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INDUCTION PLASMA HEATING:

System Performance, Hydrogen Operation and Gas Core Reactor Simulator Development

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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 Manger for NASA.

ABSTRACT

The induction plasma heating system has been studied and optimized. A reliable 80 kW 3 in. diameter sheath system has been developed which permits efficiently heating argon core gas to arc temperatures surrounded by a high velocity sheath of hydrogen. This unit will permit studies of mixing, fuel addition and other related phenomena associated with such a heat addition system. Other studies of hydrogen heating and particle injection into the arc are described.

INDUCTION PLASMA HEATING: SYSTEM PERFORMANCE, HYDROGEN

OPERATION AND GAS CORE REACTOR SIMULATOR DEVELOPMENT

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SUMMARY

The objectives of this experimental program were first to demonstrate pure hydrogen heating with an induction device and thereby produce large diameter high temperature hydrogen streams so that absorption studies could be made, and secondly, develop an induction plasma heating system which would permit pumping large amounts of power into a low velocity argon core surrounded by a high velocity sheath of hydrogen, this latter system to act as a simulator for a gas core nuclear reactor and thereby permit studies of mixing, heat addition, radiation and gas retention times within such a proposed reactor motor.

The induction heating system has been carefully studied calorimetrically and its performance optimized. Devices have been developed to permit continuous operation on premixed mixtures of hydrogen-argon up to 70 percent with overall power coupling efficiencies in the range of 70 percent. It has also been demonstrated that either higher powers than 60 kW at 4 MHz or higher frequencies will be required to achieve pure hydrogen operation at one atmosphere with this type of gas heating device.

A 3 in. diameter high velocity hydrogen-argon sheath simulator has been operated at 4 MHz and 60 kW r.f. using 120 SCFH of argon and over 4,000 SCFH of hydrogen at one atmosphere. At the beginning of this program a design objective of 30:1 hydrogen to argon velocity ratio with equal areas of sheath and central argon core was established. A continuously operating, reliable system has been developed with this capability.

INTRODUCTION

The gas core reactor is one of the schemes proposed for high thrust deep space propulsion. Such a system is schematically shown in Fig. 1. It will involve a fissioning core of uranium producing a temperature in the order

of 50,000°K. with a cool sheath of hydrogen surrounding it to carry away the heat and act as the propulsion fluid. The hydrogen gas will be seeded with a material like carbon black to approximately 3 percent by weight. Thus, carbon black will absorb energy from the uranium and heat the hydrogen and will also act as a radiation shield to prevent overheating of the chamber walls.

In anticipation of the possible development of the gas core reactor or other nuclear propulsion devices using hot hydrogen, basic knowledge will be required in areas of the mixing and stabilization mechanisms which are likely to occur in such a unit, the attainment of a long retention time of material in the central heat generation core, maximizing the ratio of hydrogen consumed per pound of fissioning material, and the amount of heat absorbed by clean and seeded hydrogen under such high radiant flux conditions.

This experimental program was undertaken for two main reasons: first, the induction plasma generator is a unique electric simulator of the nuclear gas core reactor; and secondly, the induction plasma generator operating on pure hydrogen would produce large diameter high temperature hydrogen streams which can be used for transmissivity studies to furnish a more basic understanding of the properties of hydrogen used in such propulsion devices.

Fig. 2 shows the similarity of the induction plasma gas heater to the proposed gas core reactor. Electrical energy is coupled into the hot central core by an intense high frequency field, generated by the coil surrounding it. A low velocity core of argon simulates the uranium and the high velocity sheath of hydrogen gas is blown by the hot core removing heat and protecting the containment walls. Once perfected, the simulator presents a unique electrical method of simulating the central core heat addition mechanism and provides a model for studying mixing, radiation, and other related phenomena to permit a better understanding of important mechanisms and to check existing mathematical model predictions. Once the simplified electrical model is understood and operating within desired operating limits it can obviously be made more like the proposed gas core reactor by use of porous or louvered walls, properly shaped exit nozzles and higher chamber pressures.

As mentioned previously, the second objective of this program involves operating an induction plasma system on pure hydrogen at high exit plasma enthalpies.

At the beginning of this program, to our knowledge, no one had ever run the sheath gas or pure hydrogen induction heating systems proposed and discussed above. The TAFA Division of Humphreys Corporation, however, has had many years experience in the direct current and induction plasma heating field, having developed, tested and marketed a line of standard commercial induction plasma generators for heating gases like air, nitrogen, oxygen, and argon-hydrogen mixtures at power levels in the range of 200 kW. It appeared from this work, our many years of experience with dc plasma generators, and the preliminary tests described in NASA CR-657[1] that operation of a sheath gas system and a pure hydrogen system appeared feasible. Hence this program was undertaken.

Apparatus and Procedure

This program involved using existing and modified high frequency and dc plasma generating systems at the TAFA facility. The initial phases of the program were involved with calorimetric instrumentation of these systems 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 induction heating system used for this work is shown in Fig. 3. It consists of a conventional 90 kW dc plate power TAFA induction plasma system. The large power unit at the left contains the 12,000 volt, 7.5 ampere, dc power supply. High voltage, low current power is transmitted from this unit either to a 450 KHz circuit in the power unit or through the coaxial lines shown to a remote, 4 MHz oscillator tank which includes the capacitor and series tuning inductor. The induction plasma generator is shown attached to the 450 KHz circuit. The control unit used to operate this system is also shown. It consists of a bank of plasma forming gas flowmeters, power supply controls and meters, and a Leeds and Northrup Speedomax H Model R indicating millivolt meter with a 16 position switch for measuring temperature rise in the cooling water passing through each component of the system.

Induction system.- The induction plasma system utilized in this program was a standard unit manufactured by TAFA and operates in the range of 2-8 MHz. This frequency range was chosen for two reasons; first, its availability, and secondly, the fact that previous experience had demonstrated that plasmas of diatomic gases like nitrogen and oxygen could be simply initiated and maintained in this frequency range. Some preliminary tests were conducted at frequencies up to 14 MHz on a machine limited to 20 kW plate power.

The heart of the induction plasma system is the torch which consists of the induction coil, water cooling, and a plasma forming gas flow pattern generator. TAFA has developed such units over the past six years and three are shown in Fig. 4. A quartz tube is used as the plasma containing wall and high velocity water is passed over the quartz tube and a closely wound inductor which carries high frequency current as shown in Fig. 2. This arrangement permits the inductor to be located as close as possible to the load, in this case the high frequency arc-heat addition region and thus have the most favorable load to coil diameter ratio resulting in maximum electric power transfer into the gas. Cooling of the quartz tube is absolutely necessary when high power densities and diatomic gases are used. Throughout this text, the region in the gas stream where the high frequency power is added and raises the gas temperature to partially ionized levels will be termed the arc region or high frequency arc.

The mechanism of power transfer from the coil to the hot gas is one of a step-down transformer. The multi-turn coil shown in Fig. 2 is supplied with high frequency current from the power unit. The high frequency arc acts as a single turn loop of conductive material into which high frequency currents are induced, much as current would be induced in a thin walled steel tube located in the same position. The circulating currents produce I^2R heating of the gas and when the coil-arc relationship is properly maintained power is transferred at high efficiency. Strangely enough, the arc acts as a solid body of material suspended in the gas stream much as a ping-pong ball is suspended in the exhaust stream from a fan. Correct velocity profiles become all important in stabilizing the arc and maintaining it within the coil region. If symmetrical flow patterns are not produced the arc will move off center and immediate wall failure will ensue. As power levels or energy densities are increased or progression is made from monatomic to diatomic gases, the preciseness of this flow pattern becomes more and more important. Standard, production gas flow pattern generators were utilized throughout these tests. They permit production of uniform, symmetrical velocity profiles of variable geometry. This is accomplished by use of multiple gas inlets with independent flowmeters on each inlet. During most of the investigations three inlets were used. This involves independently metering the amount of axial gas flow along the wall, the swirl gas added to this axial flow, and the axial flow center core gas which consists of approximately 75 percent of the total tube area.

Conventional induction heating theory of metals[2] shows that r.f. heating takes place in a thin skin on the outside of the load within the coil. Such heating mechanism can be demonstrated with the plasma by inserting a small diameter

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water cooled probe through the axis of the arc region and coil and observing that a cold region exists around the probe and that the coupling efficiency, coil currents and voltages do not change when such a probe is inserted. A second test involves injecting a small diameter (1/8 in.) gas stream up the axis of the torch (1 in. diameter induction arc). Under these circumstances a black cold region can be observed with the arc becoming an annular ring. Under these circumstances the plate power meters and grid current do not change when the probe gas is turned on and off, thus indicating the electrical characteristics of the load are not affected when the HF arc core is cooled. This demonstrates experimentally that heat addition is occurring near the outside of the hot arc, not at its center core. A further extension of this theory would indicate the isotherms presented by Reed[3] are incorrect. Maximum temperatures occur in the current conducting region (skin) near the outside of the fire ball and not at its center. Reed's measurements indicated maximum temperatures occurring on the axis. However, the author feels this data resulted from an improper symmetrical model assumption that the Abel inversion developed by Olsen[4] for a symmetrical dc arc applies to the r.f. system.

A schematic of the electrical circuit is shown in Fig. 5. The water flow to various parts of the circuit was isolated as shown. A complete heat balance was simply obtained (since all components between the oscillator tube and the plasma torch were water cooled) by subtracting all heat losses from the dc plate power impressed on the oscillator tube. All reference to efficiency throughout this report is related to plate power efficiency, i.e. the dc power to the oscillator tube is measured with an ammeter and voltmeter, and this, in each case, is considered 100 percent of the power impressed on the circuit. The accuracy of the various components used in the calorimetering are as follows: Plate amperes and volts $\pm$ 2 percent; thermocouple system including Leeds and Northrup indicator 1-3 percent (recorder has accuracy of $\pm$ 0.3 percent of full range); water flow by weight $\pm$ 1 percent.

A differential thermocouple system was used in each cooling water line so that the temperature rise across each isolated section of the system could be measured. When taking a heat balance a complete set of data points could be recorded within 45 seconds. In addition to this, runs were reproduced when discrepancies appeared or unusual trends developed to assure reliability. In the case of plasma operation it was determined that the heat in the plasma leaving the torch could be determined by difference. All cooling water losses which included the oscillator tube, transmission circuit, and torch inductor and torch walls were subtracted from the plate power input. The remaining energy was assumed to be in the exit plasma. To check this a special calorimeter

shown in Fig. 6 was mounted on the exit of the torch and cooled separately. This permitted collection of 100 percent of the energy in the system. Comparative data showing $\pm$ 5.75 percent agreement is shown in Table I.

The bottom row of data presented in Table I shows agreement at both one atmosphere and vacuum operation. Typical measured energy distribution within the system is also shown. The metal containing wall used (rather than quartz) produced an unfavorable load to coil ratio for this particular set of runs, which appears in the data as a reduced amount of heat in the gas leaving the torch.

Metal load calorimeters.- To completely understand the relationship of various components in the system, to determine the maximum efficiencies which could be achieved, and to determine the difference between metal and gas loads within the inductor load coil, a series of tests were run using water cooled metal calorimeters. These calorimeters were inserted in the standard plasma torches used for this work to determine accurately the effect of load to coil diameter ratio and separate the two sources of heat loss to the torch water, i.e. inductor I^2R heating and radiation and convection from the plasma. In addition to this, the calorimeters could be run in conventional copper tube load coils without the torch, simulating torch dimensions to determine the effect, if any, of copper coil cross section and torch design, i.e. water cooling the inductor by running water over the coil rather than through it. The calorimeters used for these tests are shown in Fig. 7 and consist of standard concentric steel pipes with pertinent dimensions given in the table below.

Outside Diameter	Inside Diameter	Length	Material	Cooling Water	Pipe Size
.540	.364	12 in.	Steel	14 lb/min.	1/4 in.
.840	.622	12 in.	Steel	49 lb/min.	1/2 in.
1.315	1.049	12 in.	Steel	75 lb/min.	1 in.
1.900	1.610	12 in.	Steel	75 lb/min.	1-1/2 in.
2.875	2.469	12 in.	Steel	75 lb/min.	2-1/2 in.

The calorimeters were operated at surface temperatures below 800°F., thus negligible energy was lost by radiation.

Torches.- All induction plasma tests covered in this report were run with one of three standard TAFA torches or modifications thereof. The three standard torches used are shown in Fig. 4. The Model 58 torch is a 1 in. uncooled quartz tube with gas flow pattern generator. The coil can be changed so that it is either a pancake design (flat) or of the solenoid type. The Model 56 torch uses a 1.5 in. i.d. quartz tube and is similar in construction to Fig. 2 and 8 with the sheath gas section removed. The Model 66 torch is an enlarged version of the Model 56 torch which can be used with either 2 in. or 3 in. i.d. quartz tubes.

The Model 58 uncooled design is limited to less than 15 kW of r.f. power and oxygen or argon operation. It was used only for the particle drop experiments reported. In some cases segmented metal walls were used inside the quartz tubing in the Model 56 and 66 torches to protect the walls from excessive heat fluxes at high powers and high hydrogen concentrations. In the case of the metal walls, the water to the torch was divided so that heat losses to the metal walls could be separated from torch coil losses. For viewing, a clear acrylic (see Fig. 9) was substituted for the standard opaque plastic body for the Model 56 and 66 torches. This permitted viewing the arc and coil regions of the torch. In the case of sheath gas addition in the 66 torch a new spacer was inserted in the center section in the torch which replaced an unused region in existing models with a desired sheath gas flow pattern generator.

