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INVESTIGATION OF HEATING OF AIR STREAM IN A WIND TUNNEL BY MEANS OF AN ELECTRICAL DISCHARGE

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by

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ABSTRACT

Experiments have been made in a 1" x 1" "blow down" wind tunnel to test the feasibility of using an electric arc for adding heat to a Mach 4 airstream. The arc column was stabilized transverse to the flow by means of a strong magnetic field, and up to 5 kilowatts of electrical power were dissipated. However, uniform heating was not obtained, because the arc had a strong tendency to concentrate in the boundary layer and appeared to fill only about 1/2 to 2/3 of the tunnel cross section.

As a means of circumventing these difficulties, several alternative electrical heating methods are proposed. It is believed that these proposed methods hold much more promise than the system which was tested.

INVESTIGATION OF HEATING OF AIRSTREAM IN A WIND TUNNEL BY MEANS OF AN ELECTRICAL DISCHARGE

I - INTRODUCTION

A wind tunnel capable of producing hypersonic air flow at much higher static temperatures than can be achieved with present techniques would be possible if a satisfactory means could be found for adding heat to a supersonic flow. An investigation of the use of an electrical discharge for this purpose has been conducted as a University of Michigan Research Project sponsored by the Exterior Ballistics Laboratory of the Army Ordnance Corps, Aberdeen Proving Ground.

This project was administered through the Engineering Research Institute of the University, and utilized the facilities of the Department of Electrical Engineering.

The first part of this report describes an experimental investigation of a particular system of electrical air heating. During the course of this laboratory program several alternative methods for using an electrical discharge were proposed. Section X of this report outlines a variety of these alternatives, many of which appear to be much superior to the method employed in this investigation.

This research was an outgrowth of a previous project at the University of Michigan sponsored by the Office of Ordnance Research. In the earlier work, dealing with electrical wind phenomena, it was shown that a diffuse discharge capable of generating a high speed air flow could be obtained by the use of a strong transverse magnetic field at pressures of the order of 0.1 mm of Hg and lower. (4)[1] One of the aims of the present project was to evaluate the use of these

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[1] References given in parentheses can be found in the bibliography.

techniques for heating a supersonic flow in a wind tunnel at static pressures of several millimeters of Hg.

For the experimental phases of this project, a small "blow down" wind tunnel was used and provided a Mach 4 flow at static pressures of about 5 mm of Hg. The test section area was of the order of one square inch. Up to 5 kilowatts of electrical power were put into a d-c discharge which was stabilized by a magnetic field transverse to the airstream, i.e., the discharge went from one side of the tunnel across the flow to the opposite side. The behavior of this type of discharge has been investigated for a variety of magnetic field configurations and stream densities. Experiments with a "pulsed" discharge were also made in which peak currents of 1500 amperes were passed through the flow. The order in which various topics appear in this report corresponds roughly with the chronological order in which the work was done. The results of this investigation are presented in a rather descriptive fashion since the type of behavior which was observed did not appear to warrant a more analytical study.

A number of considerations are involved in the choice of the air density which offers the most advantageous conditions for heat addition. At sufficiently low gas densities the heat addition is much more diffuse and uniform; however, an appreciable fraction of the energy which is added to the gas does not appear immediately as thermal energy, but persists as excited and ionized states of the gas molecules. This effect becomes more pronounced at low densities. The seriousness of this situation for a practical wind tunnel application has not yet been determined. Appendix II is a copy of a letter from Dr. W. B. Kunkel of the University of California in which he describes some of the constituents to be encountered in these afterglows.

Appendix I is an analysis of the compressor power requirements for a wind tunnel with supersonic heating. This analysis was made by Mr. James L. Amick under the direction of Prof. James E. Broadwell. Mr. Amick is associated with the University of Michigan Wind Tunnel at Willow Run, and Prof. Broadwell is a member of the faculty of the Aeronautical Engineering Department. The analysis shows that the required compressor power is less if the heat is added to the airstream at low values of Mach number, i.e., near the front end of the tunnel where the gas density is higher. At these densities, however, the problem of obtaining a diffuse discharge becomes more difficult.

II - METHOD FOR STABILIZING A d-c ARC IN AN AIRSTREAM

At gas densities corresponding to pressures of the order of ten millimeters of Hg and higher, approximate thermal equilibrium exists between the electrons and ions and the neutral gas particles in an electrical discharge. (This situation is true only for low values of E/p. (1)[1]) The temperature of the plasma is high enough to produce thermal ionization in accordance with Saha's equation. The power input to the discharge is just enough to balance the loss of heat from the arc column and to maintain a high enough temperature to provide the required degree of ionization.

Under these conditions, an arc column established transverse to an airstream will move downstream at the same velocity as the flow. The air motion relative to the electrodes carries the heated gas with it, and the arc column grows in length as illustrated in Fig. 1a. There is no mechanism by which the arc can move from the region of heated gas into the colder air without the action of a magnetic field. When the arc gets too long it will extinguish because of losses resulting from its greater length. If the open circuit voltage across the electrodes is sufficient to break down the gap, the arc will re-ignite and will again blow out downstream, resulting in the unstable behavior indicated by Fig. 1a.

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1) Reference (1), p. 44. References given in parentheses can be found in the bibliography.

