ELECTRICAL AUGMENTATION OF NATURAL GAS FLAMES

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I INTRODUCTION

Many industrial processes could make advantageous use of an economical source of heat at temperatures intermediate between those of combustion flames and those of electric arcs. This need has provided the incentive for numerous attempts to combine electrical energy with the heat released by combustion.

Combustion flames are, of course, limited in their heat release rate by reaction kinetics, and are limited in their ultimate temperature by the partial dissociation of the products of combustion.

The electric arc is not thus limited, but it has its own disadvantages. It is inherently a device characterized by extreme temperature gradients; that is, the electrically conducting path in the working fluid tends to contract into a very narrow, superheated channel, while the parallel surrounding paths carry little or no current and are relatively cold. The arc is further characterized by a relatively low voltage gradient along the conducting path; hence, it requires a high current if it is to dissipate substantial power in the gas. The high current, in turn, creates serious electrode maintenance problems, because the area of attachment of the arc at the electrodes is extremely small at any given instant. With a low voltage gradient through the gas, the energy dissipated as electrode losses (which are primarily a function of current density) is a relatively high proportion of the total energy input, thus tending to make the arc an inefficient means for heating the gas. In addition, the higher unit cost of electrical energy (versus combustion energy) puts the arc at an economic disadvantage.

Past research on electrical augmentation of flames, such as that of Southgate,[1] has utilized an electric arc in conjunction with the flame. Materials problems associated with the arc put a severe limitation on this technique, and interest in electrical augmentation of flames virtually disappeared until recently.

Renewed interest in the subject was initiated by a patent issued to Karlovitz[2] and by the preliminary development work on the patent concepts, by A. D. Little, Inc.[3,4] This work demonstrated that large amounts of electrical energy could be imparted to a flame, in the form of a high-voltage, low-current discharge that was dispersed throughout the flame volume. Subsequently, several other publications[5,6] have dealt with this subject. This paper will attempt to describe some of the performance characteristics obtained with the improved burner design.

II DISCUSSION OF THE DIFFUSE ELECTRICAL DISCHARGE

Gases at ordinary temperatures are very poor electrical conductors, because they have a very low concentration of free electrons and positive ions. As the temperature is raised, polyatomic gases tend to become more and more unstable and to dissociate into their constituent atoms. However, in most cases the constituent atoms are themselves highly resistant to further dissociation into ions and electrons. Only at extremely high temperatures (above 5000°K) do such elements as oxygen, nitrogen, hydrogen, and carbon begin to ionize to an extent sufficient to impart significant electrical conductivity to the gas.

In the region between 5000°K and 20,000°K, the extent of ionization of common gases is an extremely sensitive function of temperature, and the electrical conductivity rises by many orders of magnitude as the temperature rises. The gases are said to have a large "positive temperature coefficient of electrical conductivity."

Because of this large positive coefficient, an ordinary gaseous conductor is an inherently unstable resistive load, and cannot be placed directly across a constant-voltage source without degenerating into a virtual short circuit. (As the gas is heated by the electrical discharge passing through it, its conductivity rises almost without limit.) A "ballast," consisting of an appropriately large auxiliary resistance or inductance, must be placed in series with the usual gaseous conductor in order to achieve control of the current drawn by the latter. This is the usual method employed to stabilize an electric arc.

A large positive temperature coefficient of conductivity also results in a second effect within the gaseous conductor. The flow of current naturally takes the path of least resistance. If there are even minor local nonuniformities among various alternative paths, the most conducting path will be heated most rapidly and will therefore increase in conductivity most rapidly. Unless this process is somehow opposed, the flow of current will very rapidly contract into a single, very narrow channel.

Two main strategies are available to counteract filament formation. The first is to reduce the positive temperature coefficient of electrical conductivity of the gas to the minimum possible value. (If it could be reduced to zero, or made negative, no further strategy would be necessary.) The second is to reduce or eliminate random local nonuniformities in conductivity before they grow too large.

