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Design of Regeneratively Cooled, High Temperature, Clean Gas Plasma

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DESIGN OF A REGENERATIVELY COOLED, HIGH TEMPERATURE, CLEAN GAS PLASMA GENERATOR

A Thesis
Presented to the
Department of Mechanical Engineering Science
Brigham Young University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Roger Carver Bartlett
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This thesis by Roger Carver Bartlett is accepted in its present form by the Department of Mechanical Engineering Science of Brigham Young University as satisfying the thesis requirements for the degree of Master of Science.

August 10, 1964
Date

Typed by Jacqueline P. Carter

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NOMENCLATURE

A = Area

Btu = British thermal unit

C = Coefficient of discharge

C_p = Specific heat at constant pressure

D = Diameter

D_1 = Pipe diameter

D_2 = Orifice diameter

g = Acceleration of gravity

$\bar{h}$ = Average convective heat transfer coefficient

i = Specific enthalpy

i^* = Reference enthalpy

i_r = Recovery enthalpy

i_{st} = Static enthalpy

i_w = Wall enthalpy

J = Mechanical equivalent of heat

k = Thermal conductivity

K = Flow coefficient $= \dfrac{C}{\sqrt{1 - (D_2/D_1)^4}}$

L = Length

M = Mach number

$\overline{Nu}$ = Average Nusselt number

$\overline{Nu}_D$ = Average Nusselt number based on diameter

Pr = Prandtl number

q = Energy transfer rate

q_c = Energy transferred by convection

q_r = Energy transferred by radiation

r_i = Recovery factor = $\sqrt[3]{Pr}$ in turbulent flow

R = Gas constant for air = 6.88×10^{-2} Btu/lb°R

Re = Reynolds number

Re_D = Reynolds number based on diameter

T_o = $273.16^{\circ}K$ = $491.69^{\circ}R$

T^* = Reference temperature

T_G = Plasma temperature (gas)

T_w = Wall temperature

V = Velocity

$\dot{\omega}$ = Mass rate of flow

Δ = Increment of change when used with a letter

β = Diameter ratio = D_2/D_1

ρ = Density

μ = Absolute viscosity

ABBREVIATIONS

^{o}F = Fahrenheit degrees

^{o}K = Kelvin degrees

^{o}R = Absolute fahrenheit degrees

atm. = Atmospheres

cm. = Centimeters

ft. = Feet

hr. = Hour

in. = Inches

KW. = Kilowatts

lb. = Pounds

psig. = Pounds per square inch gage

psia. = Pounds per square inch absolute

sec. = Seconds

CHAPTER I

INTRODUCTION

The objective of this thesis was the design of a regeneratively cooled, high temperature, clean gas plasma generator facility.[1] This facility was desired to extend the high temperature research capabilities of the Department of Mechanical Engineering.

During the past decade, activity in the field of electric arc heating of gases has increased immensely (1,2)[2]. This increased activity has largely been brought about through the influence of the nuclear and aerospace industries. Particularly in these industries, there is a need to be able to produce high temperature environments for engineering research. Current research efforts are involved in simulating the high temperature conditions encountered in thermonuclear reactions and in aerodynamic heating (3,4). Aerodynamic heating raises the surface temperature of bodies placed in a high speed fluid stream or of bodies moving at high speed through a stagnant fluid. An example of the latter is the heating of the skins of high speed airplanes and missiles.

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[1] Plasma generator is defined as an electric arc device for sustained heating of gases to high temperatures. In some cases, the temperature of the emergent gas stream may not be high enough to have caused appreciable ionization of the gas. However, the designation plasma generator is commonly applied to all arc heating equipment regardless of the temperature of the emergent gas stream.

[2] Numbers in parentheses refer to references cited in the Bibliography.

The facilities commonly used to produce high temperature environments for research are shock tubes, exploding wires and electric discharges in a gas. The former two methods produce very high temperatures but only for short periods of time, i.e., less than one second. The high temperature produced by a continuous electric discharge in a gas is limited only by the structural integrity of the electrodes. Thus, the plasma generator becomes an ideal tool for high temperature research (4).

Design configurations of plasma generators are many and varied, but most designs contain the following fundamental features: coaxial electrodes between which the arc current passes; introduction of the working fluid in a way that will cool the generator components and stabilize the arc itself; approximate rotational symmetry about a central axis (1,2). Plasma generators have been developed using a.c. and d.c. voltage. Power levels range from a few kilowatts to several megawatts (5,1).

Although published literature on plasma generation by means of an electric arc discharge in a gas is extensive, the technical data describing the generator and its performance is usually very general. All to often, little if any data is given regarding the engineering design. In this regard, the author's findings verify those of John and Bade (1). According to the findings of John and Bade, plasma generating equipment often has considerable proprietary interest; hence, only scant information concerning design and performance capabilities appear in technical journals. Information concerning existing units is often obtained only by word-of-mouth.

The Thesis Problem

The design of a regeneratively cooled, high temperature, clean gas plasma generation facility was developed under the following constraints:

1. Air was to be the working fluid.
2. At least twenty kilowatts of electrical power were to be transferred to the air.
3. The plasma generator was to have the capability of operating at higher power levels by increasing the flow rate of cooling air.
4. Electrode erosion was to be kept to a minimum by cooling the electrodes and having arc rotation.
5. The plasma generator was to be capable of stable operation for any desired test interval.

The following features were incorporated to achieve the objectives of the thesis problem:

1. The electrodes were to be manufactured from oxygen free copper to minimize power loss.
2. Air was to be tangentially introduced at the electrodes. This prevents electrode erosion by cooling the walls and causing arc rotation.
3. A high purity alumina ceramic tube was to provide a confined passage for the arc and serve as an electrical insulator between the electrodes. The confined passage increases current density of the arc column and, hence, air temperature.

4. The electrical discharge was to pass longitudinally along the axis of the ceramic tube. This increases the air temperature by keeping it in contact with the arc column.
5. The arc length was to be varied by inserting different lengths of ceramic tube between the electrodes.
6. A portion of the air entering upstream of the arc was to pass through lattice-type screens to vary its intensity of turbulence. The turbulent fluctuations cause an increase in electrical power dissipation in the arc column and, hence, increased air temperature.
7. Regenerative cooling was to be used to increase the efficiency of the plasma generator.

Method of Approach to Problem

High temperature thermodynamic and transport properties of air as well as high temperature data on materials were needed in order to design the plasma generator.

Materials used in the components of the plasma generator were selected on the basis of their high temperature physical and electrical properties.

Data treating the thermodynamic and transport properties of high temperature air as a real gas are surprisingly few. In this field, the more prominent authors are Hilsenrath, Gilmore and Treanor. Comparison of their data on air indicates agreement within two percent on the tabulated properties. Their original data was not available for this study; however, graphs from their data were available in references 6 and 7.

Hansen and Heims (7) claim that equilibrium thermodynamic properties of air can be determined with an accuracy of two to five percent. They also give semiempirical formulas from which estimates of the properties of equilibrium air can be obtained. These estimates provide data that are reliable within ten to twenty percent of actual values.

The accuracy of the analytical work can be estimated as follows: all convective energy transfer calculations used properties of air in thermodynamic equilibrium. This assumption would give an accuracy of five to fifteen percent of the actual value if thermodynamic equilibrium was attained. The air temperature probably varies throughout the length of the arc chamber; thus, the air would not remain at a given temperature long enough to achieve thermodynamic equilibrium. The tabulated properties of all materials at high temperature will contain some degree of error. This error enters in when determining energy transferred through the components by conduction. Thus, the theoretical performance of the plasma generator should be within fifteen to twenty percent of actual performance.

The design of the plasma generator was approached with the objective of obtaining a high temperature gas stream free from contamination by electrode or ceramic material.

The high temperature gas was obtained by confining the arc column in a small diameter ceramic tube. This increases the current density in the arc column and, hence, the gas temperature (5). Contamination of the gas stream was prevented by cooling the generator components (i.e., anode, cathode and ceramic tube), and introducing wall cooling air tangentially into the arc region to cause arc rotation.

Design of the sharp edge orifice plates for the air metering system was accomplished with the standard A.S.M.E. codes for flow measurement.

CHAPTER II

SURVEY OF THE LITERATURE

Articles describing performance or design of plasma generators were of prime importance in reviewing the literature. Many other articles, while not specifically dealing with design, were important in providing information on contamination levels of the plasma stream.

