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SOME NASA CONTRIBUTIONS TO THE USE OF PLASMA JET TECHNOLOGY IN CHEMICAL PROCESSING

By Howard C. Ludwig

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SOME NASA CONTRIBUTIONS TO THE USE OF PLASMA JET TECHNOLOGY IN CHEMICAL PROCESSING

by

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ABSTRACT

Due mainly to the impetus of the Space program's specifications for testing materials under conditions of air atmosphere reentry simulation and for space travel and guidance control, space-oriented Federal agencies are concerned with the technology of high temperature air heating and other plasma producing devices.

In the fulfillment of these tasks it is always desirable that the acquired technology provides spin-off applications which contribute to the nation's industrial progress.

It is the purpose of this writing to point out the economic and technical potentialities of some plasma producing devices in chemical processing, where it is felt the greatest impact on economic welfare may be realized.

CONTENTS

CHAPTER 1

Potentialities and Requirements

A technology previously limited mostly to scientific investigation but now on the verge of widespread practical application may enrich the economy both by reducing the cost of existing commodities and by creating new goods. A new industry may be established to supply the apparatus needed for the various new processes, but unless new products are developed by the technology, its growth will of necessity be somewhat at the expense of established equipment industries.

Many intermediate and finished items will be influenced by any reduction in cost or improvement in attributes brought about by use of the plasma jet process. This is particularly true of plastics, synthetic resins, and fertilizers. The largest industrial potential for plasma jet technology is in the chemical and petro-chemical industries. There is a possibility that some presently highly speculative processes may eventually prove to be successful. Such areas would include petroleum refining, improved man-made fibers, and soaps and detergents.

One interesting possibility is cheap on-site manufacture of fertilizer in the world's under-developed countries. Plasma chemistry developments on the fixation of nitrogen might lead to this, particularly in areas where water power is available to produce electricity.

There is also considerable experimental activity in other areas, but economic evaluations must await future developments. Plasma jets may figure in the production of cyanogen, hydrogen, carbon black, pyrographite, fluorocarbons, and uranium carbide.

Several industries may experience growth as a result of future plasma jet innovations. The industry now manufacturing plasma jet devices at an annual rate of $1 million would show an expansion. Application of the plasma jet to produce acetylene is approaching economic feasibility. The market price of acetylene is currently over $150 million a year. The cutting, welding, facing, and spraying industries part of which are already using plasma jets operate at an annual rate of $30 to 40 million. It is possible that the plasma jet will penetrate the chemical synthesis and processing industry which is at a $2 billion rate.

Based on past experiences with new technologies, it seems highly likely that beyond the next decade entirely new chemical products will appear as a direct result of the continuous very high temperatures that can be achieved with the plasma technique. It is, of course, impossible to do more than conjecture in regard to the nature of the products and it would be even more imprudent to attempt to gauge the economic impact.

Energy Levels

The thermal energy levels attained by the flowing medium in a plasma jet place its atoms and molecules in electronically excited and ionized states. This increases the free valencies and chemical reactivity of the participating materials. The successful development of continuously operating plasma jet devices of production size would enable industry to adopt new processes which have looked promising when investigated on a small-scale laboratory basis.

Plasma jet devices are used now for spray coating, cutting and welding at power loadings to 50 kW, but may have a greater economic impact on the chemical industry, where the required power loading is in the megawatt range. Space programs have prompted advances in the design of plasma jet hardware in an ever widening range of power input capacity. Plasma jet devices have operated on a continuous basis in the multimegawatt range, Fig. 1, and as low as 50 watts, Fig. 2. That highly powered plasma jet devices developed for wind tunnel applications are adaptable to chemical processing has been shown by recent studies of acetylene production which indicated improved yields.(1)

Arc Physics

High pressure arc discharges have been long recognized as a source of heat and radiation reaching temperatures of 5000 to 50,000°K which are as high and higher than those attainable in combustion flames. Arcs are maintained and controlled at pressures ranging from tens of mm Hg to about 100 atmospheres and in convected flow velocities from a few meters per second up to the hypersonic range. Heat contents of arc-heated gas can be developed to values approaching 200,000 Btu/lb. in some cases.

Electrical current flows in an arc through potential drops across the terminals in three regions: the cathode space, positive column, and anode space. The principal charge carriers in the arc are free electrons and positive atom ions, although molecular ions of negative or positive charge, less important for charge transportation but significant to chemical reaction, may be present as a consequence of the thermal ionization of certain chemical compounds. The expended electrical energy is transformed into heat and radiation through Joule heating by the electrical conduction process of the arc, which is characterized by its composition, its pressure, and the power loading. An energy balance is maintained by dissipation of the input energy through heat conduction, convection and radiation. Thermal equilibrium is continually disturbed by the energy dissipation processes. The arc column consists of a heavily radiating mixture of free electrons, positive ions, negative ions and highly excited atoms, constituting what is called plasma, through which the energy exchange processes develop.

An important consideration in the energy balance is the radiative process, which can result in severe energy loss to the walls of the arc-confining space. Radiation may constitute a large fraction of the transformed electrical energy expended in a plasma jet device particularly as the power input and operating pressure increase. Radiation is emitted by the thermally energized plasma when the plasma constituents lose energy in some of the exchange processes. The nature of the radiation, which depends on the energized medium, pressure, and energy level attained, is characterized by emission, band, line or continuous spectra. Emitted radiation quanta have a cooling effect on the plasma as a result of this energy loss. The transport of radiation may be enhanced by repeated absorbtion and re-emission until it develops in the outer zones of the arc. Certain wavelengths of the radiation which are capable of repeated absorption and re-emission by excited atoms are produced more effectively, by increased emission developed within the arc column. In arcs of molecular gases, low energy level band spectra are emitted in the outer low temperature zones of the arc column. In the regions of higher temperature, the spectral lines of excited atoms are emitted.

At temperatures above 10,000°K, intense ion lines of the gas are also emitted. Therefore to understand the total radiation behavior it is important to know in which regions of the arc the greatest energy is converted. The operating power levels, the properties of the arc plasma, (composition, pressure, etc.), and the composition and design of electrodes all determine the radiative output and spectral characteristics of the discharge. For example, in the carbon arc, over 80% of the total radiation is emitted by the glowing anode. In the case of mercury or inert-gas high-pressure arcs between tungsten electrodes, the radiation from either electrode is small in comparison to that emitted by the arc column. In a xenon high pressure arc, most of the radiation comes from a small spherically shaped zone situated immediately in front of the cathode. In the Gerdien arc, burning in an internally water-sprayed plasma jet device, an enormous energy density of 11,000 kW/cm^2 is obtained.(2) The radiative output is extremely low because of the small number of emitting centers consisting of excited atoms and ions of hydrogen and oxygen at a temperature of 50,000°K. In contrast, large fractions of the power input can be transformed into radiation by operation at high pressure and high power loading when using certain gases. For example, Kivel and Bailey(3) show the variation of power radiated per unit of thermally energized air (N_2 and O_2) as a function of enthalpy and pressure, Fig. 3.

In high radiative output arcs, the radiation, unless absorbed or recaptured by properly introduced reactants, is absorbed by the cooled walls of the arc-confining space. The importance of the high radiative output from arcs used in highly powered plasma jet devices is recognized by NASA and is presently under investigation. As will be discussed later, the emitted radiation can be profitably utilized in certain chemical reactions. Therefore, design of plasma jet devices for a particular chemical process, depends heavily on the specific knowledge of the plasma chemistry of participating reactants.

CHAPTER 2

The Design of Plasma-Jet Devices

In the design of plasma jet devices, two important guidelines must be considered: (1) the power loading required must be determined, to attain the enthalpy level and temperatures necessary to achieve the particular function (thrust for propulsion, cutting, welding or dissociation in a chemical process) and (2) the heat transfer capacity of the heat exchanging system must be sufficient to handle the losses encountered at the required power loading. The engineering of the optimum design requires; (1) adequate knowledge of the thermodynamics and chemistry of the plasma medium, (2) the physics of the arc discharge and (3) the dynamics of the plasma flow. All of this knowledge is culminated in a theoretical model that should specify a conservation of energy equation which includes a quantitative measure of each mode of energy dissipation, namely radiation, convection and conduction. Having all of the information necessary, one could predict the operating characteristics of a plasma jet device designed around the theoretical model. Unfortunately, adequate knowledge for determining optimum designs is not available, nor are arc discharges and practical conceptions of hardware configurations simple enough in geometry to undergo calculation in a rigorous manner. At best, models are simplified so that some calculations may be made to serve as a phenomenological guide to the analysis of the energy transfer processes involved.

In general, the arc discharge of a plasma jet device can operate in either an unconstricted or constricted configuration.[4] The unconstricted configuration is one in which the arc is free-burning. Solid walls or fluid and magnetic forces do not confine the arc to the extent of altering the shape or the cross sectional dimension of the arc column. The constricted configuration is one in which the arc is confined in a specified manner. The constricted configuration is more realistic in practical design but the special nature of the constricting forces in each case makes it difficult to develop an all encompassing theoretical model. Some of the various forms of unconstricted and constricted arc configurations are schematically illustrated in Figs. 4 and 5 respectively. Fig. 6 illustrates a special form of toroidal shaped electrodes on and between which the arc is rotated. The arc rotation is achieved by crossing the current-carrying arc column with an external magnetic field. This design--a NASA Langley contracted development--was used in the plasma jet device, shown in the photograph of Fig. 1 and the illustration of Fig. 6. It was originally developed for wind tunnels but more recently was applied to chemical processing. In the electrode design, the arc is not severely constricted by solid walls but by the radial magnetic field interaction with arc current. The interaction results in a force causing the arc to assume a circular motion. The arc is constricted by self-magnetic field developed by the flow of arc current (pinch effect) and by the convection losses due to the mixing action of the arc as it rotates in the flowing gas.

