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The design, construction, and evaluation of a vortex stabilized plasma generator

Ronald Ray Williams

THE DESIGN, CONSTRUCTION, AND EVALUATION OF A VORTEX STABILIZED PLASMA GENERATOR OPERATING ON ARGON

BY

RONALD RAY WILLIAMS

A

THESIS

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ABSTRACT

This report presents the design, construction, and evaluation of a vortex stabilized arc plasma generation facility operating on argon.

The facility consisted of five basic systems; the plasma generator, the electrical power system, the argon flow system, the cooling system, and instrumentation.

The facility was designed to meet four general requirements; stable arc operation, low electrode deterioration, low cost of construction, and provisions for determination of the operating character istics and thermal properties of the plasma.

Experimental results obtained in the laboratory agreed well with the design conditions. The rate of energy dissipated in the electric arc varied from 7. 8 to 17. 3 kilowatts. The calculated stagnation temperature of the plasma varied from 9, 000 to 16, 000 degrees Rankine, with corresponding enthalpies of 1, 110 to 2, 120 Btu per pound. Flow rates from 5. 61 to 25. 30 pounds per hour were used.

ACKNOWLEDGEMENT

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INTRODUCTION

By passing a gas through a region containing an electric arc, the gas may be heated to very high temperatures. The value of using an electric arc to heat a gas lies principally in laboratory simulation of thermally severe conditions. The added advantage of an arc plasma generator is its ability to produce these high enthalpy or high temperature conditions for extended periods of time.

The word plasma as defined by Thompson (1) strictly denotes an electrically neutral gas containing a high concentration of electrons and heavy ions. In most arc plasma generators, the temperature of the emerging gas stream is not sufficiently high to produce an appreciable amount of ionization. In this sense, the term plasma generator when applied to such units is a misnomer, but regardless, it is the common terminology.

In this paper, the term "arc plasma generator" will be used to describe all devices which use an electric arc to heat gases and the term "plasma" will be used to refer to the stream of heated gases produced.

Various types of arc plasma generators exist, differing in such characteristics as the electrode materials, electrode size and shape, and the method of stabilizing the electric arc. The configuration of the generator is generally a function of the application for which it was produced.

The process of using an electric arc to heat gases has many applications. They include chemical synthesis, refractory processes, re-entry simulation, high temperature research, and space propulsion. It is apparent that a plasma generator used for cutting refractory materials, which would require high temperature focused on a relatively small area, would not necessarily be the proper configuration for a plasma generator to be used for space propulsion with the desired result of maximum thrust.

The process of generating plasma in a vortex stabilized type plasma generator involves the interrelationship of many thermodynamic, fluid mechanic, electrical, energy transfer, microscopic, and macroscopic quantities. Among these various quantities are the independent variables, such as, the electrode spacing, the electrode materials, the power supply characteristics, the gas to be heated, and the flow rate of the gas. The dependent quantities include the arc voltage and current, and the properties of the plasma.

A stable arc is the primary requirement which must be satisfied to establish quasi-steady-state conditions of operation. If the movement of the arc is dictated only by its own characteristics, a random motion of the arc would result and the properties of the plasma generated would fluctuate erratically. Therefore, a means must be provided to establish regular motion of the arc.

Other requirements which must be satisfied for stable operation include a constant flow rate of the gas to be heated and the proper cool-

ing of the electrodes. In addition, a D. C. power supply with accompanying ballast resistance for a drooping voltage versus current relationship must be provided.

It is evident from the large number of variable quantities involved in the generation process that determination of the interrelationship of all variables would be a lengthy research task. Therefore, the research reported herein was directed toward obtaining an understanding of the general, over-all relationship of the variable quantities rather than focusing attention on the individual phenomena which are involved in the total process.

REVIEW OF LITERATURE

In the early 1900's, Birkeland and Eyde (2) developed an industrial process for the synthesis of nitric oxide from air using an electric arc. In 1910, Mathers (3) patented a unit designed for heating high temperature furnaces by the use of an electric arc heated gas. Numerous subsequent patents describe arc devices for cutting, welding, and spraying of refractory materials. John and Bade (4) lists a number of patents pertaining to generator configurations and a sizable list of papers concerning applications of arc plasma generators.

Since 1955, the urgent need for facilities capable of evaluating ablative materials under simulated re-entry conditions has caused the rapid development of arc plasma generation technology. Because of the extreme competition existing in this field, information with regard to engineering design or performance characteristics rarely appears in technical journals. Descriptions of existing equipment are generally found only in patents.

In the development stage of the plasma generator for re-entry simulation, it became apparent that the device was also attractive as a low thrust space engine. Considerable investigation along this line is presently being performed in anticipation of future demands. Information resulting from this work is also highly guarded.

EQUIPMENT DESIGN

The facility was designed to meet four general requirements; stable arc operation, low electrode deterioration, low cost of construction, and provisions for determination of the plasma generator operating characteristics and thermal properties of the plasma.

The basic systems of the plasma generation facility were the generator, the power supply and external electric circuit, the gas supply system, the electrode cooling system, and instrumentation.

A discussion of each of these systems and its relation to satisfactory over-all operation of the facility follows.

Vortex Stabilized Plasma Generator - Fig. 1 is a scale drawing of the plasma generator. The outer casing was made of 6 inch steel pipe. The disks on either end of the outer casing were made of 0.375 inch steel plate. The cathode was made of 1 inch diameter thoriated tungsten press fit into 1 inch outside diameter copper tubing. A small water jacket made of steel surrounds a portion of the cathode. Transite was used to electrically insulate the cathode from the rest of the generator. The anode nozzle was made of copper with a 0.125 inch wall thickness. The water jacket surrounding the nozzle was made of 4 inch steel pipe, 0.375 inch steel plate and 0.25 inch steel plate. The vortex generator was constructed of 4 inch steel pipe.

The over-all length of the plasma generator, including the 9 inch copper tubing extension of the cathode, was 18 inches. This extension