At Vidya Inc. (3), a plasma generator has been developed that produces specific enthalpy levels greater than 10,000 Btu per pound mass at a pressure of 400 psia and air flow rates of 0.001 to 0.1 pounds mass per second. Electrical power input to the arc is 1.4 to 1.5 megawatts. The efficiency (efficiency of a plasma generator is usually defined as calorimeter power divided by arc input power) of the plasma generator ranged from 50 percent at 15 psia chamber pressure to 20 percent at 500 psia chamber pressure. The decrease in energy conversion efficiency with increasing chamber pressure is characteristic of plasma generators operating at high pressures (1). The electrodes of the Vidya plasma generator consist of a pair of concentrically positioned water cooled copper rings located between the pole faces of an electromagnet. The electromagnet produces a 6,000 gauss field to drive the arc at high rotational velocities around the electrode annulus. Cooling of the electrodes with water along with rotation of the arc prevent contamination of the gas stream due to electrode erosion.

A typical test run is of approximately four minutes duration. Of particular significance is a cumulative testing time of approximately thirty minutes with no discernable loss of electrode material. This fact indicates achievement of an exceptionally clean plasma stream.

Another plasma generator using copper for both electrodes has been developed by the Westinghouse Corporation (8). The electrodes are two coaxial water cooled copper toroids placed in parallel planes. The arc is driven around the periphery of the toroids by a magnetic field. Cooling and arc rotation on the electrodes has kept the contamination level in the plasma jet below a maximum of 0.2 percent. Further reductions in this level are contemplated. Design of the Westinghouse generator allows for a test duration of ten minutes out of each two hour period.

Working fluid can be either air or nitrogen at a flow rate of 1.2 pounds mass per second at a chamber pressure of 1000 psia. The generator was operated on d.c. voltage at a power of 2.7 megawatts with an enthalpy level of 4600 Btu per pound mass. The article reports an efficiency of heat transfer to the gas in excess of 50 percent, but the chamber pressure at which this occurred is not given.

A ten million watt plasma generator developed by Avco-Everett Research Laboratory (9) is of particular interest to show how high power levels can be achieved. The high power level is achieved by five d.c. arcs that exhaust into a single four inch spherical plenum chamber. Working fluid is high pressure air. The air is injected tangentially at the anode to stabilize and distribute the arc. Electrodes are composed of a water cooled copper anode and a water cooled graphite cathode.

No data was given on contamination levels in the plasma or the efficiency of energy conversion.

Kenny and Sparrow (10) have developed a regeneratively cooled d.c. plasma generator using a porous graphite anode and a tungsten cathode. Regenerative cooling is accomplished by passing the gas through channels that run concentrically around a chamber enclosing the cathode. From there, the gas passes through a porous graphite anode providing transpiration cooling. The plasma jet is composed entirely of the transpiring gas.

An energy conversion efficiency of eighty to ninety percent was obtained at a flow rate of 0.0083 pounds mass per second. Chamber pressure at which the efficiencies were obtained was not given. The power level at which these efficiencies occurred ranged from two to four kilowatts.

The great majority of references searched indicated that the common electrode materials are carbon or tungsten for the cathode and either carbon or copper for the anode. The use of copper for both electrodes is not as common.

The high heat flux in the arc fall region that has been reported by some authors (1,11) is the probable reason for not using copper for the cathode. They propose that the arc fall region must be a zone of high energy dissipation since there exists a fall potential of several volts with a high current density. The cathode fall region is extremely thin, i.e., one-third to one-fourth of an electron mean free path. Thus, a substantial fraction of the energy generated within the cathode fall region must be accepted by the cathode. However, the current density and the fall potential vary with gas type, chamber pressure, current level and arc geometry; and the literature is often in wide disagreement (1, 5, 11).

From the sources encountered in this literature search, it appears that additional research is needed in order to fully explain the mechanism of energy dissipation occuring at the electrodes (12,13).

It should again be noted that, with adequate cooling and forced arc rotation, the performance of plasma generators using copper for both electrodes is comparable with those using refractory materials as one or both electrodes. Also, the contamination level of the plasma is usually below that of the generators using refractory electrodes (1,3,8).

CHAPTER III

ANALYTICAL METHODS IN DESIGN

Analytical design of the plasma generator was accomplished with the following restrictions and simplifying assumptions forming a basis for the analysis: flow of the air is one-dimensional; steady state conditions exist; the air is in equilibrium; wall temperature of the copper electrodes and ceramic tube is 1000°F; flow rate of air into the arc chamber is 0.006 pounds mass per second; and twenty kilowatts of electrical power are dissipated to heat the air.

The power to the arc (in Btu per second) was determined assuming that twenty kilowatts of electrical power are dissipated in heating the air. The change in enthalpy (Δi) of the air was calculated using the maximum flow rate of air (in pounds mass per second). Forming the dimensionless ratio $\Delta i/RT_o$ and assuming an arc chamber pressure of one atmosphere, a maximum air temperature of 7000°F was estimated (14).

The air heating process was approximated by Raleigh flow since all of the energy addition occurs in a constant area cylindrical duct. Stagnation temperature necessary to achieve sonic velocity at the end of the constant area duct was determined using Raleigh-type heat addition as discussed by Shaprio (15). For an air flow of 0.006 pounds mass per second, the temperature necessary to achieve sonic velocity is double the maximum air temperature expected. Thus, it is concluded that the phenomena of choked flow will not occur at the maximum design power level. A similar calculation was also performed for flow through the cooling air channels. In this case, because of higher friction loses, Raleigh-type flow is not as good an approximation to actual flow conditions; however, it provides important design information.

The "reference enthalpy" method of Eckert (16) was employed to determine a reference temperature from which air properties could be found. This method accounts for compressibility effects, variation in properties with temperature and some dissociation of the air. All air properties are introduced into the equations at the reference temperature determined from the reference enthalpy.

The empirical equation for reference enthalpy is

$$i^* = i_{st} + 0.5\,(i_w - i_{st}) + 0.22\,(i_r - i_{st}).$$

A reference enthalpy is i^* was calculated from this equation (see Appendix A). Reference temperature T^* was determined using this value of i^* (14). The thermodynamic and transport properties of the air were determined at T^* and one atmosphere pressure.

Next, a Reynolds number based on diameter of the arc chamber was calculated from the relation $Re_D = 4\dot{\omega}/\pi D\mu$. From the product of the dimensionless ratios $Re\ Pr\ D/L$, and assuming a parabolic velocity profile, an average Nusselt number ($\overline{Nu}_D$) was estimated from data on force convection inside tubes (17). An average convective heat transfer coefficient was calculated from the equation $\bar{h} = \overline{Nu}_D\, k/D$ using the average Nusselt number. This film coefficient assumes a fully developed velocity profile. Since the air is introduced into the arc chamber as vortex flow, this would not be an exact assumption. Thus, a corrected Nusselt number was used to account for variation in $\bar{h}$ due to vortexing of the air. The correction factor applied to $\overline{Nu}_D$ was taken from data obtained empirically by Kreith and Margolis (18). The data allows for a given percentage increase in Nusselt number based on a vortex ratio (diameter to wire twist) and tube diameter. The vortex pattern in the arc chamber was estimated to be approximately the minimum vortex ratio presented in reference (18). A sixty-percent increase in the Nusselt number and hence, in $\bar{h}$ was calculated using this vortex ratio.

At this point, it is well to note that there is some experimental evidence available indicating that vortex flow is effectively damped out by heat addition. Tempelmeyer and Rittenhouse (19) have experimentally measured pressure profiles in Gerdien and constricted-arc plasma generators before and after striking the arc. Their findings suggest that performance of these types of air heaters would not be significantly different for vortex and non-vortex flows except at very low power levels. This lends support to the validity of applying non-rotating energy exchange theories to vortex-flow air heaters.

Energy exchange between the plasma stream and walls of the components was calculated using the principles of convective heat transfer (see Appendix B). These calculations were performed using the simplifying assumptions of constant convective heat transfer coefficient and constant wall and gas temperature .

Energy transfer by radiation from the plasma stream to the walls was estimated to be much less than one percent of that convected to the walls. Thus, it was neglected in calculating the energy transferred from the plasma (see Appendix C). Also, the transport of energy from the plasma stream by conduction is not significant to this problem.

To maximize the cooling air flow, it was assumed that all energy transferred to the walls of the components was conducted through the walls and absorbed in the cooling air. Thus, the cooling air flow rate was calculated knowing the amount of energy to be absorbed and allowing an increase in the air temperature of 1000°F (see Appendix C).

The steady state temperature of each component of the plasma generator was calculated assuming that all energy received by it is conducted radially out through its walls.