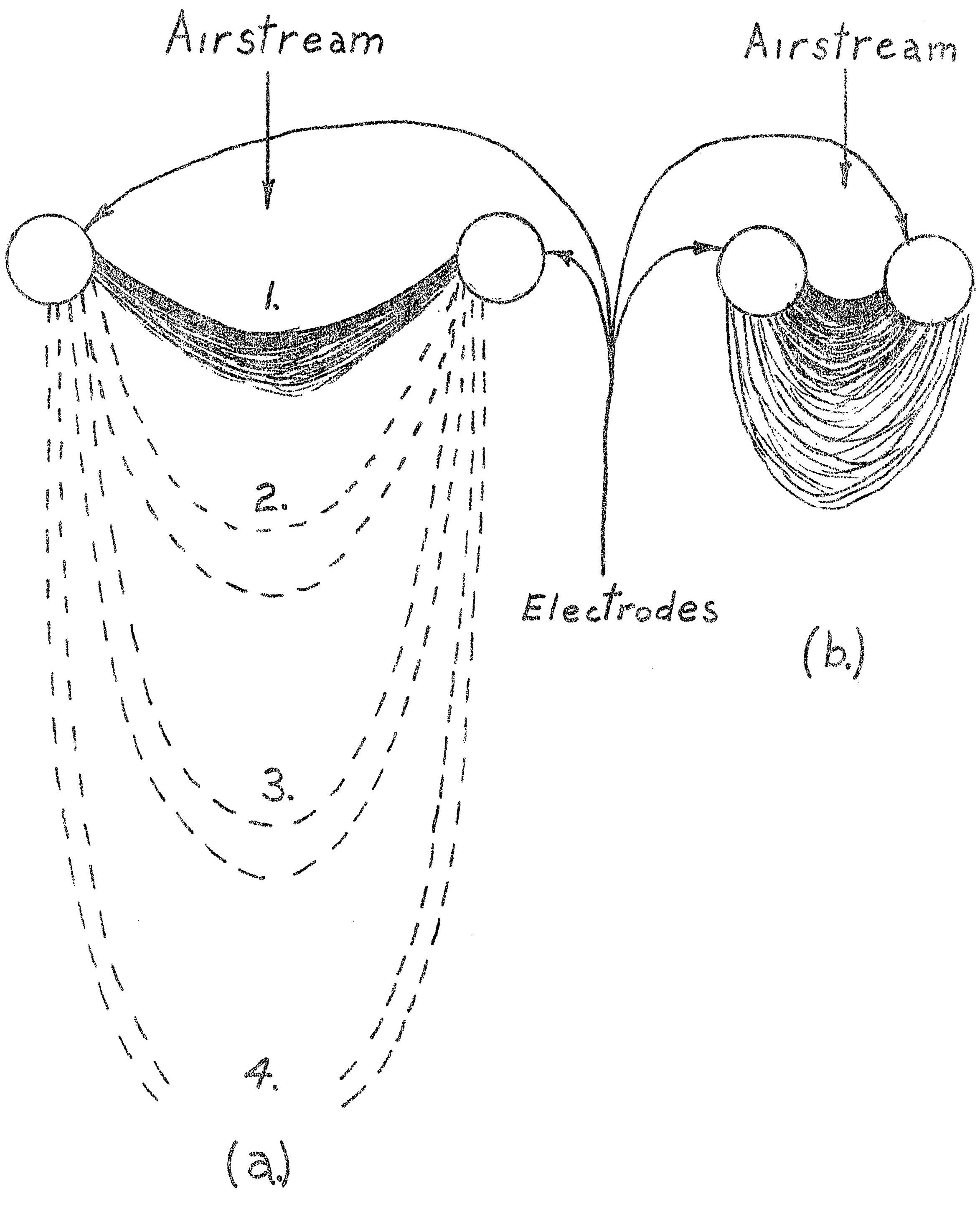


Fig 1. Arc in an Airstream Without a Magnetic Field

An exception to this situation exists when the spacing between the electrodes is about the same as the cross section of the arc. This occurs at low densities where the size of the discharge becomes very large. Under such conditions, illustrated in Fig. 1b, the voltage gradient along the leading edge of the arc is sufficient to produce the required amount of ionization for the arc to exist in a stable fashion transverse to the air flow.

When a magnetic field is established at right angles to the current flow in an electrical discharge, a force is exerted on the charged particles. The magnitude and direction of this force are given by: Force per unit volume = J x B, where J is the current density and B is the magnetic flux density. This magnetic force causes a d-c arc to move in a direction perpendicular to both the magnetic field and the current flow. With a sufficiently strong field, an arc can be made to travel at speeds of several thousands of feet per second. It can be shown that under these conditions the air which is intercepted by the arc column is not heated to the temperature required by the Saha relation (even at pressures as high as one atmosphere). Thus, the magnetic field forces the arc to move through essentially cold air, and in so doing, raises the air temperature only a few hundred degrees Kelvin instead of 5000 or 6000 degrees which would occur if thermal equilibrium were established.

One of the objectives of this research program was to investigate the use of a magnetic force to stabilize the position of a d-c arc across a supersonic air stream. In the wind tunnel application, an arc would be established transverse to the air flow, and a magnetic field would be oriented to produce a force on the charged particles directed upstream. In this way, the aerodynamic forces tending to move the discharge downstream could be approximately balanced by the magnetic force.