To implement the first strategy, the familiar tactic of "seeding" the flame is employed. Alkali metals (and their compounds) are much more easily ionized than are the constituents of the common gases. For example, as shown in Fig. 1, potassium chloride (added in low concentration to a flame) can approach complete ionization of the outer electron of the potassium atom at temperatures several thousand degrees Kelvin lower than those at which any significant ionization of the bulk flame gases occurs. Thus, the conductivity of such a seeded flame is provided almost entirely by the additive, and once the latter reaches a state of essentially complete ionization, the temperature coefficient of conductivity of the flame assumes a relatively low value. Only a few parts per million of "seed" material is required to furnish adequate conductivity for the flame to be able to dissipate a large amount of power at relatively modest voltages.

Implementation of the second strategy is possible in principle because the overheating of a conducting path (relative to its surroundings) and the contraction of that path into a narrow filament are both time-dependent phenomena; therefore, it should be possible to oppose them by means of the powerful mixing action that can be provided by turbulence. Such mixing would tend to level out any local nonuniformities in temperature and conductivity before they could develop too far.

A mathematical treatment of the condition required for prevention of filament formation has been described by Karlovitz.[4] This treatment leads to the concept of a "critical voltage gradient," above which the rate of mixing provided by turbulence is inadequate to prevent the intensification of local inequalities in heating rate. Below the critical voltage gradient, the theory predicts that turbulence can act within a time interval comparable to that required for filament formation; this prediction has been verified experimentally. Thus, the two main tactics required for reduction of the diffuse discharge principle to practice are both available.

The initial mathematical model of Karlovitz is admittedly simplified, and will have to be refined to take into account such perturbing effects as dissociation of the working gas, nonequilibrium ionization (particularly during exothermic chemical reactions), and nonequilibrium electron capture (reported to be important during endothermic chemical reactions).[7] Nevertheless, the simple theory has been found to provide a very useful guide for design.

III DESCRIPTION OF EXPERIMENTAL DEVICE

The work described here was conducted with a burner designed to operate on natural gas and air, at flow rates up to those corresponding to a maximum combustion heat release rate of 342,000 Btu per hour (equivalent to 100 kw of combustion energy).

The fuel and air were premixed and seeded with a dilute aerosol of potassium chloride. Combustion occurred in a constant-area duct and the diffuse electrical discharge was established in the fully combusted gases, immediately downstream of the combustion zone.

Figure 2 is a schematic representation of only the final stage of the device (in which the diffuse discharge takes place). This stage consists of a tube of refractory, electrically insulating material, bounded at both ends by metal electrodes. Provisions for cooling the tube and the electrodes are not shown in the diagram.

The electrodes are connected to a single-phase, 60-cycle power supply nominally designed for a power output of 100 kw, and actually capable of providing up to 150 kva at output voltages variable between about 2 and 8 kv. Inductive ballasting is provided, with the amount of inductance variable up to a maximum value sufficient to limit the short-circuit current to about twice rated current.

IV EXPERIMENTAL RESULTS

The initial burner configuration was similar to the original design described by Karlovitz, in that the discharge zone coincided with the combustion zone. Visually, the discharge did appear to be reasonably uniformly dispersed throughout the burner volume, and photographs taken with exposure times of the order of 1/50 second, such as that in Fig. 3, confirmed this impression. However, when high-speed photographs were taken, such as that in Fig. 4, the discharge was shown to consist of one (or at most a few) rapidly wandering, contracted arc filaments. Regardless of the concentration of ionizing additive or the degree of approach stream turbulence employed, the contracted nature of the discharge persisted if more than 10% electrical augmentation was attempted.

At this point, the possibility had to be considered that the zone in which turbulent combustion was in process did not have the properties necessary to sustain a powerful diffuse discharge. Especially near the gas inlet end of the discharge tube, the ionizing additive could not be expected to be fully vaporized and uniformly dispersed, and severe local temperature and electrical conductivity gradients were likely to be present.