CHAPTER IV

DESIGN OF PLASMA GENERATOR AND SUPPORTING EQUIPMENT

Materials in Design

High conductivity oxygen free copper was selected for the electrode material. Selection was based on the following data: Oxygen free copper is used for bus bars, bus conductors and other electrical conductors. It is also used for electrical conductors that operate in reducing atmospheres (20). Electrical conductivity of oxygen free copper is 101 percent IACS which is as high as any copper used in the electrical industry. It has a minimum copper content of 99.92 percent. Thermal conductivity of oxygen free copper varies linearly from 242 Btu per hour per foot per degree fahrenheit at 360°R to 218 Btu per hour per foot per degree fahrenheit at 2520°R (21). Data on compressive strength of copper at high temperature was not readily available. However, its tensile strength is 32,500 pounds per square inch at 1200°F. Since metals usually show greater strength in compression, it is assumed that compressive strength of copper is at least as good as its tensile strength.

Lucalox[3] tubing, a 99.99 percent pure alumina ceramic, was selected as the high temperature insulating material used to separate the

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[3] Lucalox is a trade name of the high purity alumina ceramic manufactured by the Lamp Glass Division of General Electric Co., Cleveland, Ohio.

electrodes and confine the arc column. High temperature properties of this material are listed in Table 1.

TABLE 1

High Temperature Properties of Lucalox

Property	Value	Temperature
Compressive strength	3600 psi	2900°F
Thermal conductivity	$2.5 \frac{\text{Btu}}{\text{hr ft }^{\circ}\text{F}}$	1000°F
Volume resistivity	$10^7 \frac{\text{ohms}}{\text{cm}}$	1500°F
Dielectric strength	$1700 \frac{\text{volts}}{\text{mil}}$	68°F*
Melting point		3700°F

*Only data available at this time.

Lucalox is a dense polycrystalline alumina with no vitreous phase present. It is completely resistant chemically, and impermeable to most gases. No permeation has been detected for helium, argon and nitrogen up to 2700°F. Oxygen shows a slight permeation rate at 2800°F. Lucalox has a hardness of 1900 to 2500 on the Knopp (K 100) scale or 85 on the Rockwell "A" scale. Thus, all cutting and polishing of this material must be done with diamond tools.

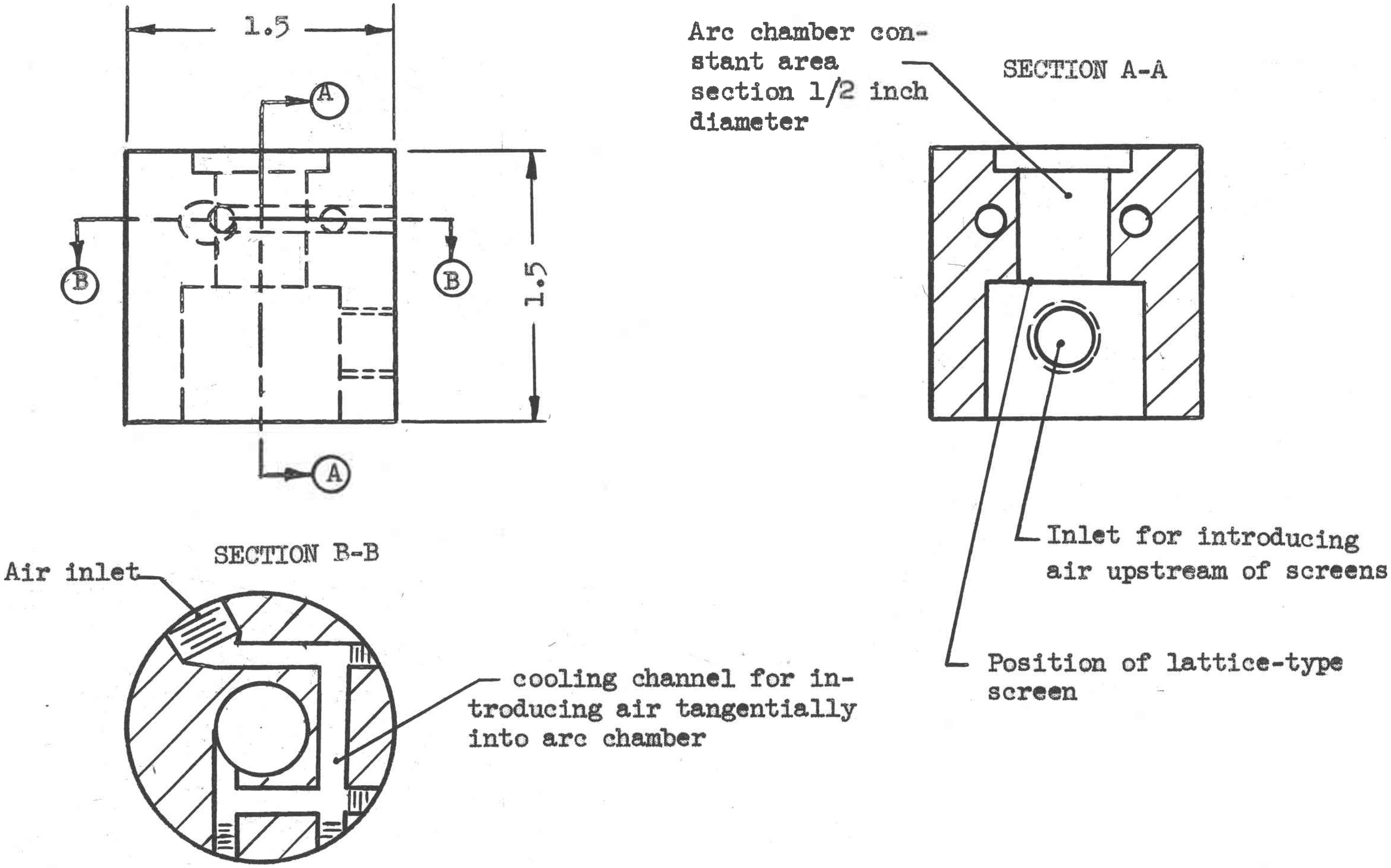
Copper tubing was used for the cooling coils because of its high thermal conductivity and workability.

Cathode

The cathode (see Figure 1) was made of oxygen free copper. Cooling was accomplished by air introduced at two positions as shown in Figure 1. The cooling air has passed through the coil surrounding the ceramic tube before entering the cathode cooling channels. A portion of this air was used to rotate the arc by introducing it tangentially into the arc chamber. The remaining portion of the cooling air was passed through a lattice type screen increasing its turbulence level prior to entering the arc region. Air flow to the cathode was controlled by brass needle valves. Stainless steel o-rings at both ends of the cathode act as seals against air leakage.

Anode

The anode (see Figures 2 and 3) was manufactured from oxygen free copper. Methods used in manufacture of the anode were as follows: a copper sleeve and cylindrical section were machined to final dimensions; thirty-two threads per inch were then cut on the two members to provide a labyrinth seal for the cooling air passages. The cooling channels were then machined into the threaded cylinder (see Figure 2). Flow cross-sectional area of the channels was approximately equal to that of a standard five-sixteenth inch copper tube. The channels were designed with approximately a one-sixteenth inch radius at the corners. This feature decreases the thickness of the boundary layer that would occur at a sharp corner, thus aiding the heat transfer to the cooling air.



Arc chamber constant area section 1/2 inch diameter

Inlet for introducing air upstream of screens

Position of lattice-type screen

cooling channel for introducing air tangentially into arc chamber

FIGURE 1. CATHODE
(All details not shown)