For this situation, the magnetic force imparts a component of upstream drift velocity to the electrons and the positive ions in the discharge. This momentum is communicated to the neutral gas molecules, and has a tendency to slow down the air flow. However, at several mm of Hg static pressure this upstream force is very small and the momentum of the flow is reduced by a negligible amount. The ionization is a fraction of one percent, and only one-third of the directed kinetic energy of the ions is transferred as directed kinetic energy to the gas particles. (4) The other two-thirds of the ion energy appears as random thermal energy in the gas. At extremely low gas densities, however, the situation is quite different and the magnetic force on the ions can be effective as a means for generating a wind. (2)(3)(4)

III - APPARATUS

The major items of equipment and the instrumentation employed by this project were available in the Department of Electrical Engineering of the University. They consisted essentially of vacuum equipment to operate the blow down wind tunnel and electrical apparatus for producing the air-heating discharge.

A steel tank measuring 28" x 30" x 96" (a volume of about 47 cubic feet) provided the vacuum reservoir. A Kinney type CVD-556 mechanical pump was used to evacuate the tank. It had a capacity of about 15 cubic feet per minute and could pump the tank down between runs to a pressure of less than a millimeter in about 20 minutes.

Dry nitrogen was used in the wind tunnel for most of the high power heating experiments; although room air was employed extensively for preliminary tests. Nitrogen was used since an electrical discharge in air forms various oxides of nitrogen which will quickly deteriorate vacuum pump oil. For most of the tests the nitrogen was supplied at atmospheric pressure from a large neoprene balloon supported at the top of the brass tube which can be seen on the right hand side of Fig. 2.

Pressure measurements constituted the primary method of instrumentation. For pressures of a few centimeters of Hg and less, an Alphatron ionization gage made by the National Research Co. was used. For higher pressures, mercury manometers were employed, the closed end variety being quite satisfactory for total head pressure measurements.

The other major pieces of equipment consisted of a magnet, the magnet power supply, and two high voltage power supplies. The magnet was designed for intermittent operation and could produce about 6000 gauss in a four inch air gap (eight inch diameter pole pieces). Tapered pole pieces were also used and resulted in a substantially higher field strength over a three inch diameter area. Fig. 2 is a photograph of a typical experimental set-up with a tunnel in place between the pole pieces of the magnet. The power supply for this magnet could deliver any desired current up to about 300 amperes (at about 75 volts).

One of the high voltage power supplies was a 10 kilowatt variac controlled supply which could provide a 12 kilovolt output. The other power supply had a 5000 volt output but could deliver up to 30 amperes for short intervals. Varying amounts of series resistance and inductance were used with these power supplies to provide a steady arc current of any desired value.

The wind tunnels used for air heating tests were constructed in the machine shops of the Electrical Engineering Dept. They were made as simple as possible and yet provided for a wide variety of tunnel and electrode configurations. The flow in the test section of the tunnels had a cross section of the order of one square inch. A variety of different tests was made at Mach numbers varying from Mach 3 to Mach 5.