A special note is taken of the plasma jet device design shown in Fig. 7 using two coaxial tubular electrodes separated by a feed stock inlet chamber.[5] One electrode has an opening for exhausting the arc plasma. A field coil surrounding the rear electrode magnetically rotates the arc. This device operates at unusually high voltages, in excess of 2000 volts. A scaling law for the above high voltage plasma jet device, (Fig. 7), was derived chiefly from experimental data obtained from three models of different arc power capacities. Although approximate, the scaling factor N, defined as the ratio of linear dimensions in the scale model to those of another device nominally rated at two megawatts input, serves well as a guide to the selection and operating conditions for a similar device to achieve a required enthalpy. It was found that the efficient air enthalpy and arc chamber pressure of an N scale device are equal to those of the basic $N = 1$ device providing the air flow rates per unit area are the same. Under these conditions, the scale model arc voltage and power will equal those of the basic device multiplied by N and N^2, respectively.

In reality, all arcs operating in a forced flow field are constricted. Therefore a theoretical model based on the unconstricted arc configuration is in error to a degree depending on the strength of the force field.

In principle, any gas or vapor can be utilized as a feed stock in a plasma jet device. The selection is based on the function to be performed. If the pressure and enthalpy are specified, the amount of energy vested in excitation, ionization and dissociation for a given feed stock can be calculated from a Mollier chart which relates equilibrium values of enthalpy to pressure, temperature and enthropy. The Mollier chart for hydrogen[6] is shown in Fig. 8.

Another important consideration is the behavior of the plasma flow, especially if a certain velocity is important to the function. The feed stock, after being heated, may pass through a constricting throat to develop a higher velocity. If the flow variables change only with respect to the axial flow direction, the flow can be mathematically treated as one dimensional, which represents only an approximation to most actual cases. The obvious heat transfer from gas to structure of the plasma jet device and the presence of a boundary layer near the confirming walls destroy the ideal flow situation.

To analyze the energy-transfer mechanisms occurring in plasma jet devices, several models have been proposed. The most obvious approach assumes the feed stock to be heated uniformly, in which case the mechanism of heating is not important. A model based on uniform heating of the feed stock can only roughly describe the operation of plasma jet devices since heating and flow nonuniformities exist. Thus far, there have been only two proposed models for constricted arcs from which an adequate analysis of the energy transfer mechanism can be made; the core flow theory[7] and the Stine-Watson or volumetric heat addition theory.[8] [9] These two theories are described below.

Core-Flow Theory

A basic feature of the core-flow model is to consider the fluid through the arc constricted zone as two flames concentrically located around a thin core flow likened to a thin wire. Referring to Fig. 9, the core flow is defined as that portion of the total flow which is electrically conducting and in which energy due to Joule heating is liberated radially through the core surface to the "inner flow." Longitudinal transport of energy through the central core is considered negligible compared to the radial transport through the core surface. The inner flow is in turn, surrounded by the outer flow of relatively cold gas. The purpose of the thin stagnate arc is to produce thermal energy and transport it to the inner flow is thus heated directly by the arc and carries the main part of the energy. The relatively cool outer flow, not heated directly by the arc, receives radiative energy from the arc and energy by thermal conduction from other parts of the plasma jet device structure. Knowing the plasma column electric field strength, the operating pressure, current and boundary conditions, the radial arc temperature distribution and the enthalpy can be calculated. The basic equations which describe the behavior of a fully developed laminar plasma column are given by:

$$\frac{1}{r}\frac{d}{dr}\left(r\, k\, \frac{dT}{dr} + \sigma E^2\right) = P_r$$

and

$$I = \int_{0}^{r_{wall}} 2\pi \sigma E \; r dr$$

for boundary conditions

$$\frac{dT}{dr} = 0 \text{ at } r = 0 \text{ and } T = T_{wall} \text{ at } r = r_{wall}.$$

where σ is the local electrical conductivity, E is the plasma column field strength, r is the radial distance from the column axis, k is the local thermal conductivity, T is local temperature, P_r is local column volumetric-radiation and I is the current.

The assumption of negligible mass flux transported through the thin current conducting core is not strictly valid. Even though the mass flux may be small, the axial temperature of the arc column can be sufficiently so high as to contain a large amount of energy. If the thermal conductivity of the core plasma is low and the conduction of heat energy to inner flow is low, then the axial convection transport of energy through the core would not be considered negligible. Probably the basic drawback of the core flow model is the inadequacy to explain the axial enthalpy flux through the conducting core. Also, the losses of energy at the arc terminals are not considered.

Volumetric Heat Addition Theory - Stine-Watson Model

In contrast to the core flow theory, the arc can be assumed to fill a large part of the constricting zone as shown in Fig. 10. The Stine-Watson model accounts for an axial convection term, considered negligible in the core flow model. The energy equation, after simplification is given by.

$$\rho V_z \frac{\partial h}{\partial z} = \sigma E^2 + \frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r}$$

$$\rho V_z \frac{\partial h}{\partial z} = \sigma E^2 + \frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r} + \frac{\partial^2 S}{\partial r^2}$$

where ρ gas density

V_z gas velocity in axial direction

h enthalpy

E electric field

r radius of constricting region

r_o arc radius

and S = heat conduction function $\int K dt$.

K is the thermal conductivity of the arc discharge plasma. The value ρV_z is assumed constant. The term $\frac{\partial h}{\partial z}$ is the enthalpy gradient. The axial heat conduction term $\partial^2 S/\partial z^2$ is neglected because of its small contribution. The radial conduction term must be retained, representing a loss to the constructing wall. This energy equation is solved for the enthalpy h(r,z) by assuming that the enthalpy of the gas can be simply related as $h = (C_p/K)\ S$ where C_p is the specific heat at constant pressure, and that the electrical conductivity $(\sigma) = AS$ where A rationalizes electrical and thermal conduction, and has the unit arc voltage. In its simplified form, the conservation equation is solved to give

$$h\ (r,z) = C\ \left(\frac{C_p}{KA^{1/2}}\right) \left(\frac{I}{r_o}\right) \left(1 - e^{-11.5\ \frac{z}{z_o}}\right)^{1/2} J_o\ \left(2.4\ \frac{r}{r_o}\right)$$

where $z_o = \frac{w\ C_p}{\pi K}$; w is weight flow rate of gas; and C is a constant depending on the units of enthalpy, J_o is a Bessel function of zero order.

The important function h (r,z) obtained by the above equation permits the calculation of several important engineering quantities such as the local heat loss from the arc, the voltage gradient, radial enthalpy as a function of axial position, the total heat loss from the arc surface, and the efficiency with which the electrical power is transferred to the working gas. An important prediction of the Stine-Watson model is that the radially averaged enthalpy leaving the plasma column is inversely proportional to the arc radius and proportional to an expressed function

$$\left(1 - e^{-11.5\ \frac{z}{z_o}}\right)^{1/2}$$

Agreement is given between the Stine-Watson theory(7) and experimental data(8) as shown in Figures 11 and 12.

Failure of either the core flow or the volumetric heat addition theory in regions near the cathode and anode region is to be expected. Both theories can be fitted to certain experimental results by appropriate choice of boundary conditions. Both models will continue to change, to more adequately treat the energy transfer mechanisms of conduction, convection and rotation as new designs of plasma jet devices are developed and as additional experimental data are obtained.

The design of a plasma jet device as shown in photograph of Fig. 1 and in the schematic drawing of Fig. 6, lends itself to a simple model of uniformly heated feed stock because of the mixing action of the magnetically driven arc. However the influence of the radiative mode of energy exchange introduces complications which make it difficult to apply such a simple theory. The radiative output from arcs in some cases cannot be neglected because of appreciable contribution to the energy balance.

Energy Exchange at the Arc Terminals

The current of an arc discharge flows along an electrically conducting gas path terminating at the electrodes. In the thermal arc, the heating source for plasma jet devices, the electrical conductivity is governed by the plasma temperature. The electrical connection of the arc to the electrodes presents a problem because the temperature must fall from a high value in the plasma column to a temperature at the electrode surface lower than its melting temperature. The electrodes, therefore, must be cooled to prevent melting and vaporization. At high power loadings the problem of protecting the electrodes from severe damage not only requires carefully designed cooling systems but also a careful consideration of the heat exchanging area over which the steep temperature gradient occurs. It has been shown that the rapid rotation of the arc by the force introduced by an external magnetic field permits larger power loadings without severe damage to the electrodes. Plasma jet devices have been built and operated to accept heat fluxes at the electrode surfaces of up to 20 million Btu/ft.^{2}hr.[1]. In achieving the extremely high electrode cooling capacities, it has been found necessary to adhere to very stringent heat exchanger design principles, to avoid bulk water boiling in the electrode cooling water passages. The evenly spaced water passages must be very close to the electrode surface exposed to the heat flux and cooling water velocities of 100 ft. per second were required. The identical design for both electrodes permits arcs to be operated with direct or alternating current as shown in Fig. 7. Some electrode configurations illustrated in Figs. 4 and 5 can only be used with direct current because of an inequality in the heat flux occurring at the anode and cathode terminals of the arc.

The mixing action produced by magnetically driven arcs helps to uniformly mix the feed stock and provide a relatively uniform temperature profile.