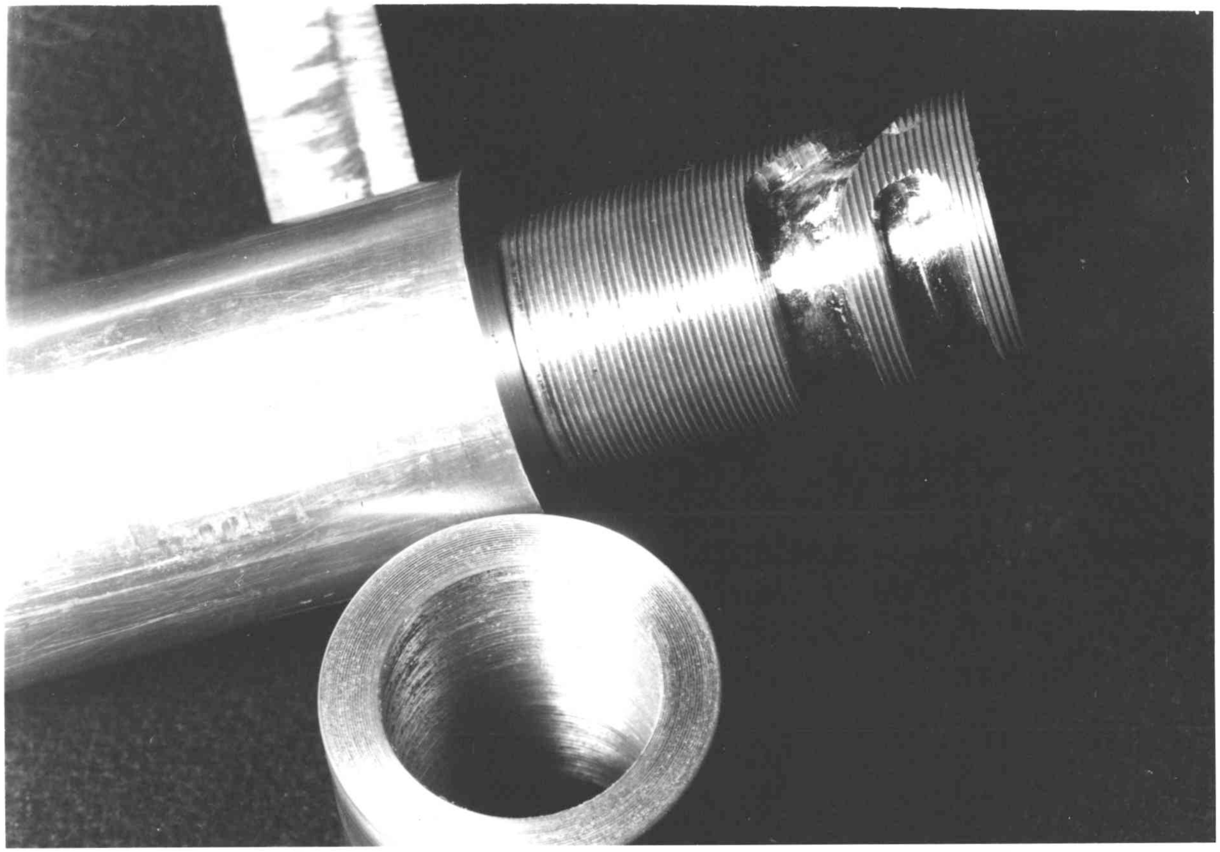
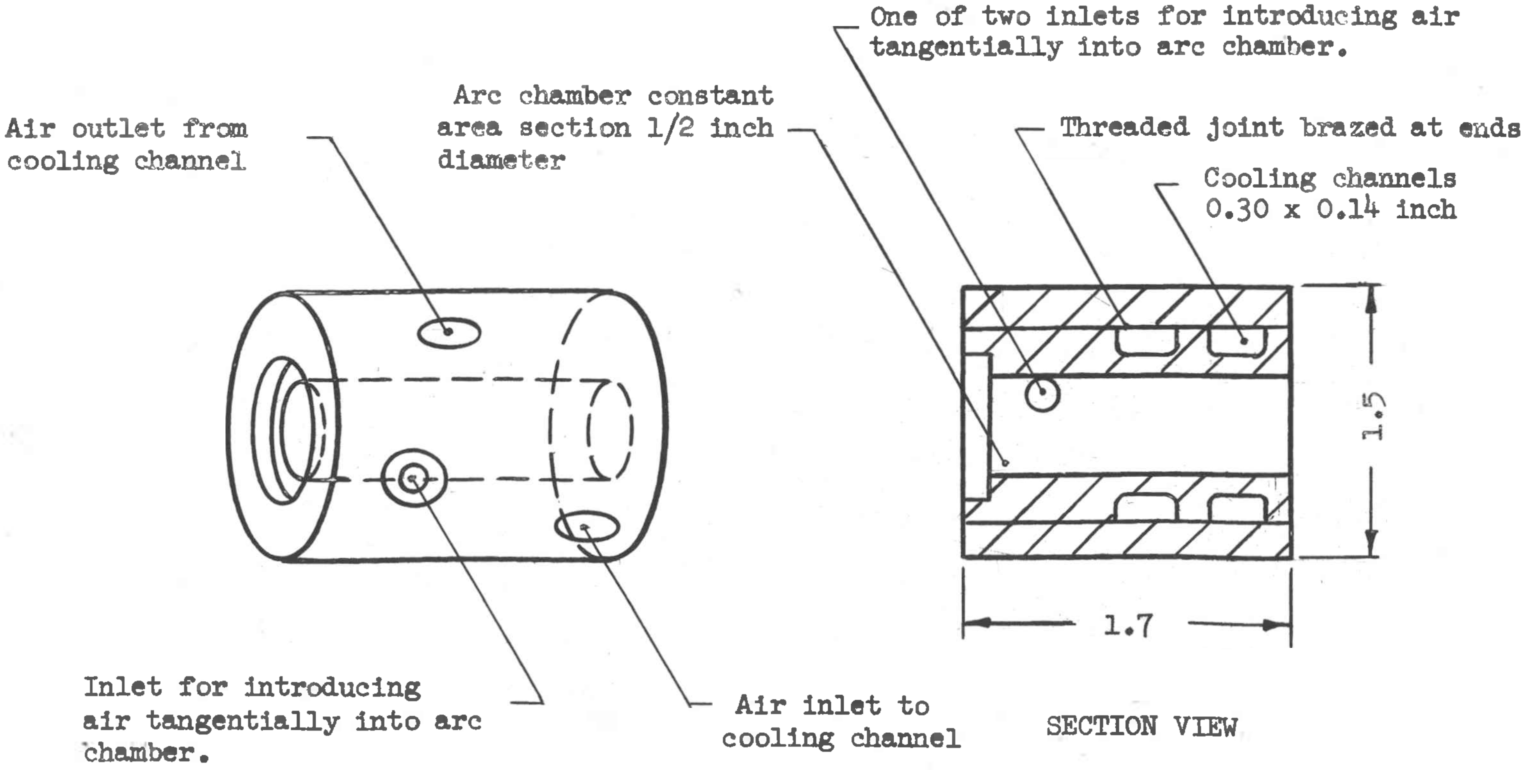


FIGURE 2. ANODE CYLINDER AND SLEEVE
(Note cooling channels and threads)



ISOMETRIC VIEW

SECTION VIEW

FIGURE 3. ANODE
(All details not shown)

Following machining of the channels, the cylindrical section and sleeve were screwed together and heliarc copper brazed at the end faces. The brazing was performed to eliminate the possibility of air leakage at the threaded joint. Next, holes were drilled and tapped to intersect the cooling channels. The arc chamber was bored, then the passages to introduce air tangentially into the arc chamber were drilled and tapped.

The anode was cooled by flowing compressed air through the cooling channels. Cooling air can be introduced tangentially into the arc chamber through two ports to cause clockwise or counterclockwise rotation of the arc. This feature was incorporated in design to study the effect on gas heating of having the arc rotated in opposite directions at the cathode and anode. Air flow to the anode was completely adjustable by brass needle valves at each inlet (see Figure 5, page 1).

Ceramic Tube

The ceramic tube was a commercial high alumina ceramic cylinder, a product of the Lamp Glass Division of General Electric Company. Overall dimensions were: inside diameter one-half inch nominal, outside diameter three-forths inch nominal, length three inches. Variable lengths of tube can be used in generator operation. High temperature properties are listed under the MATERIALS IN DESIGN section of this thesis.

Cooling System for Ceramic Tube

To provide adequate cooling for the ceramic, it was necessary to minimize the resistance to heat transfer between the ceramic tube and the cooling coil. To accomplish this, copper tube was chosen as the material from which to manufacture a cooling coil. However, to take full advantage of the high thermal conductivity of the copper in minimizing resistance to heat transfer, the void formed between a round tube and a flat surface had to be eliminated. To eliminate this void, it was necessary to fabricate a coil with an inside area of contact approximating that of a smooth cylinder.

The cooling coil was fabricated of five-sixteenth inch copper tube according to the following process: the tube was flattened until the surface showed a degree of concavity by passing it through a series of rollers. This flattened tube was then annealed. The coil was formed by wrapping the annealed tube on a three-fourths inch steel rod. Wrapping the coil causes further collapse of the tube. The annealing process was repeated. With the coil on the steel rod, hydrostatic pressure was applied to expand the copper tube. At 2400 ± 50 psig, the copper tube expanded forming a tube cross-section approximately the shape of a D. A tightly wound cooling coil formed in this manner effectively minimizes the contact resistance to heat transfer between the copper and ceramic while maintaining uniform cooling of the ceramic cylinder.