Procedure.- Collection of data was straightforward. In cases where the apparatus could be run continuously all parameters were adjusted to predetermined operating conditions and the unit allowed to come to equilibrium. Once the equilibrium point was reached, usually within 60 seconds, all measurements were made. The water pressure to the machine and all components were held constant with regulators, however, water flows were measured by weighing for each test.

Results and Discussion

As discussed previously, the induction plasma heater operates by creating a conductive gas region (arc) within the load coil, maintaining the arc's position with the proper gas flow pattern, and then surrounding the arc with a cooled containing wall which withstands the heat fluxes generated. To better understand reported results the important parameters affecting the arc will be discussed at this time.

By operating the induction system on loads of various resistances one can estimate the reflected resistance of the arc within the coil when operating on a gas. It would appear from dc measurements by others[5] that the temperature of the arc in which currents are flowing is such that at least 10 percent ionization exists. The calculated resistivities (at 10 percent of ionization) of various gases and a comparison of some important solid and plasma properties is shown in the following table.

Material	Resistivity Ohm/cm.	Enthalpy (5,7) 10% Ionization Kcal/mole	Btu/lb.	Thermal Conductivity kW/cm.°K[8]	Plasma[5] Temperature for 10% Ionization °K
Hydrogen	10^{-1}[6]	255	229,000	7×10^{-5}	10,000
Nitrogen	2.5×10^{-2}[6]	400	25,000	2×10^{-5}	11,000
Argon	10^{-2}[6]	90	4,000	0.6×10^{-5}	12,000
Graphite	10^{-3}	--	--	--
Steel	2×10^{-5}	--	--	--
Copper	2×10^{-6}	--	--	--

(5) vonEngle, A: Ionized Gases. Oxford University Press, 1965, p. 84
(6) Reboux, J: Chalumeau a plasma haute frequence et hautes temperatures. Procede S.T.E.L. - C.N.R.S. Vitry, 1962
(7) Reed, T. B.: The Application of Plasmas to Chemical Processing. M.I.T. Press, edited by Baddour and Timmins, 1967, p. 27
(8) vonEngle, A, p. 271 (Thermal conductivity averaged over range 0-12,000°K)

It can be shown[9] that the resistance of an induction plasma is given by

$$r = 2\pi^2 \frac{d}{l} \sqrt{\mu \rho f}$$

where d = diameter of plasma, ℓ = length of plasma,
f = frequency of applied electrical energy, ρ = re-
sistivity of the gas (as given previously), μ = mag-
netic permeability (1 for non-magnetic materials) r
= plasma resistance.

The magnetic permeability of steel is approximately 1,000 (plasma = 1)
so the resistance of a steel calorimeter load from the above equation gives a
very good simulation for argon or nitrogen plasmas. The induction generator,
which is designed to heat steel loads, with a manufacturer's rated efficiency
of 56 percent, in fact is admirably suitable for the generation of argon and
nitrogen plasmas with efficiencies over 70 percent.

Figure 10 shows schematically the similarities between the dc arc and
the high frequency arc and the effect of various gases on the arc configuration.
The upper portion of this figure illustrates three dc arcs (of constant length and
power) and the influence of various gases on the effect known as thermal pinch.
The argon arc is largest since the energy required to ionize this monatomic mole-
cule is relatively low. The estimated energy to ionize 10 percent of this gas is
4,000 Btu/lb. (see previous table). The arc is therefore relatively large in di-
ameter and the thermal pinch due to the surrounding gas small. When the same
arc is run in a nitrogen atmosphere the enthalpy required for 10 percent ioniza-
tion is approximately 25,000 Btu/lb. This increase in ionization energy comes
about because of the dissociation energy required by the nitrogen. Note that
the effect of the resulting increase in thermal conductivity (previous table,
column 5) is to constrict the arc. This also results in an increase in voltage
gradient within the arc, raising the arc voltage from 20 volts to approximately
60 volts under the same conditions. The very high thermal conductivity of
hydrogen extends this thermal pinch effect still further, resulting in a higher
rise in the voltage of the constant length-constant power arc to 120 volts. It
should be noted that the ionization potential of argon, nitrogen and hydrogen
respectively are 15.7, 14.5 and 13.6 ev; and they in no way contribute to the
pinch phenomena or change in arc voltage. The lower portion of Fig. 10 illus-
trates a similar thermal pinch effect within the induction plasma torch. With
argon the induction arc is relatively large; as nitrogen is added to the argon
the arc can be seen to visually contract until pure nitrogen operation is reached.
As hydrogen is added to argon it becomes obvious to the operator that the re-
sistance of the arc is being drastically increased and the arc's diameter rapidly
reduced.

Other things affecting arc size are gas velocity and gas velocity pro-
file produced by the gas injector. For example, higher velocities through the

torch tend to constrict the arc at a given power. With a 1-1/2 in. tube this constriction is not noticeable in the range of 50 to 150 SCFH, however, as one raises the gas flow to 300 SCFH the arc size can be seen to be reduced by 20 percent. When using such high flows the gas must be blown up the wall in annular fashion so that the arc is not overly disturbed. In the case of argon a flatter velocity profile can be used, however, a noticeable increase in arc resistance is noticed. In the case of diatomic gases, essentially no gas can be blown up the center core (except as a small diameter gas jet issuing from a water cooled probe) without excessively disturbing and/or extinguishing the arc. The diameter of a given size arc can be increased by increasing power to the point of wall failure. Figure 11 shows the operating limits of a 2 in. tube operating in the Model 66 torch with argon and nitrogen. One can see from these curves that the operating limits discussed previously, i.e. at high powers the containing tube fails, at too low a gas flow aerodynamic forces on the arc are not adequate to maintain it stably within the center of the tube and it moves off the axis resulting in tube failure. At low powers a point is reached where ionization cannot be maintained, resulting in arc extinguishment.

It was not clear when these investigations were begun: 1) whether plasmas acted as more conventional solid loads within the work coil, 2) whether the effect of particular torch construction had an effect on induction heating efficiency. A comprehensive calorimetric investigation was therefore instituted to better understand system performance, develop experimental "feel" and techniques for optimizing system performance, and provide a base of knowledge for future work.

Dundas[9] shows the efficiency of power input to a solid load is:

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

where D = inside diameter of work coil, H = height of work coil, d = diameter of load, h = height of load, ρ = resistivity of load, ρ' = resistivity of work coil material (copper)

For the gaseous system used this formula can be simplified to:

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$$\mathcal{P} = \cfrac{1}{1 + K\,^D/d} \qquad \text{where K is a constant}$$

A theoretical curve is shown on Fig. 12 in order to compare with experimental data. This formula assumes constant oscillator and transmission losses which is essentially correct for a load/coil diameter ratio (d/D) greater than 0.2.

It was first experimentally determined that the plate power to the load obviously varied with grid drive and reached a maximum with the machine used at 1.1 grid amps (see Fig. 13A). Operating the grid drive above and below the optimum point resulted in a reduction in efficiency; for example, at 1.1 grid amps and all the components of the circuit optimized, the power into the steel load calorimeter was 73 percent. When the grid current was increased to 1.5 amps the percent of plate power into the load was reduced to 66 percent. This was not the case when a plasma was substituted for the steel load. Note in Fig. 13B that the percent of plate power to the plasma leaving the torch rises continuously as the grid current is increased up to the maximum recommended rating of the oscillator tube. The grid current therefore should be operated at relatively high values with all plasma tests to maximize efficiency and produce comparative results. All plasma test results reported used grid currents in the range of 1.2 to 1.4 grid amps. Values lower than 1.5 amps were used on recommendations of the tube manufacturer who felt that continuous operation at 1.5 amps would detrimentally affect tube life.

Figure 12 shows the effect of varying the load diameter in a fixed coil. It was determined experimentally that the coil configuration in the Model 66 torch, which involved water flowing over the coil, produced similar results to a similarly shaped copper tube coil in which the water flowed through the copper tubing and the space between each coil filled with air. The data shown in Fig. 12 then is applicable to copper tube solenoid coils as well as the particular water cooled torch design used in the plasma torches tested here. As a generalization, it can be seen that the oscillator tube loss in a properly matched circuit is in the range of 20 percent and that the oscillator loss (tuning inductor, capacitor, and high voltage transmission line) is 2 to 3 percent. The inductor coil I^2R loss increases as the load diameter is decreased due to poorer coupling and resulting higher r.f. currents for a given power input. Likewise, dielectric heating of the water within the torch increases slightly as the load diameter is reduced because the higher r.f. currents increase the voltage

drop between coil turns. It can be seen from this figure that maximum power to the load is achieved with high ratios of load to coil diameter. From a practical standpoint the arc load cannot be made as large as a metal load in a given coil. This comes about because of the need for a tube to contain the gas and physically isolate the coil from the arc region. In addition to this, a cold gas sheath must exist between the tube and the arc to prevent over-heating. This space is in the range of 1/4 in. to 1/2 in. in a 3 in. tube. With the 1/4 in. dimension and 0.100 in. allowed for the thickness of the plasma containing tube, this gives a load to coil (d/D) ratio (3 in. tube) in the range of 0.73. This is a typical maximum d/D ratio for torches in the range of 3 in. If double walled quartz tubes are used to contain water and the conventional solenoid coil is located outside the second tube the efficiency is reduced another 5-10 percent.

It is further shown in Fig. 12 that the maximum percent of plate power in the plasma leaving the torch is in the range of 50 percent in the torches used in this program. Arc diameters in the torch were measured using a mirror system focused into the exit end of the torch. A calibrated grid was placed on the mirror for direct measurement of the arc diameter which was assumed to be the same as the bright core seen by eye and shown in a typical photograph in Fig. 14. As a generalization, approximately 70 percent of the plate power ends up in the arc region within the torch, of which approximately 20 percent is lost by convection and radiation to the wall as the hot gases travel out of the device. The data presented in Fig. 12 was developed with a 3 in. plasma containing wall operating in the range of 75 kW plate power except for desig-nated points which indicate this data is applicable to other diameters and geo-metries up to the 3 in. tested. A similar curve was developed for the Model 56 torch with a 1-1/2 in. containing tube operating at 40 kW plate power. This smaller unit when operated at twice the power density within the tube produced 47 percent of the plate power in the exit gas. The metal calorimeters used to generate this information are shown in Fig. 7. Results were not affected by the axial position of the calorimeter as long as it was completely within the coil, i.e. the coil could be located in the middle of the calorimeter or at its end without affecting the heat balance.

This work did point out an obvious, simple experimental method of determining when the maximum efficiency of any circuit has been obtained, that is to measure and minimize the percent of plate power dissipated in the oscillator tube.

Pure Hydrogen

One of the objectives of this program was to heat pure hydrogen inductively and produce large diameter, low velocity, high enthalpy jets for transmissivity investigations. The approach taken was to test existing water cooled plasma torches at the 50 kW r.f. power level. Previous investigations with hydrogen were limited to approximately 25 kW r.f. power. At this power level when using a 1-1/2 in. diameter water cooled quartz tube approximately 70 percent hydrogen could be added to argon before the arc contracted to a diameter where it extinguished. The work reported here at the higher power levels did not improve the percentage of hydrogen in argon for two reasons: first, with quartz containing tubes, larger torches were required to contain the plasma resulting in a negligible increase in power density over previous tests; secondly, when metal containing tubes were substituted for quartz less favorable load to coil ratios resulted in little effect on power density. Considerable insight into the problem has been obtained however and many apparatus problems which did not come to light with prior short run tests have been solved.

The equipment used for this work (shown in Fig. 3) has been previously described. With the calorimetric apparatus it was possible to select circuit components and the torch coil so that optimum coupling resulted, i.e. maximum power into the load and minimum oscillator tube loss.

The torches used for this work were the Model 56 and 66 shown in Fig. 4. The equipment was operated in a conventional manner: igniting with argon, turning up the dc plate power to approximately 18 kW, and then adding hydrogen. Hydrogen addition caused arc constriction and power was increased to maintain operation. This step-by-step hydrogen addition-power increase process was repeated until the maximum power of the machine was reached at maximum hydrogen concentration. The power could not be turned up to maximum with argon alone since the plasma containing tubes would not contain the resultant large diameter arc. Many series of tests were run to optimize the various parameters of the torch and circuit, since load characteristics varied over wide ranges as power and hydrogen concentrations were changed.

It was obvious when operating with high hydrogen concentrations that radiation from the plasma increased considerably. Since hydrogen is not considered a good radiator the increase in radiation intensity is probably caused by higher power densities and resulting higher argon temperatures. The heat flux

on the quartz tube became so high at hydrogen percentages above 50 percent that devitrification occurred after one to two minutes of operation. This resulted in stresses and eventual cracking of the tube. The percentage of plate power leaving the torch as heat was in the range of 20 to 30 percent (compared with 50 percent air operation) with the additional loss occurring within the torch. The metal calorimetry discussed previously showed that load coil losses with metal calorimeters simulating the plasma load were normal and of a low value, i.e. 20 percent tube loss and 70 percent plate power to load. The added losses to the torch when operating with the high hydrogen concentrations compared with air then were due to convection, conduction and radiation to the torch walls from the arc and hot gases. Later work with a high velocity gas sheath near the wall eliminated the excessive convective and conductive heat transfer to the wall and showed that the efficiency could be increased by approximately 20 percent. This gives an indication of the order of magnitude of the convection and conduction effects. It was determined through analysis of failures that as the power and hydrogen concentrations were increased the quartz wall usually failed about 1 in. downstream of the coil region (toward the exit of the torch). It appeared that the hydrogen plasma was diffusing to the wall in this region and it was this additional heat flux which caused failure.

