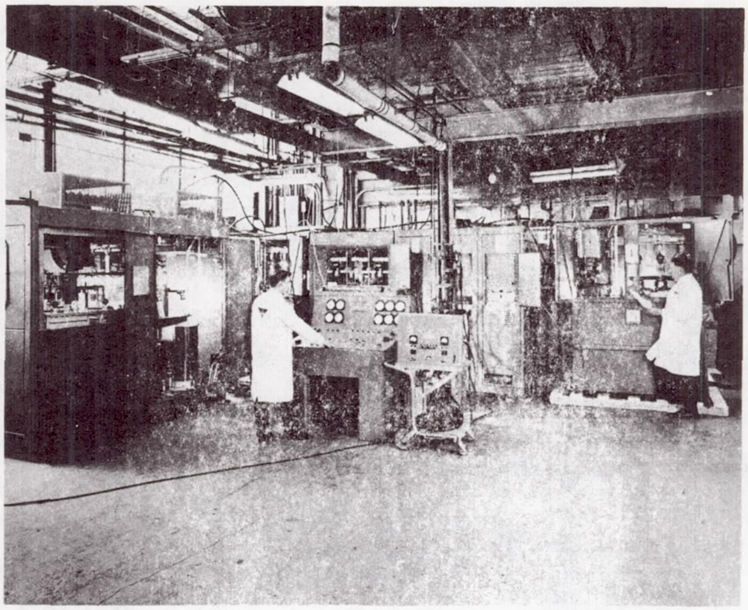


FIG. 12

1000 KW PLATE POWER 450 KH_z POWER UNIT USED FOR TESTING