Cooling Air Metering System

The air metering system was designed as follows: using the A.S.M.E. codes (22, 23), sharp edge orifices were designed for use in two-inch pipe with vena contracta taps. Standard schedule 40 two-inch black pipe was used (see Figure 4). Sharp edge orifice plates were fabricated from stainless steel. Orifices were inspected according to specifications outlined in the A.S.M.E. flow measurement codes (22). Orifice sizes are listed in Table 2. See Appendix D for flow coefficients at design flow rates.

TABLE 2

Orifice Sizes, Air Metering System

Orifice Number	Size (inches)
1	0.2659
2	0.2650
3	0.3727
4	0.3707

The orifice size was determined by measuring the diameter on three diameters and then taking the mean value. Measurements were made with a Central Scientific Company Measuring Microscope, model 72935. The microscope has an accuracy of 0.01 millimeter.

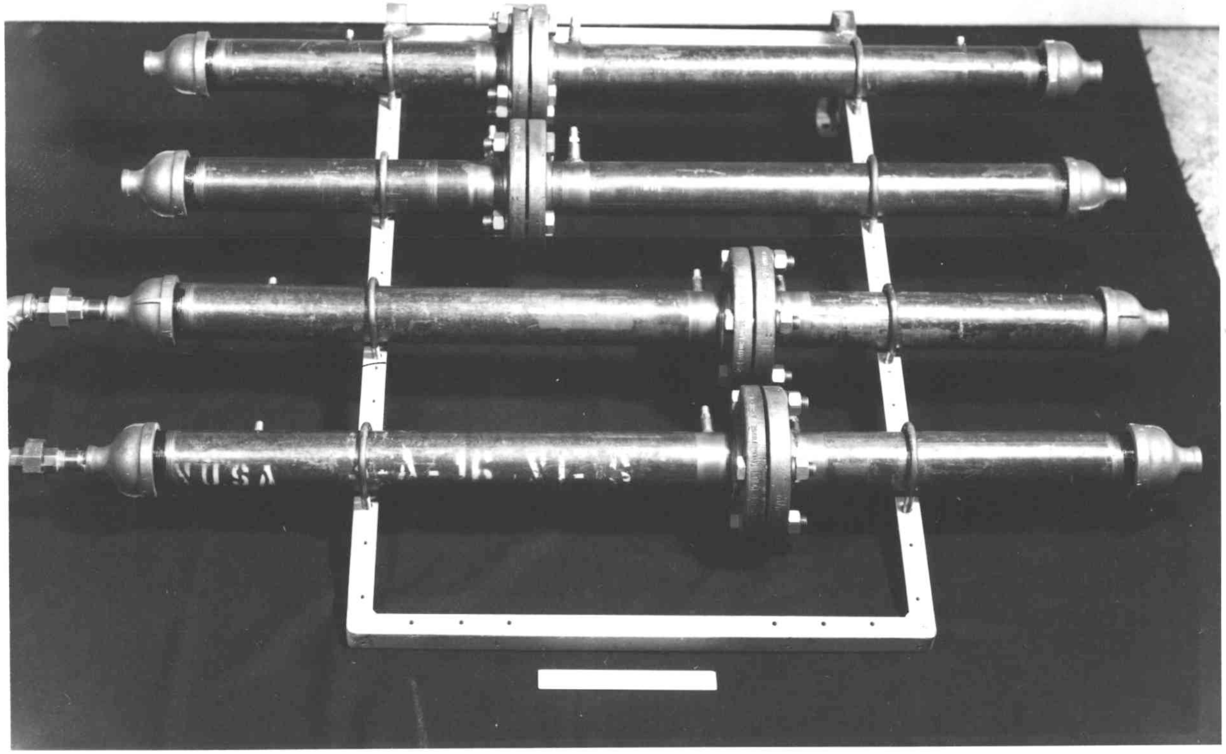


FIGURE 4. AIR FLOW METERS

Assembly of Plasma Generator

The plasma generator was designed so that all components were in compression in the final assembly (see Figure 5). This feature provides a practical method of assembly and utilizes the maximum material strenth of the components. At elevated temperatures, the compressive strengths of the copper and the alumina ceramic are greater than their tensile strengths.

Compression loading of the components was accomplished by installing the electrodes and ceramic tube between a fixed plate and a movable plate. The compressive force was applied to the plates by four tension bolts in conjunction with coil springs. Coil springs allow thermal expansion without an excessive increase in load and make it possible to determine the compressive force simply by measuring the spring length. The coil springs are two-inches long uncompressed, and have a spring constant of forty-four pounds per one-eighth inch.

The anode was electrically grounded, and thus was not electrically insulated from the steel compression plate. The aluminum compression plate at the cathode end was electrically insulated from the cathode by an asbestos-cement washer. Transite is the commercial name for the insulating material. The dielectric strength of Transite is approximately 300 volts per mil. As a further precaution, the cathode compression plate was electrically insulated from the tension bolts. This was accomplished by a cloth filled phenolic insulator that served as a base for the coil springs as well as preventing contact between the tension bolt and the plate.

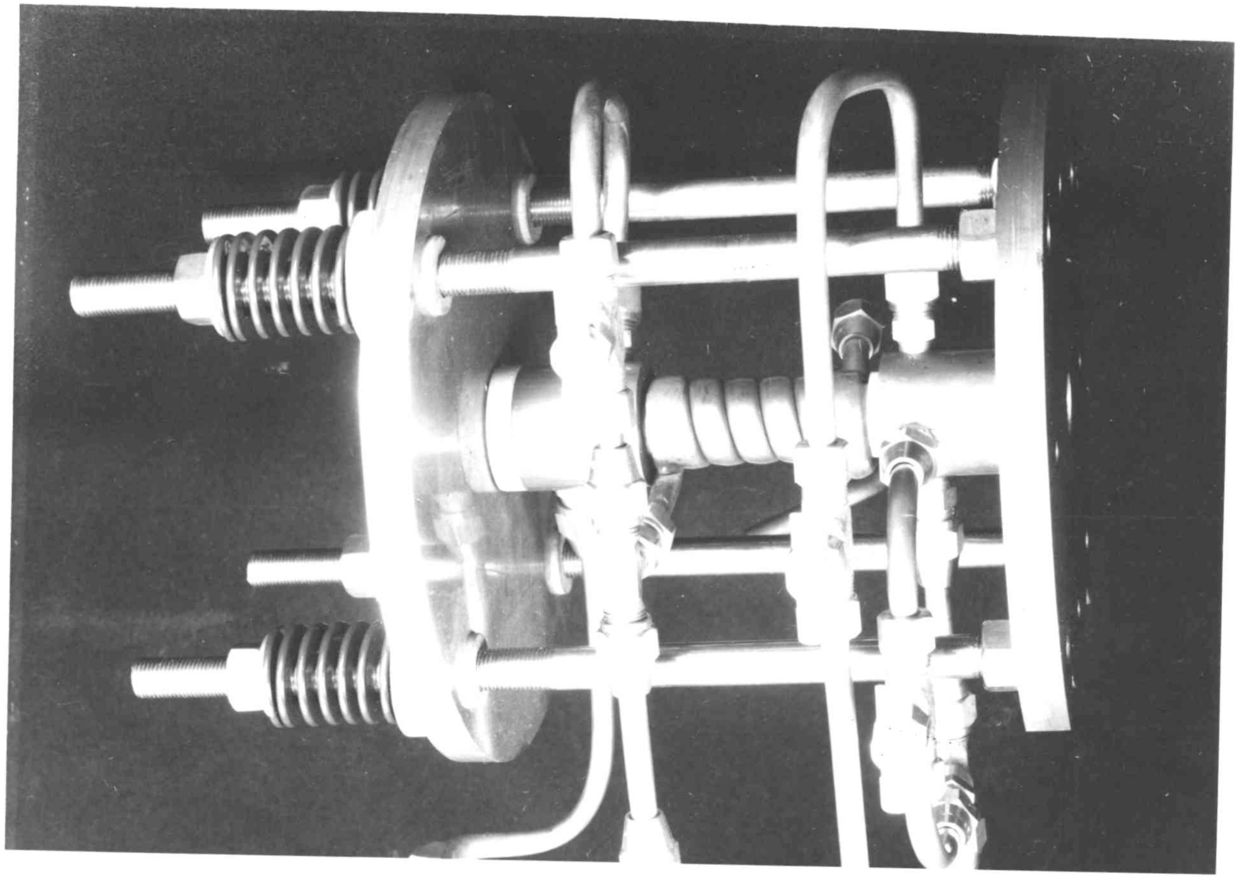


FIGURE 5. PLASMA GENERATOR

Design Instrumentation

All temperature measurements were made with iron-constantan or chromel-alumel thermocouples. Chromel-alumel thermocouples were used in measuring temperature of the arc components. The iron-constantan thermocouples were used primarily in the air metering system.