For the tunnel design used most extensively, the tunnel

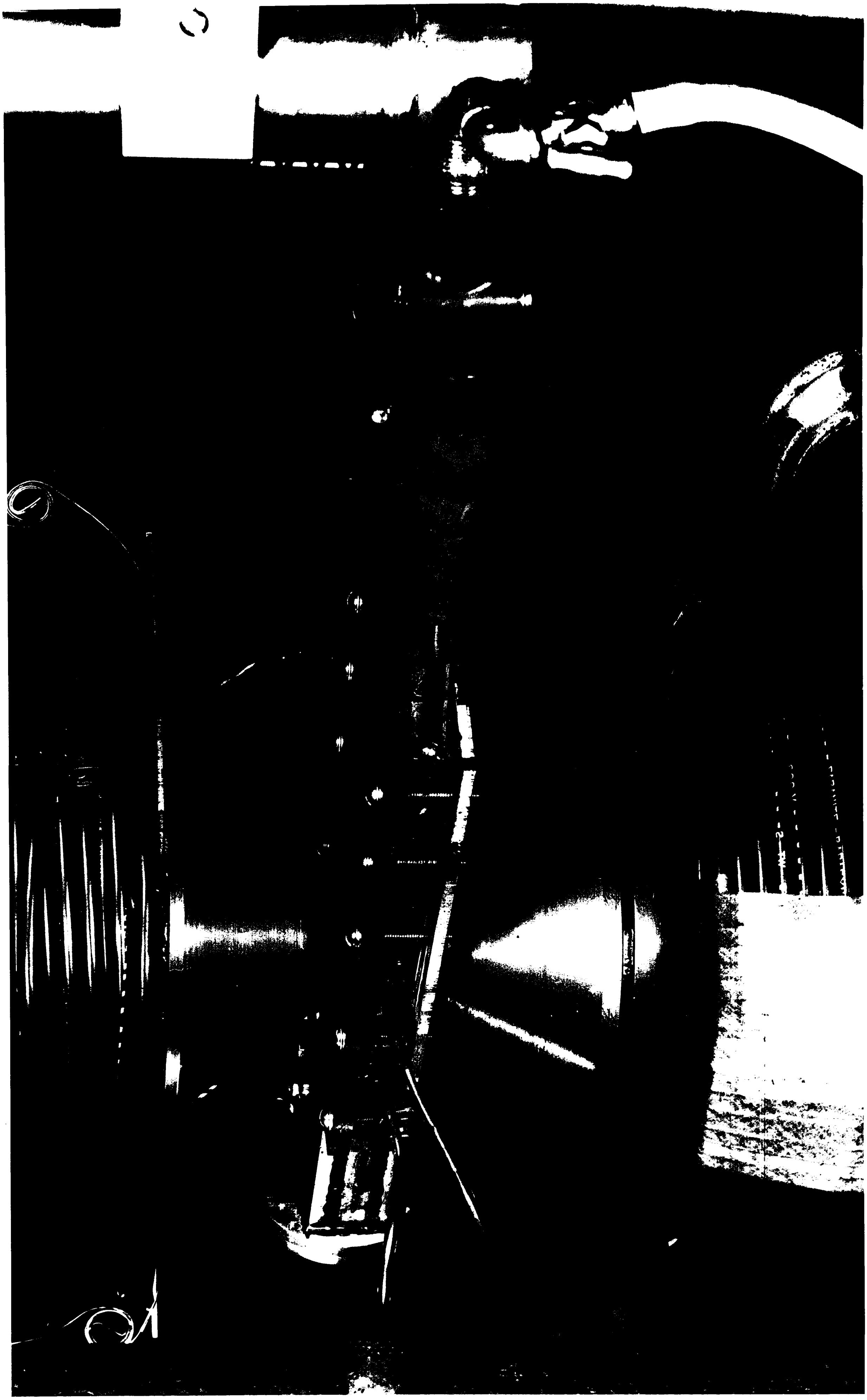


Fig. 2

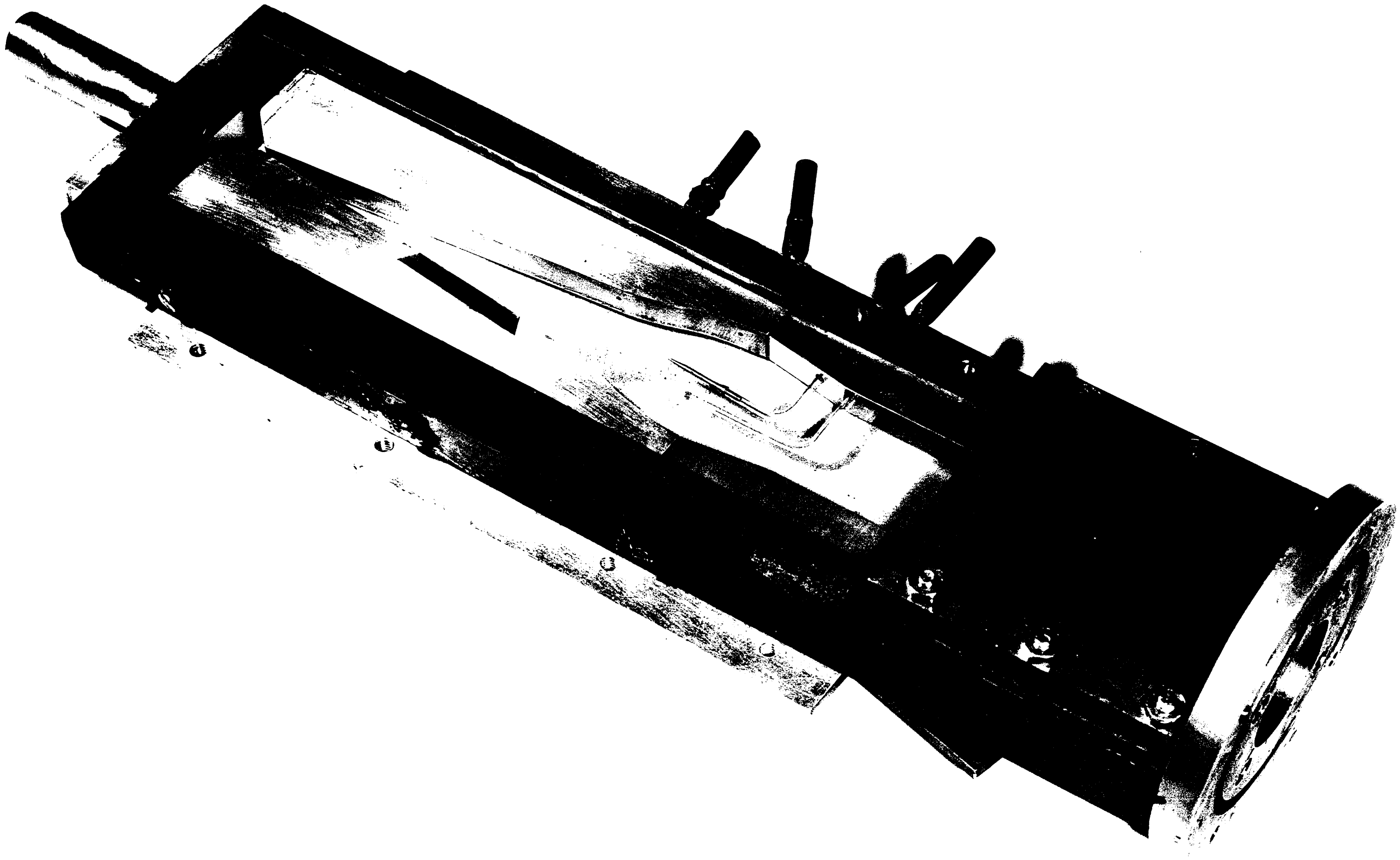


Fig. 3

had a rectangular cross section with two straight parallel sides. The other two sides diverged at about 11° included angle forming a wedge-shaped nozzle. An example of this type of tunnel is shown in Figs. 2 and 3. Straight sides were used in the nozzles, resulting in radial flow at the exit. As far as the air heating experiments were concerned the radial flow appeared to be of no consequence and the simplicity of straight sides was a great convenience in construction.