Attempts were made to run at the minimum flow rates which continued to maintain the arc centered in the tube to determine if this would improve hydrogen concentration at which the apparatus could be run. However, when this was tried failure of the quartz tubes occurred in the coil region close to the center of the coil where the largest diameter of the arc existed. Tests of 2 in. and 3 in. quartz tubes all pointed to these same failure problems in the range of 50 to 60 percent hydrogen in argon. Numerous attempts to solve the problem by conventional means such as higher gas flows, extension of water cooled metal torch ends closer to the coil from the front and rear of the torch (to act as heat shields), careful cleaning of quartz to prevent radiant energy pickup, use of smaller exit nozzles, were tried without significant improvement.

It was obvious from the above quartz containing wall work that a wall capable of withstanding higher heat fluxes was required. The obvious solution

was a water cooled copper, and based on previous metal wall experience and the requirement that the wall be permeable to the electric field, a segmented copper wall was fabricated for the Model 66 torch under test. Such a metal walled device is shown in Fig. 15. This device consists of a number of 1/8 in. diameter copper tubes soldered into manifolds at either end and spaced approximately 0.010 in. apart. This design provides a simple method of constructing a water cooled wall of minimum thickness to maximize load to coil ratio and to provide narrow enough strips to permit the electric field produced by the induction coil to pass through without excessive energy absorption.

Standard torches were modified (Fig. 15) so that the metal walls could be inserted inside the existing torches and quartz tubes. This permitted maximum testing with minimum fabrication effort using standard gas flow pattern generators and torch components. Obviously, the metal walled device reduced the diameter of the plasma containing tube (using a constant coil diameter) and thus the arc diameter. Later in the program larger diameter metal walls were fabricated to simulate the inside diameter of the original quartz tubes. When this was done, however, the coil diameter had to be increased beyond that in the conventional torches. In either case, it was not possible to exactly duplicate the coil and containing tube diameters with the metal and quartz walled torches, and this resulted in less favorable load to coil diameter ratios for the metal units. The performance of the torches with and without a segmented metal containing wall is shown in Table II. It can be seen from this table that the oscillator tube loss was in the 14-20 percent range, indicating good circuit matching. It can also be seen that when the steel calorimeter was operated inside the coil it received the same amount of energy irrespective of the use of the metal wall (Runs 3 and 4). In addition, good agreement with the calorimeter-load to coil diameter data presented in Fig. 12 is obvious.

The metal wall, then, solved the heat flux problem and provided a means of operating at higher hydrogen concentrations continuously without torch damage and deterioration. Well designed units were fabricated for each tube size investigated and further quartz tube work with premixed hydrogen-argon mixtures was discontinued.

Considerable effort was devoted to maximizing hydrogen percentage at a given power level using the metal walled device and the maximum power available (88 kW plate power). Typical data comparing system performance with the metal walls of various diameters and premixed hydrogen-argon and air is given in Table III. This table includes comparative steel load data using steel calorimeters close to the observed diameter of the arc under the hydrogen concentrations indicated. The heat remaining in the gas leaving the torch is in the range

of 20 percent. This low value is caused for two reasons: first, it can be seen from the comparable steel load data that the coupling efficiency was very low due to the poor load to coil diameter ratio; secondly, the high convection, conduction and radiation losses with hydrogen as discussed previously were apparent. The identical equipment when operated with air produced efficiencies of 35 percent as indicated in Run 7. This was almost twice the efficiency of the hydrogen-argon arc load with other conditions equal. Run 8 shows operation (identical to Run 7) without the metal wall; by comparing Run 7 and 8 the effect of the metal wall on efficiency at this diameter range can be seen.

An envelope of experimental hydrogen power data is shown in Fig. 16. Within the power range available it was found that the maximum hydrogen concentration which could be run reliably was 65-70 percent. From the data presented it can be seen that it was difficult to estimate the power required for 100 percent hydrogen due to the narrow data spectrum, however, extrapolation of this data indicates plate power levels in the range of 160 kW would be required to achieve operation.

A second approach to operation at higher hydrogen concentrations in a premixed torch design is through the use of higher frequencies. The equipment available for the work reported here was limited to 7 MHz. The previous data indicates the effect of plate power on percent hydrogen which could be run in the 3.5 MHz range. The effect of frequency on hydrogen percentage is shown in Fig. 17. Extrapolation of this data again is difficult because of the narrow data range; however, the trend appears unmistakable, i.e. higher frequencies permit higher hydrogen concentrations. This trend appears even more obvious to the operator of the equipment. The addition of hydrogen becomes much easier and the arc more stable as frequency is increased. From this data it would appear that frequencies in the range of 15 to 20 MHz would permit pure hydrogen operation at one atmosphere and 80 kW r.f. Some tests were conducted in the 10-14 MHz range on an existing 10 kW power supply to more positively identify this trend but it was soon determined that powers much greater than this would be required to achieve high concentrations of hydrogen in this frequency range.

Low Pressure Operation

Because of the unsuccessful attempts to operate on pure hydrogen with the power levels and frequencies available as discussed previously, preliminary tests were run with available torches at low pressures. A water cooled metal

calorimeter as shown in Fig. 7 was mounted on the exit of the torches under investigation and the outlet connected to a vacuum pump. The calorimeter cooled the exit gases from the torch to approximately 125°F. so that the torch and vacuum pump could be operated continuously. The pressures used (125 torr) are still in the thermal arc regime[10] which has a transition at 50-100 torr to a glow discharge.

Investigations were conducted with air and nitrogen to determine if operation could be sustained at lower powers at lower pressures, the reasoning behind this being that gases are more easily ionized at lower pressure and that the thermal pinch effect would become less, thus sufficient ionization for stable operation would be maintained at significantly lower powers (hopefully, within the power range available). Results of these tests were quite disappointing.

It was determined that conventional operation could be sustained at low pressures with argon, however, arc radiancy and diameter appeared identical to one atmosphere operation when comparing 125 torr with one atmosphere operation. It was not possible to operate with air at low pressures with the standard quartz containing tube because of quartz overheating. Air was operated at low pressures (see Table I) with the metal containing wall discussed previously, however, arc voltages, arc diameters, and minimum powers and efficiencies were identical when compared with one atmosphere operation. It was therefore concluded that low pressure arc regime operation in the ranges investigated would not improve percent hydrogen capability. It should be noted that it is possible to operate hydrogen in the glow discharge region (30 torr) at 2 kW and 16 MHz, but this arc regime was not investigated here.

Sheath Gas Operation

A second objective of the program was to achieve a stable sheath gas system operating with a core of argon and a high velocity sheath of hydrogen. Figure 2 is a schematic of a system which has been found to operate quite satisfactorily at power ranges to 88 kW plate and hydrogen to argon velocity ratios in the range of 10-60:1. A specific model operated successfully is shown in Fig. 9. It was determined that metal and quartz plasma containing walls worked equally well with hydrogen sheath flows over 1,000 SCFH utilizing this 3 in. diameter system. The quartz tube failure problems which plagued premixed hydrogen operation and required substitution of metal walls for quartz to maintain continuous operation were eliminated. The quartz wall is adequately protected by the high velocity sheath of hydrogen and the hot gases are prevented

from diffusing to the quartz wall. This experimentally demonstrated that the major reason for quartz failure in the conventional premixed hydrogen work was due to the added convective and conductive heat transfer to the wall with hydrogen.

The main requirement for satisfactory operation of the system was found to be the addition of a separating wall between the argon and the hydrogen which was permeable to the electric field produced, thereby permitting the arc to be initially established within the argon flow stream before it began to mix with the hydrogen. It was determined that the specific position of the end of this electrically permeable wall relative to the first coil of the inductor was not critical, i.e. operation 1/4 in. before the inductor and 1 in. into the coil produced similar results. Designs which used a cooled or uncooled metal ring in place of the quartz separator tube shown did not produce satisfactory operation and the arc established itself in front of the separator tube permitting little hydrogen sheath flow before arc extinguishment occurred. Typical performance of this device is shown in Table IV. It should be noted that load to coil diameter ratio with this system is as favorable as premixed torch designs previously studied. Most satisfactory operation was achieved with annular flow in the hydrogen sheath region rather than swirl gas. It also appeared that buffer gas flow which produced equal velocities of argon and hydrogen in the transition region produced more stable arc as demonstrated by high speed photographs and observation of dc plate voltmeter and ammeter stability. A photograph of the assembled sheath system is shown in Fig. 9 and the end view of a metal walled unit operating in Fig. 18.

A stable sheath gas system has thus been developed which will permit continuous operation of hydrogen to argon velocity ratios greater than 30:1 with no operating or apparatus failure problems at the 88 kW plate power available. The measured operating limits of this sheath system are shown in Fig. 19. The maximum power limits of both the metal and quartz containing walls are estimated based on 70°F. as being the maximum tolerable cooling water temperature rise. The minimum power limit is caused by arc extinguishment.

Preliminary tests were run seeding the hydrogen with carbon black to determine its effect on operation. From these tests it appears that the carbon black seeding in the hydrogen sheath gas does not affect electrical coupling characteristics of the system.

18

Powder Injection into the Arc Region

In the gaseous core nuclear reactor engine uranium will be injected into the fireball. Preliminary tests were run with the arc system described herein to simulate the injection.

The Model 58 torch (1 in. i.d., uncooled quartz) was set up with the flame operating in a downward direction as shown in Fig. 20. Both 200 micron silica and tungsten powder were fed from a feeder located in the upper part of the photograph through a plastic hose to a 1/8 in. diameter hole located on the axis of the quartz containing tube and exiting into the tube about 2 in. above the arc region. The powder was then allowed to free fall to the arc. Normally when this torch is used for melting powders a 1/4 in. water cooled probe with a 1/16 in. central hole is positioned about 1/4 in. into the top of the arc region, and adequate carrier gas used to push the powder into the fireball region. With this latter arrangement powder can be made to penetrate the arc region. Further observations of this phenomena have been made during this program with the idea that materials addition, retention time of gases within the arc region, and flow patterns are important and related to gas core technology in that they will influence maximum uranium retention times in the final motor.

It was determined that the arc acted as a solid impenetrable body with gas flowing around. When silica and tungsten particles were dropped at free fall velocities onto the top of the arc as shown in Fig. 21A they appear to bounce off at an angle related to the curvature of the plasma at the point of impact. In addition, small jets of gas impinging on the surface deflect at a similar angle. High speed photographs (a few frames of which are reproduced in Fig. 21B) vividly demonstrate this phenomena. Individual particles can be traced and their deflection demonstrated. At this point the reason for this phenomena is not understood, however, it has been demonstrated by others[11, 12] a similar phenomena occurs in dc arcs. In one case[11] it has been shown through high speed photographs that a dc arc stabilized in a supersonic air stream acts as a solid strut with particles within the arc travelling perpendicular to the supersonic stream and all gas flow flowing around the arc region. It thus appears that the high temperature gas region produced by an electric arc creates an unusually impenetrable media due to gas expansion, magnetic properties, high viscosities or some other physical phenomena unexplainable at this point. The demonstration of the phenomena with dc as well as high frequency arcs would indicate that it has no relationship to the r.f. field produced in the equipment under investigation in this program.

CONCLUSIONS

The work has resulted in a clearer understanding of the relationship between the parameters affecting induction heating of gases, an assessment of the problems connected with pure hydrogen heating, and the development of specific hardware for electrically simulating a gas core reactor.

Specific conclusions are as follows:

1)   It is possible to simulate with a steel calorimeter, the loading characteristics of an induction plasma arc to a 4 MHz or 450 KHz induction heating power supply.

2)   The induction plasma arc is an excellent load for heating by this technique and 70 percent of the dc plate power can be coupled into the arc load. Radiation, conduction and convection losses from the plasma within the torch before it leaves the exit nozzle vary with torch geometry, torch construction, and gas type. The water cooled torches used in these investigations had plasma containing tubes of 1.1 to 3 inches i.d. With this apparatus the free plasma exiting from the devices contained approximately 50 percent of the dc plate power with air operation and 15-30 percent with 70 percent hydrogen in argon.

3)   Continuous operation of a metal walled 1.1, 2 and 3 in. i.d. induction torch has been demonstrated at 80 kW plate power (4 MHz) and 70 percent hydrogen in argon. Extrapolations of experimental data indicate at least 160 kW plate power will be required to sustain pure hydrogen operation at the above frequency, and above 20 MHz will be required to sustain pure hydrogen at 88 kW plate power.

4)   Three inch i.d. quartz and metal wall sheath gas systems have been developed and run continuously without deterioration using a 2 in. argon core in the center (125 SCFH typical) and hydrogen gas in the

surrounding 1/2 in. thick sheath (5,000 SCFH typical). This unit operates over a wide range of hydrogen sheath flows from 1,000 to 5,000+ SCFH at 80 kW plate power. A clear walled torch permitted viewing the arc and mixing regions during operation. It should be noted that over 98 percent hydrogen in argon has been run continuously with this system as compared with 70 percent with the premixed test discussed in (2).

5)   Attempts to operate hydrogen-argon mixtures at arc pressures in the range of 100 to 700 torr (4 MHz and 80 kW plate power) did not increase the maximum hydrogen capability of the torch. It was also noted during these lower pressure tests that the arc diameter and overall torch efficiency (heat to plasma) changed little with pressure.