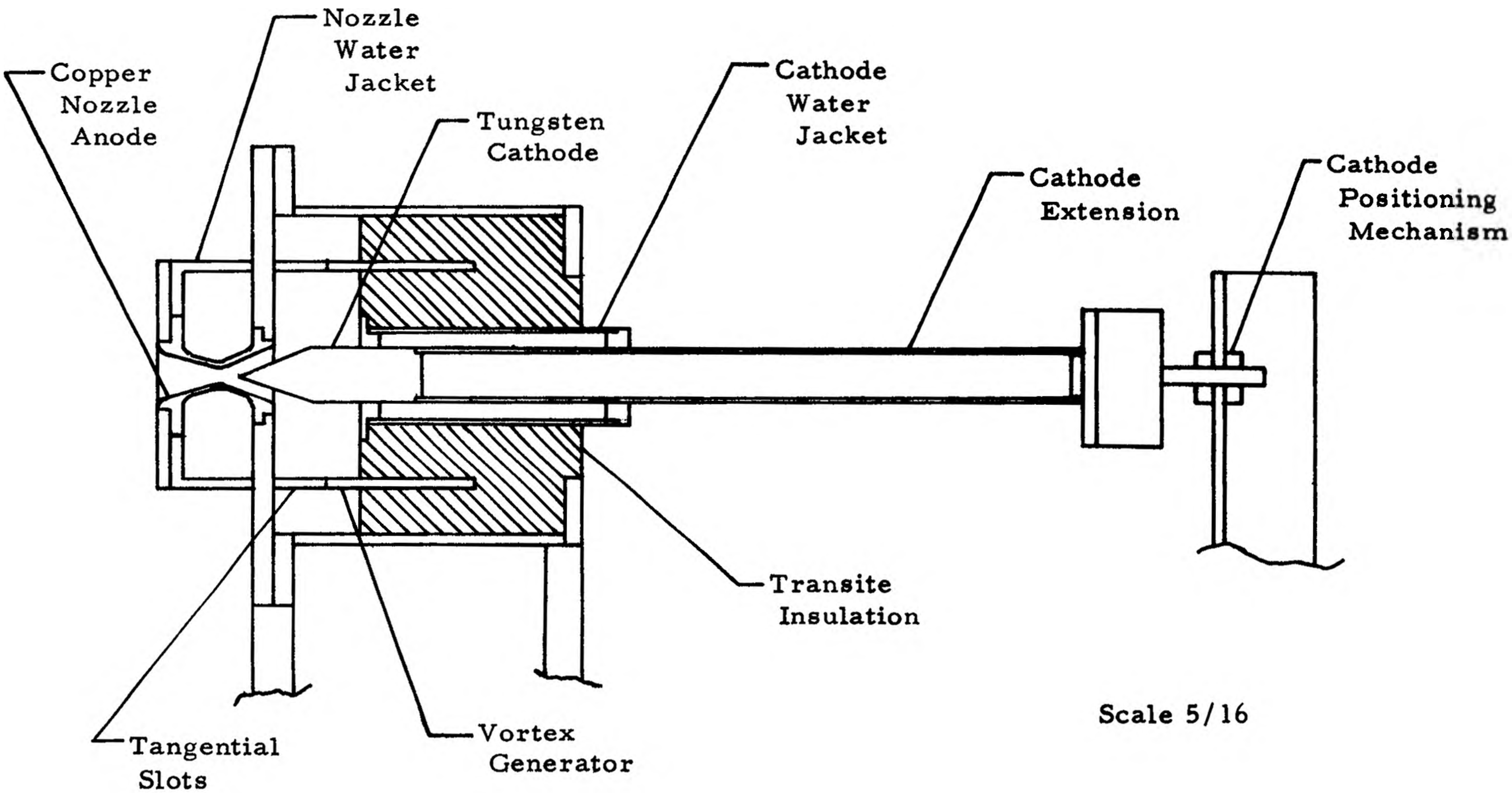

Figure 1

Vortex Stabilized Plasma Generator

was incorporated to facilitate electrical connection to the cathode, water inlet to the cathode cooling jacket, and positioning of the cathode. At the end of the cathode extension was the cathode adjustment and locking mechanism.

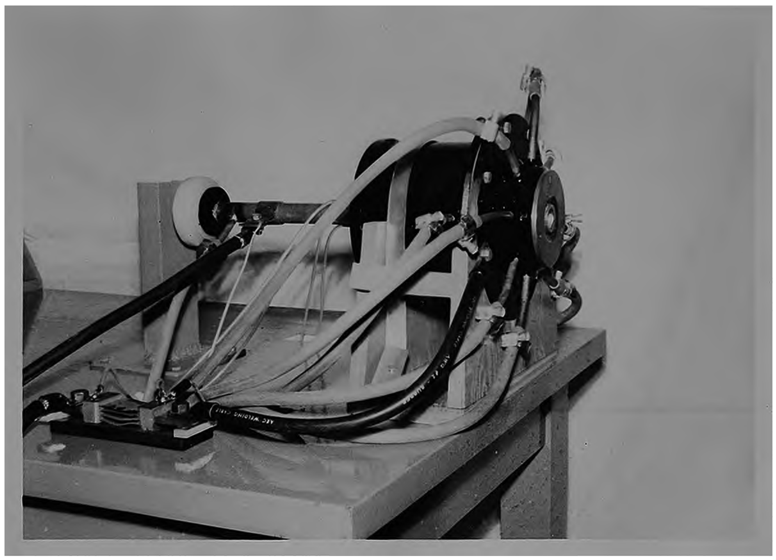

Figure 2

Service Connections to Plasma Generator

Fig. 2 is a photograph of the generator displaying the service connections. Electrical connections were made to the copper tubing cathode extension and to the outside of the generator proper. Eight water tubes were connected to the nozzle cooling water jacket. Water connections for the cathode cooling jacket were made on the copper tubing cathode extension and the rear of the cathode water jacket. The

argon was introduced into the generator at two positions. One of these positions may be seen in Fig. 2 just to the left of one of the water lines to the nozzle water jacket.

Stable operation of the arc plasma generator was a basic requirement of this work. This required a stable arc between the copper nozzle anode and the tungsten cathode. Two such arcs may exist; one which remains relatively still or one which moves in a regular pattern at a constant speed. Since a still arc would result in eventual destruction of the copper nozzle, due to electrical heating in a small area, the moving arc was selected. The problem of obtaining constant motion of the arc was solved by the incorporation of the vortex generator shown in Fig. 1. Slots 1 inch long and 0.063 inch wide were cut in a section of 4 inch pipe tangent to the inside surface of the pipe. As the gas entered the chamber through these slots, it was forced to travel in a direction tangent to the inside surface, thus creating a vortex around the tungsten cathode. The interaction of this vortex and the arc kept the arc in constant motion.

A stable moving arc also prevented deterioration of the electrode. By causing the arc to move, localized heating due to the arc attachment on the copper nozzle was held to a minimum.

Fig. 3 shows the plasma generator operating on argon. In the photograph a tungsten welding rod inserted in the plasma stream was heated to a temperature above its melting point (greater than 6,000 degrees Fahrenheit).

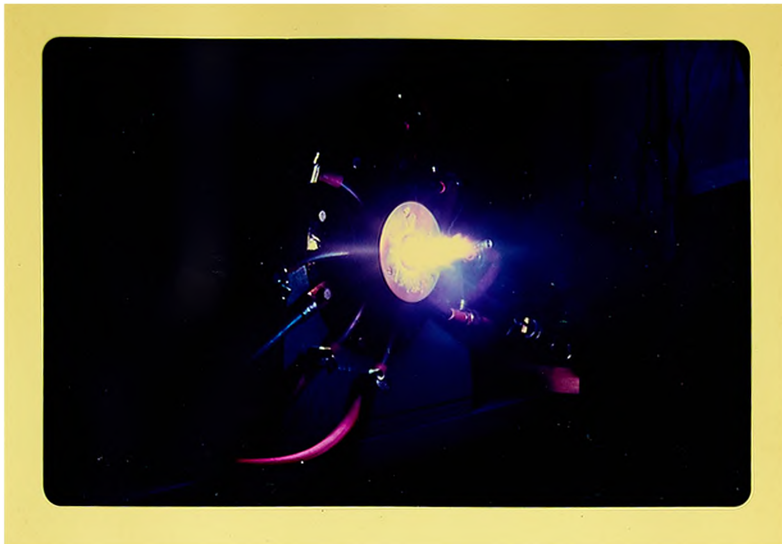

Figure 3

Plasma Generator Operating on Argon

Electrical System - The required electrical energy is provided by the General Electric motor-generator set in the Mechanical Engineering Laboratory. This unit is capable of supplying up to 320 amperes at a constant direct current voltage of 250 volts. Direct current was used to increase the stability of the system. Alternating current would have produced a constantly changing arc which may have made stable operation difficult.

Had this constant voltage power supply been connected directly across the anode and cathode of the generator, a slight change in the resistance of the arc would have caused a large change in the current flowing in the circuit. To avoid this problem of instability, the circuit used was that in Fig. 4. The incorporation of the ballast resist-

ance in the circuit causes the arc voltage versus arc current relationship to have a negative slope. If it is assumed that the change in the value of the ballast resistance due to electrical heating during operation is negligible, the voltage versus current relationship will also be linear. The total effect of the ballast resistance was to provide a "drooping" load line.

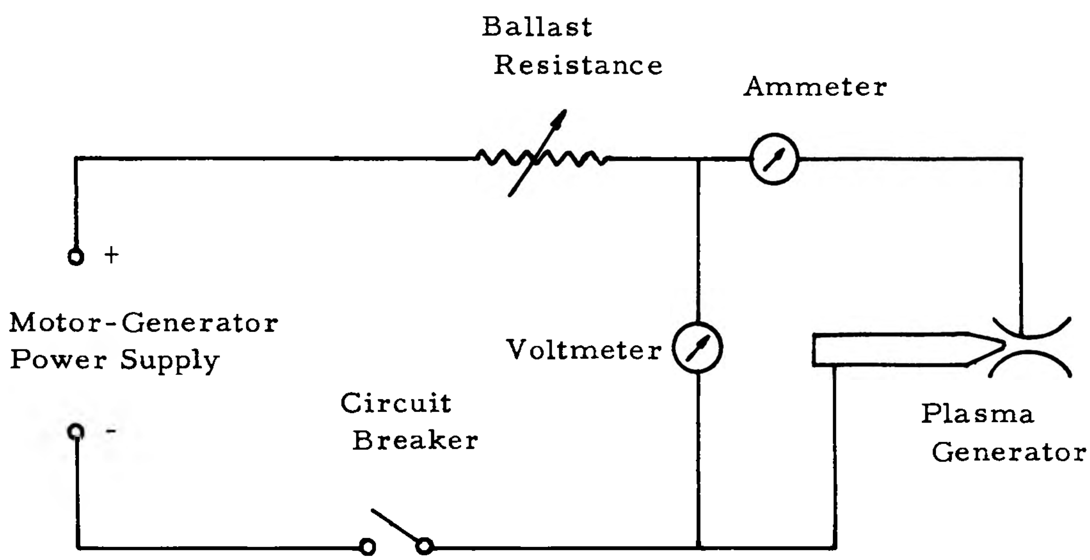

Figure 4

Schematic Diagram of Electrical Circuit

As the magnitude of the ballast resistance is increased, the slope of the drooping load line becomes more negative and a change in arc resistance has even less effect on the power operating characteristics of the plasma generator.