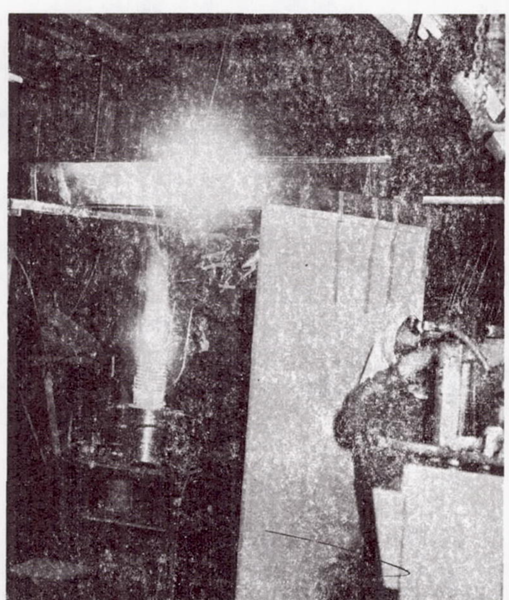
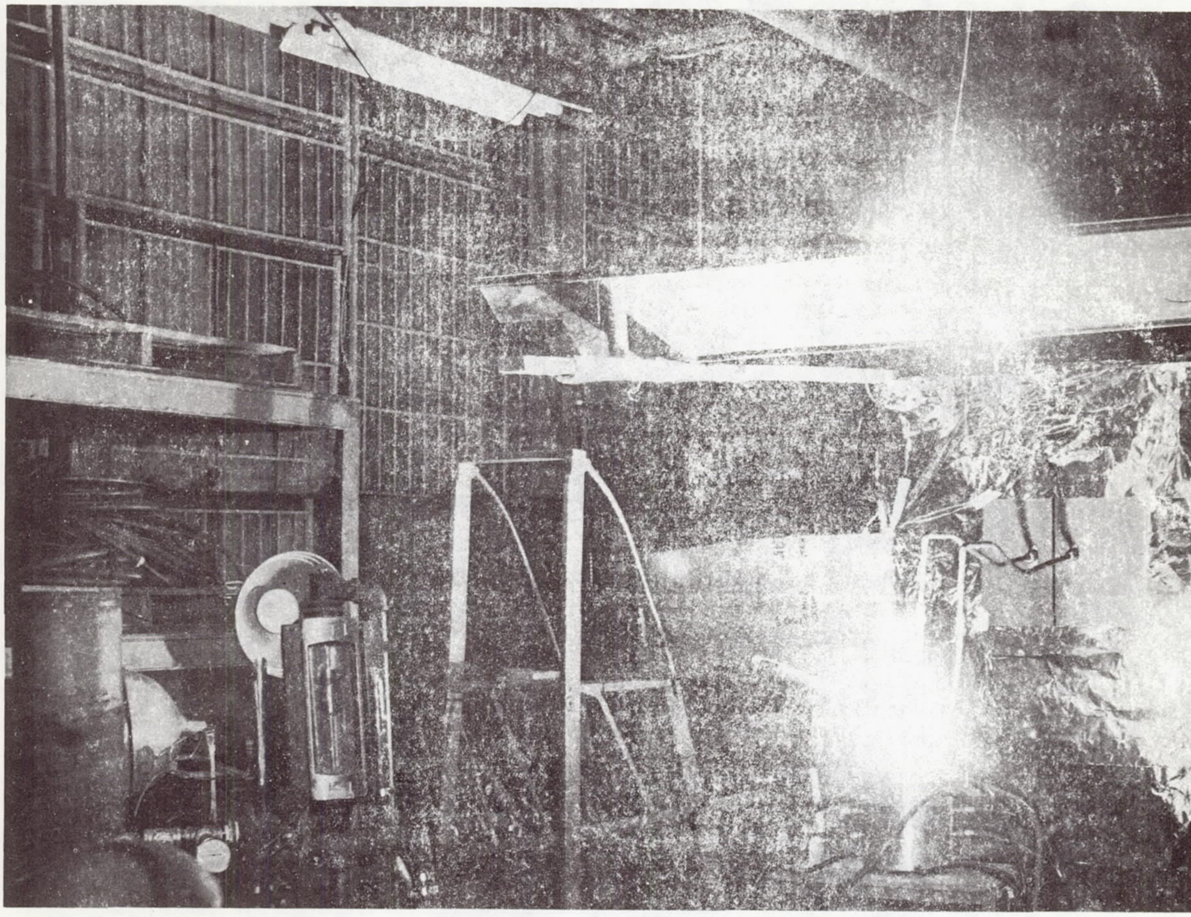