IV - "CONTOUR ELECTRODE" TUNNEL

Description

A simple arrangement for establishing a d-c arc in a supersonic flow is to use the two diverging contours of a wedge nozzle as the arc electrodes. This arrangement has proved reasonably satisfactory and was used extensively in this investigation.

The details of a tunnel of this type can be seen in Fig. 3 which is the same tunnel shown in Fig. 2 with the top cover removed. It was designed so that a wide variety of "contour electrode" geometries could be tested without having to alter the basic tunnel structure. The structural members consisted essentially of two side rails running the length of the tunnel. They were braced at the front end by a brass cross-piece which supported the inlet tube, and were secured to the vacuum flange on the downstream end by means of two brass plates. One side rail was made of a dielectric material (phenolic laminate) to simplify the electrical insulation problem. Thin rubber gaskets on these members provided a vacuum seal when the top and bottom cover plates were bolted together as shown in Fig. 2.

The two parallel interior walls of the tunnel were made of a dielectric material so as not to short circuit the contour electrodes. Pyrex or Vycor glass (Vycor contains a high percentage of fused quartz) were used for these walls in order to withstand the heating and also provide visual observation of the discharge. The separation between these parallel glass walls was usually one inch; however, it was cut to one-half inch in many instances in order to reduce the mass flow and provide longer running times. When the one-half inch spacing was used, as shown in Fig. 3, the inner glass plates were not fitted in a vacuum-tight manner. Experimentally, it was found more convenient to use additional cover plates of Plexiglass outside of the Pyrex or Vycor liners, and to make the vacuum seal between the Plexiglass covers and the side rails.

In this type of tunnel the heat addition took place at the nozzle exit which in all cases was about one inch wide. Downstream from the nozzle and the discharge region a wide variety of configurations was used. These contours ranged from a two inch constant area section and adjustable second throat to a drastically divergent section. For the tunnel shown in Fig. 3 a divergent geometry was used, followed by a slight constriction to aid in pressure recovery and increase running time.

Aerodynamic Measurements

Pressure Measurements - Static pressure measurements were used extensively to determine the flow conditions in the tunnel. When different contours were first tested several pressure checks were made to insure that the tunnel was functioning properly from an aerodynamic standpoint before the heating discharge was operated.

For several contours a series of static pressure measurements was made at various stations along the nozzle wall. All of these readings agreed reasonably well with values calculated from the area ratios, assuming isentropic expansion and non-viscid flow. With a throat spacing of 0.080 inches, the calculated Mach number at the nozzle exit was 4.2, while a typical value of measured Mach number was 4.0, indicating the formation of a moderate amount of boundary layer.

Static and impact pressures were also measured in the center of the flow by means of probes located about 1/2 inch downstream from the nozzle exit as shown in Fig. 3. These probes were made from three millimeter Pyrex tubing. The head of the static pressure probe was a brass needle about 3/4 inch long and 0.066 inches in diameter with several small holes located halfway down its length. Typical values of static and impact pressure were 4.0 and 89 mm of Hg, respectively, which appear to be in fair agreement with calculated values for a Mach 4-plus flow.

Shadowgraphs - Shadowgraph techniques were tried as a means of instrumentation of the initial tunnel designs. In these tests the separation between the parallel sides of the tunnel was one inch and pieces of high quality optical plate glass were clamped onto the side rails instead of the Plexiglass cover plates shown in Fig. 2.

A 25 watt Western Union concentrated arc light with a spot diameter of 0.029 inches was used as a light source. The best results were obtained with divergent light, and the "point source" located about three feet from the tunnel. Several attempts were made to use a good quality lens for obtaining parallel light, but the results were less satisfactory than with the divergent light.

Fig. 4 is a shadowgraph of the shock wave from a 7° half-angle double wedge. The wedge was supported from the downstream end by a 0.12 inch diameter rod. The wedge span was about 3/4 of an inch, and thus, did not extend all the way to the top or botton of the tunnel. In these tests one contour of the test section was a continuation of the straight nozzle wall while the opposite contour was curved at the nozzle exit so as to be parallel to the straight side, thus forming a constant area section with a 1" x 1" cross section. The transition from the diverging nozzle to the parallel test section contour can be seen in the upper left of Fig. 4.

Very high contrast film and development were used for making the shadowgraphs. Consequently, the γ (contrast ratio) in Fig. 4 is about three or four times normal. This has the effect of emphasizing the slight imperfections in the plate glass windows and the presence of tiny dust specks; however, it brings out details which cannot be seen visually.