The ballast resistance used was the resistance bank existing in the laboratory normally used to dissipate electrical energy generated

by one of the dynamometers. The resistance bank consisted of cast iron bars arranged in a parallel circuit. The value of resistance may be varied from 0. 0 to 1. 1 ohms.

Referring again to the general conditions to be satisfied by the plasma generation facility, the stability of the facility was greatly enhanced by restricting the power characteristics of the generator to a drooping load line.

Gas Supply System - Fig. 5 is a schematic drawing of the gas flow system. The argon was stored in bottles and the pressure upstream of the throttle valve was regulated by use of a pressure regulator connected directly to the argon bottle. The orifice type flow meter used to measure the flow rate of argon to the generator was constructed and calibrated. The argon was introduced in the plasma generator at two locations. This was done to aid in the creation of the vortex. A section of rubber hose was used between the generator and the tubing transporting the argon to the plasma generator to electrically isolate the gas flow system.

The stability of the plasma generator was affected by the stability of the argon flow rate. At a steady flow rate of argon, the vortex created was steady and the arc movement was stabilized. Also, the length of the arc was affected by the magnitude of the argon flow rate. At conditions of unsteady argon flow, the arc would tend to fluctuate and produce changing plasma. With steady argon flow, the arc length was maintained relatively constant.

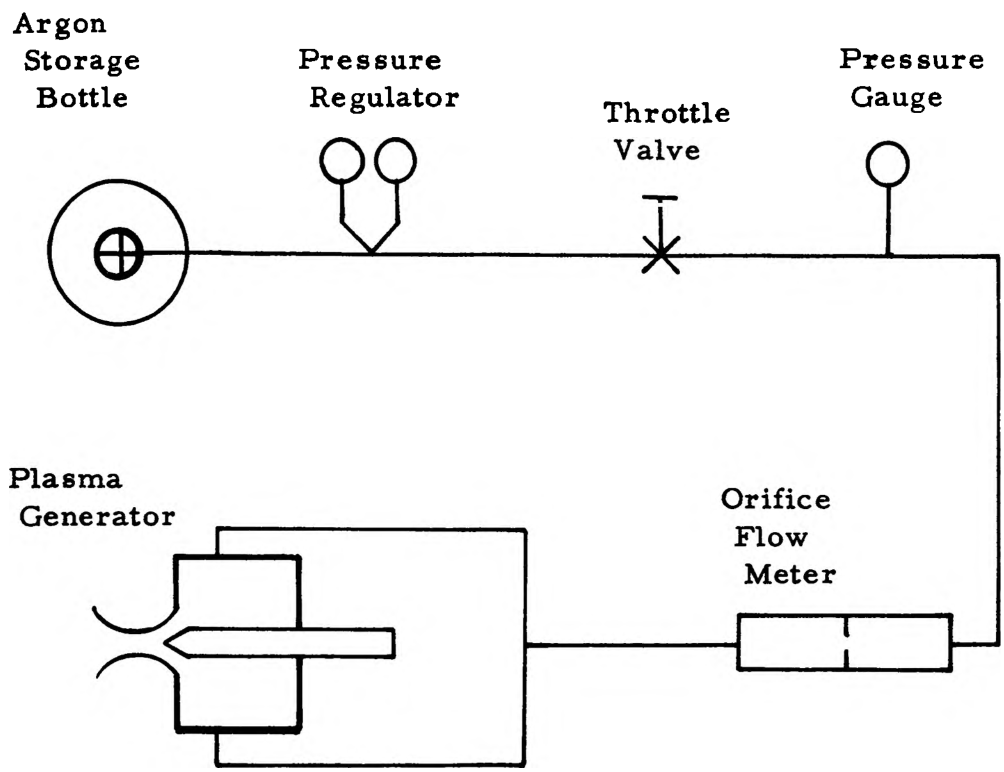

Figure 5

Schematic Diagram of Gas Flow System

Electrode deterioration was largely prevented by the use of argon, an inert gas. Had a gas which would react with tungsten, such as air, been used, the tungsten electrode would have been eroded at an unacceptable rate. The plasma stream produced by the generator would also have been contaminated by tungsten oxides and other compounds formed.

Cooling System - Water was used to cool both the copper anode (the nozzle) and the tungsten cathode. Fig. 6 shows the cooling flow

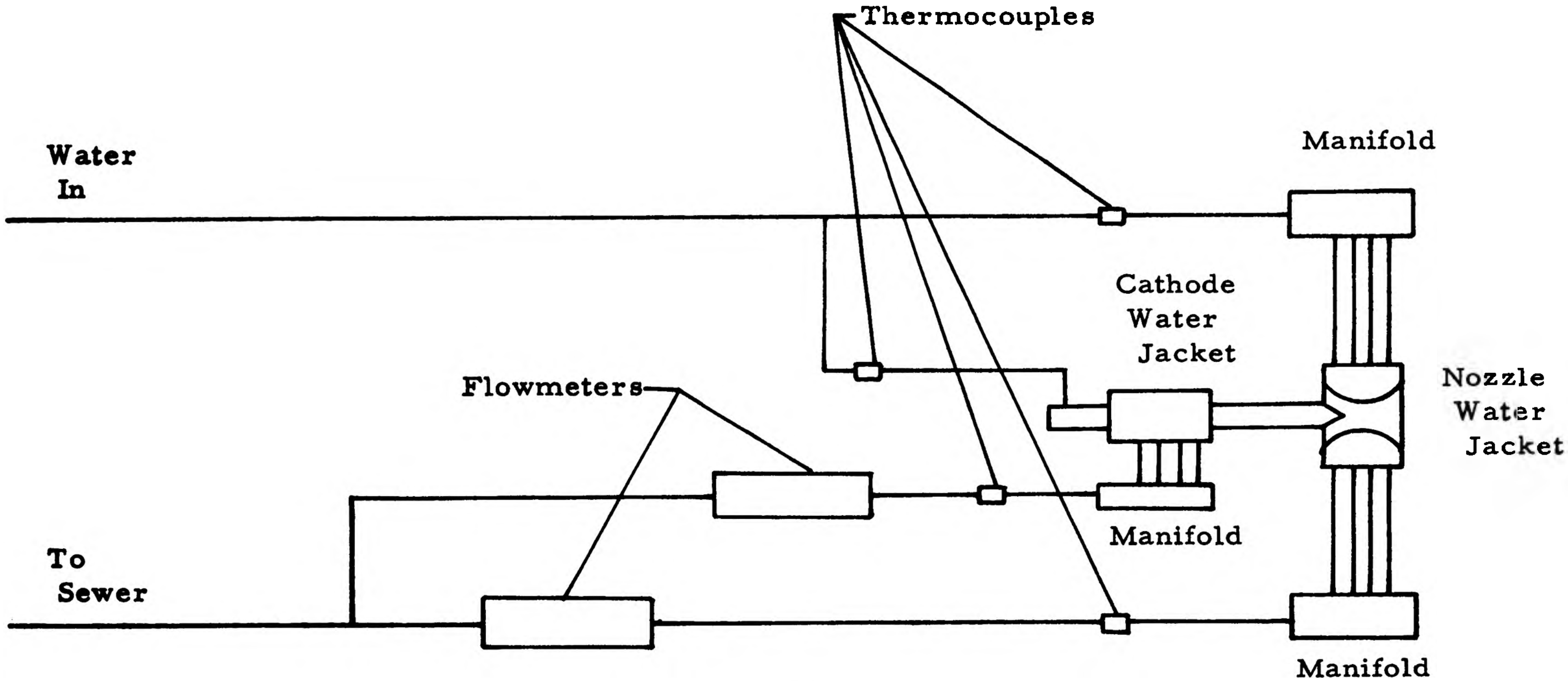

Figure 6

Schematic Diagram of Cooling System

system used. Water was brought into the nozzle cooling jacket by four copper tubes and taken out by four other tubes. Manifolds were used at both inlet and outlet. The cathode cooling system was much the same as the nozzle cooling system, with the exception that the water was brought into the cathode cooling jacket through the copper tubing extension of the cathode and out four small diameter tubes in the rear of the water jacket. The use of four small tubes was dictated by space limitations. Sections of rubber hose were used to electrically isolate the cooling system from the plasma generator.