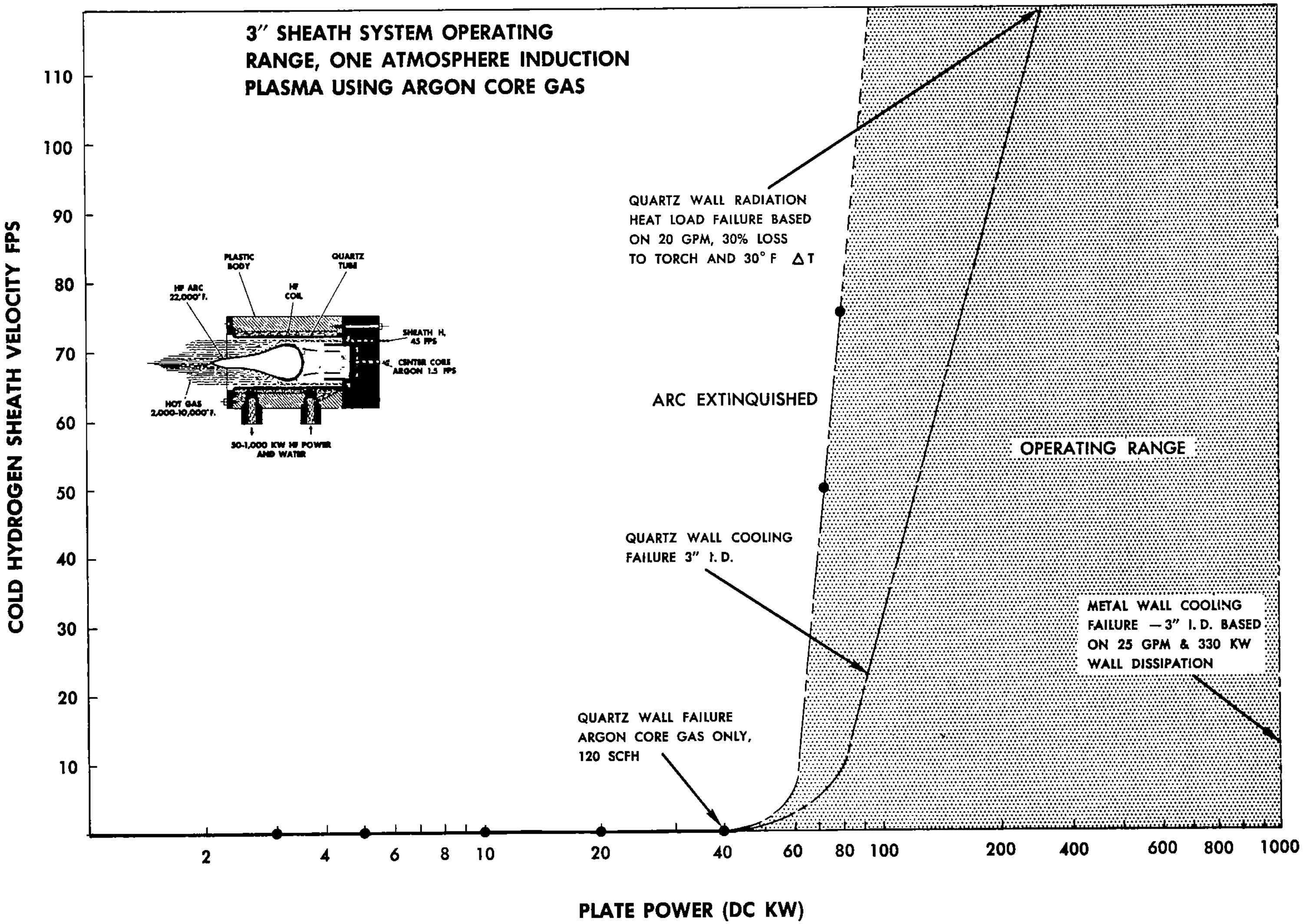
FIG. 13

6 IN. TORCH OPERATING IN SHEATH MODE AT 533 KW
(SEE RUN 4, TABLE I)



3.25 IN. METAL SEPARATOR OPERATING AT 324 KW
WITH MONITORING RADIATION HEAD
(SEE RUN 36, TABLE I)

FIG. 14



● EXPERIMENTAL DATA

FIG. 15

ATTACHED TO 190 KW UNIT

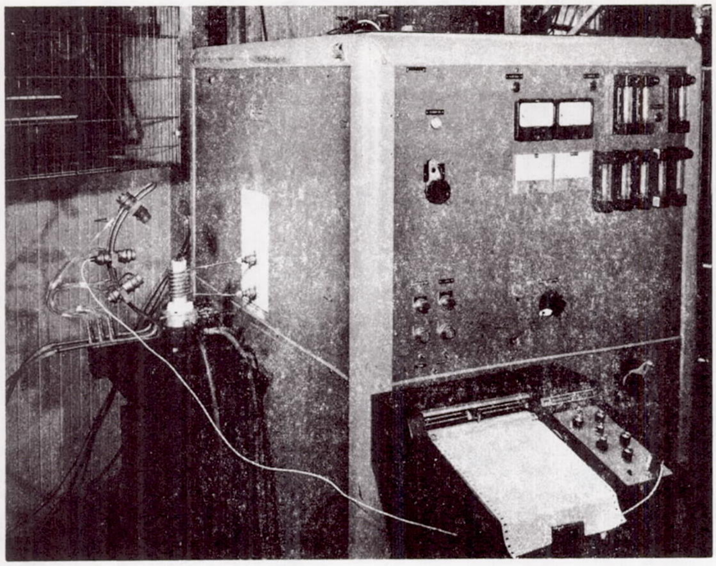


FIG. 16

STABILITY LIMITS FOR PURE HYDROGEN AS A FUNCTION OF GAS FLOW RATE & PLATE POWER USING 1.1" TORCH & TAFA 32 X 100 MC POWER UNIT