To accurately determine the cooling air flow rate, it is necessary to know the mixing cup temperature of the air. The mixing cup temperature was obtained by the following system: air entering the two-inch metering pipe passes through two baffles causing thorough mixing of the flow (see Figure 6). It then passes through a three-inch long pine wood nozzle. The wood nozzle was designed to have turbulent air flow (Re approx. 18000)and minimize heat conduction and radiation from the area in which the temperature is measured (see Figure 7). An iron-constantan thermocouple was inserted into the air stream through the center of the wood nozzle. Temperature of cooling air leaving the plasma generator was measured in air flowing through a thermally insulated five-sixteenth inch tee. Estimates of the Reynolds number in air flowing through the tee indicate that turbulent flow prevails down to a flow rate of 0.002 pounds mass per second. This, plus the fact that the system was thermally insulated, enables the measured temperature to closely approximate the mixing cup temperature.

All pressure measurements were made with differential manometers using either water or mercury as the manometer fluid. Manometer scales are graduated in tenth-inch increments.

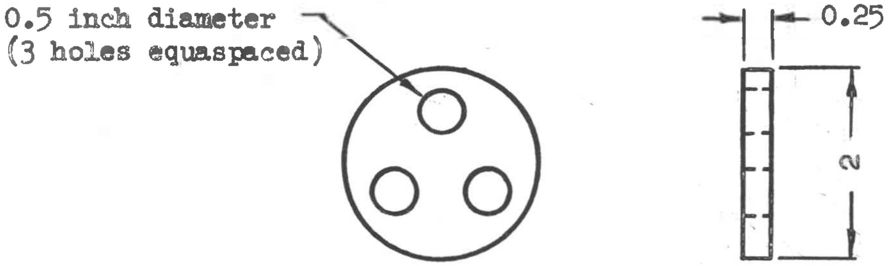
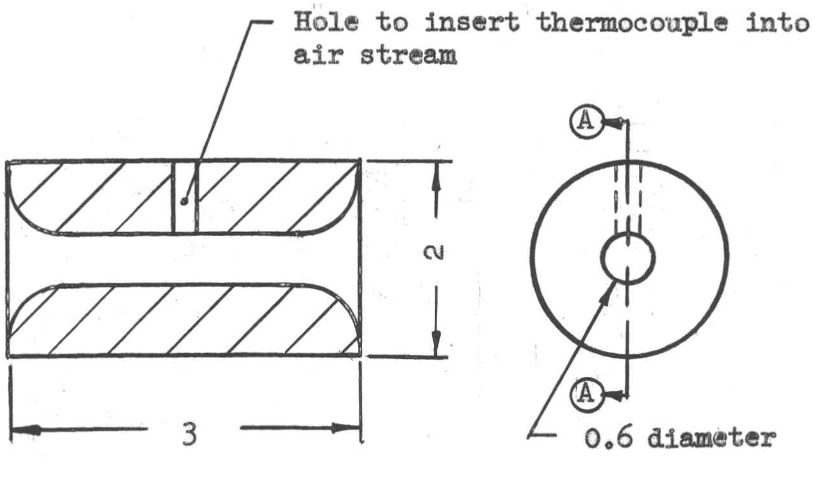


FIGURE 6. AIR MIXING BAFFLES

Two baffles are joined in series when installed in the air metering system. Baffles are positioned so that the hole pattern is 180 degrees out of phase.



SECTION A-A

FIGURE 7. TEMPERATURE MEASUREMENT NOZZLE

D.C. Power Supply

Three General Electric Selenium Rectifiers were available for d.c. power, one model 6RS957FD5 and the other two model 6RS956F5. Each of the units is capable of supplying a maximum power of fifteen kilowatts. Voltage control is achieved through three General Electric Voltage Regulators, model 9P85LF32E.

To achieve electrical stability, a variable ballast resistor is placed in series with the power supply. As the arc varys in resistance due to its changing length, the ballast resistor acts to prevent voltage fluctuations that would extinguish the arc. Since the ballast resistor dissipates some electrical power, it is desirable to keep its resistance as low as possible and still maintain stable arc operation. When efficiency of the plasma generator is defined as calorimeter power divided by input power, the necessity of having a minimum ballast resistance is evident.

Test Chamber

The plasma generator is used in conjunction with a test chamber designed by W. R. Clarke (24). The test section is twelve inches square by thirty-six inches long. The chamber is equipped with a vacuum pump, observation windows, mechanism to introduce specimens into the plasma stream and a heat exchanger to cool the gases prior to exhausting them.

Screen Turbulence Generators

Screens of various wire diameters can be used to vary the level of turbulence in the incoming air. To illustrate the turbulence level achieved with a given screen, consider a screen with wire diameter one-thirtieth inch, mesh size one-tenth inch. At a distance of two inches downstream, the turbulent fluctuation velocity is six percent of the free stream velocity (25). Accordingly, the turbulent intensity increases upstream and decreases downstream from this point.

Increasing the turbulence level of the incoming air may have a beneficial or a detrimental effect on air heating in the arc region. The detrimental effect would occur by rapidly transferring energy from the heated air to the walls due to a large convective heat transfer coefficient (in fully developed turbulent pipe flow the $\bar{h}$ is of the order of 100 $\bar{h}$ for the laminar case). The beneficial effect would be to increase the air temperature. This higher air temperature would occur through an increase in length of the arc column due to the turbulent fluctuations. The increased length causes an increase in arc column resistance thus greater power dissipation and a higher air temperature.

Evidence that an electric arc will operate successfully in a turbulent stream is shown in an article on "Augmented Flames" (26). This article discusses an apparatus that utilizes an electric arc discharge in conjunction with a chemical flame to obtain high temperature gases. The highly turbulent flow causes variations in arc resistance due to the changing arc length; however, the variations in resistance were not of sufficient magnitude to extinguish the arc and stable operation was achieved.

Analytical prediction of the two possible effects is doubtful without better physical properties of the air and arc data. Thus, an actual measurement of energy of the plasma stream is necessary to justify operation with or without the screens.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

In the preceding chapters, the design of a regeneratively cooled, high temperature, clean gas plasma generator has been presented. Materials used as well as design methods have been discussed. Calculations involving the fundamental ideas basic to the development of the thesis were presented in detail.

In conclusion, it is felt that the proposed objectives of design have been accomplished. The estimates of energy transfer from the plasma are considered to be quite liberal, thus cooling air flows specified should be adequate to meet design conditions.

The following recommendations are offered to continue the development of the plasma generator facility. A test program should be conducted to experimentally verify the design parameters. The plasma stream should be completely characterized. In addition to the above recommendations, a very exhaustive study on the theory of electrode processes should be undertaken. The author feels that a thorough understanding of this theory is necessary prior to uprating the generator to higher power levels, particularily those approaching the megawatt range.

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APPENDICES

APPENDIX A

REFERENCE TEMPERATURE CALCULATION

The reference temperature was determined using the following simplifying assumptions: the wall temperature and the gas temperature were constant at 1000°F and 7000°F respectively. Arc chamber pressure was one atmosphere.

The equation for reference enthalpy as given by Eckert (16) is

$$i^* = i_{st} + 0.5\,(i_w - i_{st}) + 0.22\,(i_r - i_{st}).$$

From NASA TN D-1333 (6) obtain $i_{st} = 92$ and $i_w = 10.5$ at their respective temperatures. Throughout this calculation, the enthalpy i designates the dimensionless enthalpy, i/RT_o.

The recovery enthalpy was determined from the equation $i_r = r_i \frac{V^2}{2} + i_{st}$. Recovery factor r_i is expressed by the equation $r_i = \sqrt[3]{P_r}$ for turbulent flow conditions. Since a dimensionless enthalpy was used, the equation for recovery enthalpy was written as

$$i_r = r_i \frac{V^2}{2Jg\,RT_o} + i_{st} \quad .$$

The velocity V was estimated to be 4000 ft/sec by determining the sonic velocity in air at 7000°F and knowing that $M = 1$ was not achieved with the given heat addition.