The cooling of the electrodes, in particular of the copper nozzle anode, greatly improves the electrode life. Had no cooling been provided to the anode, it would have melted in a very short time.

Instrumentation - The following instrumentation was provided to assist in the determination of the plasma generator operating characteristics and the thermal properties of the plasma stream. Fig. 7 is a photograph of the instrument panel.

An ammeter and a voltmeter were installed as part of the facility for measuring the arc current and voltage. The existing output voltmeter of the motor=generator set provided the line voltage.

An orifice type flow meter was constructed and calibrated to indicate the flow rate of argon to the plasma generator. The pressure upstream of the orifice and the pressure differential across the orifice plate were obtained from a Bourdon-tube pressure gauge and a water manometer, respectively.

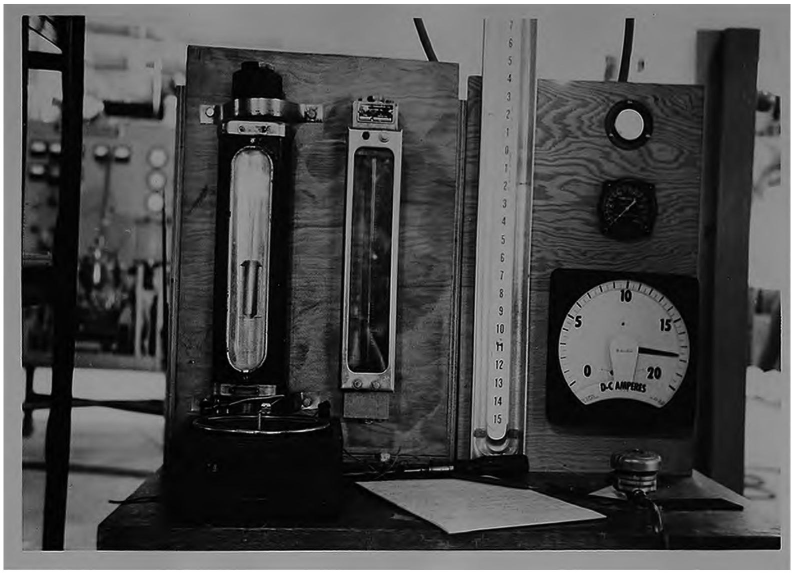

Figure 7

Instrument Panel

Variableareaflow meters were used to measure the flow rates of cooling water to the water jackets. The inlet and outlet water temperatures were measured using iron-constantan thermocouples in conjunction with a recording potentiometer.

The orifice type flow meter calibration curve is given in Appendix A.

Summary - Stability of the plasma generator was obtained by producing a vortex stabilized arc, providing a steady flow rate of argon, using a direct current electrical power supply, and restricting the

arc characteristics to a drooping load line.

Deterioration of the electrodes was minimized by incorporation of a moving arc, argon as the gas to be heated, and water cooling of the electrodes.

The use of existing materials and equipment where possible lowered the cost of construction. Argon and electrical cable were the major cost items.

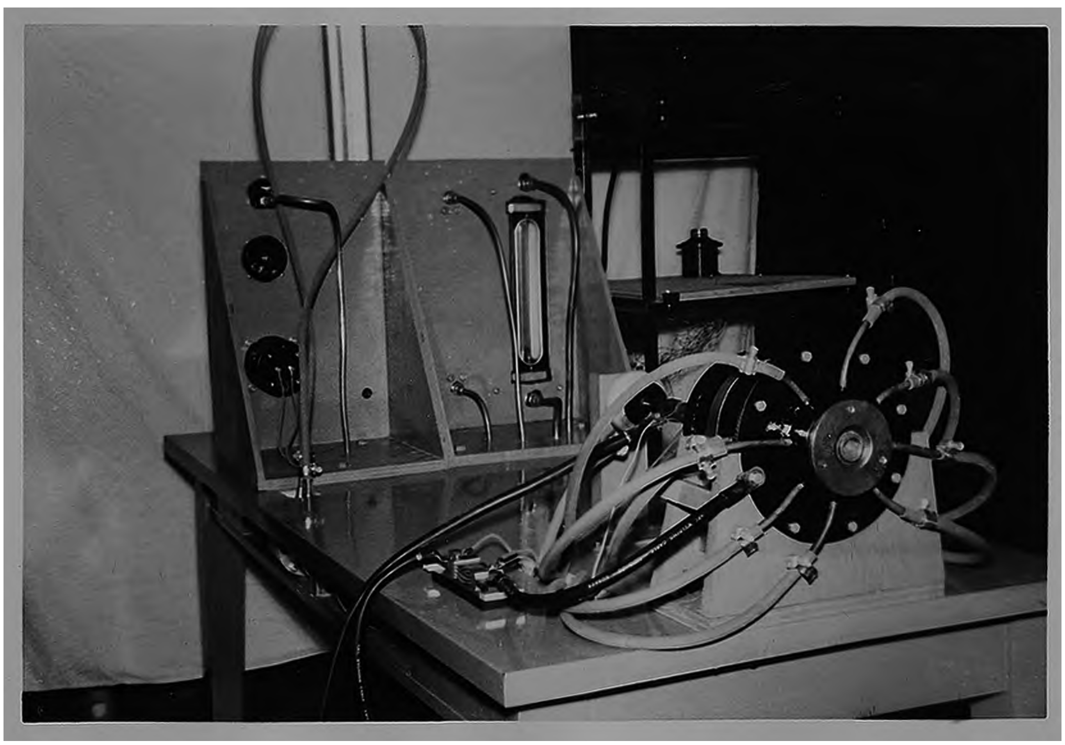

Figure 8

Over-all View of Plasma Generation Facility

EXPERIMENTAL PROCEDURE AND RESULTS

The plasma generator was started and operated by the following procedure. After checking all electrical, cooling, and gas supply connections, the water valve was opened allowing the water to flow through the cooling jackets. Next, the circuit breakers completing the electrical circuit were closed. At this point, the argon throttle valve was opened to a point allowing a large flow rate of argon to pass to the plasma generator. Upon establishment of a steady high argon flow rate, the electric arc between the tungsten cathode and the copper nozzle anode was initiated by inserting a copper wire in the nozzle until it touched both the nozzle and the cathode. Creation of a short circuit between the copper nozzle and the cathode allowed a high current to flow in the circuit which immediately destroyed the copper wire, replacing it with the desired electric arc. The argon flow rate was then decreased until stable operation of the generator was reached.

To determine the operating characteristics of the facility, the effects of the following independent variables were studied; argon flow rate, cathode-anode arc gap, and magnitude of the ballast resistance.

At a point of stable operation, the instruments were read after allowing sufficient time for the systems to reach steady state conditions. Readings of arc voltage, arc current, pressure upstream from and pressure difference across the orifice flow meter, and cathode

and nozzle cooling water flow rates were taken at each condition.

Table II in Appendix A summarizes the experimental data obtained during operation of the plasma generator.

Eye protection is necessary when observing the plasma stream due to the intense ultraviolet radiation emitted. Shade 10 arc weldor's filter lenses were used. Precautions were also taken to protect the observer's skin from burns caused by the thermal radiation from the plasma stream.

Visual observation indicated the following characteristics. At high argon flow rates, the electric arc extended beyond the end of the nozzle causing great instability in the plasma generator. At these high flow rates, movement of the arc around the outside of the generator indicated the vortex generator was performing as expected.

At low argon flow rates, the arc was contained in the copper nozzle with the exception of an occasional "zap" (extension of the arc followed by immediate return to stable operation). With the arc contained in the copper nozzle, operation of the plasma generator was stable.

Melting of a tungsten rod when inserted in the plasma stream provided the initial estimate of the temperature level (greater than 6,000 degrees Fahrenheit).

DISCUSSION OF RESULTS

The experimental data were analyzed to determine the general over-all interrelationship of the many parameters involved in the operation of the arc plasma generator.

Table I gives the range of the results of the data and analysis.