6)   Particle drop experiments and photographs are discussed in which 200 micron tungsten and silica was seen to bounce off the arc within the induction torch. These observations indicated the apparent hardness of the arc and the probability of negligible gas flow through the arc region, i.e. the arc acts as a solid strut with gas and powder flowing around it. This has significance in that this may indicate the possibility of long retention times of material within the heat addition region--a desirable feature in the proposed gas core reactor.

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TABLE I

ENERGY DISTRIBUTION IN INDUCTION PLASMA TORCH WITH 1.1" I.D. METAL CONTAINING
WALL[a] AT VARIOUS PRESSURES IN ARC REGION USING 115 SCFH AIR

Run no.	1	2	3	4	5	6	7
Plate amperes	7	6	5	7	7	7.1	7.1
Plate volts	9400	8300	7900	9300	9000	8900	8800
Arc pressure (mm)	760	250	250	250	125	190	250
DC plate power kW	65.8	51.8	39.5	65.1	63.0	63.2	63.5
Loss to oscillator tube, %[b] .	22.6	22.9	22.5	21.3	21.7	23.6	24.0
Loss to tank, transmission, %	2.8	2.6	3.7	2.5	2.4	2.5	2.5
Loss to metal wall, % . . .	30.0	19.5	22.0	27.1	25.7	24.2	23.9
Loss to torch, %	19.8	16.0	21.9	16.1	14.8	14.6	15.0
Heat in gas leaving torch (by calorimeter), %	32.4	36.8	37.2	31.4	31.2	32.1	33.6
TOTAL %	107.6	97.8	107.3	98.4	95.8	97.0	99.0

[a]See figure 15.

[b]See figure 5.

TABLE II

COMPARISON OF METAL AND QUARTZ WALL TORCH PERFORMANCE
USING STEEL CALORIMETER LOAD

Run no.	Metal wall i.d.	d/D Load/Coil	Plate kW	Plate power energy distribution - %					Torch model
				Calorim-eter	Osc. tube	Metal wall	Torch coil	Tank circuit	
1	1.1"	0.45	57.3	51.3	19.0	9.8	14.4	3.7	56 – with metal wall
2	1.5"	0.35	55.0	48.0	19.4	6.8	18.6	5.4	66 – with metal wall
3	2.5"	0.58	79.0	63.6	18.2	3.0	15.8	2.7	66 – with metal wall
4[a]	None	0.58	66.0	62.5	14.4	0	16.3	3.5	66 – without metal wall

[a]Torch identical to run 3 in all respects except metal wall removed.

TABLE III

PERFORMANCE OF METAL WALLS IN PLASMA TORCHES[a] WITH METAL,[b]
AIR, HYDROGEN-ARGON PLASMA LOADS AT 3.1 - 3.5 MHz

Run no. Load	1 Steel	2 Plasma	3 Steel	4 Plasma	5 Steel	6 Plasma	7 Air	8 Air
Quartz i.d.	3	3	2	2	1.5	1.5	1.5	1.5
Coil turns	5	5	5	7	7	7	7	5
Metal containing wall i.d.	2.5	2.5	1.5	1.5	1.1	1.1	1.1	None
Load	Steel (0.82")	Arc (1")	Steel (0.82")	Arc (1")	Steel (0.82")	Arc (3/4")	Arc (3/4")	Arc (1")
% Hydrogen in argon . . .	0	50	0	67.0	0	56	0	0
Total gas flow SCFH . . .	0	H_2-Ar. 38	0	H_2-Ar. 99	0	H_2-Ar. 109	Air 113	Air 113
KW plate power	50.7	75.4	55.0	82.3	57.3	78.6	81.0	47.5
% Plate KW								
To oscillator tube . . .	23.4	16.2	19.4	17.8	19.0	21.2	21.9	21.6
To tank circuit	5.2	3.3	5.4	2.6	3.7	3.1	2.8	4.3
To torch	36.0	31.3	18.6	21.0	14.4	13.0	11.8	28.6
To steel load	27.6	---	48.0	---	51.3	---	---	---
To metal wall	5.9	30.5	6.8	35.6	9.8	43.8	29.6	---
To plasma leaving torch	---	18.7	---	23	---	18.8	35.0	45.7

[a]Model 56 & 66 torches - see figure 15.
[b]Diameter chosen to simulate plasma diameter.

TABLE IV

TYPICAL INDUCTION PLASMA SHEATH GAS HEATER PERFORMANCE
USING 3" QUARTZ TUBE, 2" SEPARATOR[a]

KW	% Plasma	% Osc. tube	% Torch	% MHz circuit	Length quartz separator	Torch turns	Argon core	H_2 sheath	H_2 buffer
84.2	43.0	25.0	28.6	3.4	1/2"	3	120	3100	850
87.5	45.7	22.0	28.6	3.7	1"	3	120	3100	1000
78.9	40.9	24.2	28.9	6.0	1/2"	2	120	3150	850
72.2	39.2	25.4	30.2	5.2	1"	2	120	2800	---
69.1	31.9	23.0	41.2	3.9	1/2"	5	120	2800	1000
74.5	38.5	23.9	35.0	2.6	1"	5	120	2900	900

[a]See figure 8.

50,000° K D_2O

5,000° K

100,000 LBS. THRUST

◁ U 235

◁ H_2
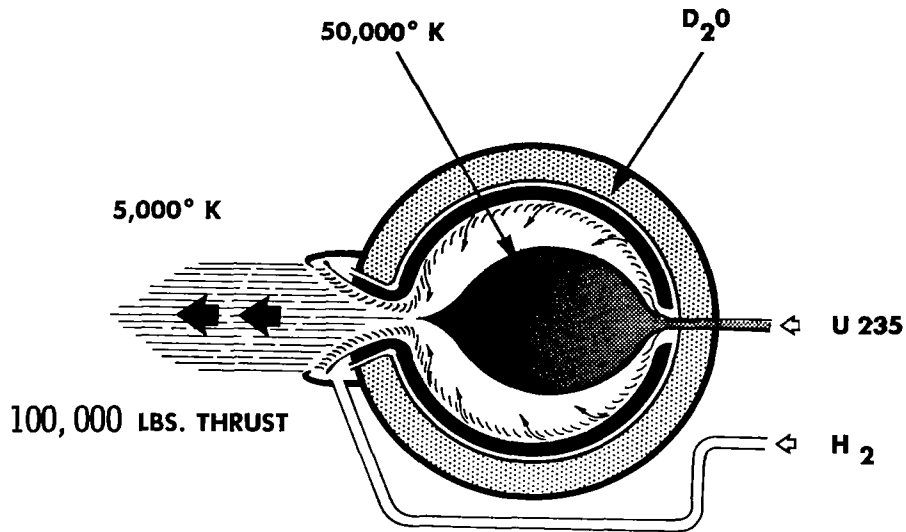
SCHEMATIC NUCLEAR GAS CORE ROCKET

FIG. 1

PLASTIC BODY   QUARTZ TUBE

HF ARC 22,000° F.   HF COIL

SHEATH H, 45 FPS

CENTER CORE ARGON 1.5 FPS

HOT GAS 2,000-10,000° F.

50-1,000 KW HF POWER AND WATER
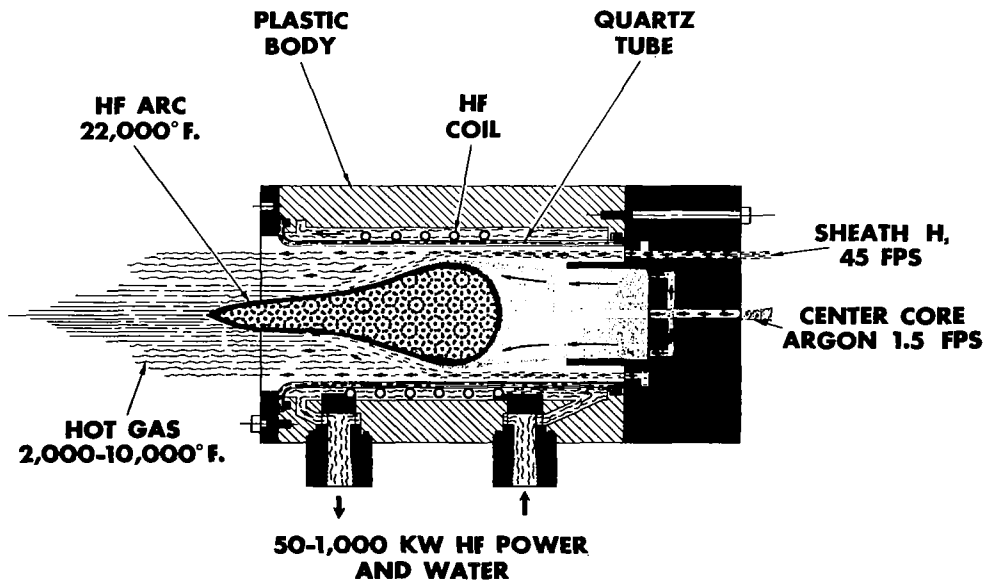
INDUCTION PLASMA HEATER WITH HIGH VELOCITY SHEATH

FIG. 2

27

RF POWER UNIT

TORCH RF CONTROLS

DC POWER UNIT

TORCH

DC CONTROLS
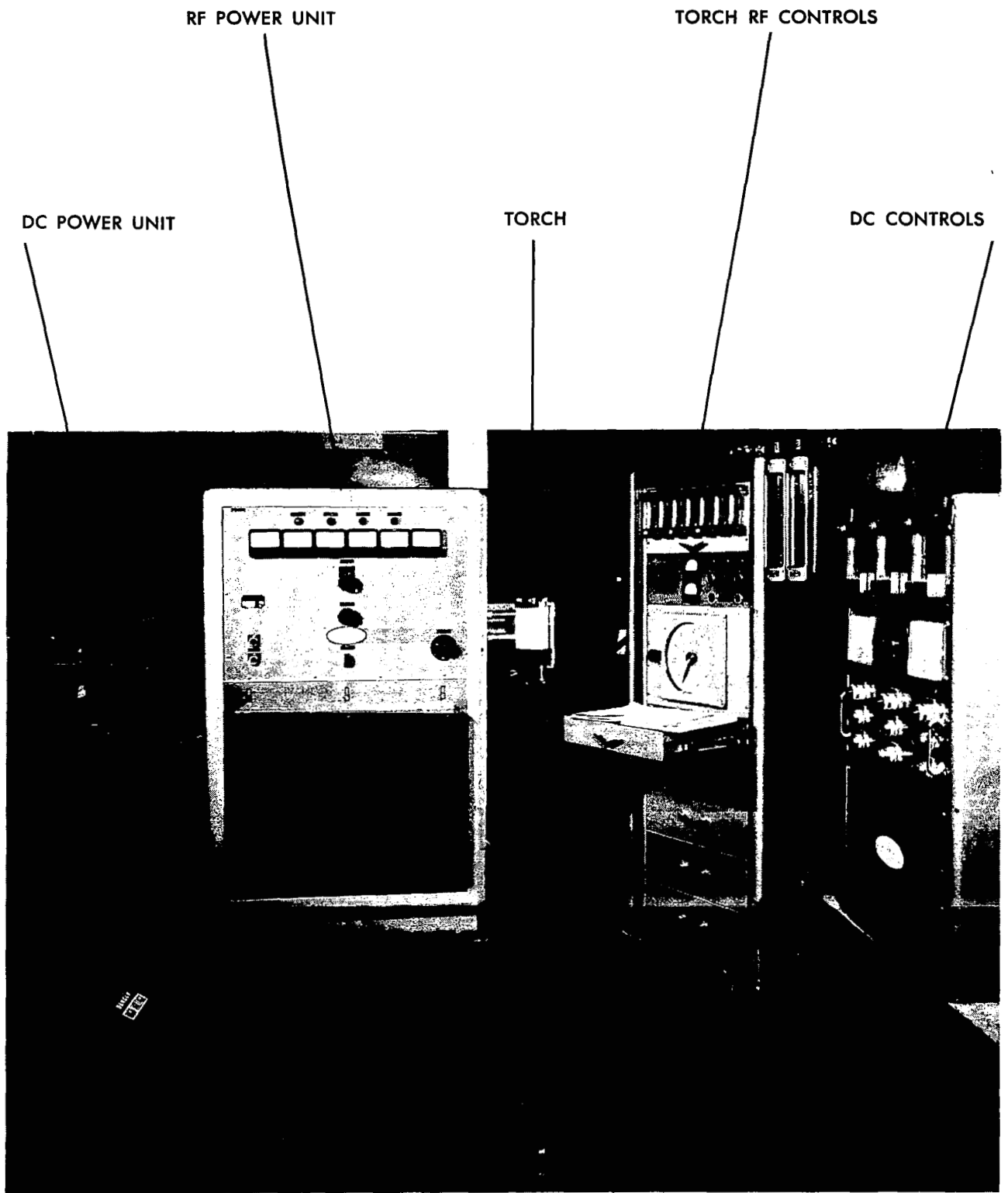
EXPERIMENTAL SETUP

FIG. 3

28

INDUCTION PLASMA TORCHES USED
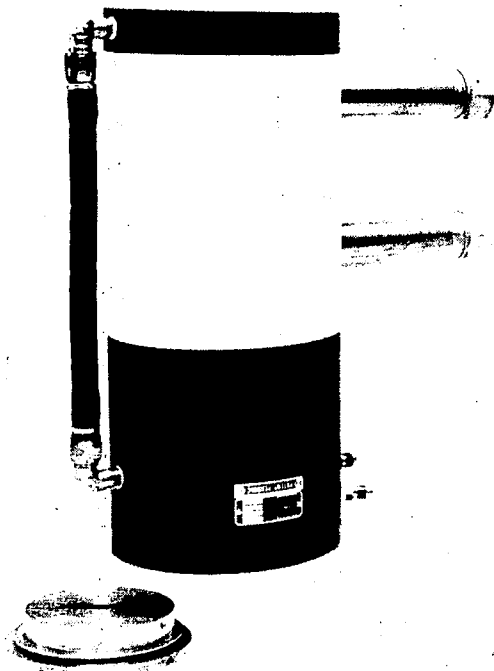
MODEL 66

3″ PLASMA (MAXIMUM)
35-100 KW RF
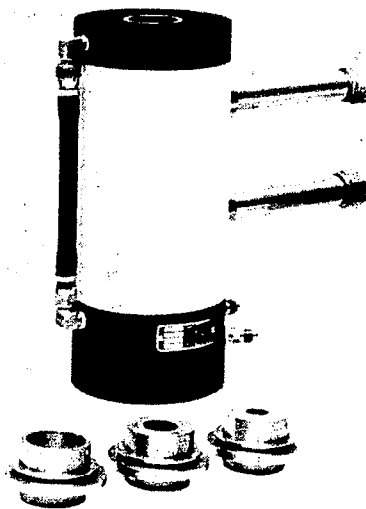
MODEL 56