A uniform radial temperature profile offers better control for heating reactants in a chemical process. A magnetic arc drive allows one to operate plasma jet devices at higher power loadings to develop higher enthalpies at higher feed stock pressures. Toroidal-shaped water-cooled copper electrodes operating with multiphase alternating current provide promising design conditions for application to chemical processing.

CHAPTER 3

The State of Technological Advancement

The advancement of plasma jet technology in recent years has been accelerated by the impetus provided by NASA. Its interests in space propulsion engines and material testing for atmospheric re-entry have contributed importantly to plasma jet technology that is equally applicable to industrial needs. Our economy can benefit both from the roaring multi-megawatt arc heaters employed in wind tunnels and the whispering small plasma jet engines designed for satellite attitude-control.

Some research and development efforts by chemical producing companies already have advanced beyond small laboratory sized investigations to production-scaled developmental programs. Progress in plasma jet technology was discussed in a recent NASA publication.(10) The chemical industry may find it helpful in hundreds of specific endothermic reactions.

Among the more promising reactions investigated is the production of acetylene from natural gas (methane) by plasma jet reaction. The research and development on a 10-megawatt plasma jet device designed for arc heating air for a wind tunnel installation at Langley Research Center has contribured importantly to the technology of plasma generation in a power capacity suited for production chemical processing. Plasma jet devices of the Langley wind tunnel type, as shown in Fig. 1, have been built for the power loading range of 3 to 20 megawatts which is sufficient for full scale chemical production. A 3 megawatt plasma jet of the toroidal shaped electrode tip with magnetically driven arc was developed to withstand the severe operating conditions imposed by continuous-duty service in a chemical processing application.

A recently published report describes the results obtained for the production of acetylene from methane. Some indication of the feasibility of applying the rotating arc principle[11] to chemical processing may be obtained by considering the high temperature characteristics of the system $C + 2 H_2$ starting with methane (CH_4). The composition of the equilibrium mixture as a function of temperature is shown in Fig. 13. The maximum acetylene ($C_2 H_2$) concentration (9 mole percent) appears at 3600 degrees K. In passing through the arc, the methane experience an average temperature of about $7000^{\circ}K$ and is therefore completely dissociated. This highly energized gas mixes with gas which is not arced in passing through the arc chamber to the downstream zone. The mixing action promotes an efficient utilization of the energy of the arc. Energy conversion rates of 2.64 kw hr./lb.[11] have been obtained in comparison to 4.5 to 6.0 kw hr./lb. reported for other electric arc processes. As exemplified by the cited results, a continuing effort on the part of chemical producers in their individual vested interests and electrical hardware manufacturers promises to yield a profitable atmosphere in a new technological activity.

Plasma jet devices designed for power consumption in the range of tens of watts to 30 kW have been proposed by NASA for use as propulsion engines to provide the main thrust and for attitude control in space travel. As a consequence of the requirements of long time service, low weight and stable operation in these devices, many improvements in design and materials have been made which are being reflected in plasma jet hardware designed for industrial application. Regenerative heat exchanging and radiation cooling principles incorporated in the design of NASA controlled developments of 2 kW and 30 kW plasma jet devices are shown in Figs. 14 and 15. These designs require the use of refractory insulation such as boron nitride and the metals tungsten and molybdenum. The pattern graph of Fig. 16 shows the measured isotherm and heat flow paths for the 30 kW plasma jet device. High-power thrustor ($>$ 100 kW) developments by NASA are now in initial stages.

Of equal importance to industrial development of plasma jets is the basic information about feed stock materials[14] documented by NASA and the Air Force, Navy, and Army. In addition to performance data on the parameters of plasma jet operating conditions, the thermodynamic properties[6] heretofore not available for many gases and materials have been developed over a temperature range up to $100,000^{\circ}K$. Research studies of magnetic field--arc interaction at the Ames and Langley Research Centers have resulted in improved understanding of this mechanism. The decrease in arc rotational velocity with increasing arc chamber pressure or decreasing field strength was satisfactorily explained by a concept based on the idea that the arc acts as though it were a solid aerodynamic body having drag.[12] The arc is driven by the electromagnetic force of the field and the resultant equilibrium velocity is that velocity at which the drag force on the arc equals the electromagnetic driving force. The effect of decreasing arc velocity with increasing arc chamber pressure is caused by the increased drag on the arc. The results of this study are considered of paramount importance to the development of plasma jet devices for chemical processing.

The field of high temperature instrumentation is richer because of the contributions of all NASA Research Centers. Outstanding among the instruments is a probe developed by the Lewis Research Center for the simultaneous measurement of static and impact pressures[10] in the cross section of plasma jet devices.

Problem Areas

Technological advancements in plasma jet devices made in the last 10 years have to a great extent eliminated severe problems of heat exchanging and material failure. However, where high enthalpy, high pressure operations are required, new concepts in convected cooling of electrodes and associated hardware are needed. A marked improvement in heat exchange has been obtained by the application of magnetic fields crossing the gas and arc current flow. The mixing action developed by the magnetically driven arc alleviates the problem but does eliminate it. A barrier in the enthalpy-pressure parameter remains under some operating conditions. At pressures above 50 atmospheres the maximum attainable enthalpy is likely limited by the heat flux of forced convection water cooling and the increased radiation output. Primarily because of radiation transport mechanisms such as adsorption and reemission, heat transfer loading of the cooled walls and electrodes exceeds their heat exchanging capabilities apparently due to radiation penetration to the confining walls. Systematic experimental studies are needed to assist in the understanding of the radiative energy transfer mechanisms as they pertain to plasma jet devices.

Absorption of radiation by injected reactants holds promise for advancements in chemical production techniques. Instead of exhibiting a barrier to operation level of a plasma jet device, the radiation developed in the arc may be utilized in producing chemicals not otherwise possible. A study of reactant injection techniques, promises new chemical products because of the excited states which the atoms and molecules of the feed stock attain. Excited atoms in flowing plasma have a much higher reactivity than do normal atoms. When two atoms or molecules collide, either a first or second kind of collision is distinguishable. In collisions of the first kind, kinetic energy is changed into excitation energy as shown by:

$$A + B + \text{kinetic energy} \rightarrow A + B^*$$

In collisions of the second kind, a reversal process is given by:

$$A + B^* \rightarrow A + B + \text{kinetic energy}$$

Other processes where an atom or molecule gives up excitation energy (*) by collision are given by;

$$A + B^* \longrightarrow A^* + B$$

and

$$AB \longrightarrow A + B$$

An example of collisions of the second kind is exhibited by mercury (Hg). When a number of Hg atoms have been brought into an excited state, $^3P_1$, by irradiation of Hg vapor with the 2537 Å resonance level spectral line, the Hg vapor reradiates the same spectral line. If thallium vapor is added to the Hg vapor, it also reradiates from about the same energy level. The collision process takes place as follows

(1) $$Hg\ (^3P_1) + Tl\ (^2P_{1/2}) \longrightarrow Hg\ (^1S_o) + Tl^*$$

Now if hydrogen (H_2) is introduced, quenching of the resonance radiation occurs with the possibility of chemical reaction taking place with the following products formed:

(2) $$Hg\ (^3P_1) + H_2 \longrightarrow Hg\ (^1S_o) + H + H + \text{kinetic energy}$$

(3) $$Hg\ (^3P_1) + H_2 \longrightarrow HgH + H + \text{kinetic energy}$$

The second and third reactions would not occur at ordinary temperatures without the presence of the excited state of mercury.

A discussion of problems related to the use of arc plasma in the chemical industry cannot be concise because of its embryonic stage of development. The field of plasma chemistry is not developed to the extent of ordinary chemistry but a basis for it is established in the field of atomic physics where the kinetics of excitation and ionization reactions have been and are being investigated. In instances where thermal equilibrium exists, the composition of a given plasma can be calculated. The interest and the use of plasma chemistry in chemical processing will continue to increase as this discipline becomes established.

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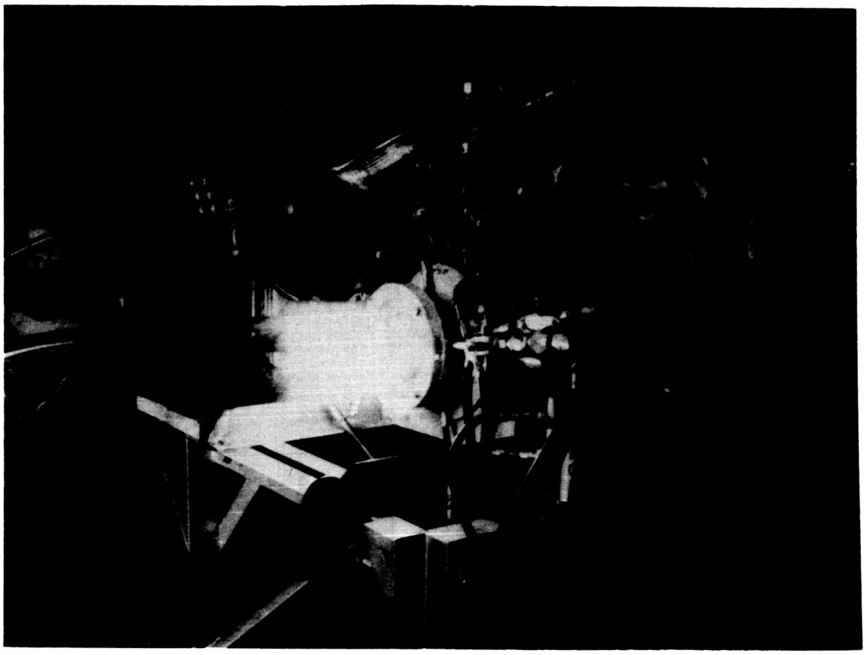


Fig. 1 Marc 30 Arc Heater
Exhaust Flame
Test N055
January 31, 1965

Fig. 2 Helium Plasma Jet Operating in an Ambient Vacuum, Input Power 50 W.