TABLE I

Range Of Plasma Generator Parameters*

	Minimum	Maximum	Units
Length Of Run	1	18	minute
Electrode Gap**	1.81	2.06	inch
Arc Voltage	42	100	volt
Arc Current	137	196	ampere
Arc Power	7.8	17.3	kilowatt
Argon Flow Rate	5.61	.25.3	lb/hr
Calculated Stagnation Enthalpy	1,110	2,120	Btu/lb
Calculated Stagnation Temperature	9,000	16,000	°Rankine
Generator Efficiency	36	68	percent

* All maximum (and minimum) values do not occur together.
** Distance from nozzle exit to cathode tip.

The stagnation enthalpy of the plasma was calculated by assuming that the only energy lost was to the circulating cooling water. Therefore, the energy dissipated in the electric arc minus the energy added to the cooling water was the energy added to the argon stream. The stagnation enthalpy was then taken as the sum of the energy added to the gas divided by the mass flow rate of argon and the initial enthalpy.

The temperature of the plasma was estimated from the enthalpy-temperature relationship as given in Fig. 9. This relationship was

obtained from ref. 5.

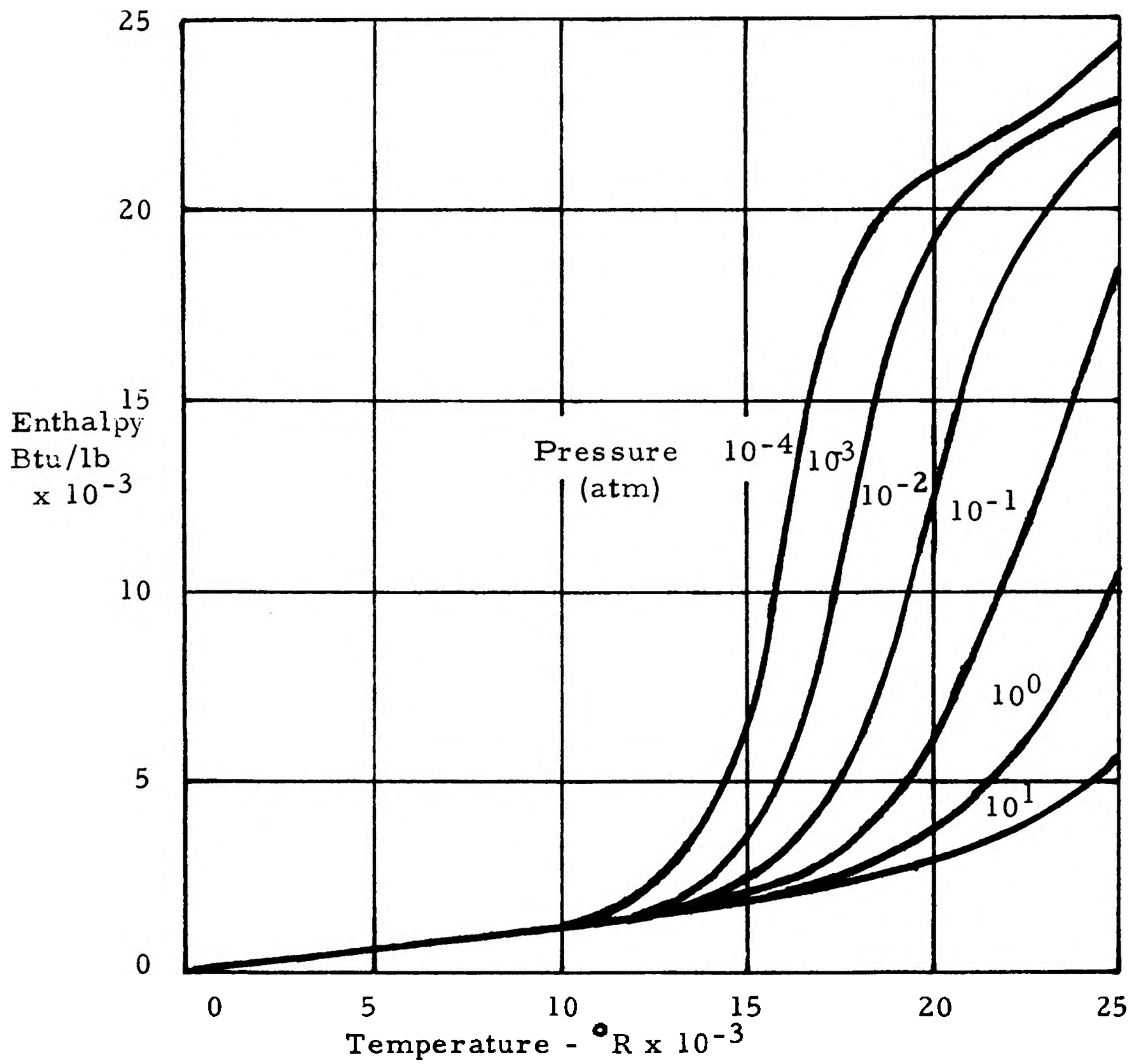

Figure 9

Enthalpy of Argon

The generator efficiency is defined as:

$$\text{General Efficiency} = \frac{\text{Energy to Argon}}{\text{Input Energy}} \times 100$$

$$= \frac{\text{Electrical Energy In - Cooling Losses}}{\text{Electrical Energy In}} \times 100.$$

This efficiency relates the ability of the plasma generator to transfer the energy dissipated in the electric arc to the argon flowing through the generator.

Electrical Considerations - The arc voltage is inversely proportional to the current when using the electrical circuit shown in Fig. 4. The sum of the potentials around the circuit is equal to zero. Thus

$$V_{mg} - IR_b - V_a = 0$$

where V_{mg} = motor generator output voltage, volts

I = current, amperes

R_b = ballast resistance, ohms

V_a = arc voltage, volts.

Rearranging the above equation,

$$V_a = V_{mg} - IR_b.$$

Assuming the magnitudes of the ballast resistance and the value of the arc resistance are constant during a period of stable operation, the arc voltage-arc current relationship is seen to be linear. The intercepts of the relationship on a voltage versus current plot may be found by considering short circuit and open circuit conditions at the anode-cathode gap.

With an open circuit, no current would flow in the circuit and

$$V_a = V_{mg} - \overset{0}{\cancel{IR}}_b$$

$$V_a = V_{mg}.$$

The potential generated by the motor-generator set would exist

across the anode-cathode gap. For a short circuit across the anode-cathode gap, the potential drop across the gap would be zero or,

$$V_a = V_{mg} - IR_b$$

$$I = \frac{V_{mg}}{R_b} .$$

Fig. 10 shows a typical drooping load line for the plasma generator. Since a constant potential is obtained from the motor-generator set, the slope of the drooping load line is a function of the magnitude of the ballast resistance.

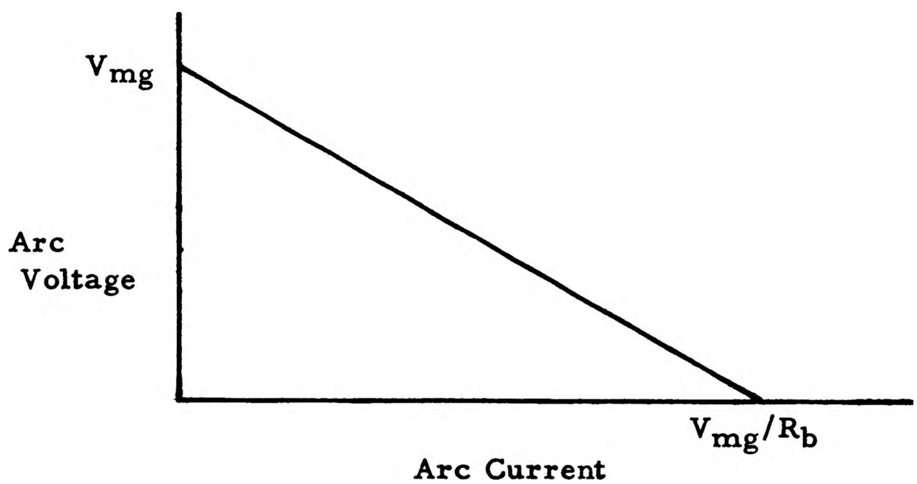

Figure 10

Theoretical Load Line

Fig. 11 shows the experimental data taken during operation of the plasma generator. The data was taken with the motor-generator set potential at 250 volts. The solid lines on Fig. 10 are the theoretical load lines on which the plasma generator would be expected to operate with the motor-generator set potential at 250 volts and for ballast

resistances of 1.1 ohms and 0.9 ohms. As can be seen from the figure, the experimental data agree very well with the theoretical load lines. The deviations are probably due to over-compensation for load changes by the motor-generator set.