1-½″ PLASMA (MAXIMUM)
5-35 KW RF
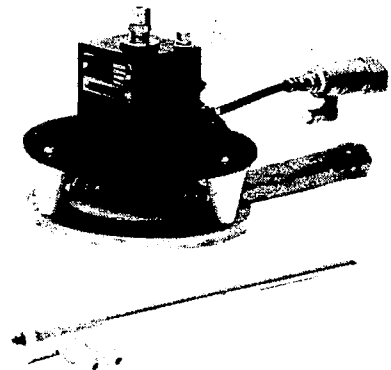
MODEL 58

1″ PLASMA (MAXIMUM)
0.5-15 KW RF

FIG. 4

ENERGY ACCOUNTING

PLATE POWER	OSCILLATOR TUBE	TRANSMISSION	COIL I^2R
88 KW 100% INPUT	17.6 KW 20% LOSS	2.7 KW 3% LOSS	5.3 KW 6% LOSS

PLATE AMMETER

BLOCKING CAPACITOR

TANK COIL

PLATE FILTER

ARC LOAD

OSCILLATOR TUBE

TANK CAPACITOR

PLATE VOLTMETER

DC INPUT

GRID AMMETER

HIGH RF CURRENT
250 AMPS

LOAD COIL
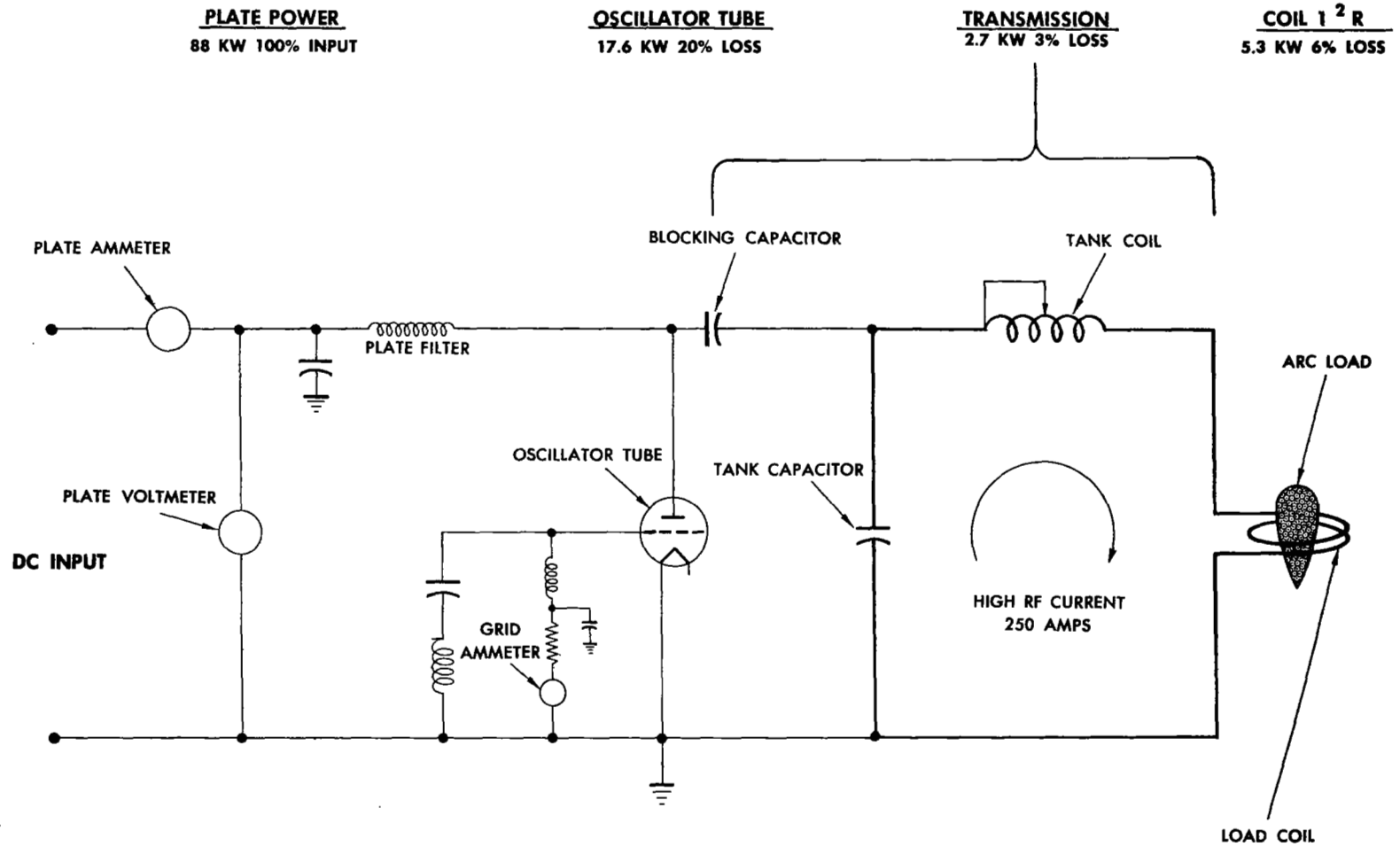
SCHEMATIC EXPERIMENTAL RF SYSTEM

FIG. 5

EXIT PLASMA
GASES
AT 125°F

CALORIMETER
WATER

RF POWER AND
COOLING WATER
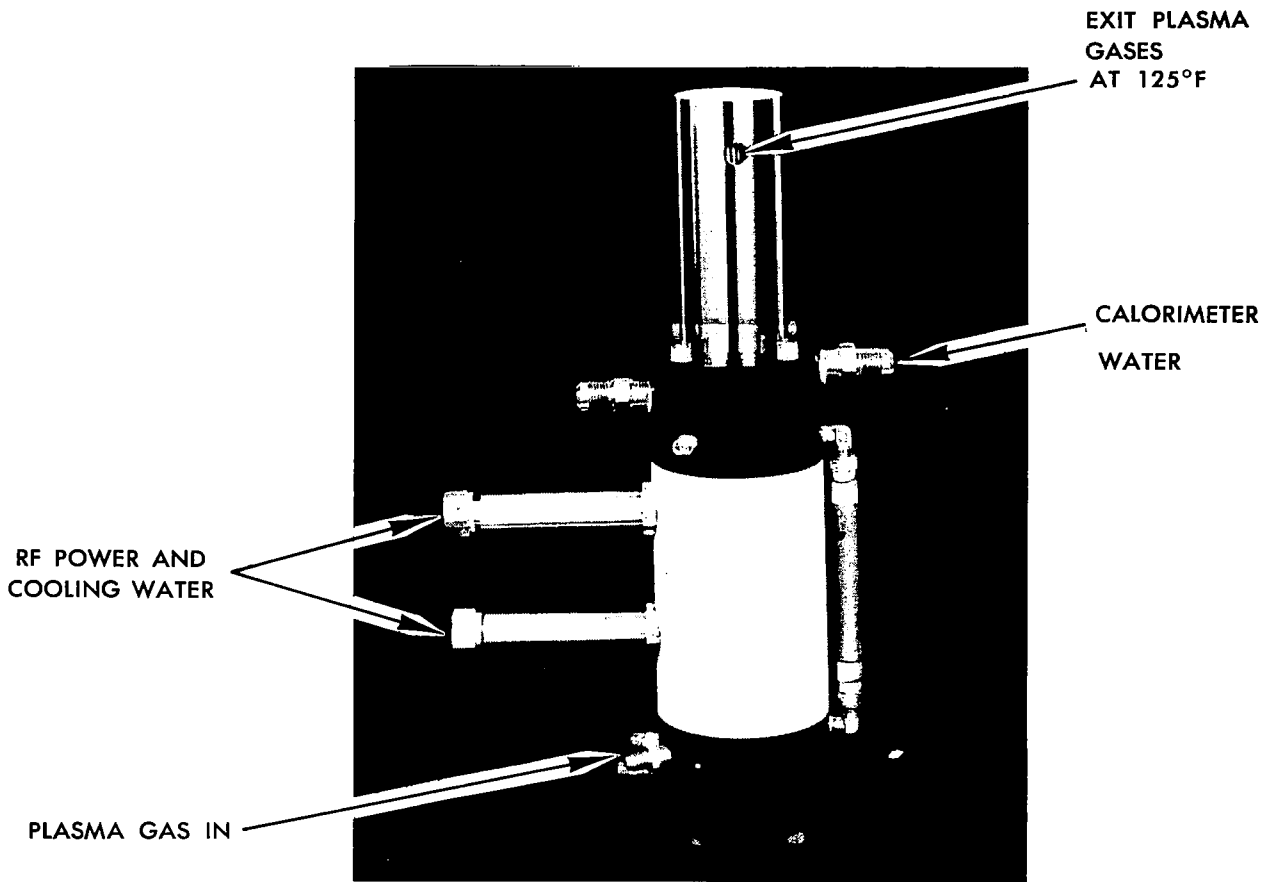
PLASMA GAS IN

**PLASMA GAS CALORIMETER MOUNTED
ON MODEL 56 INDUCTION PLASMA TORCH**
(1.5″ QUARTZ TUBE)

FIG. 6
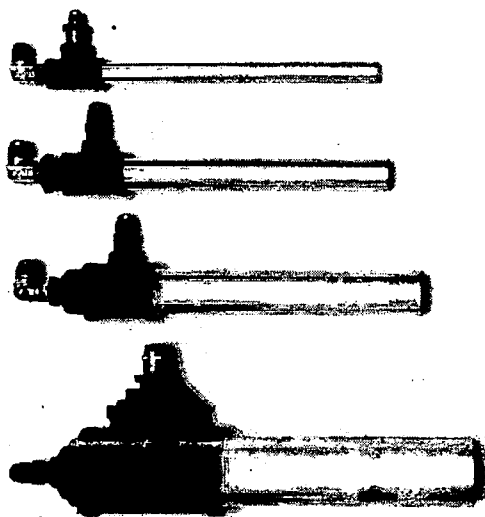
METAL CALORIMETERS
(LARGEST 2.875″ DIAMETER)