This shadowgraph illustrates several features of the flow which were encountered in a tunnel of this size at these

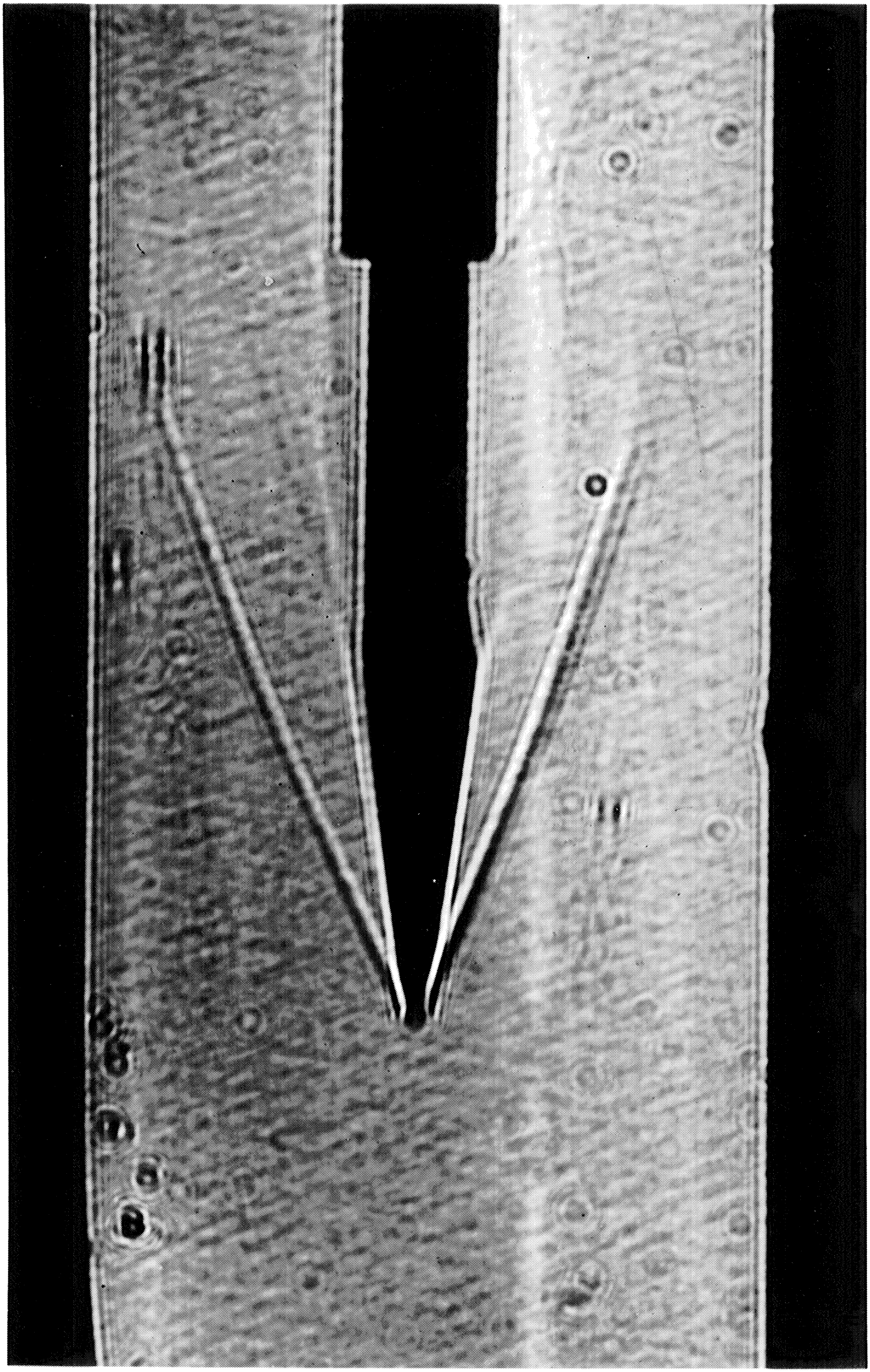


Fig. 4

Mach numbers. A strong bow wave from the wedge can be observed which ends abruptly a short distance from the walls of the tunnel, probably due to the presence of a moderately thick boundary-layer. On the straight side of the tunnel, noticeable boundary-layer thickening can be seen. This may be due to a combination of the boundary-layer shock wave interaction from the bottom of the wedge and a compression wave from the turning of the flow just ahead of it. A measurement of the shock angle indicated a Mach number of 3.1. Static pressure measurements just ahead of the wedge indicated a Mach number of a little less than 4. This disagreement probably indicates a reduction in Mach number in this region due to two sets of compression waves: those originating from the change in tunnel contour at the end of the diverging nozzle, and those caused by the boundary-layer thickening.

Second Throat - The first tunnel designs had a two inch long constant area section followed by an adjustable second throat. In preliminary tests, placing even a small wedge or probe in the constant area test section caused a very large increase in the static pressure. Since this appeared to be a consequence of over-constriction of the second throat, measurements were made on the effect of varying this spacing.