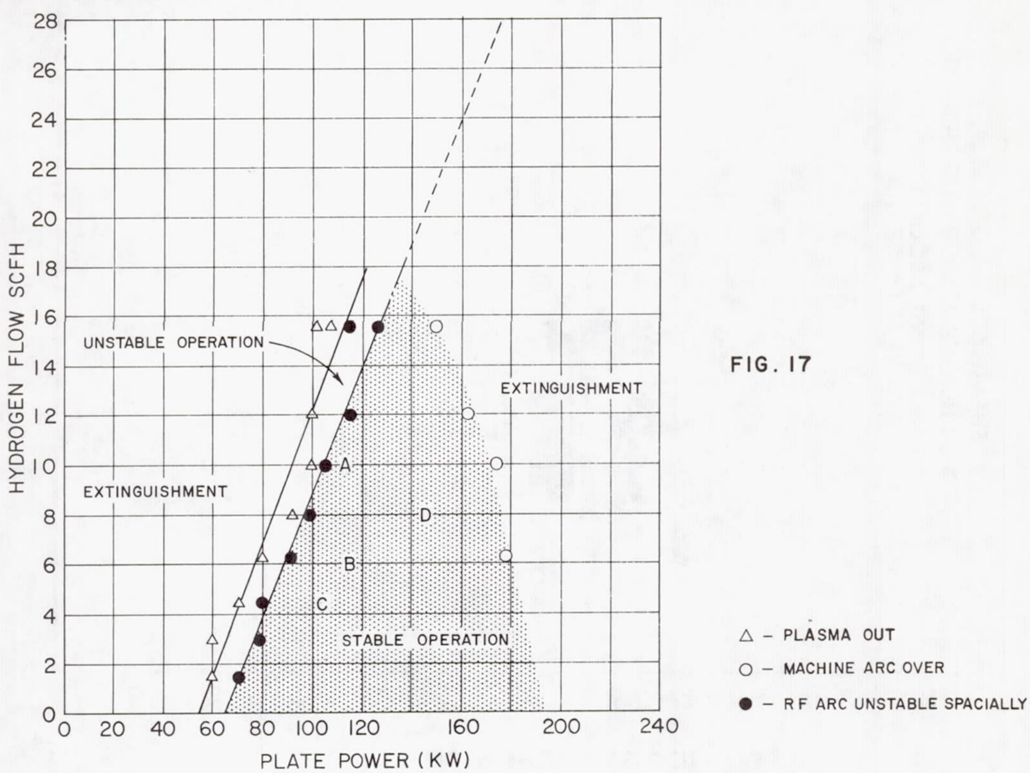


FIG. 17

EFFECT OF GAS FLOW THROUGH 1.1" TORCH ON MINIMUM SUSTAINING POWER

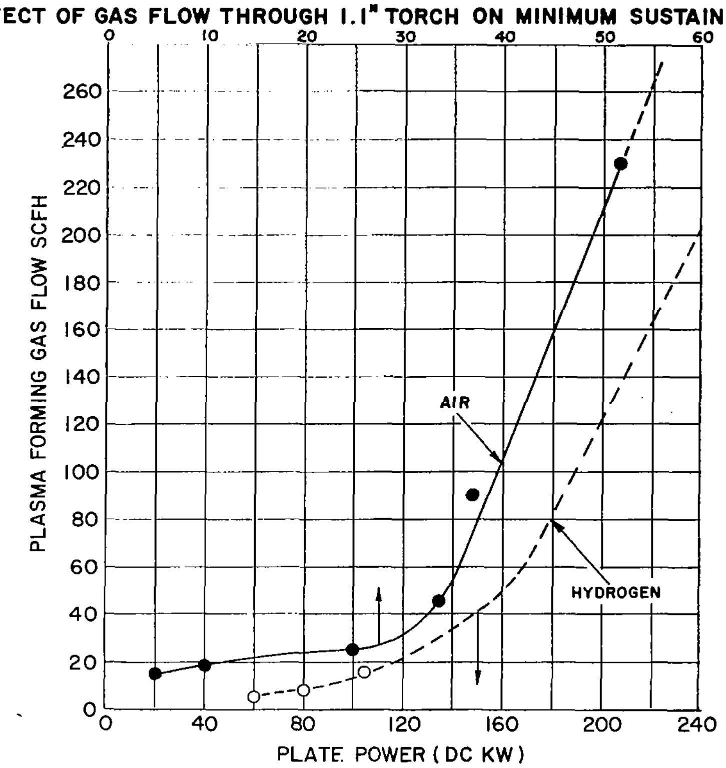