FIG. 7

31

MODEL 66 TORCH
REFERENCE

ARC

QUARTZ SEPARATOR

BUFFER H$_2$ OUTLET

WATER & POWER
LEADS

SHEATH GAS
PASSAGE

RADIAL H$_2$

SWIRL H$_2$

BUFFER H$_2$ INLET

ARGON CORE GAS

WATER

STANDARD BACK END
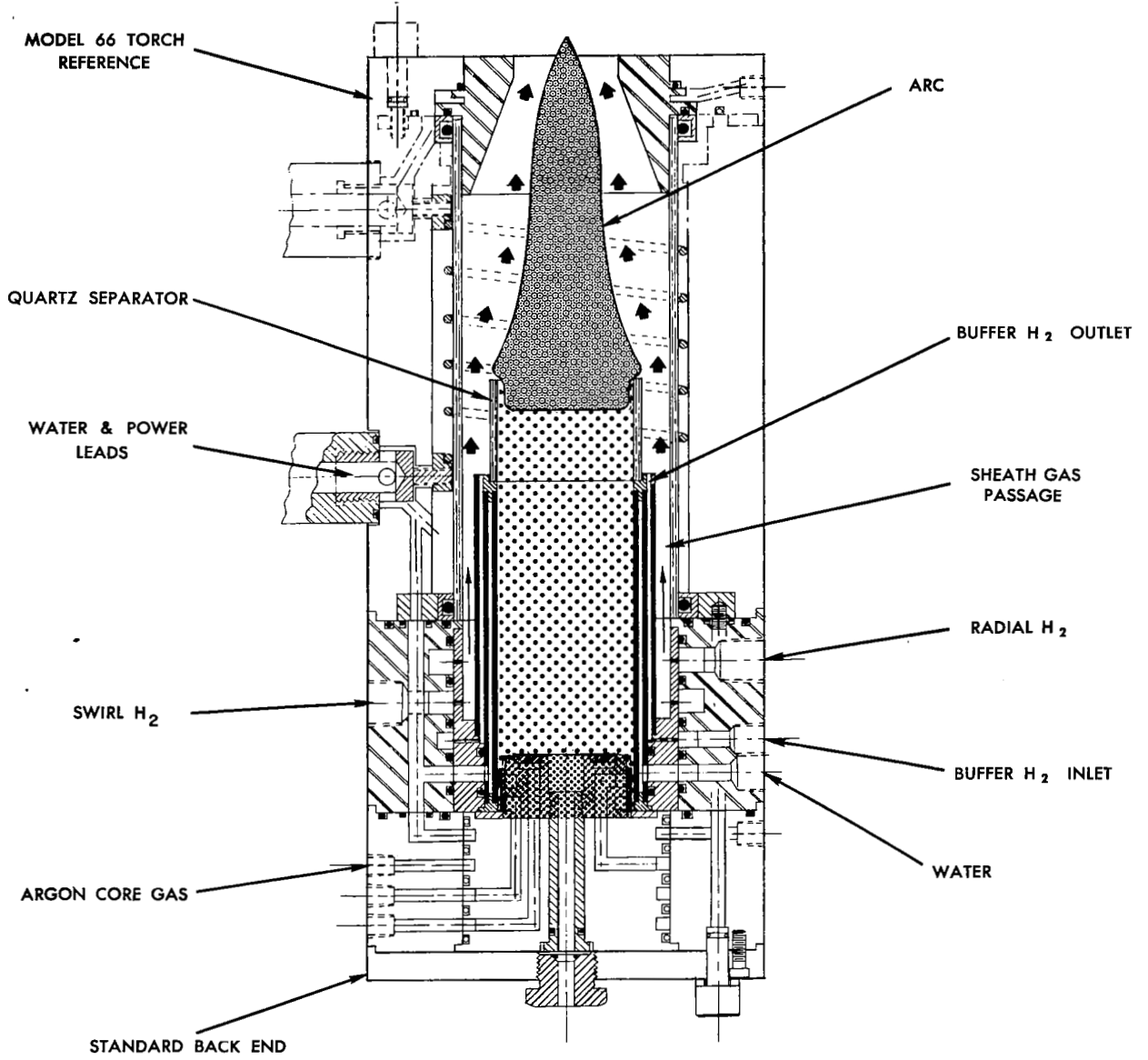
THREE INCH SHEATH GENERATOR

ARGON CORE GAS

PLASMA ARC

SHEATH GAS FLOW

FIG. 8

32
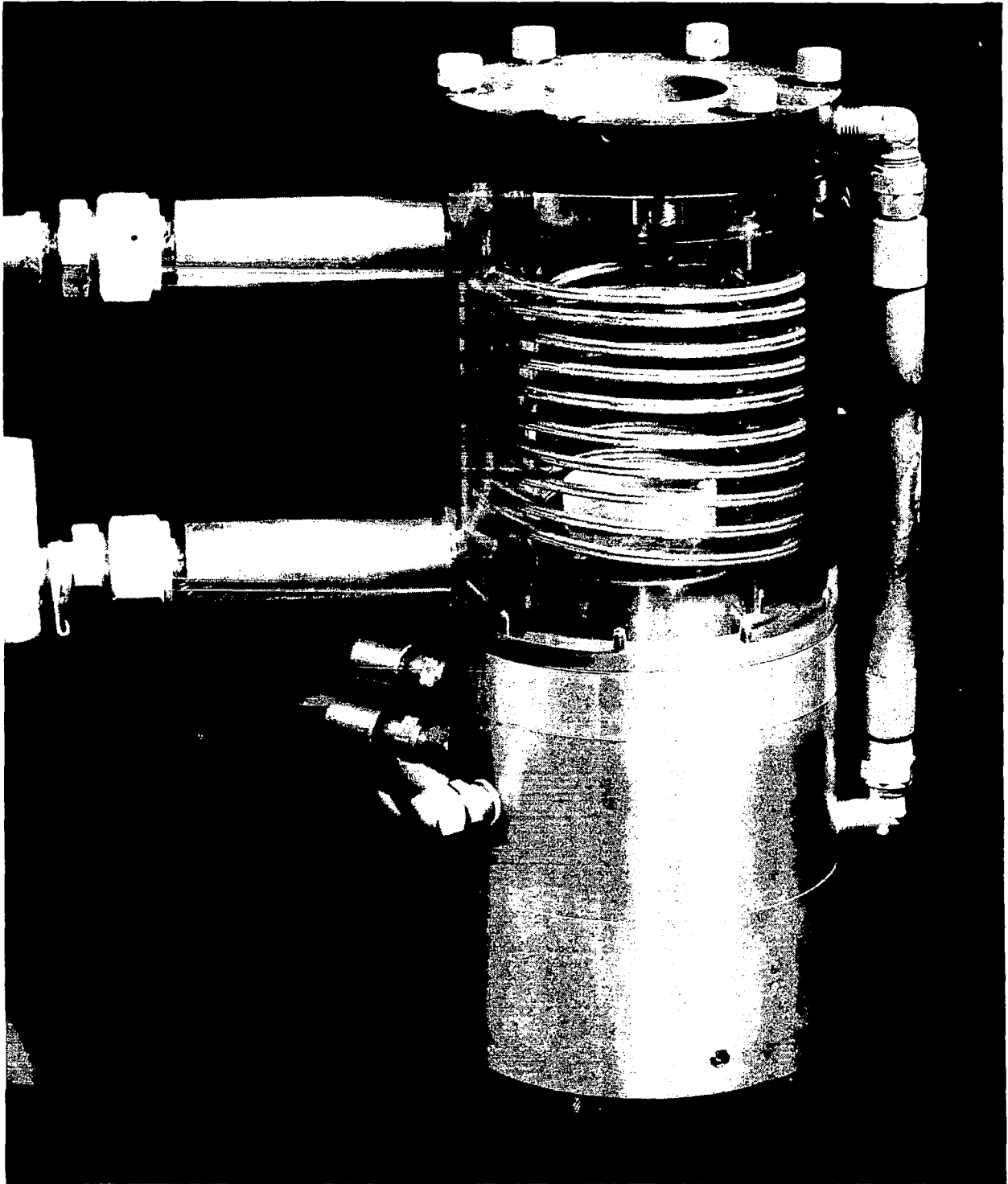
THREE INCH SHEATH SYSTEM
(SEE CROSS SECTION FIG. 8)

FIG. 9

DC ARCS

ARGON
20 VOLTS
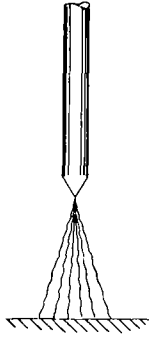
NITROGEN
60 VOLTS

HYDROGEN
120 VOLTS
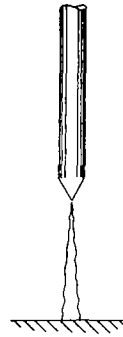
RF ARCS
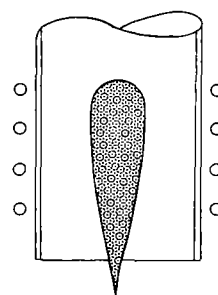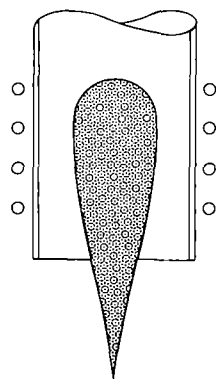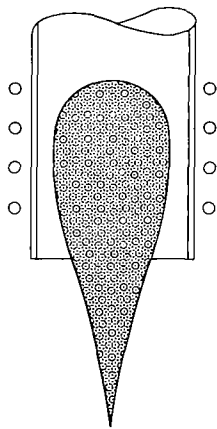
**EFFECT OF GAS ON ARC DIAMETER AT
CONSTANT POWER, PRESSURE AND APPARATUS SIZE**

FIG. 10

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OPERATING LIMITS INDUCTION PLASMA TORCH (MODEL 66)

ARGON — 2 OR 3″ I.D. TUBES

GAS FLOW SCFH

1000
800
600
400
200
0

OXYGEN — 2″ I.D. TUBE

GAS FLOW SCFH

1000
800
600
400
200
0

ARC EXTINGUISHED

EXCESSIVE HEATING

ARC UNSTABLE SPACIALLY

NITROGEN — 3″ I.D. TUBE

GAS FLOW SCFH

1000
800
600
400
200
0

0   10   20   30   40   50   60   70   80

PLATE POWER (KW)
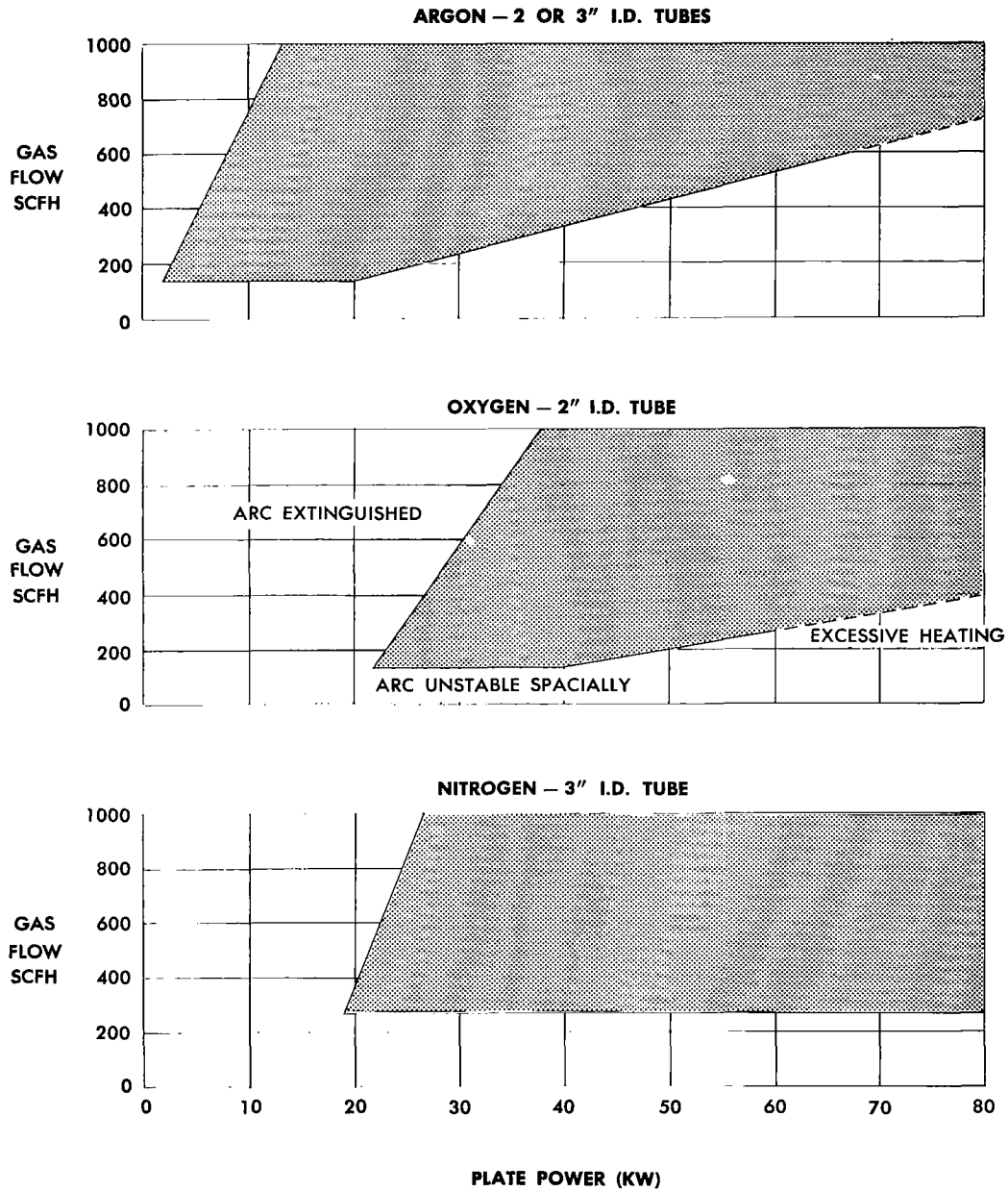
*   STANDARD CUBIC FEET PER HOUR

▒ AREA OF STABLE CONTINUOUS OPERATION

FIG. 11

35

ENERGY DISTRIBUTION IN AN INDUCTION PLASMA SYSTEM

(STEEL CALORIMETER, 3" TUBE MODEL 66 TORCH)