The nature of the discharge changed drastically when another section of the duct was added downstream of the combustion zone, and when the discharge was established in this final stage. Figure 5 is a frame from a high-speed movie (3000 frames per second), showing such a discharge at that point in a single half-cycle of a.c. corresponding to peak power. The average electrical power per cycle dissipated by the discharge during this movie was 100 kw, and the peak electrical power at the instant of the frame shown in Fig. 5 was over 200 kw, on the basis of simultaneous oscilloscopic records of discharge current and voltage. Stoichiometric proportions of natural gas and air were employed, at a total flow rate equivalent to 100 kw of combustion power.

The photograph shows that, under these conditions, no filamentary structure can be discerned in the discharge column. Other frames from the same film (such as that shown in Fig. 6) occasionally show a short length of arc filament immediately adjacent to the electrode (mainly next to the upstream electrode, during that half-cycle when it has negative polarity); however, this is not surprising, because the discharge generally anchors at a relatively small spot on the electrode, thus necessitating a very high current density in the relatively cool and nonconductive boundary layer surrounding the electrode. With proper preconditioning of the working gas, the main portion of the discharge column remains completely diffuse.

By permitting combustion to proceed to completion prior to the superposition of the electrical discharge, any undesirable nonequilibrium ionization due to exothermic chemical reactions during the

discharge is avoided. In fact, the combustion products have the desirable property of being able to undergo endothermic dissociation, thus providing a self-contained heat sink that should tend to help avoid localized overheating of the gas by the discharge. Another way of stating this is that the slope of the conductivity versus enthalpy curve is reduced by dissociation. This slope may be regarded as an even more direct criterion of the susceptibility of the gas to filament formation than is the slope of the conductivity versus temperature curve.

Further confirmatory evidence of the diffuse nature of the discharge in a well preconditioned gas is provided by oscilloscopic traces of current and voltage, such as those shown in Fig. 7. These may be contrasted with the traces shown in Fig. 8, obtained from a contracted arc superimposed on a seeded, turbulent, combusting gas stream, like that illustrated in Fig. 4. Several important differences between the two cases may be pointed out. First, during each half-cycle at a given average power level, the ratio of voltage to current (representing the instantaneous ohmic resistance of the discharge) fluctuates between much wider limits, and drops to much lower values at peak current, in the arcing case than in the diffuse case. Second, there is no pronounced rise in voltage during the extinction period in the case of the diffuse discharge. Third, the arcing case exhibits a rapid, high amplitude fluctuation in voltage that does not appear in the diffuse case. (In an inductively ballasted circuit, the current is prevented from undergoing rapid changes by the reactive back--emf developed across the inductance; therefore, any rapid fluctuations in discharge conductivity are exhibited as voltage fluctuations to a much greater degree than as current fluctuations.) An arc in a highly turbulent medium is stretched and distorted in a random fashion so that it would be expected to exhibit just the sort of random fluctuations in conductance as are observed. A diffuse discharge, on the other hand, has a cross-section that is large compared with the scale of turbulence, so that its average conductance is less easily perturbed by turbulent mixing.

One further observation may be cited in support of the conclusion that the discharge illustrated in Fig. 5 is truly diffuse. At a given power level, the total luminosity of the discharge region is remarkably low, compared to that of the arcing discharge. This low luminosity is consistent with the absence of superheated filaments. We have not quantitatively examined either the absolute intensity or the spectral distribution of the emitted radiation.

The theoretical enthalpy of the augmented stoichiometric, natural gas-air flame (referred to 298°K) is shown in Fig. 9, plotted against the augmentation ratio (the ratio of electrical power to nominal combustion power). The discharge has been successfully maintained in the

diffuse mode at average augmentation ratios up to, and even slightly in excess of unity, and at peak ratios more than twice as high as the average. At peak power in each half-cycle of a.c., the total enthalpy of the gas is so high that only the dissociation of the initial combustion products prevents the temperature from rising to a level at which the conductivity would rise excessively because of ionization of the bulk gas.