With the pressure ratios obtainable, supersonic flow could not be established with a second throat spacing less than 0.5 inches. When the spacing was 0.55 inches, the running time was 20 seconds; however any wedge or probe in the test section would break up the flow. When the second throat was opened up all the way (1.0 inches) so that a straight section of about 6 inches followed the nozzle, the running time was reduced to 5.5 seconds, but sufficiently small obstacles could be tolerated without upsetting the flow. In all of these tests, the static pressure, measured at the nozzle exit, was very consistent and varied only one or two tenths of a millimeter for different second throat spacings. Since a few seconds of running time was considered sufficient for most of the electrical experiments, the second throat was eliminated in all subsequent tests.

V - APPEARANCE AND BEHAVIOR OF A d-c ARC IN THE "CONTOUR ELECTRODE" TUNNEL

With a magnetically stabilized arc in the contour electrode tunnel, several general observations immediately become apparent. The most obvious characteristic is that the discharge has a strong tendency to orient itself slantwise across the tunnel. The cathode end of the arc always tends to be downstream from the anode end. The upstream boundary of the discharge is at an angle of from 20° to 70° to the direction of the air flow, depending upon experimental conditions.

Another more important observation is that the arc has a very strong preference for the boundary layer region. The cross section of the arc column is not round, but is three or four times greater in the dimension parallel to the flow than in the transverse direction. It appears as a uniformly bright sheet located adjacent to one of the dielectric walls of the tunnel. The discharge is probably initiated in the boundary layer and then grows out into the higher velocity flow as the power and diffusivity are increased. Slight changes in the thickness of the top or bottom boundary layer or in the orientation of the magnetic field make the discharge jump from one dielectric wall to the other. There are two reasons why the arc has a strong preference for the boundary layer. First, the gas density in the boundary layer is less than the free stream density by a factor of two or three. Secondly, the heat loss from the arc column, and consequently the energy requirements, are less in the boundary layer because of the lower velocity flow.

The most obvious effect of the magnetic field is the force that is exerted upon the charged particles. This enables them to counteract the wind forces and when these two forces are made to balance approximately, a stable arc can be established across the stream. With a sufficiently strong magnetic field, on the other hand, the discharge can be made to move upstream and right through the throat. Strengthening the magnetic field tends to straighten out the skewed orientation of the arc column; however, this action can be carried only so far before the greater field strength drives the discharge too far upstream. A strong magnetic field also tends to increase the diffusivity of the discharge, thus improving the uniformity of heating. It appears highly desirable to use as strong a magnetic field as possible consistent with stable operation.

It should be noted that without a magnetic field the discharge is completely unable to withstand the action of the wind. It immediately blows out downstream and will prefer a path a foot or more in length rather than cross one inch of high velocity flow.

The magnetic field can also be oriented parallel to the applied electric field instead of transverse to it as in the situation described above. In this case the arc column tends to be collimated along magnetic flux lines; however, the aerodynamic forces on the discharge cause it to angle off in a slantwise manner and thus cut across the magnetic flux lines. When this happens there is a component of current flowing at right angles to the magnetic field which gives rise to a magnetic force on the arc in the J x B direction in the same manner as described above. This makes the arc deflect towards one wall of the tunnel and results in an inherently skewed orientation. The parallel magnetic field does not appear to have any significant merit as far as stabilizing a discharge in a high velocity flow is concerned.

Increasing the discharge current tends to make the arc column grow in size and thus fill more of the tunnel cross section. It is difficult to obtain a good estimate of the size of the arc because of the skewed orientation which it assumes. In one case a four kilowatt discharge carrying 10 amperes appeared to fill about three-fourths of the tunnel in the Mach 4 region, and was crossing the tunnel at about a 45° angle. The separation between the parallel tunnel walls was 1/2 inch and the downstream contour was highly divergent, as shown in Fig. 3. The apparent size of the discharge column was probably misleading, since high speed motion pictures (to be described later) indicate that the position of the arc column was fluctuating rapidly, creating the impression of greater diffusivity than actually existed.

Increasing the current beyond a certain level, however, appears to increase the current density. This gives rise to more intense heating. It also increases the effective magnetic force on the arc, thus causing it to run upstream. Some compensation can be made by decreasing the magnetic field; however, if the field is decreased too much, the discharge is apt to blow out downstream. If the power is increased beyond the 4 or 5 kilowatt level, in the contour electrode design, an unstable condition arises where the discharge either runs up into the higher density flow just below the throat (where it constricts into a very small channel), or blows out downstream.

With an increase in power it was found necessary to open up the tunnel contours downstream from the heating section, in order to prevent the tunnel from "choking". In one design a 1" x 1" constant area section about one inch long followed the nozzle. The flow in this section was about Mach 4 and the mass flow was approximately 10 grams/sec. When 4.8 kw of power were put into the arc, a uniform discharge was obtained which filled about half of the tunnel cross section and did not appear to upset the flow. However, when the power was increased beyond this level, the discharge became much more brilliant and luminous as is characteristic of arcs at high pressure and temperature. The static pressure in the constant area section also jumped from about 5.5 mm of Hg to about 35 mm of Hg. These effects appeared to be the result of excessive heat addition in the constant area section and a resultant choking of the flow.

In Appendix III the amount of heat required to choke the flow under these conditions is calculated based on certain idealized assumptions. It is shown that in a constant area section the addition of 2.16 kilowatts of heat to the air stream will bring the flow from Mach 4 to Mach 1. The experimental observation that supersonic flow was still present even though the amount of electrical power into the arc was theoretically more than sufficient to choke the flow appears to indicate that a substantial amount of the added energy was going to the tunnel walls or being carried downstream in the form of excited and ionized molecules. However, it is significant that adding a sufficient amount of energy to the flow *in the constant area section* did choke the tunnel.