LOAD/COIL DIAMETER RATIO
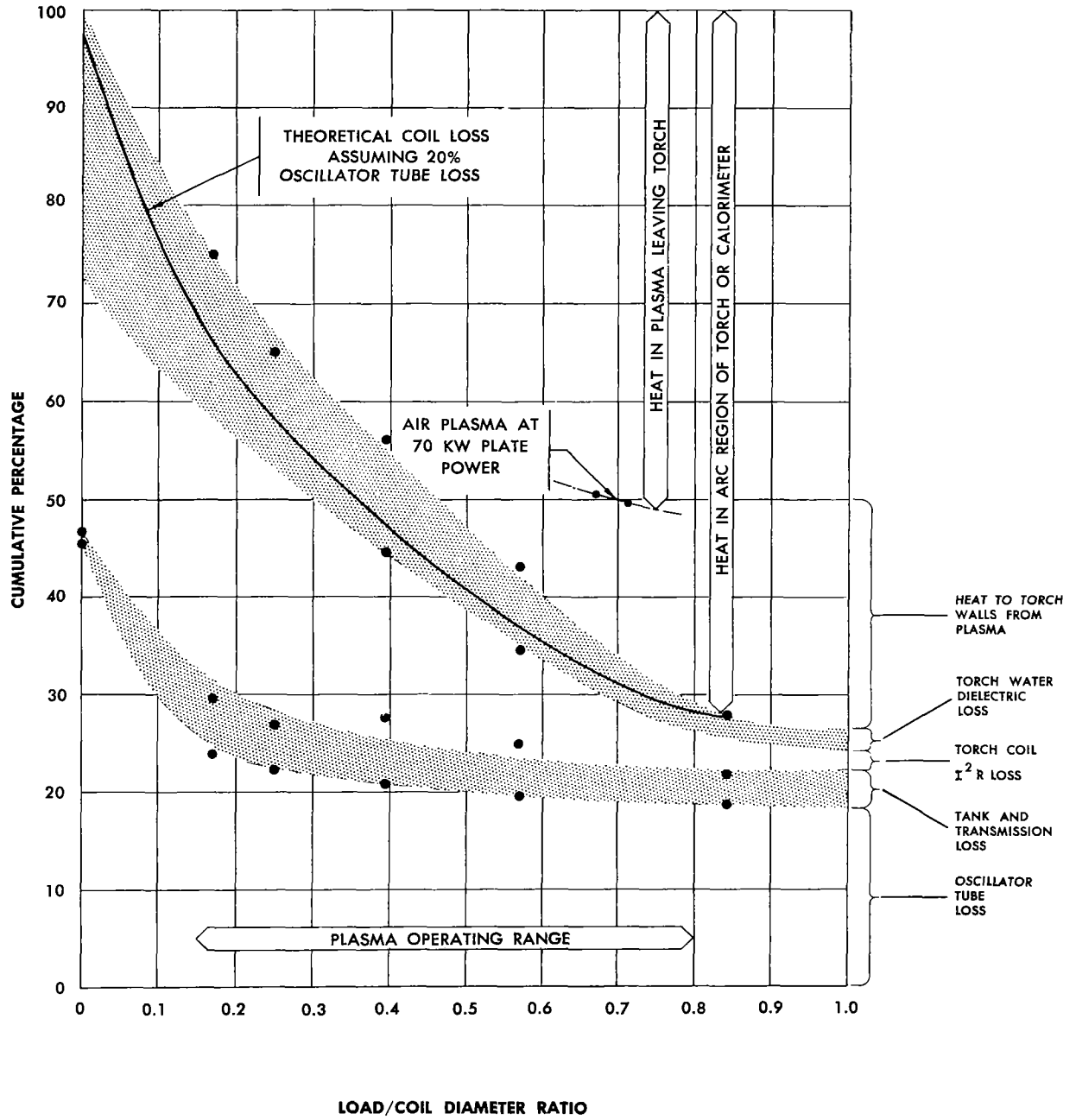
FIG. 12
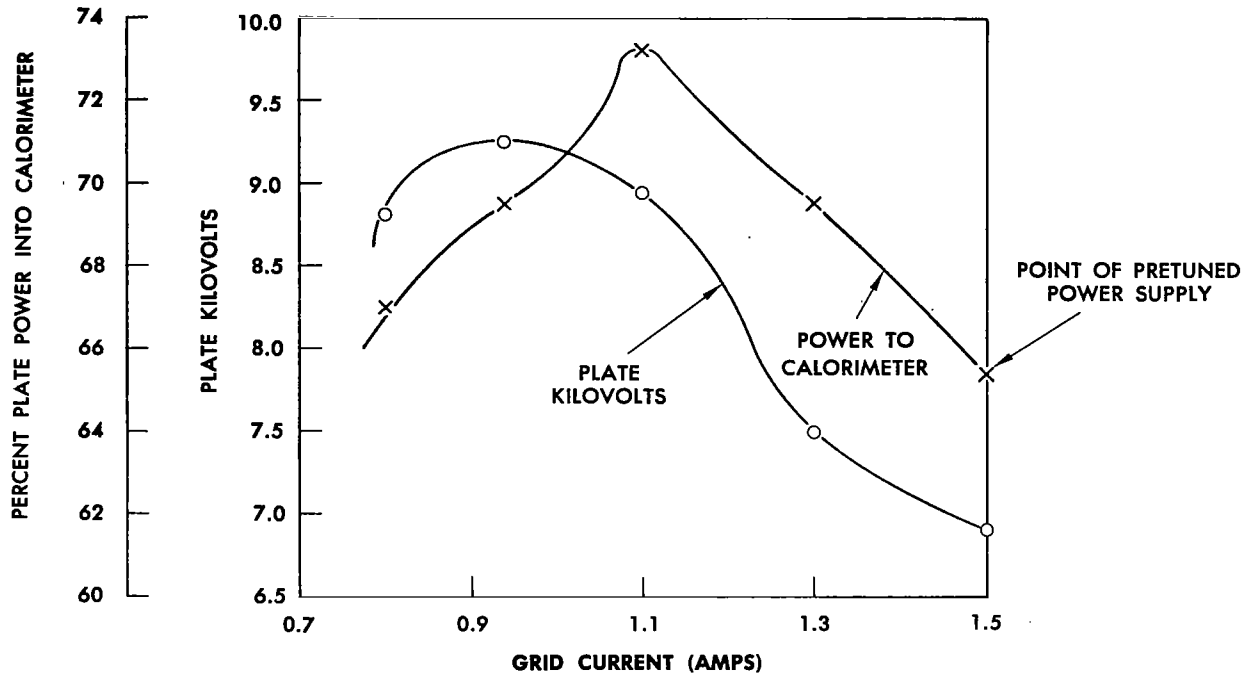
VARIATION OF EFFICIENCY AND VOLTAGE WITH GRID
DRIVE USING WELL MATCHED 2.83" STEEL LOAD

FIG. 13A
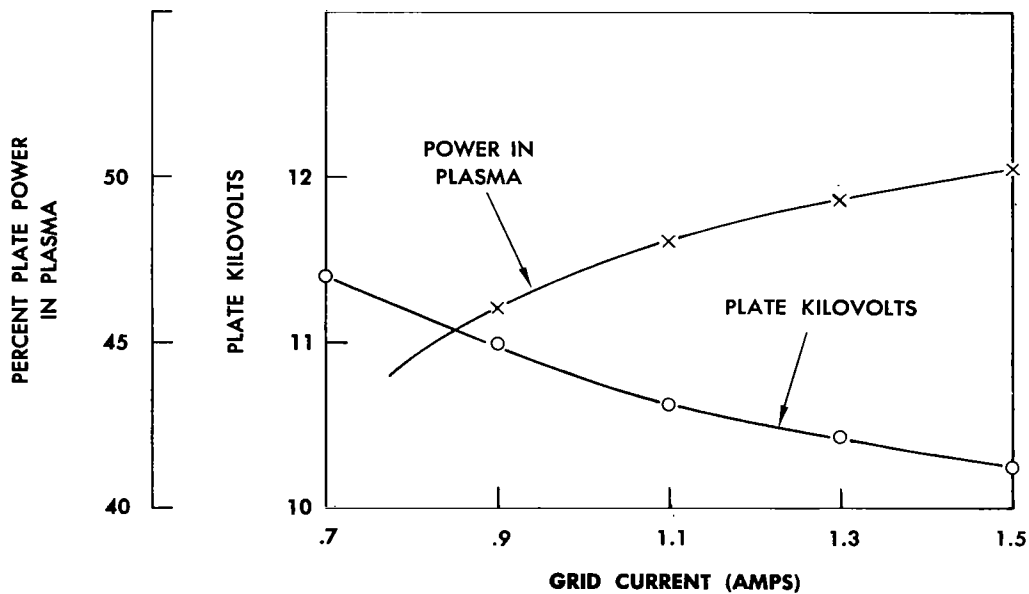
VARIATION OF EFFICIENCY AND VOLTAGE WITH GRID
DRIVE USING A WELL MATCHED AIR PLASMA LOAD

FIG. 13B

37
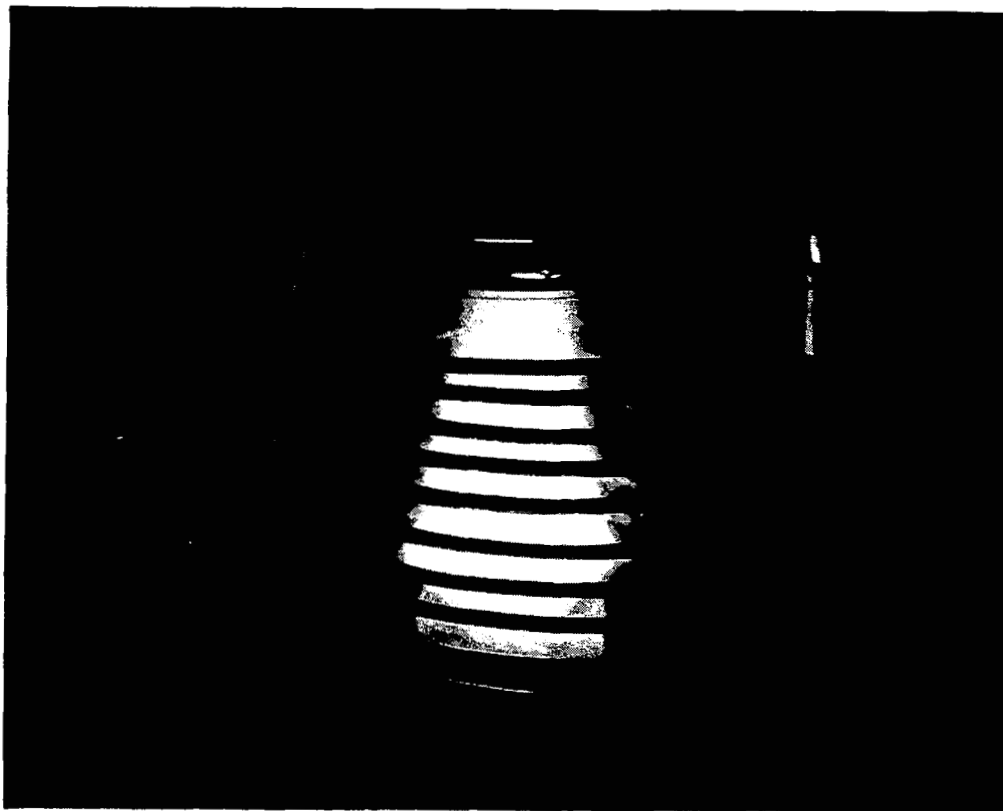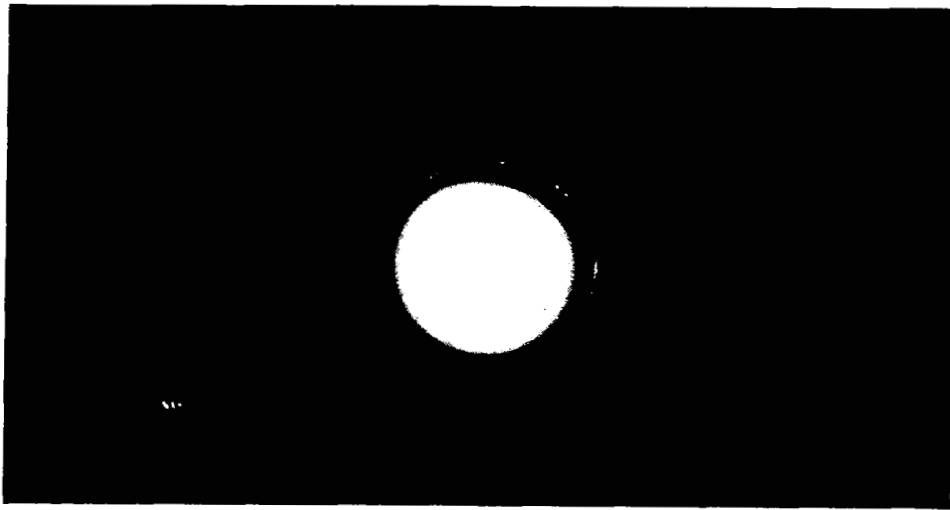
END VIEW