Curve 578653-A

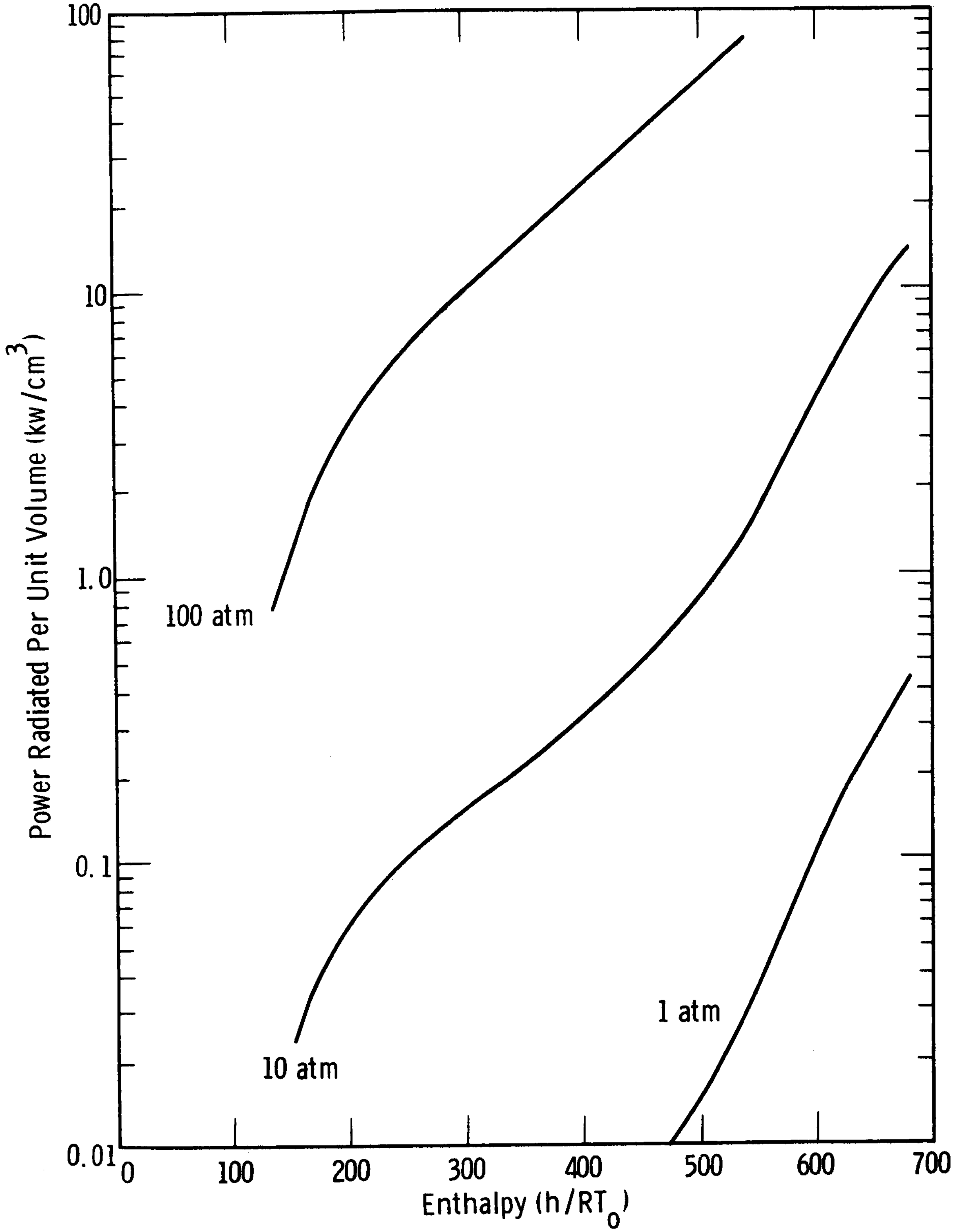


Fig. 3— Radiative power loss from heated air

Dwg.852A088

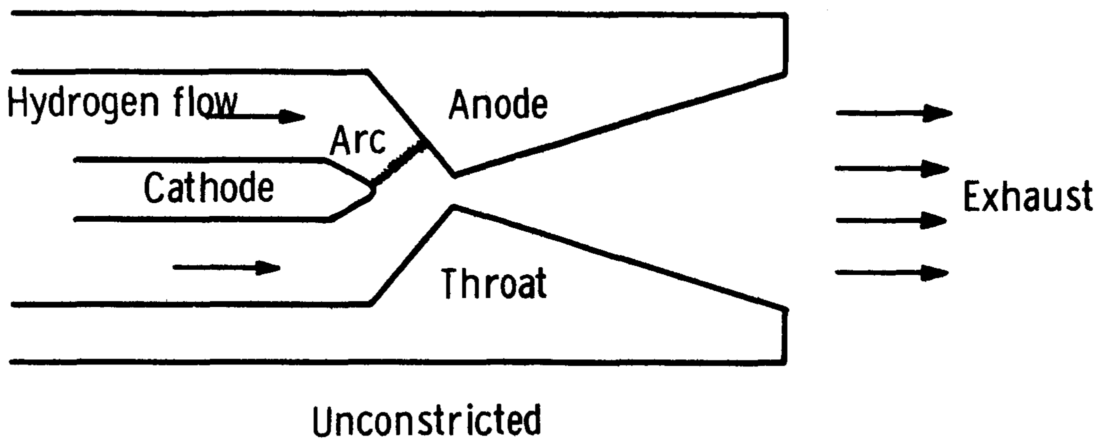
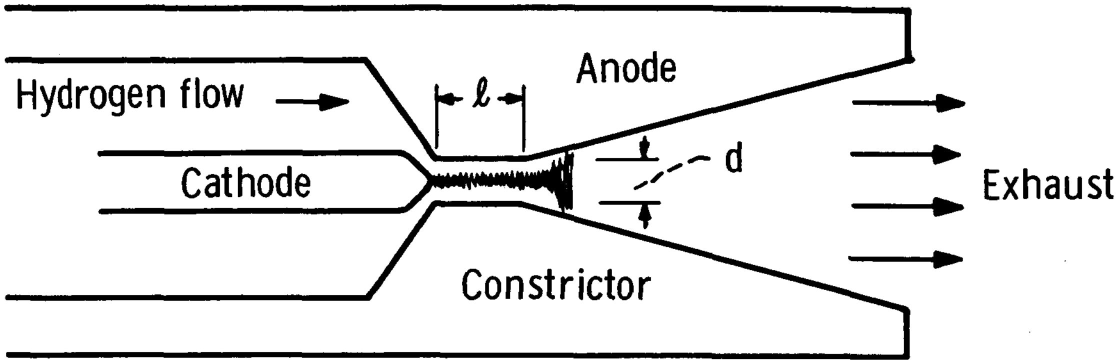
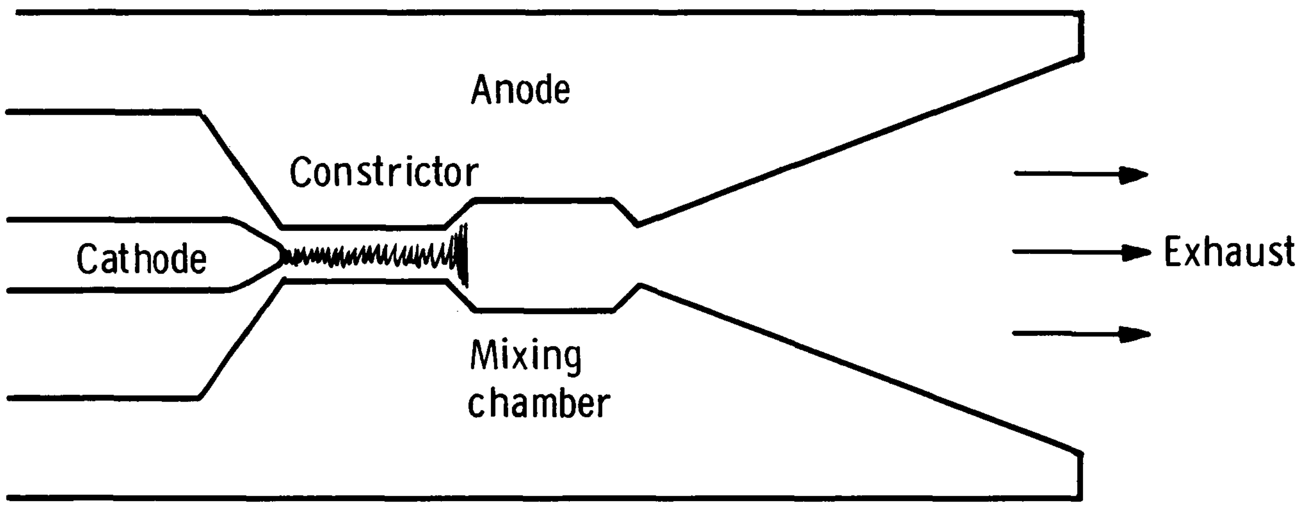