The theoretical equilibrium temperature and composition of a stoichiometric methane-air mixture are shown plotted versus total enthalpy, in Fig. 10. These data were obtained with the aid of a machine computation program developed in the course of this study, with the assistance of Dr. Stuart Brinkley of Combustion and Explosives Research, Inc. Experimental gas compositions for the effluent gases from the augmented burner indicate a close approach to equilibrium, after allowance is made for recombination reactions occurring in the sampling probe.

The experimentally determined rate of heat transfer from the augmented flame to a transient-type flux probe in shown in Fig. 11, as a function of total enthalpy and of distance from the burner exit plane. It may be seen that the over-all heat transfer coefficient is considerably higher than that typical of unaugmented flames, a result attributable to the effect of recombination reactions on the probe surface.

V SUMMARY

An improved version of an electrically augmented burner has been described in which a powerful, 60-cycle electrical discharge can be maintained in the combustion products from a natural gas-air flame, and in which the discharge can be maintained in a completely diffuse mode.

Proper preconditioning of the gas appears to be the most essential factor tending to oppose contraction of the discharge into an arc filament. A high degree of turbulence, both in the discharge zone and in the approach stream, also assists in combating filament formation, the effect being most noticeable at high electrical power levels.

The diffusely augmented flame has potential technical and economic advantages over other sources of high temperature heat, that are expected to be significant to chemical, metallurgical, and other industrial uses. Experimental work with respect to various such applications is continuing.

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6. "Proceedings of the Tenth Symposium (International) on Combustion," London, Butterworth, 1965

7. Atallah, S. and W. A. Sanborn, "The reduction of the electron density of a plasma by endothermic reactions," XV International Astronautical Congress, Warsaw, Poland, September 1964