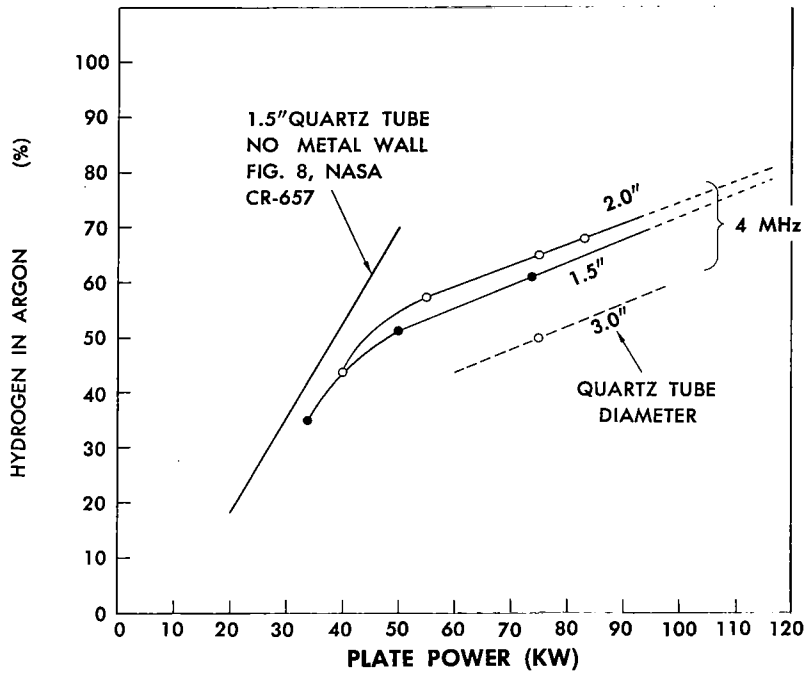SIDE & END VIEW OF MODEL 66 TORCH OPERATING
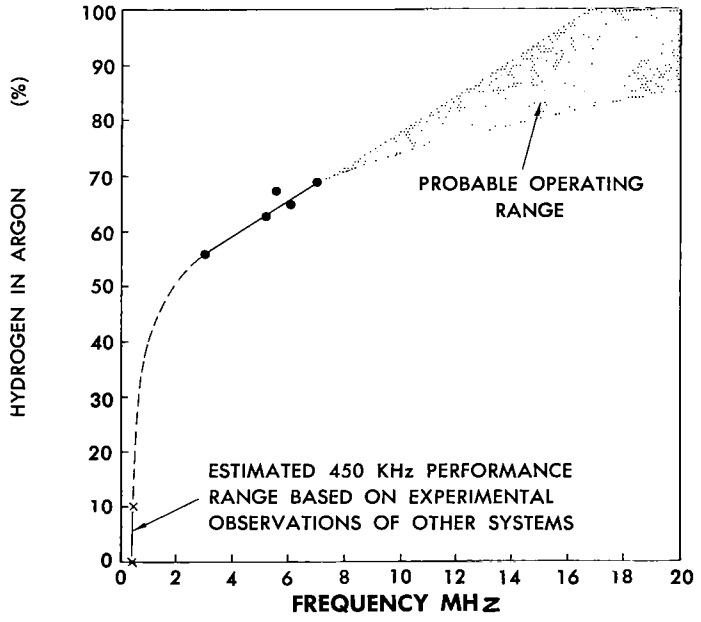
FIG. 14

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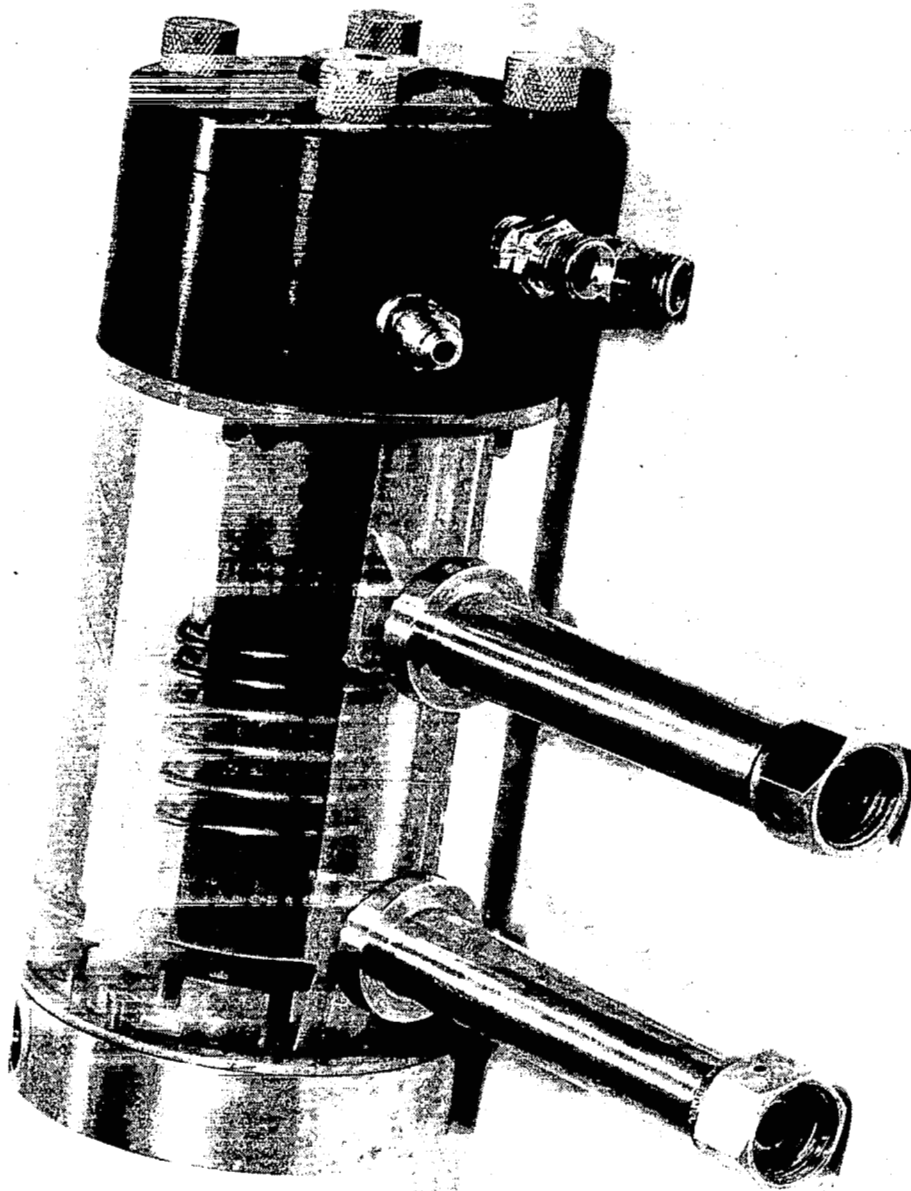
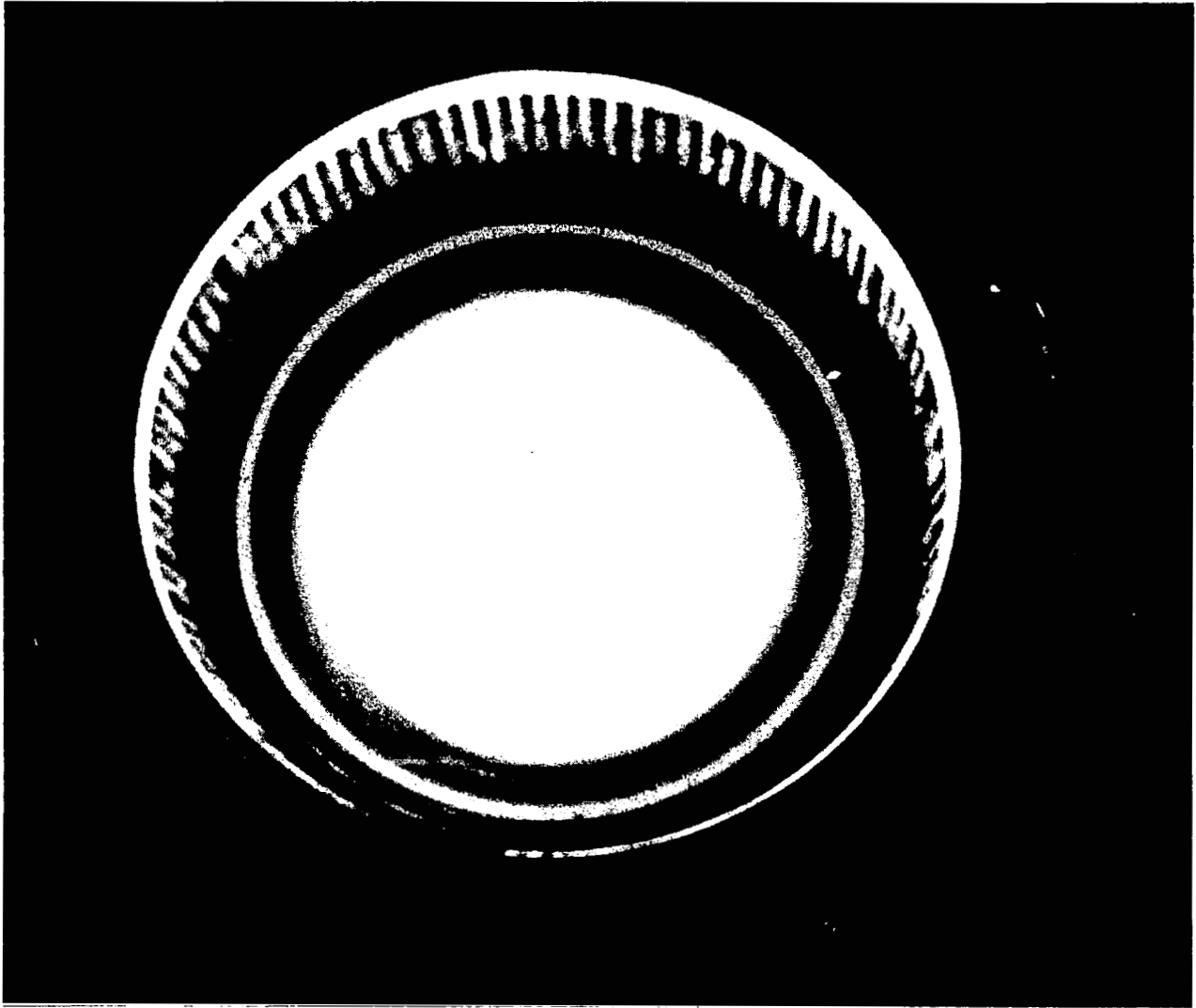**SEGMENTED METAL WALL (1.1" I.D.)
INSTALLED IN MODEL 56 TORCH**

FIG. 15

ENVELOPE OF DATA SHOWING
VARIATION OF HYDROGEN CAPABILITY WITH PLATE POWER   **FIG. 16**
WITH METAL WALL PLASMA CONTAINER

ENVELOPE OF DATA SHOWING
VARIATION OF HYDROGEN CONCENTRATION IN ARGON WITH   **FIG. 17**
FREQUENCY AT 65-80 KW PLATE POWER USING
1.1″ I.D. METAL WALL

END VIEW METAL WALLED SHEATH SYSTEM OPERATING

3" SHEATH SYSTEM OPERATING RANGE, ONE ATMOSPHERE INDUCTION PLASMA USING ARGON CORE GAS

COLD HYDROGEN SHEATH VELOCITY FPS

QUARTZ WALL RADIATION HEAT LOAD FAILURE BASED ON 20 GPM, 30% LOSS TO TORCH AND 30° F ΔT

ARC EXTINQUISHED

OPERATING RANGE

QUARTZ WALL COOLING FAILURE 3" I.D.

METAL WALL COOLING FAILURE — 3" I.D. BASED ON 25 GPM & 330 KW WALL DISSIPATION

QUARTZ WALL FAILURE ARGON CORE GAS ONLY, 120 SCFH

PLATE POWER (DC KW)

● EXPERIMENTAL DATA

FIG. 19

PARTICLE DROP APPARATUS

FIG. 20

GAS STREAM
LINES

FREE FALL
PARTICALS
BEING DEFLECTED
BY ARC

RF COIL

ARC
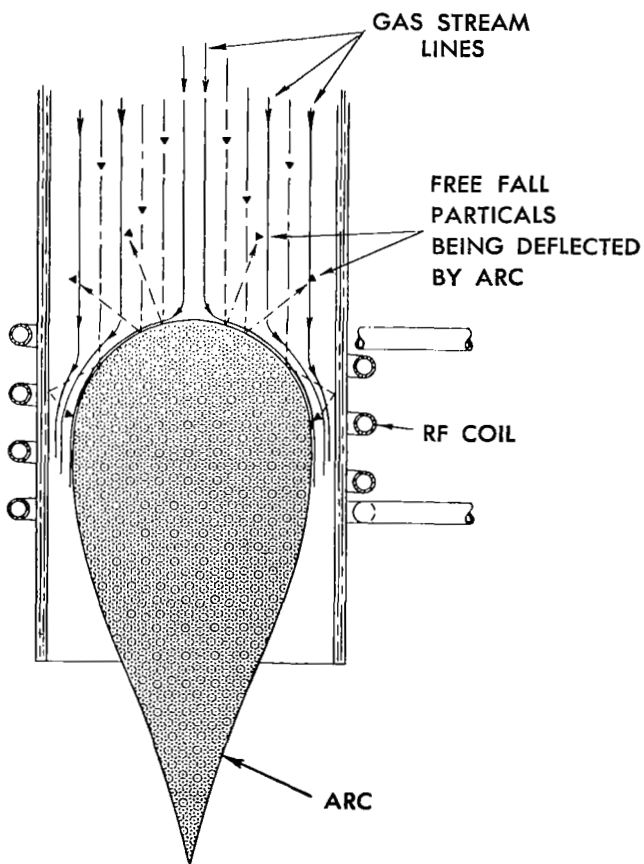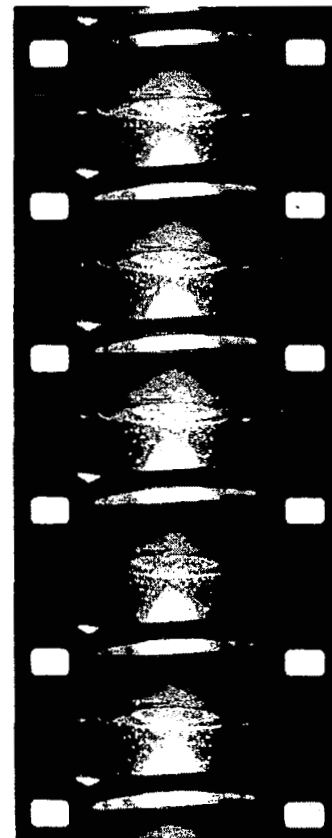
FIG. 21A

200 MICRON SILICA DEFLECTED BY ARC

(1500 FRAMES/SEC. ARGON GAS)

FIG. 21B

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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