Fig. 4– An unconstricted arc

Dwg. 852A089



(a) Constricted arc



(b) Constricted arc with mixing chamber

Fig. 5— Constricted arc (a) without and (b) with mixing chamber

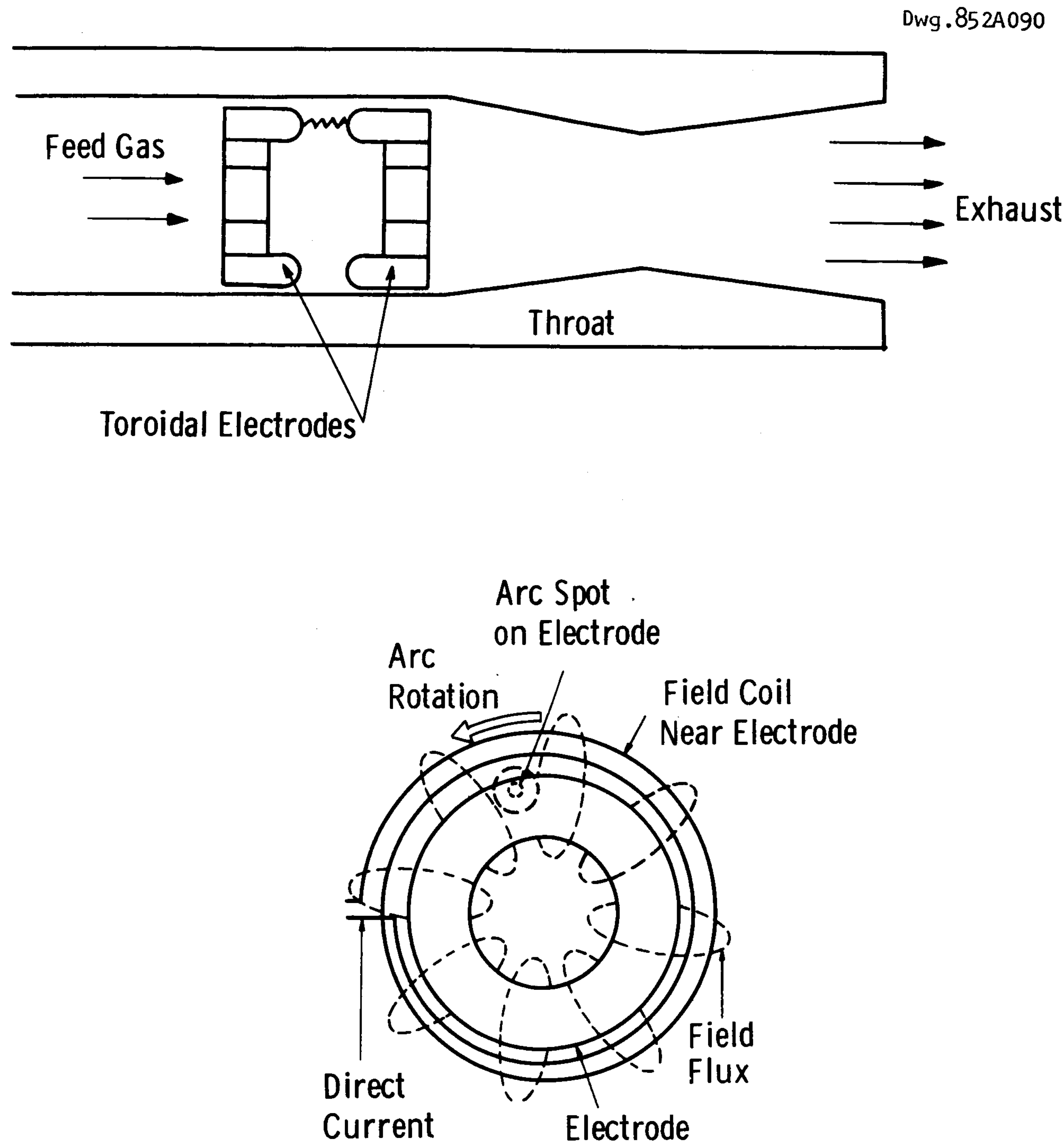


Fig. 6— Rotating arc heater