FIG. 18

MAXIMUM OPERABLE PERCENTAGE OF HYDROGEN IN ARGON AS A FUNCTION OF PLATE POWER

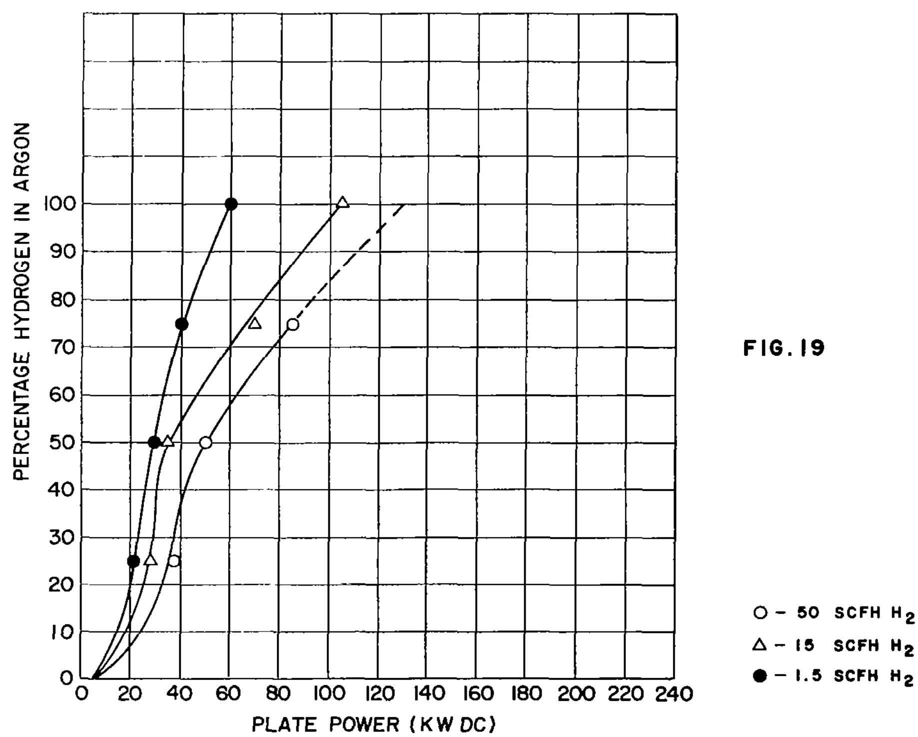