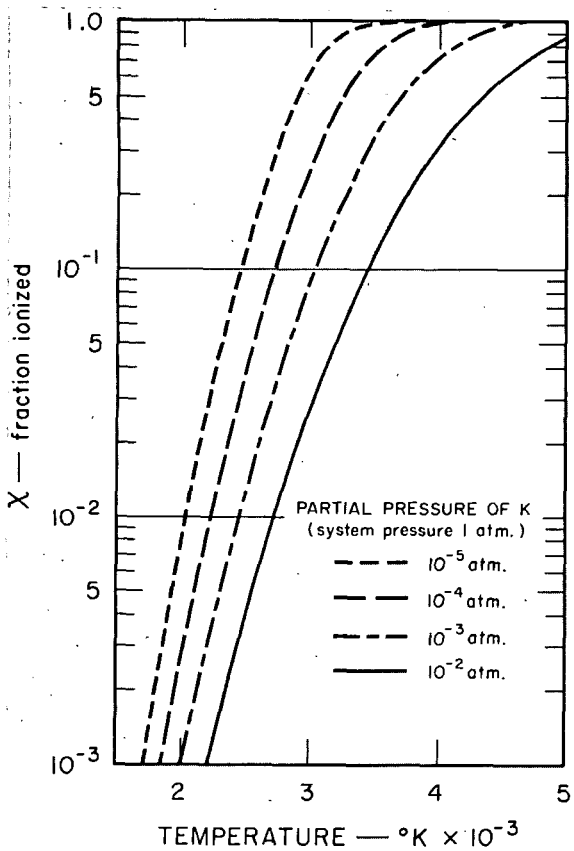


Fig. 1.-TEMPERATURE DEPENDENCE OF EXTENT OF IONIZATION

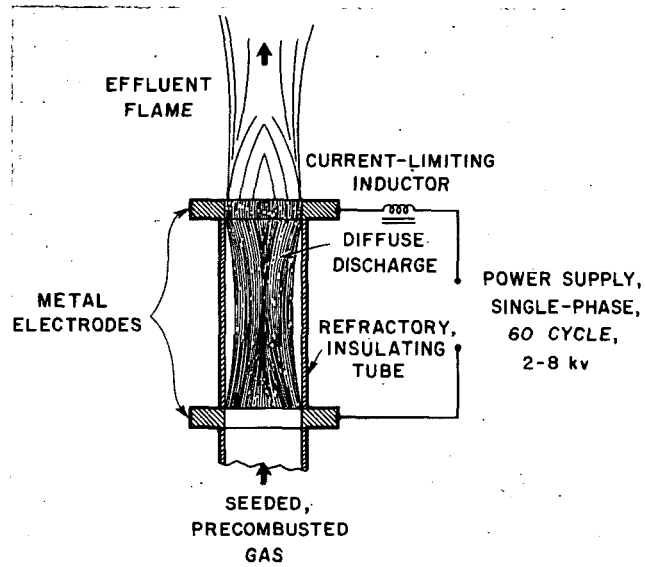


Fig. 2.-SCHEMATIC DIAGRAM OF FINAL STAGE OF ELECTRICALLY AUGMENTED BURNER

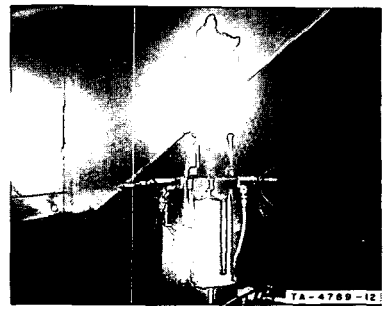


Fig. 3.-DIFFUSE APPEARANCE OF FILAMENTARY DISCHARGE AT SLOW SHUTTER SPEED

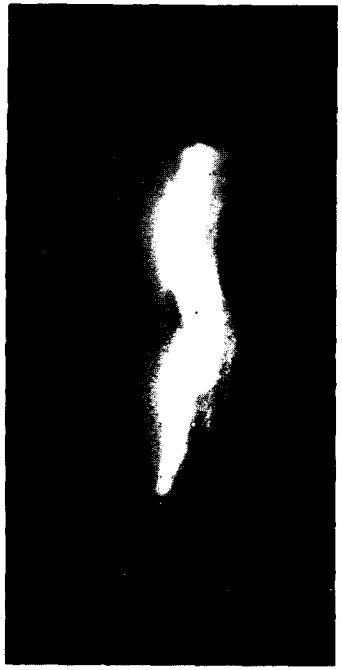


Fig. 4.-APPEARANCE OF FILAMENTARY DISCHARGE AT FAST SHUTTER SPEED

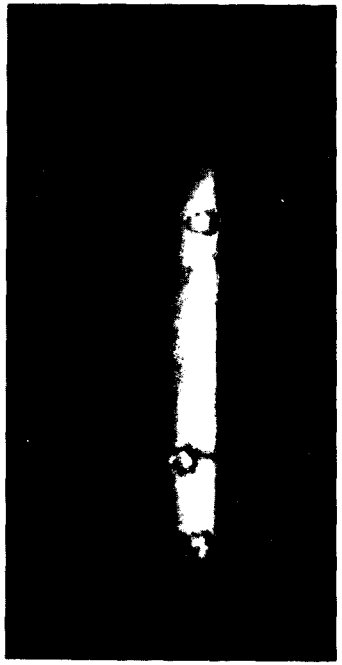