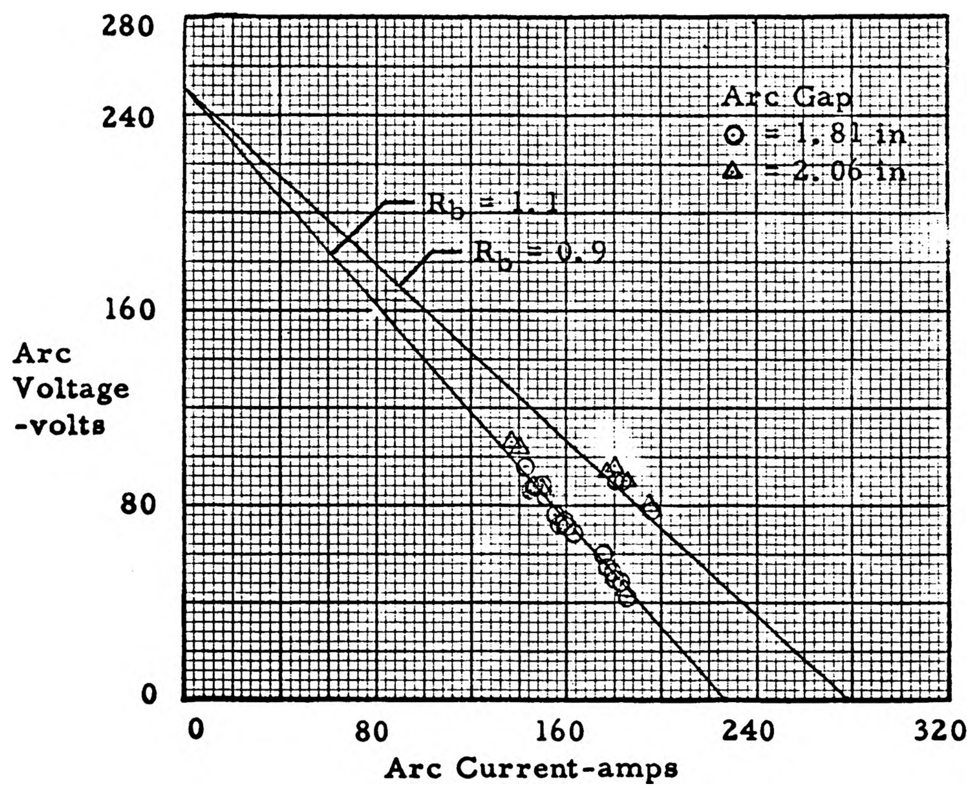

Figure 11

Arc Voltage versus Arc Current

Argon Mass Flow Considerations - Theoretically, as the mass flow rate of argon is increased, the length of the anode-cathode arc is increased. An increase in the length of the arc would cause the

arc to have a greater resistance, thereby increasing the electrical energy dissipated in the arc.

Fig. 12 shows the experimental data of arc energy versus the argon mass flow rate. The trend of the data is to higher arc energies at higher argon mass flow rates. The curve levels off as the length of arc reaches that of the nozzle. When the arc is long enough to reach the exhaust end of the nozzle, an increase in argon flow rate can have no further effect on the length of the arc.

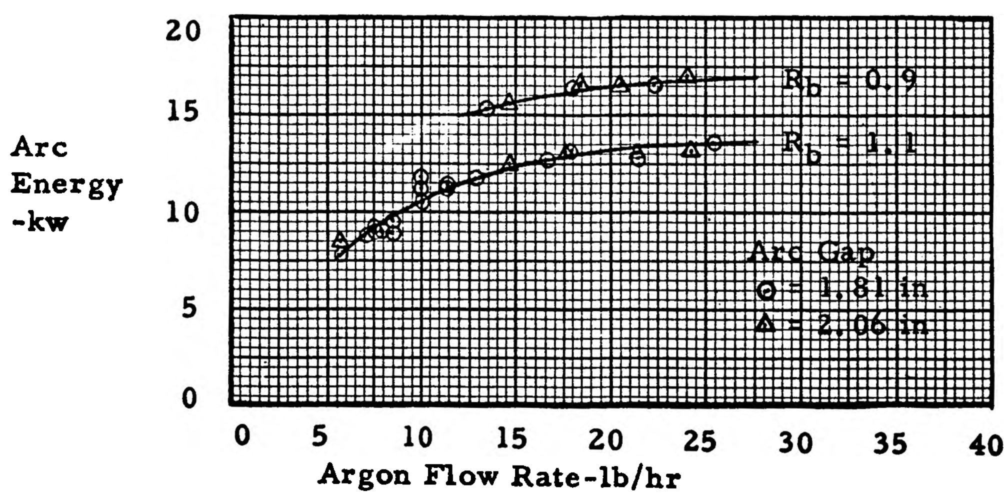

Figure 12

Arc Energy versus Argon Flow Rate

The theoretical effect of decreasing the magnitude of the ballast resistance in the circuit is to increase the energy dissipated in the

anode-cathode arc. This is borne out by the experimental data in Fig. 12.

Fig. 13 illustrates the experimental relationship between the argon flow rate and the generator efficiency. The generator efficiency is observed to increase with an increase in argon flow rate. This is because of the greater amount of argon subjected to the electric arc at the higher argon flow rates. To heat a large quantity of mass to a low temperature is easier than attempting to heat a small amount of mass to a temperature approaching that of the heating element. Also, at high mass flow rates, the arc length is greater and provides more area for energy transfer.

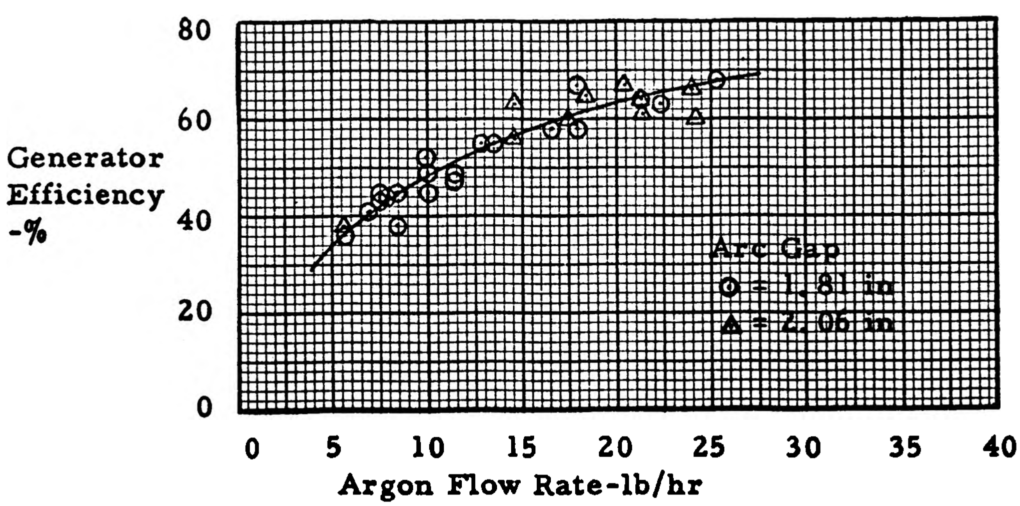

Figure 13

Generator Efficiency versus Argon Flow Rate

The calculated stagnation enthalpy of the generated plasma is shown as a function of the argon flow rate in Fig. 14. Although considerable scatter exists in the data, a trend to higher enthalpies at lower argon flow rates may be detected. This is as expected, since at low flow rates each molecule of argon remains in the arc region for a longer period of time than at high flow rates, and consequently acquires more energy. For argon, enthalpies of 1, 110 to 2, 120 Btu/lb correspond to temperatures of 9, 000 to 16, 000 degrees Rankine, respectively.