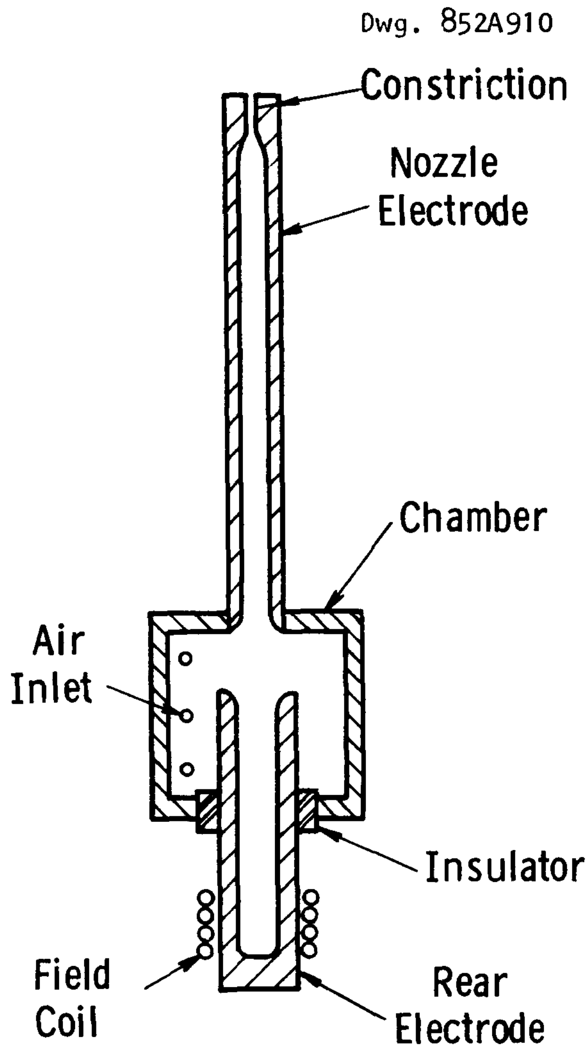


Fig. 7—High voltage arc heater schematic diagram
WADD TR 61-100

Curve 578654-8

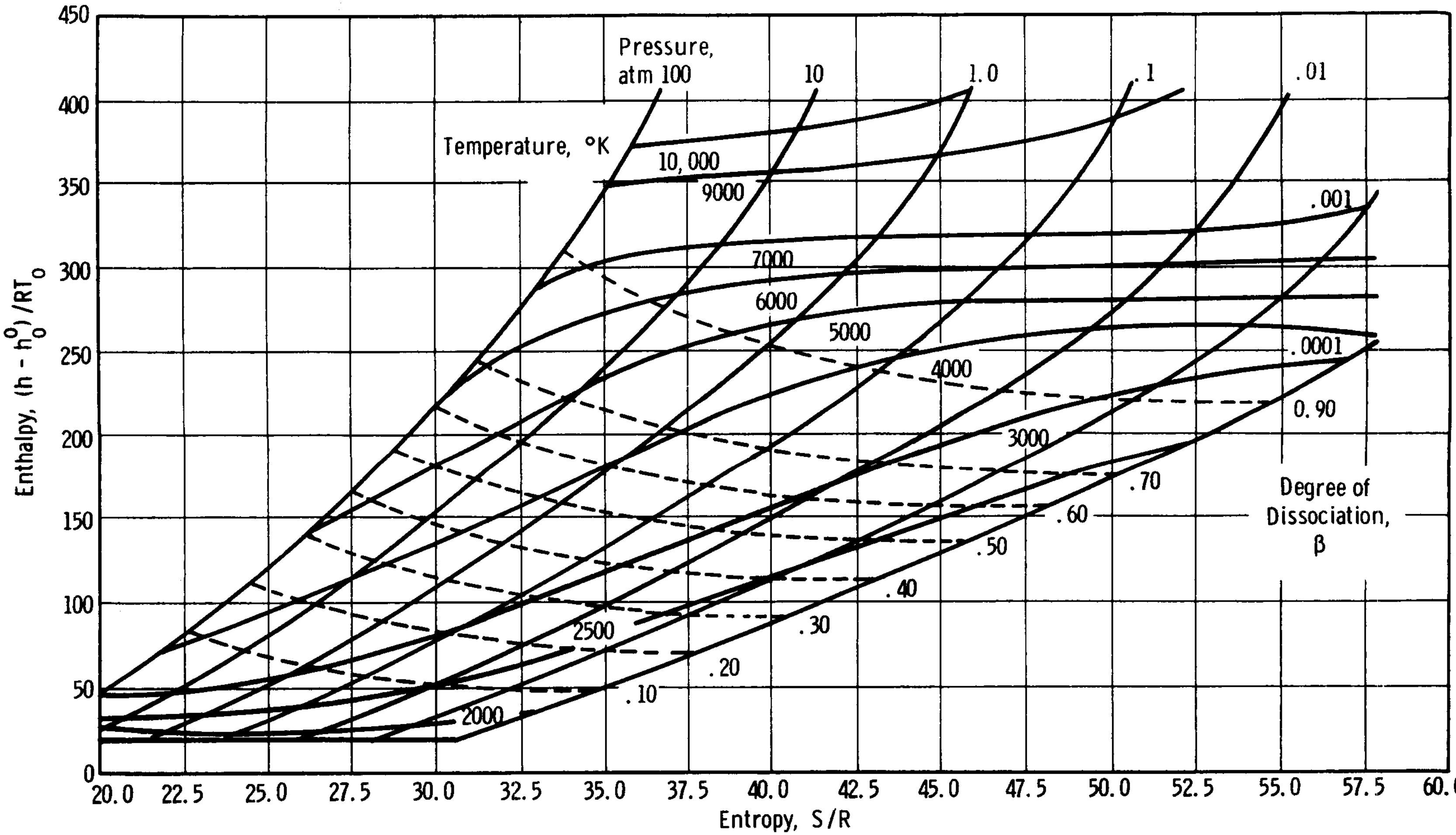
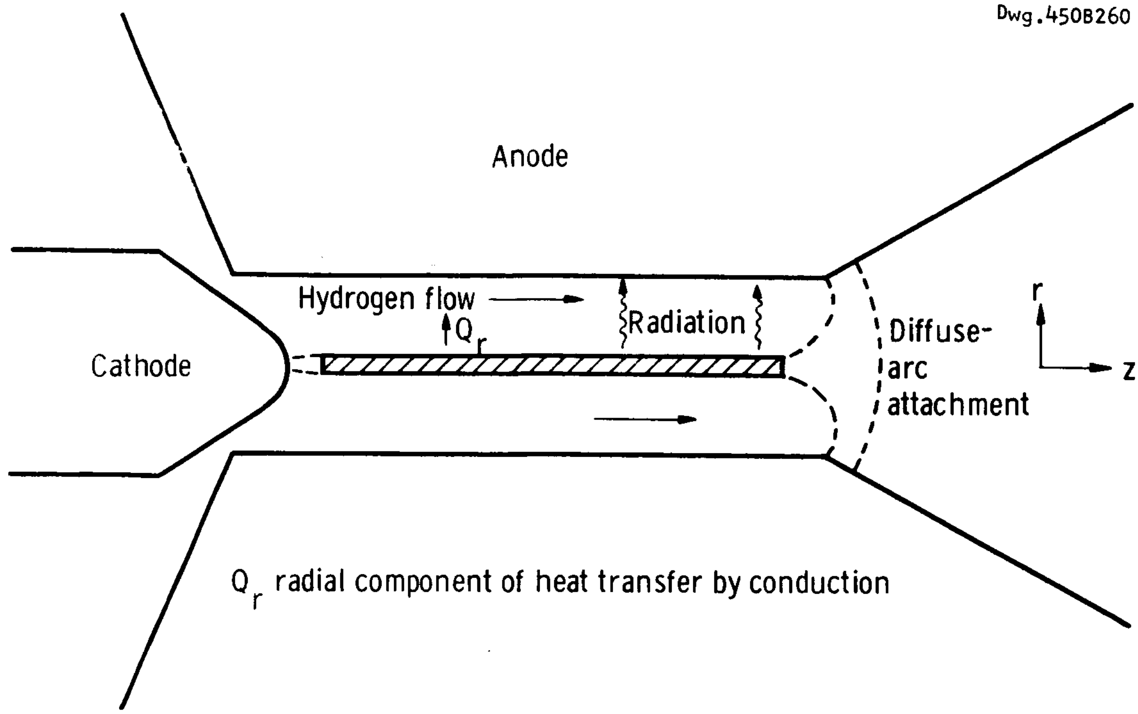
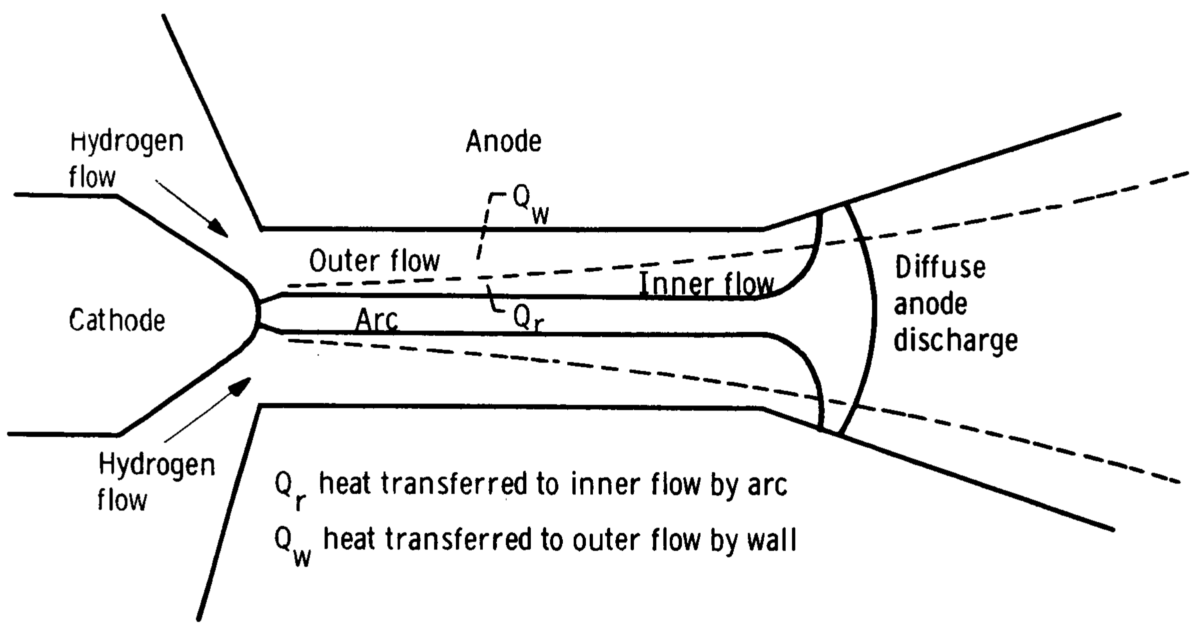