Fig. 5.-APPEARANCE OF DIFFUSE DISCHARGE AT FAST SHUTTER SPEED

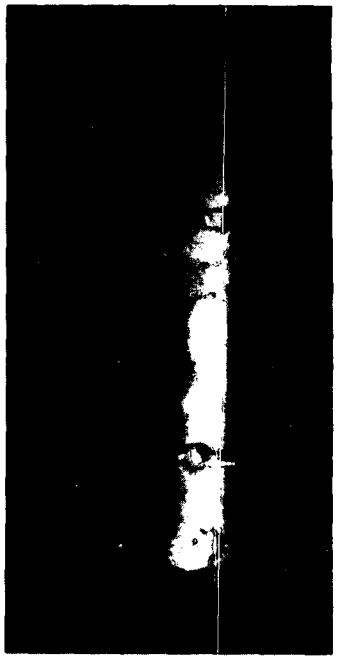
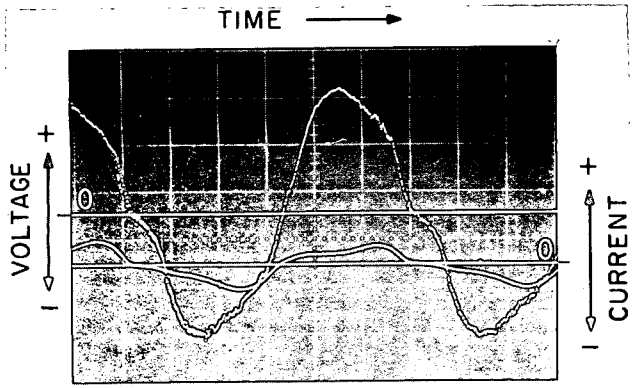
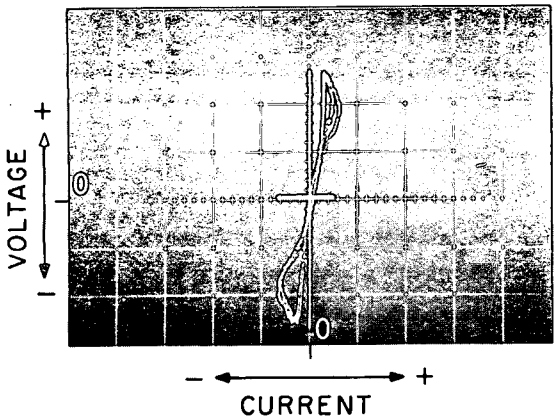


Fig. 6.-MAXIMUM EXTENT OF FILAMENT FORMATION NORMALLY OBSERVED WITH DIFFUSE DISCHARGE

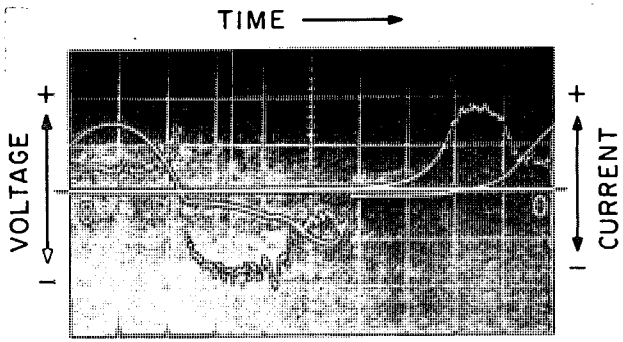


(a)

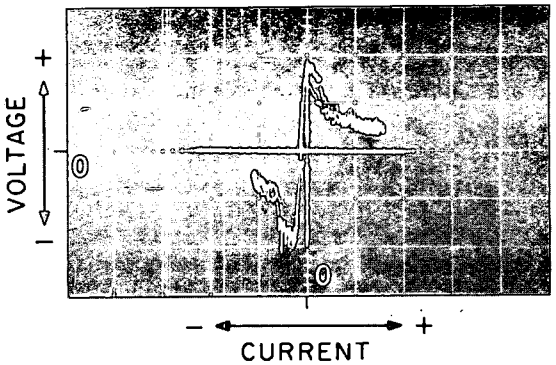


(b)

Fig. 7.-VOLT-AMPERE CHARACTERISTIC OF DIFFUSE DISCHARGE



(a)



(b)

Fig. 8.-VOLT-AMPERE CHARACTERISTIC OF FILAMENTARY DISCHARGE (at the same average power as that of Fig. 7)