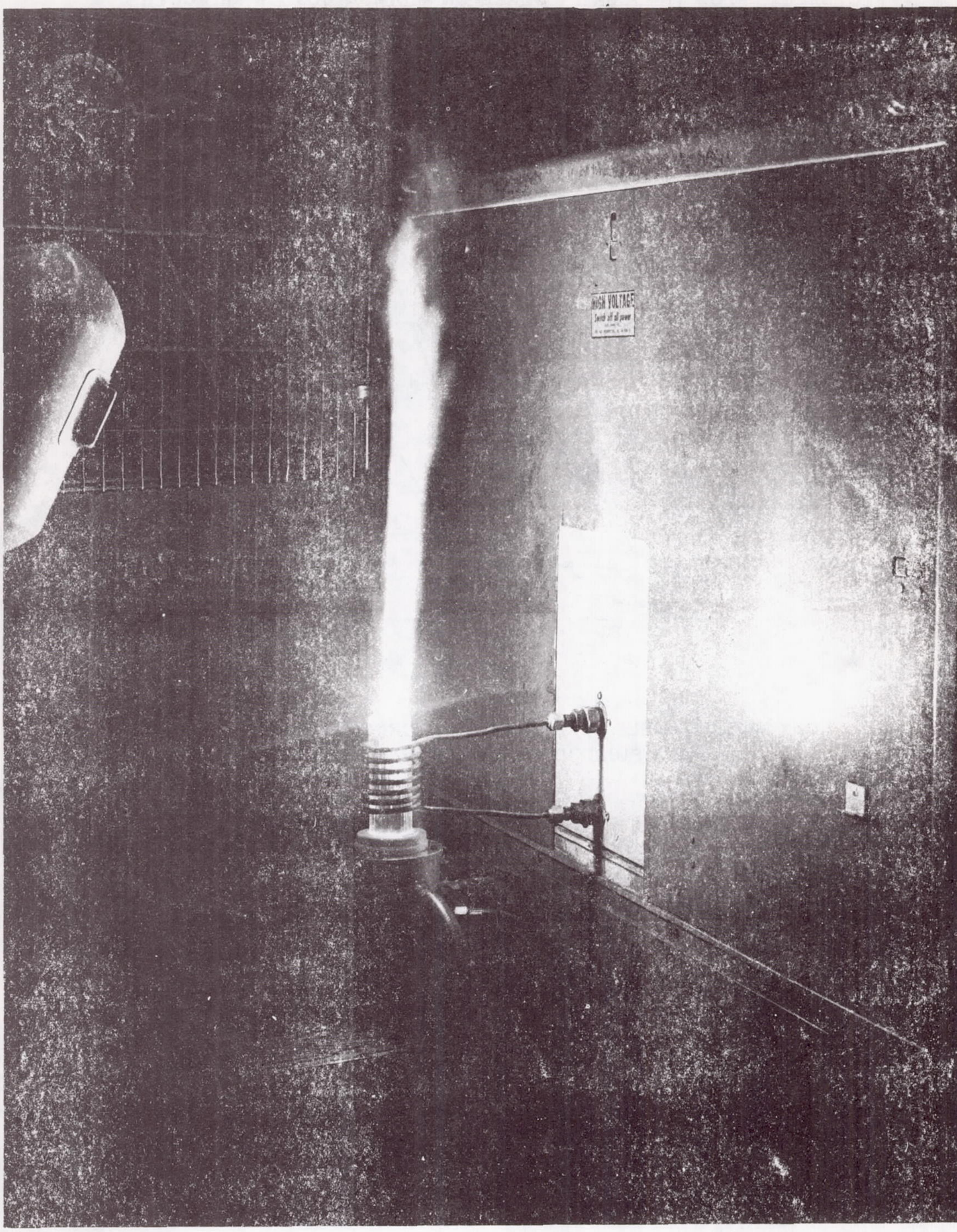


FIG. 19



PURE HYDROGEN OPERATION WITH 1.1 IN. I.D. METAL SEPARATOR
100 KW, 6 SCFH HYDROGEN

FIG. 20

NASA-Langley, 1969 —— 22 E-4797