Fig. 8— Mollier chart for hydrogen

Dwg. 450B260



Mechanisms of heat transfer in core-flow model



Regions of flow and energy source for each in-core-flow model

Fig. 9— Core-flow model

Dwg.852A091

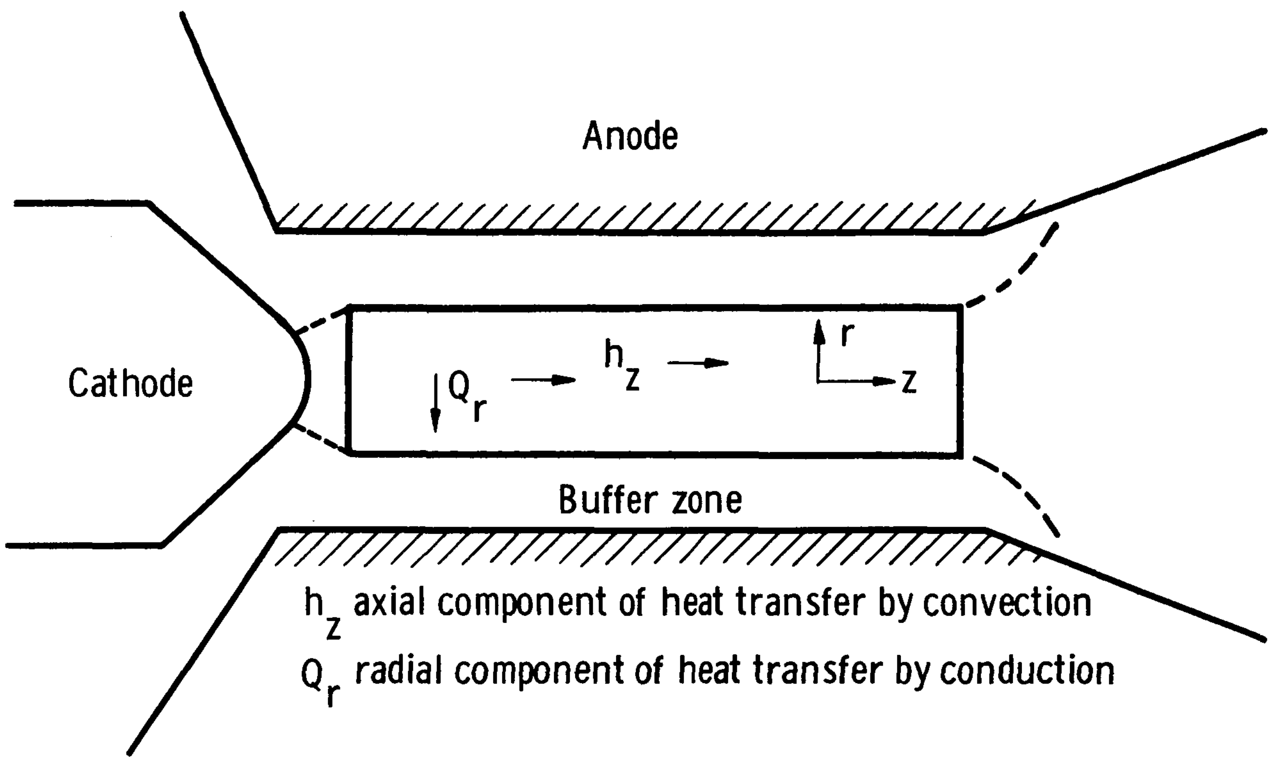


Fig. 10–Mechanisms of heat transfer in Stine-Watson theory

Curve 578655-A

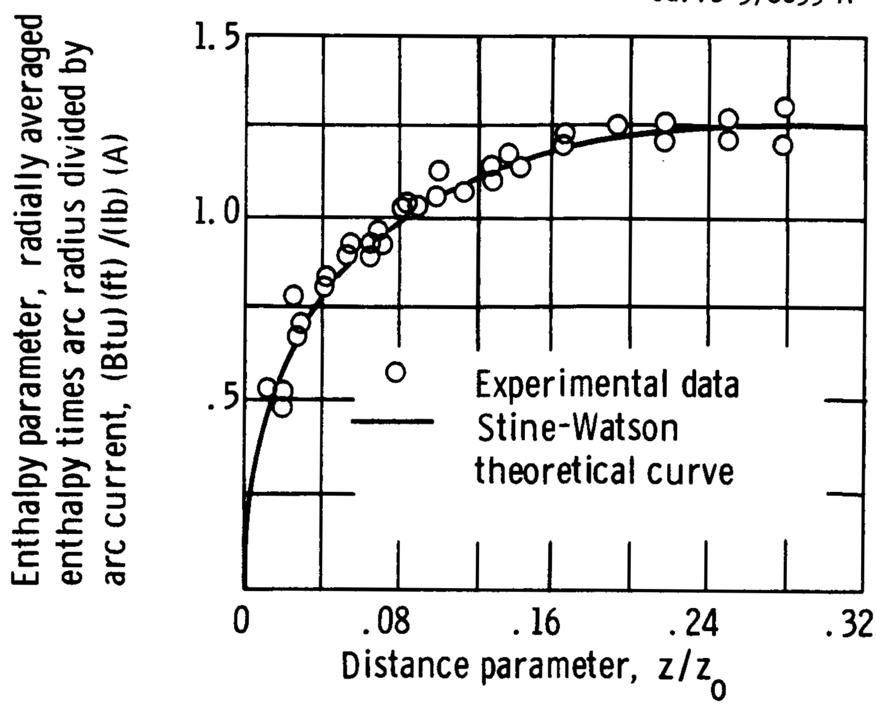


Fig. 11 – Variation of enthalpy parameter with dimensionless distance parameter. Comparison of experiment with Stine-Watson model for nitrogen.

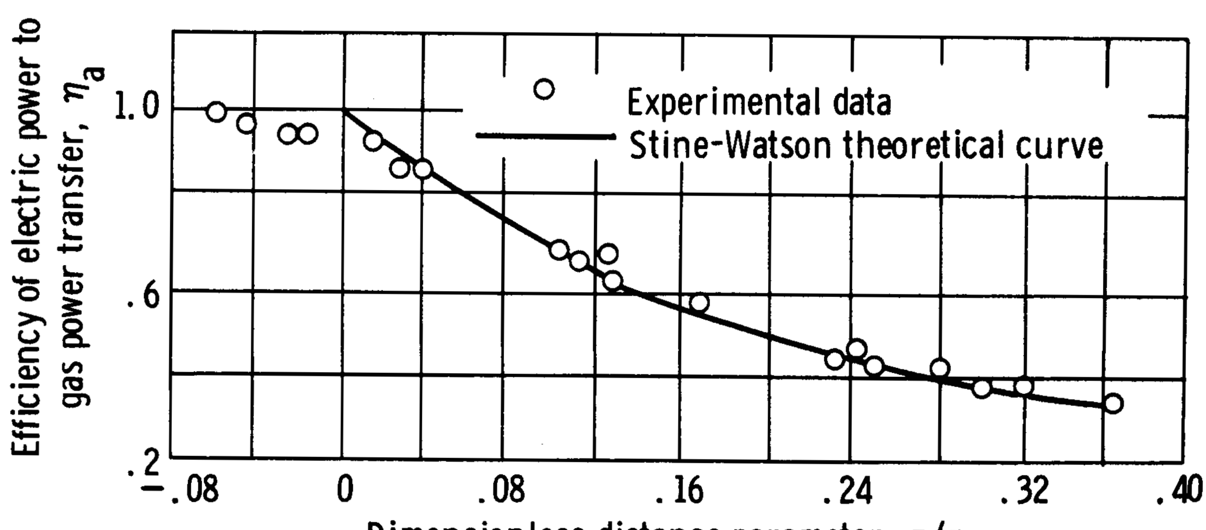


Fig. 12 – Variation of arc efficiency with dimensionless distance parameter. Comparison of experiment with Stine-Watson model

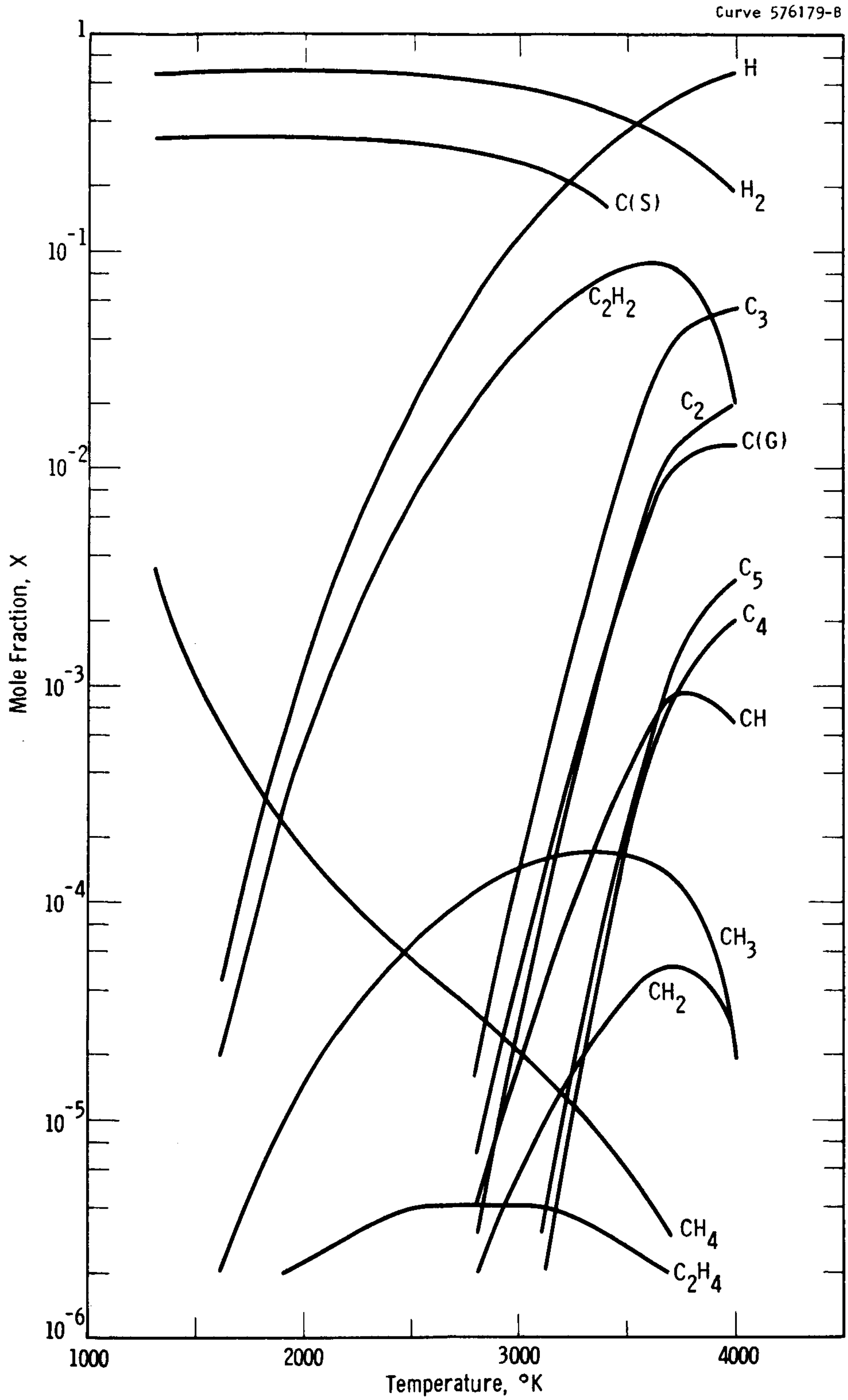


Fig. 13—Calculated C + $2H_2$ as a function of temperature (Total P = 1 atm)