The P_r is approximately equal to 1.8 at 7000°F, therefore, $r_i = \sqrt[3]{P_r} = 1.21$. Using the above relations, the recovery enthalpy was determined.

$$i_r = (1.21)\left(\frac{1.60 \times 10^6}{1.69 \times 10^6}\right) + 92 = 93.1$$

The reference enthalpy was

$$i* = 92 + 0.5\ (10.5 - 92) + 0.22\ (93.1 - 92)$$

$$i* = 92.0 - 40.8 + 0.24 = 51.4.$$

A reference temperature $T* = 5300^{\circ}R$ was estimated from the mollier diagram for equilibrium air (14).

APPENDIX B

CALCULATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT

This section presents the method used in determining the convective heat transfer coefficient in the arc chamber. The convective heat transfer coefficients for the various cooling air passages were determined in a similar manner.

The Reynolds number based on the arc chamber diameter (arc chamber is a constant area passage) was defined as

$$Re_D = \frac{VD\rho}{\mu} = \frac{\dot{\omega}D}{A\mu} = \frac{4\dot{\omega}D}{\pi D^2 \mu} = \frac{4\dot{\omega}}{\pi D\mu} .$$

Air flow rate at the cathode was 0.004 pounds mass per second. Using a value of absolute viscosity determined at the reference temperature T* (7), the Reynolds number was calculated to be

$$Re_D = \frac{4(0.004 \text{ lb}_m\text{/sec})\ (12 \text{ in/ft})}{\pi(0.5 \text{ in})\ (5.15 \times 10^{-5} \text{ lb}_m\text{/ft sec})} = 2380.$$

The value of Prandtl number at T* was estimated to be $P_r = 1.54$.

Length of the constant area chamber was taken to be six inches (actual length of the chamber is 6.4 inches, but air is introduced approximately one-half inch from the end). Forming the product of the dimensionless numbers Re P_r D/L obtain $(2380)(1.54)\frac{(0.5)}{6} = 305$. Assuming a parabolic velocity profile and using Re P_r D/L x $10^{-2} = 3.05$, an average Nusselt number $\overline{Nu}_D = \frac{\bar{h}D}{k} = 12$ was obtained. The Nusselt number was obtained from data on forced convection inside tubes (17).

Using a value of k determined at T*, the average convective heat transfer coefficient was calculated to be

$$\bar{h} = \frac{\overline{Nu}_D \, k}{D} = \frac{12 \left(0.181 \frac{Btu}{hr\ ft\ {}^oF}\right) \left(12 \frac{in}{ft}\right)}{0.5\ in}$$

$$\bar{h} = 52 \frac{Btu}{hr\ ft^2\ {}^oF} .$$

This value of $\bar{h}$ assumes a fully developed velocity profile.

A new value of Nusselt number was determined from the data of Kreith and Margolis (18) to account for variation in $\bar{h}$ due to vortex flow of air in the arc chamber. The new value was

$$\overline{Nu}_{D_1} = \overline{Nu}_D + 0.6\ \overline{Nu}_D = 1.6\ \overline{Nu}_D .$$

The new convective film coefficient was

$$\bar{h}_1 = \frac{1.6\ \overline{Nu}_D\ k}{D} = 83 \frac{Btu}{hr\ ft^2\ {}^oF} .$$

Comparison of the calculation of $\bar{h}$ by the method of tube-flow with other common methods is presented in reference (28). Experimentally determined $\bar{h}$ versus distance along nozzle is plotted with theoretical predictions of $\bar{h}$ for high temperature air flowing in a cooled convergent-divergent nozzle. Calculation of $\bar{h}$ by the method of tube-flow is in close agreement with experimental data in the subsonic flow region of the nozzle. Only fair agreement with experimental data is obtained in the sonic and supersonic regions of the nozzle.

APPENDIX C

CALCULATION OF ENERGY TRANSFER RATES

Energy transfer rate between the plasma and the wall of the anode will be presented. The determination of energy transfer rate to the other components was accomplished by a similar procedure.

Energy transfer to the anode was determined under the assumptions of constant heat transfer coefficient and constant wall and plasma temperature.

$$\bar{h}_1 = 83 \frac{\text{Btu}}{\text{hr ft}^2 \ {}^\circ\text{F}}$$

$$T_W = 1000^\circ\text{F}$$

$$T_G = 7000^\circ\text{F}$$

$$A_W = \text{surface area of anode arc chamber}$$

$$= \pi DL = \pi(0.5 \text{ in}) (1.7 \text{ in.})$$

Energy convected to the anode wall was

$$q_W = \bar{h}_1 \pi DL (T_G - T_W) = 9200 \frac{\text{Btu}}{\text{hr}} .$$

CALCULATION OF COOLING AIR FLOW RATE

Calculation of the flow rate of cooling air to the anode will be presented. Flow rate of cooling air to the other components was determined by a similar procedure.

The following restrictions and assumptions were used in determining the flow rate: air was supplied at 40 psia and 80°F. Cooling air absorbs all energy supplied to the anode. The allowed change in air temperature was 1000°R.

$$C_p = 0.251 \frac{\text{Btu}}{\text{lb}_m\,^{\circ}\text{R}} \quad \text{at } 1000^{\circ}\text{R and 4 atm.}$$

Flow rate of air was

$$\dot{\omega}_a = \frac{q_w}{C_p\,\Delta T} = \frac{(9200\ \frac{\text{Btu}}{\text{hr}})}{(0.251\ \frac{\text{Btu}}{\text{lb}_m\,^{\circ}\text{R}})(1000^{\circ}\text{R})(3600\ \frac{\text{sec}}{\text{hr}})}$$

$$\dot{\omega}_a = 0.010\ \frac{\text{lb}_m}{\text{sec}}.$$

ESTIMATION OF RADIATIVE ENERGY TRANSFER

The following calculations are presented to support the assumption that energy transfer by radiation was negligible in this design configuration. The data used was taken from the article by John and Bade (1); however, the original source was the work by Kivel and Bailey, "Tables of Radiation from High Temperature Air." This data was estimated to be accurate to within a factor of two or three.

For an arc at atmospheric pressure and an enthalpy $i/RT_o = 100$, the power radiated per unit volume is 0.001 KW/cm^3 obtained by extrapolating the curve. The radiation loss to the ceramic tube will be considered for calculation purposes. The ceramic tube has a chamber volume of 0.588 cubic inches. Converting the radiative power into energy transfer by radiation gives

$$q_r = 33.0 \text{ Btu/hr}$$

transferred to the tube. Forming the ratio of radiative to convective energy transfer for the cermaic tube gives

$$\frac{q_r}{q_c} = \frac{33.0}{16000}(100) = 0.2\,\%.$$

It is felt that the extrapolated value of 0.001 KW/cm^3 was conservative; thus, the ratio of radiative to convective energy transfer was actually less than 0.2 percent.

The total radiative energy transfer is approximately double that given above, or $q_r = 66$ But/hr when all other generator components are considered.

APPENDIX D

ORIFICE FLOW COEFFICIENTS

Flow coefficients, K, for the metering orifices,were calculated for design flow rates using vena contracta taps in two-inch pipe (22, 23). Figures 8 and 9 give orifice flow coefficient as a function of orifice temperature. In all calculations, it was assumed that steady state conditions exist and orifice and pipe temperature is the same as air temperature. This assumption is justified since the high temperature system was thermally insulated and calculations indicate turbulent flow exists through the two-inch pipe and the orifice.

In calculating the flow coefficient, corrections were made for: (1) variation in absolute viscosity of air with temperature, (2) area change of the orifice and two-inch pipe with temperature. Variations in the diameter ratio,β, with temperature occur only in the fourth decimal place. The consistancy of β with temperature occurs because the coefficients of thermal expansion for plain carbon steel and stainless steel are nearly the same (22). Tabulated values of β are given to only three decimal places (23). Beta was considered constant over the temperature range of 80 to 900°F since variations with temperature occur only in the fourth decimal place.

The flow coefficients presented in Table 3 are based on design flow rates of 0.010 pounds mass per second for 0.2659 inch orifice and 0.018 pounds mass per second for 0.3727 inch orifice.