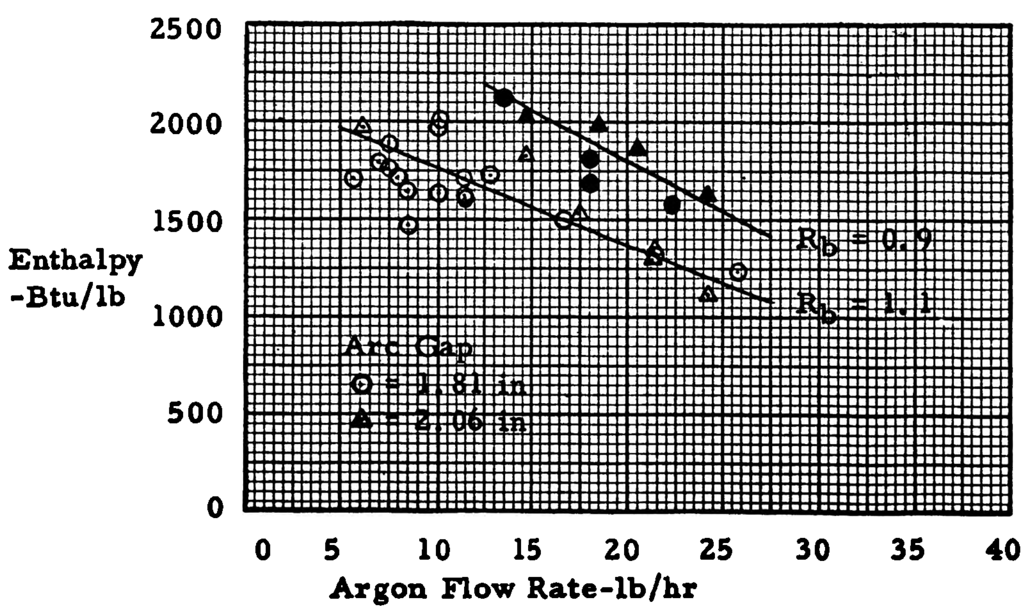

Figure 14

Calculated Stagnation Enthalpy versus Argon Flow Rate

The scatter of the data in Fig. 12, Fig. 13, and Fig. 14 is probably due to inaccuracy of the argon flow rates and water temperature thermocouple readings. At low flow rates, it was difficult to observe changes in the flow rate on the instruments. The thermocouple readings were affected by stray electrical signals.

Incorporating external ballast resistance in the electrical circuit restricted the arc characteristics to a drooping load line. Because of over compensation by the motor-generator power supply, the actual experimental load line was higher than the theoretical load line. However, the experimental load line had the same slope as the theoretical load line.

As the magnitude of the ballast resistance was decreased, the plasma generator became more unstable, indicating the point of operation was less well defined. Because a decrease in ballast resistance provided a load line with a less negative slope, a slight change in the argon flow rate produced greater changes in the arc characteristics. Thus, the decrease in ballast resistance did cause some instability of the plasma generator.

Variation of the argon flow rate caused the following changes in the operating charcteristics of the plasma generator. As the flow rate of argon was increased the arc voltage increased and the arc current decreased with an over-all effect of a decrease in arc power. The generator efficiency decreased as the argon flow rate decreased. At high argon flow rates, the system was unstable due to arc blowout.

At extremely low mass flow rates, the system was unstable due to vortex breakdown.

The effect of variation of the anode-cathode arc gap on the operating characteristics cannot be discerned from the experimental data obtained. Theoretically, an increase in arc gap should cause an increase in arc resistance and consequently higher arc power. Higher arc power should produce higher generator efficiency and higher plasma stagnation enthalpy.

CONCLUSIONS AND RECOMMENDATIONS

Satisfactory performance was obtained from the vortex stabilized arc plasma generator studied while operating on argon. Stable operation was obtained, producing plasma with a range of thermal properties. Electrode deterioration was held to a minimum.

However, it is felt that better understanding of the plasma generation parameters could be obtained by an improved configuration of plasma generator and refinement of the accompanying instrumentation. Also, if stable sources of electrical power and cooling water could be obtained, it is believed the reproducibility of the system operation would be increased.

The instrumentation should be refined, if more accurate results are to be obtained. In particular, the thermocouples used to indicate the temperatures of the cooling water should be shielded to prevent data scatter by stray electrical signals. Also, the argon flow meter should be improved by replacement of the existing orifice plate with one capable of indicating low flow rates more accurately.

Appendix B contains a description of a vortex stabilized plasma generator configuration recommended to produce more stable operation over a wider range of operating conditions. Basically, the design calls for a long region for arc containment followed by a converging nozzle.

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APPENDICES

APPENDIX A

Fig. 13 is the calibration curve for the orifice flow meter constructed.