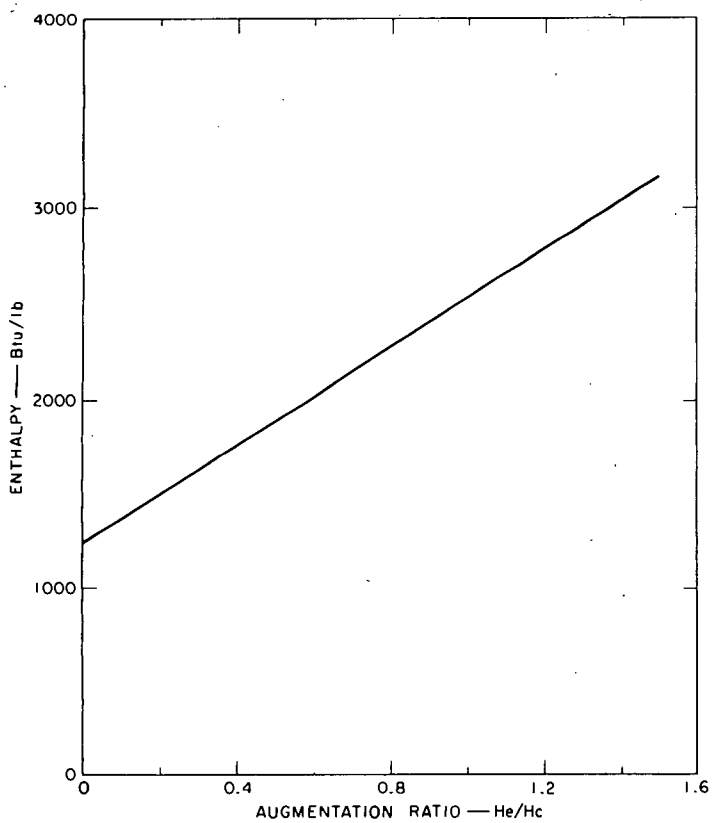


Fig. 9.-THEORETICAL ENTHALPY AS A FUNCTION OF ELECTRICAL AUGMENTATION RATIO

Figure to be distributed at meeting

Fig. 10.-THEORETICAL EQUILIBRIUM TEMPERATURE AND COMPOSITION AS A FUNCTION OF TOTAL ENTHALPY

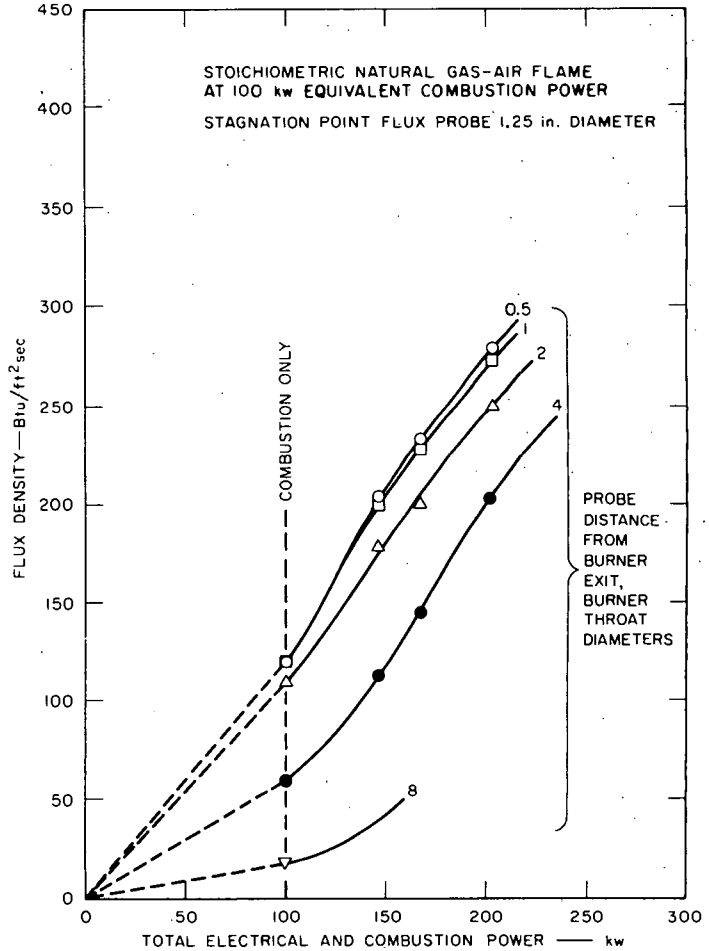


Fig. 11.-HEAT TRANSFER FROM ELECTRICALLY AUGMENTED BURNER TO A COLD-WALL, STAGNATION-POINT PROBE