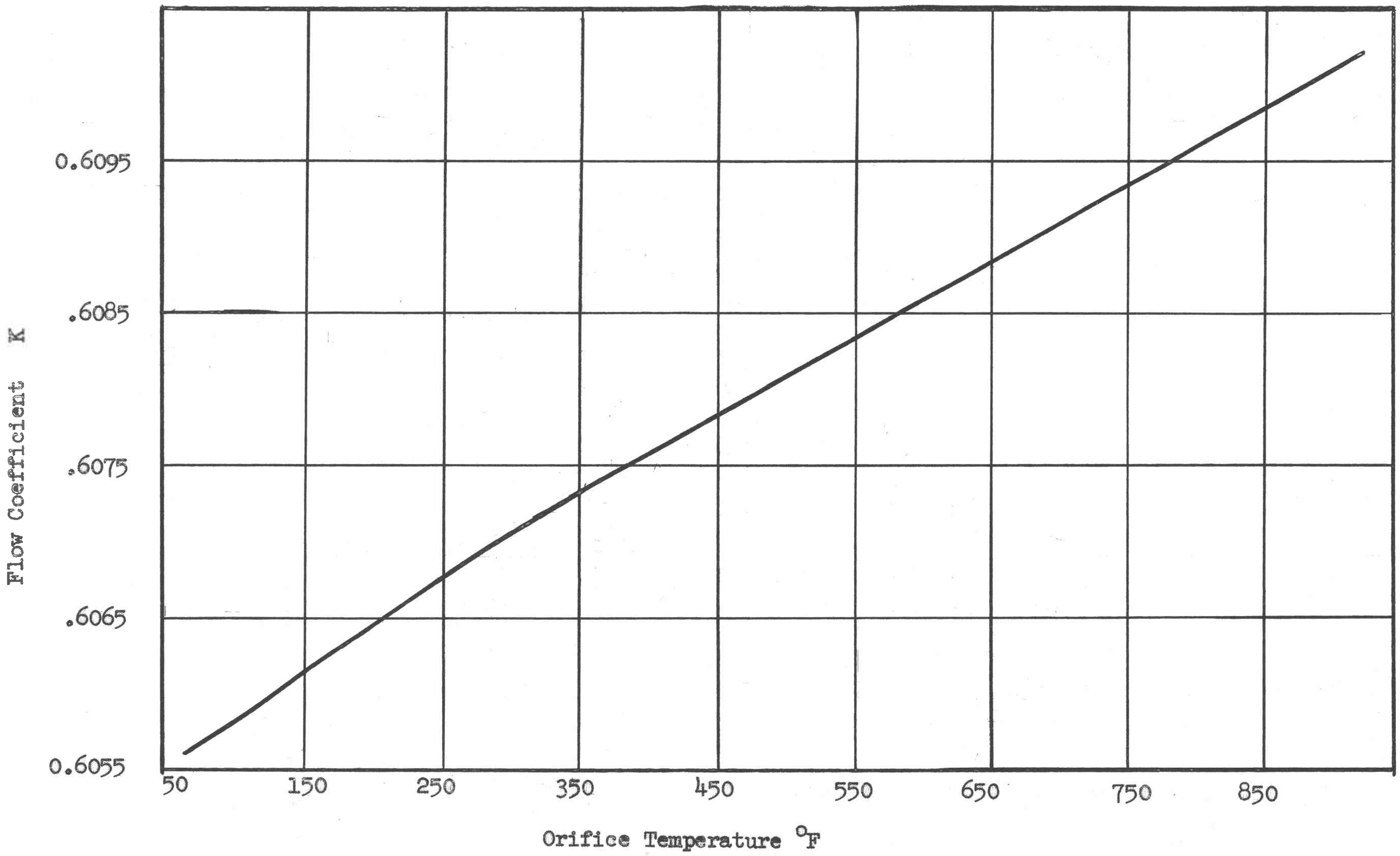

FIGURE 8. ORIFICE FLOW COEFFICIENT AT DESIGN FLOW RATE (0.008 lb_m/sec). Orifice Diameter 0.2650 inch.

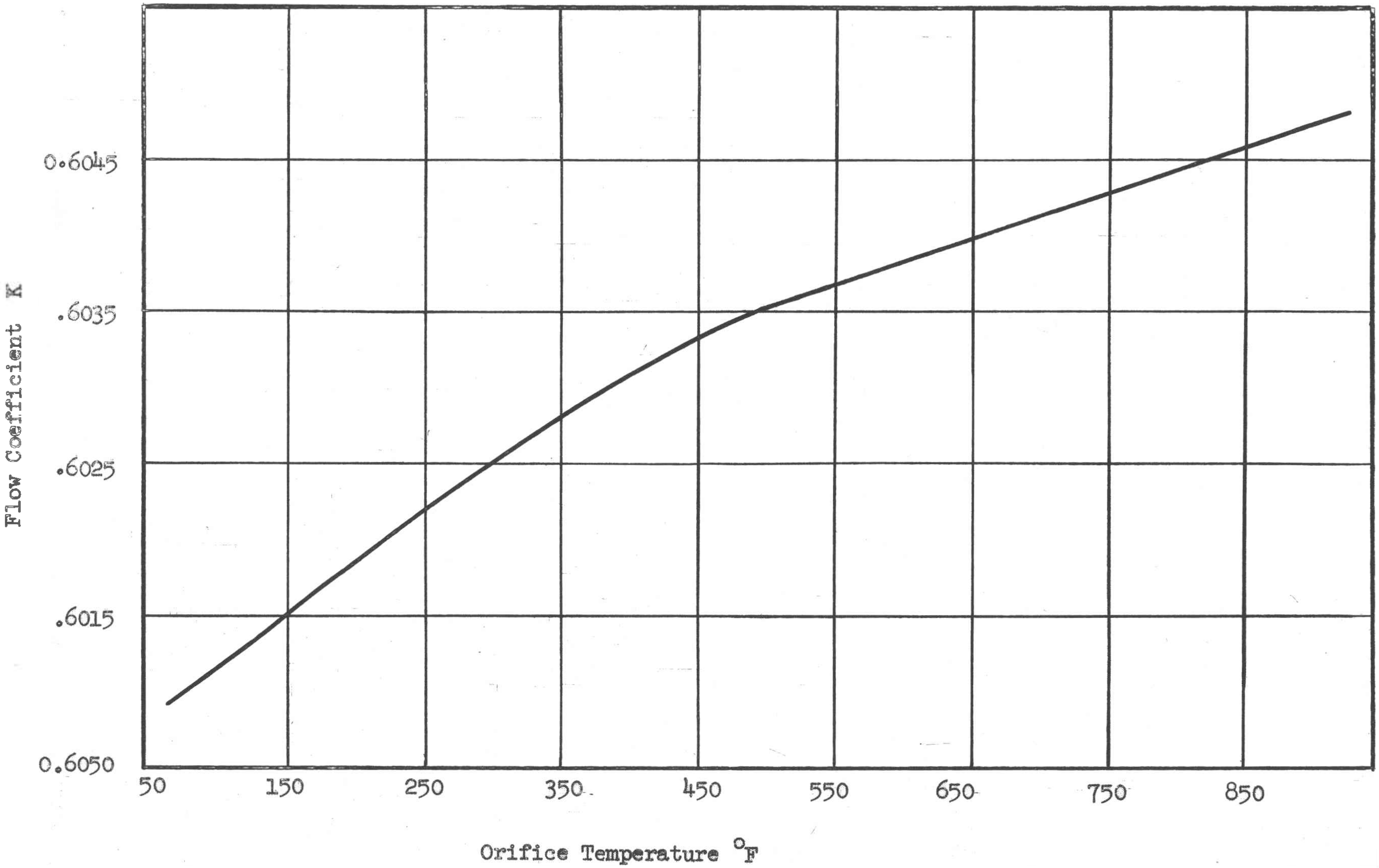

FIGURE 9. ORIFICE FLOW COEFFICIENT AT DESIGN FLOW RATE (0.014 lb_m/sec)
Orifice Diameter 0.3707 inch.

TABLE 3

ORIFICE FLOW COEFFICIENT

Orifice Size	Flow Coefficient* (K)
0.2659	0.6044
0.3727	0.6005

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*Based on an air temperature of 80°F and the design flow rates.

DESIGN OF A REGENERATIVELY COOLED, HIGH TEMPERATURE, CLEAN GAS PLASMA GENERATOR

An Abstract of a Thesis
Presented to the
Department of Mechanical Engineering
Brigham Young University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Roger Carver Bartlett
July 1964

ABSTRACT

The object of this thesis was to design and build a high temperature, clean gas, regeneratively cooled plasma generator.

The plasma generator was designed and built using air cooled copper electrodes. Air was used not only as the regenerative cooling fluid, but also as the working fluid of the plasma. Regeneratively heated air is introduced tangentially to cause arc rotation on the surface of both electrodes.

The plasma generator is designed to operate using direct current voltage at a power level of twenty kilowatts. Maximum air flow to the arc is 0.006 pounds mass per second giving a theoretical maximum plasma temperature of $7000^{\circ}F$.

An air metering system was designed and built to accurately measure the air flow rates to the plasma generator. The primary metering elements are sharp edge orifices designed using A.S.M.E. flow measurement codes.