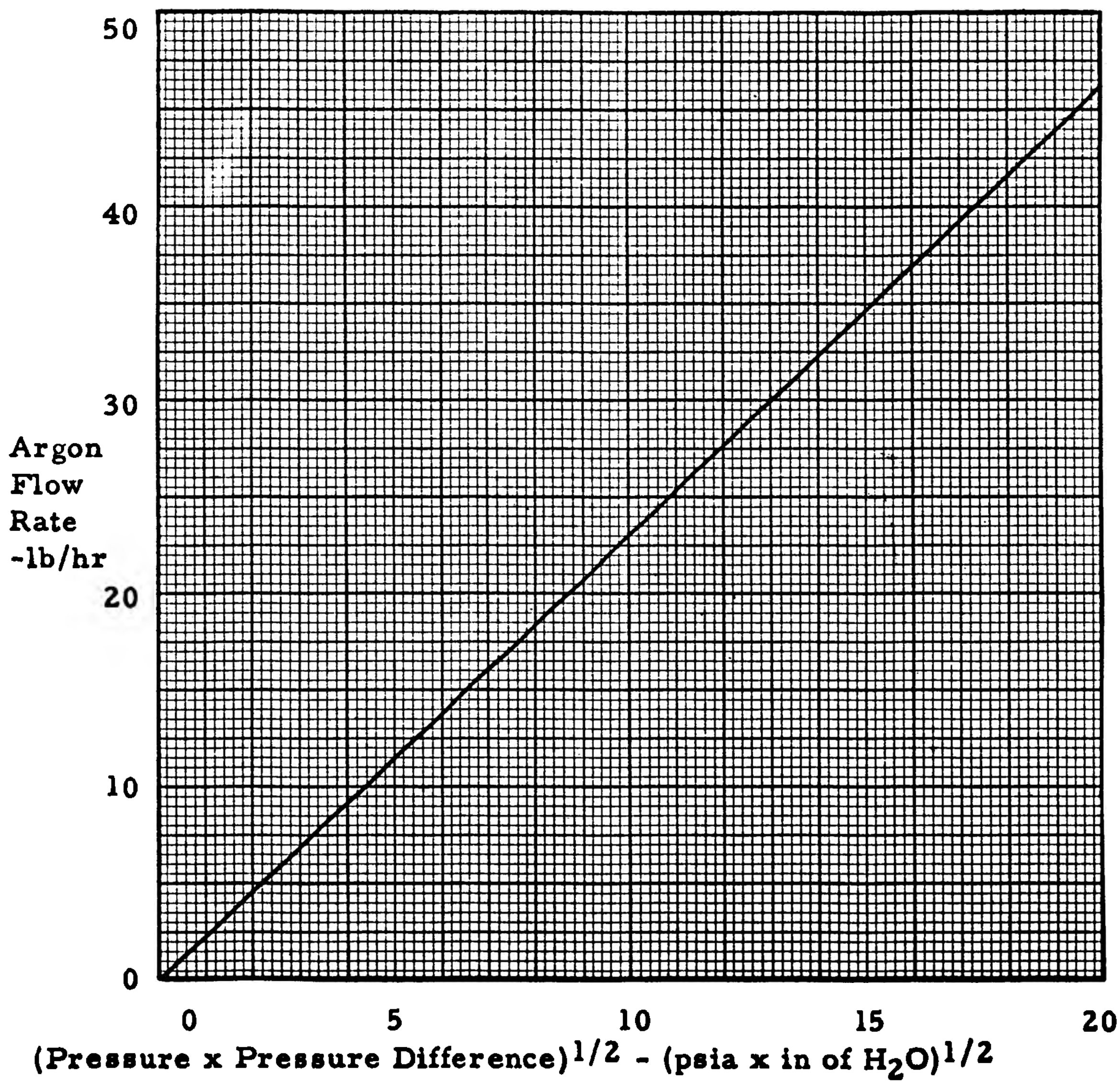

Figure 13

Orifice Flow Meter Calibration Curve

TABLE II

EXPERIMENTAL DATA

Run	Cathode Cooling lb/hr	Nozzle Cooling lb/hr	Cathode ΔT °F	Nozzle ΔT °F	Orifice Upstream Pressure psia	Orifice Pressure Difference in. of H_2O	Arc Voltage volt	Arc Current amp	Arc Gap in	External Resistance ohm
1	189	2, 560	9	5	15. 67	3. 8	90	147	1. 81	1. 1
2	181	2, 480	11	6	14. 67	0. 9	50	180	1. 81	1. 1
3	181	2, 480	12	6	14. 62	0. 8	50	180	1. 81	1. 1
4	181	2, 480	12	6	14. 59	0. 7	52	179	1. 81	1. 1
5	189	2, 560	12	7	14. 90	1. 6	72	157	1. 81	1. 1
6	189	2, 560	12	5	16. 86	6. 9	96	142	1. 81	1. 1
7	189	2, 560	12	6	14. 59	0. 7	50	180	1. 81	1. 1
8	189	2, 560	12	6	14. 55	0. 6	48	182	1. 81	1. 1
9	189	2, 560	14	7	15. 26	1. 2	76	155	1. 81	1. 1
10	181	2, 480	14	7	14. 90	1. 6	72	160	1. 81	1. 1
11	181	2, 480	12	7	15. 26	1. 2	60	175	1. 81	1. 1
12	189	2, 560	12	7	14. 67	0. 9	54	177	1. 81	1. 1
13	181	2, 480	12	6	14. 50	0. 4	42	186	1. 81	1. 1
14	189	2, 560	14	7	14. 90	1. 6	72	158	1. 81	1. 1
15	189	2, 560	14	6	15. 60	3. 6	88	149	2. 06	1. 1
16	189	2, 560	14	6	14. 50	0. 4	46	185	2. 06	1. 1
17	189	2, 560	14	6	16. 20	5. 2	94	140	2. 06	1. 1
18	189	2, 560	14	6	16. 60	6. 5	96	137	2. 06	1. 1
19	181	2, 480	14	7	16. 66	6. 4	96	180	2. 06	0. 9
20	181	2, 480	15	7	15. 75	4. 0	90	185	2. 06	0. 9
21	189	2, 560	16	8	15. 25	2. 6	80	195	2. 06	0. 9
22	198	2, 620	13	5	16. 20	5. 2	88	146	1. 81	1. 1

TABLE II (continued)

EXPERIMENTAL DATA

Run	Cathode Cooling lb/hr	Nozzle Cooling lb/hr	Cathode ΔT °F	Nozzle ΔT °F	Orifice Upstream Pressure psia	Orifice Pressure Difference in of H_2O	Arc Voltage volt	Arc Current amp	Arc Gap in	External Resistance ohm
23	198	2,620	13	6	15.50	3.3	84	151	1.81	1.1
24	198	2,620	13	6	15.05	2.0	74	159	1.81	1.1
25	198	2,620	13	6	15.26	1.2	69	163	1.81	1.1
26	198	2,620	14	7	16.35	5.6	92	180	1.81	0.9
27	198	2,620	14	8	15.67	3.8	90	183	1.81	0.9
28	198	2,620	14	8	15.10	2.2	78	196	1.81	0.9
29	198	2,620	14	5	16.20	5.2	88	146	2.06	1.1
30	198	2,620	13	5	15.25	2.6	86	145	2.06	1.1
31	198	2,620	14	6	16.10	4.9	94	176	2.06	0.9

TABLE III

CALCULATED DATA

Run	Cathode Cooling Btu/hr	Nozzle Cooling Btu/hr	Arc Power kw	Argon Flow Rate lb/hr	Plasma Stagnation Enthalpy Btu/lb	Plasma Stagnation Temperature °R	Generator Efficiency %
1	1,700	12,800	13.23	17.96	1,690	13,000	67
2	1,990	14,880	9.00	8.40	1,650	12,500	45
3	2,170	14,880	9.00	7.96	1,720	13,000	44
4	2,170	14,880	9.31	7.45	1,890	14,500	45
5	2,270	17,920	11.30	11.38	1,620	12,500	48
6	2,270	12,800	13.63	25.30	1,240	10,000	68
7	2,270	15,360	9.00	7.45	1,760	13,500	43
8	2,270	15,360	8.74	6.86	1,780	14,000	41
9	2,650	17,920	11.78	9.96	1,970	15,000	49
10	2,530	17,360	11.52	11.38	1,710	13,000	49
11	2,170	17,360	10.50	9.96	1,640	12,000	45
12	2,270	17,920	9.56	8.45	1,470	11,500	38
13	2,170	14,880	7.81	5.61	1,710	13,000	36
14	2,650	17,920	11.38	11.38	1,610	12,500	47
15	2,650	15,360	13.11	17.45	1,530	11,500	60
16	2,650	15,360	8.51	5.61	1,970	15,500	38
17	2,650	15,360	13.16	21.36	1,350	10,250	61
18	2,650	15,360	13.15	24.18	1,110	9,000	60
19	2,530	17,360	17.28	24.04	1,620	12,000	66
20	2,725	17,360	16.65	18.48	1,990	15,500	65
21	3,020	20,480	15.60	14.66	2,030	15,500	56

TABLE III (continued)

CALCULATED DATA

Run	Cathode Cooling Btu/hr	Nozzle Cooling Btu/hr	Arc Power kw	Argon Flow Rate lb/hr	Plasma Stagnation Enthalpy Btu/lb	Plasma Stagnation Temperature °R	Generator Efficiency %
22	2, 570	13, 100	12. 85	21. 36	1, 320	10, 250	64
23	2, 570	15, 720	12. 68	16. 64	1, 500	11, 500	58
24	2, 570	15, 720	11. 75	12. 78	1, 720	13, 000	55
25	2, 570	15, 720	11. 25	9. 96	2, 020	15, 250	52
26	2, 770	18, 340	16. 56	22. 27	1, 590	12, 000	63
27	2, 770	20, 960	16. 47	17. 96	1, 810	14, 000	58
28	2, 770	20, 960	15. 29	13. 40	2, 123	16, 000	55
29	2, 770	13, 100	12. 85	21. 36	1, 310	10, 500	64
30	2, 570	13, 100	12. 47	14. 66	1, 830	14, 000	63
31	2, 770	15, 720	16. 54	20. 43	1, 860	14, 000	67

APPENDIX B

Fig. 16 is a representation of the plasma generator configuration recommended to produce stable generation over a wider range of operating conditions. It is felt by allowing a large region for arc containment, the length of arc would depend on the argon flow rate more than on the length of the nozzle. The converging nozzle would serve to concentrate the plasma generated and assist in containing the arc. By designing the vortex generator of the same diameter as the arc containment region, perhaps a steadier vortex flow would be produced.

The problems associated with this design include cooling of the long arc containment region, initiating the arc, and maintaining arc movement at low argon flow rates.

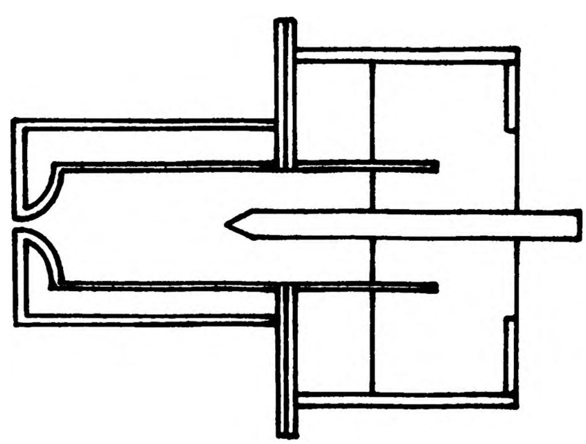

Figure 16

Improved Plasma Generator Configuration

VITA

The author was born May 15, 1940 in Dexter, Missouri. He received his primary education in several Missouri towns and received his secondary education in Overland, Missouri. He received a Bachelor of Science degree in Mechanical Engineering from the University of Missouri School of Mines and Metallurgy in June, 1963, through the co-operative program with McDonnell Aircraft Corporation.

He has been enrolled in the Graduate School of the University of Missouri School of Mines and Metallurgy since June, 1963, and has held a Graduate Assistantship in the Mechanical Engineering Department for the period September, 1963 to June, 1964.

The author is a student member of American Society of Mechanical Engineers and Society of Automotive Engineers. Honor societies of which he is a member are Pi Tau Sigma, Tau Beta Pi, and Sigma Xi.