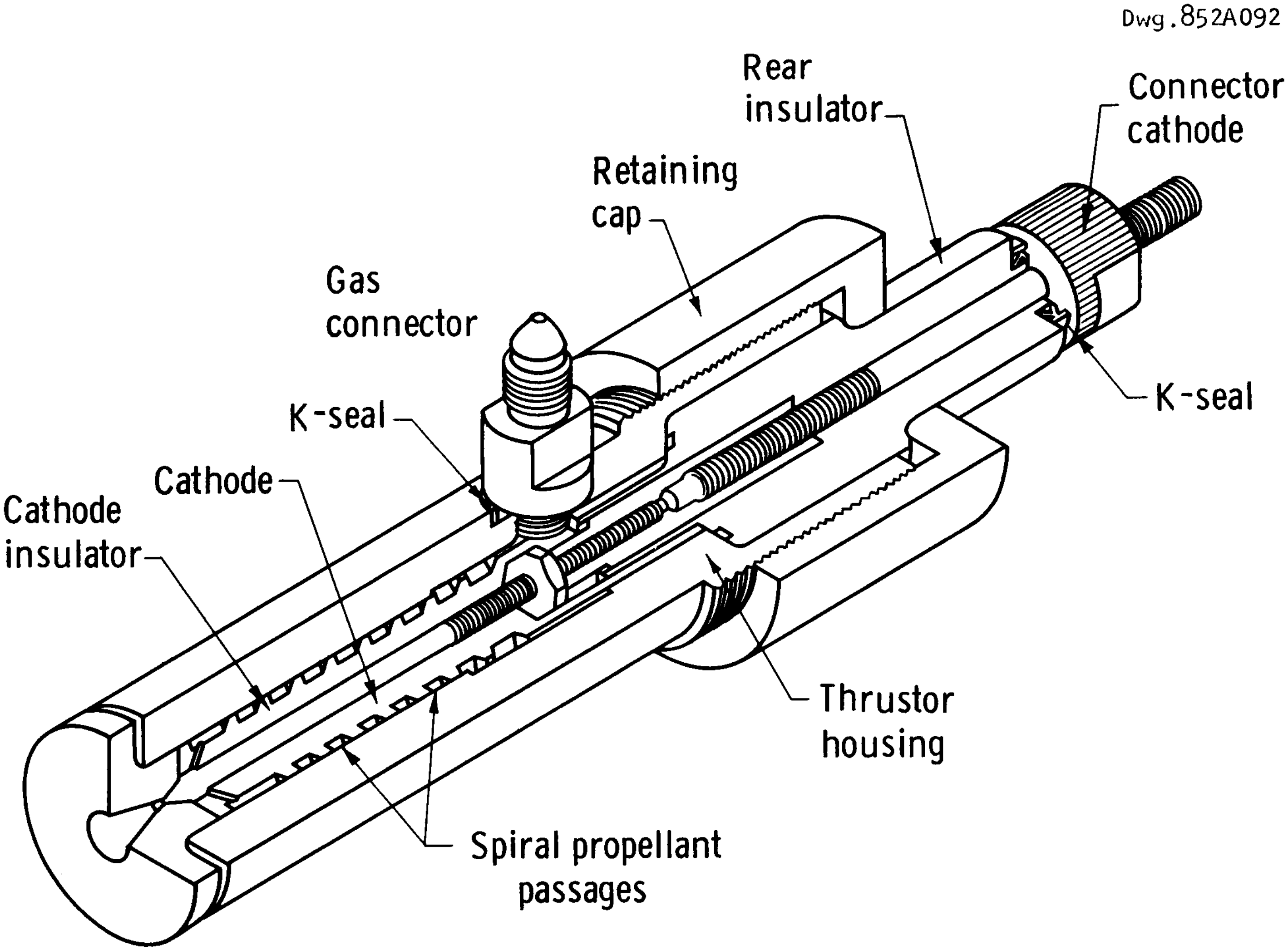


Fig. 14– Two-kilowatt direct-current arc jet (designed for NASA by Giannini Scientific Corporation)

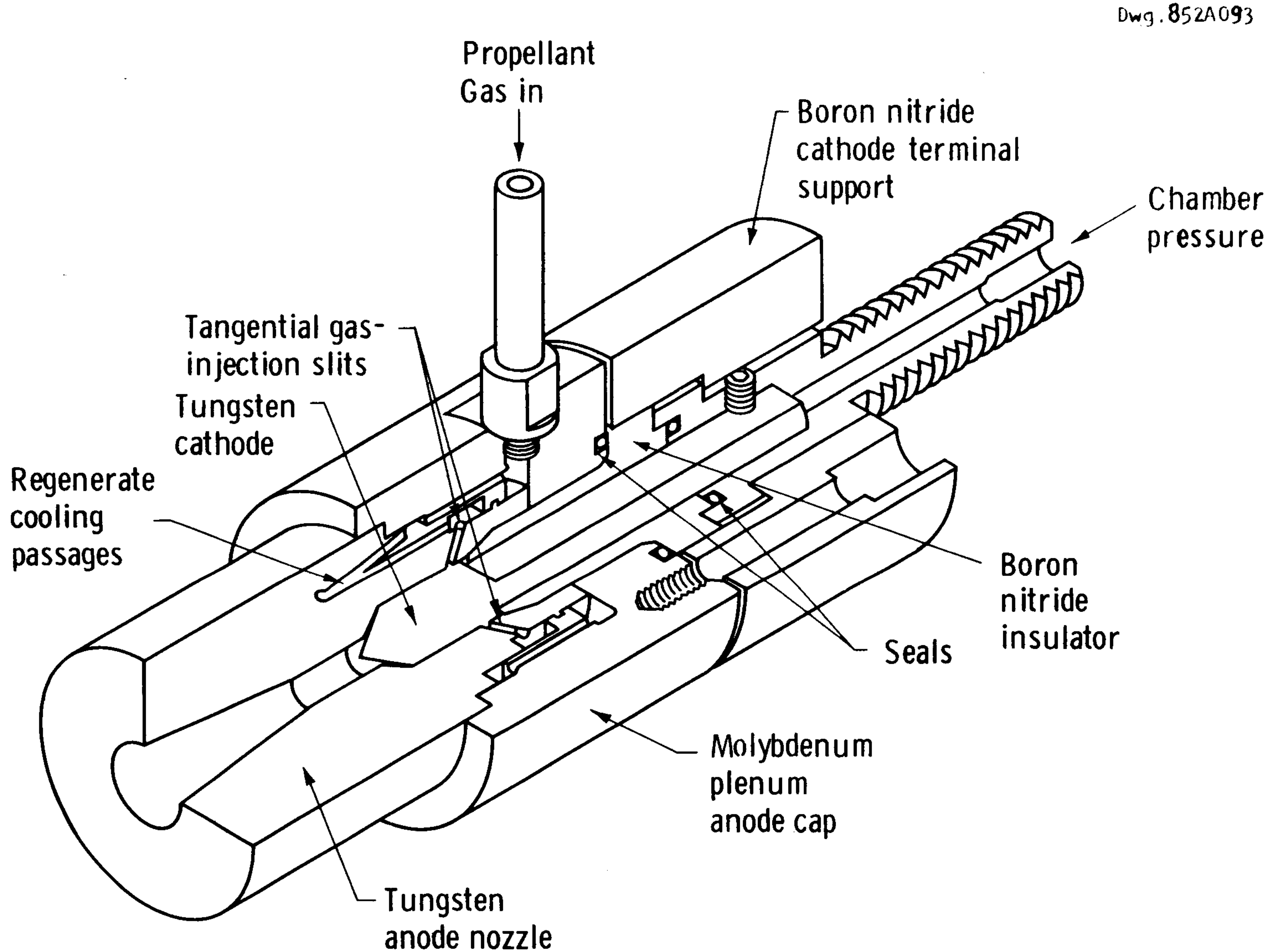


Fig. 15— Schematic diagram of 30-kilowatt direct-current radiation-cooled arc-jet engine (designed for NASA by Avco Corporation)

Curve 578656-A

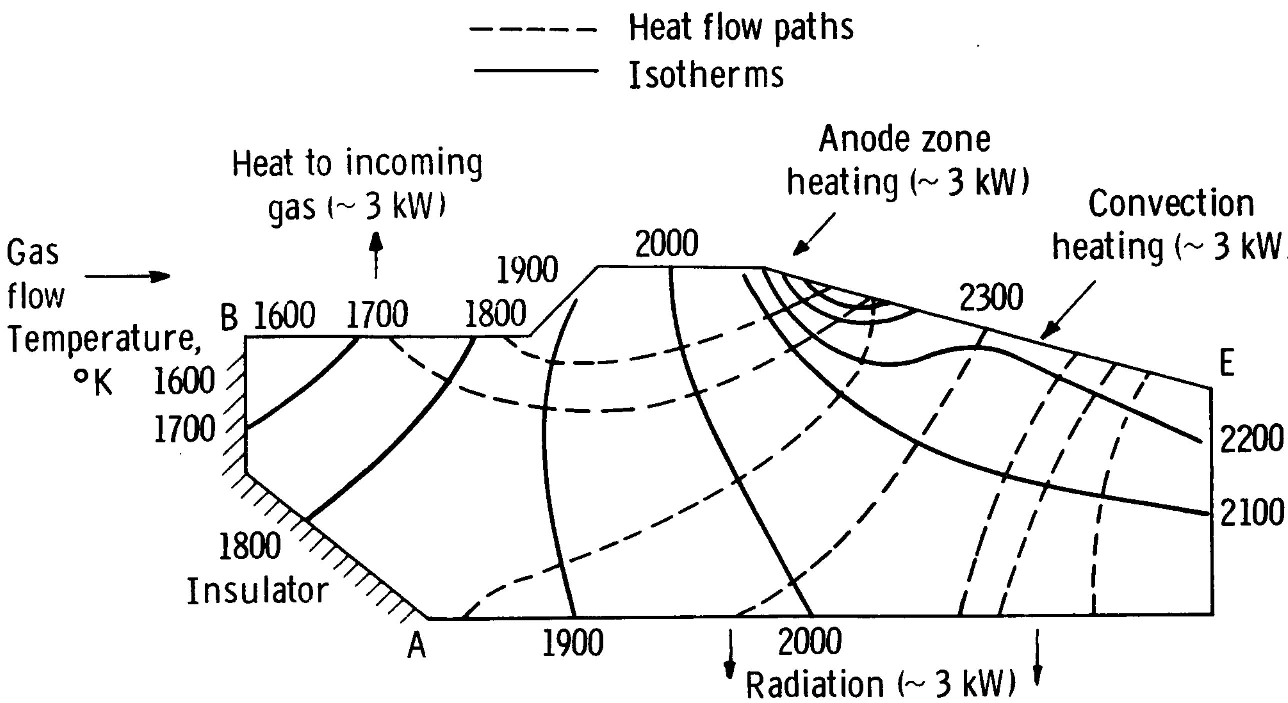


Fig. 16— Engine isotherms and heat flow paths for 30-kilowatt arc-jet engine

NASA-Langley, 1967 —— 25 CR-813