In order to avoid this condition, the tunnel cross section was opened up by a considerable amount downstream from the heat addition section, as shown in Fig. 3. When the highly divergent contours were used at the nozzle exit the choking tendency did not appear to be present; however, the running time was reduced to about for or five seconds.

In general, pressure measurements made while the heating discharge was operating were less consistent and gave higher readings than without the discharge. The amount of the pressure increase was of the order of 10% and was roughly proportional to the power input. Measurements made in the heating region were quite erratic, since the discharge did not fill the whole cross section of the stream, and the increase in pressure was usually considerably higher than observed elsewhere. An increase was also observed in the static pressure measured at a point slightly upstream from the discharge. This was probably caused by a situation similar to boundary layer shock wave interaction in which the arc produced a discontinuity in the flow.

It was difficult to obtain reliable pressure measurements because of the short running times involved. Small holes and tubulation had to be used, and at these low pressures the time required for the system to reach equilibrium was about the same as the length of the run. Most readings were only a rough indication of the pressure since true equilibrium was never actually reached.

Measurements made by the pressure probes downstream from the discharge were also erratic, but tended to be more consistent than measurements made in the discharge region. The downstream static and impact pressures both showed the same general increase observed upstream; however, the ratio of impact to static pressure decreased slightly. Based upon the Rayleigh relation, this indicated a moderate lowering of the Mach number downstream from the arc. Highly divergent contours, as shown in Fig. 3, were used in these tests. This additional expansion prevented the large decrease in Mach number which would have been experienced had a constant area section been used.

Pressure readings taken while the discharge was operating were considered to be of limited value. Without uniform heating there was undoubtedly considerable turbulence in the flow. This appears to be substantiated by the erratic pressure variations which were observed experimentally. The ratio of impact to static pressure provides an indication of Mach number. However, in order to determine the other flow parameters, a third independent measurement is necessary, since the total energy of the air stream has been increased by the heat addition.

VI - EXPERIMENTS TO IMPROVE DIFFUSIVITY AND STABILITY OF ARC IN "CONTOUR ELECTRODE" TUNNEL

An important requirement of any air heating system is to add the heat uniformly throughout the cross section of the flow in order to minimize inhomogeneities and turbulence. The major objective of this investigation was to obtain a discharge of sufficient diffusivity to meet this requirement of uniform heating. A further goal was to devise a means for stabilizing the position of the arc and correcting the skewed orientation. Most of the experimental work on this contract was directed towards a solution of these two problems.

Experiments at Reduced Gas Densities

Previous work at the University of Michigan has shown that a diffuse discharge can be maintained in a high-speed airstream at densities corresponding to a static pressure of a fraction of a millimeter of Hg and at temperatures of many hundreds of degrees Centigrade. In the present wind tunnel situation, the very low stream temperature makes the density greater than would seem to be indicated by the static pressure. This density corresponds to a room temperature pressure of many millimeters, and under these conditions the discharge tends to be far from diffuse. An obvious approach to this problem was to decrease the stream density in the discharge region to obtain the desired diffusivity.

Several different experiments were conducted with this goal in mind. The parameters which were varied were the Mach number (area ratio), the initial pressure (p_o), and the initial temperature (T_o). The flow conditions in the tunnel were determined from static pressure measurements made without the discharge running.

Increase in Mach Number - The simplest procedure for obtaining a lower stream density was to increase the Mach number by narrowing the throat opening. Tests were made with the throat spacing varied between 0.100" and 0.022" with the tunnel shown in Fig. 3. Table A serves to summarize the results of these experiments. It gives values for a calculated Mach number and a measured Mach number. The calculated Mach number was based upon the measured area ratio and the assumption of isentropic inviscid expansion. The so-called measured Mach number was derived from the measured static pressure at a point just forward of the nozzle exit, also assuming isentropic expansion.

TABLE A

Throat Width	Calculated Mach Number	Measured Mach Number
0.100"	3.9	3.8
0.080"	4.2	3.9
0.060"	4.5	4.2
0.040"	5.0	4.5
0.022"	5.7	4.9

An examination of these data shows that the discrepancy between measured and calculated Mach number was appreciable when the throat spacing was decreased below 0.060". Excessive boundary layer thickening at the higher Mach numbers was believed to be the explanation of this discrepancy. The effect of this boundary layer growth was probably accentuated by the elongated rectangular cross section of the nozzle exit (1" x 1/2"). Measurements of the static and impact pressure with the pressure probes just downstream from the nozzle also confirmed this general behavior.

An attempt was made to reduce this boundary layer formation by increasing the Reynolds number. This was done by increasing the initial pressure (p_o) and expanding to an even higher Mach number. With the pressure regulator available, it was possible approximately to double p_o using the same throat widths as listed in Table A. These experiments were even less fruitful than the tests in which p_o was atmospheric, and when only the area ratio was varied.

The few electrical tests that were made in a higher Mach number flow appeared to confirm the assumption of excessive boundary layer thickening. Although the discharge was noticeably more diffuse, it had a very strong tendency to remain close to the dielectric boundaries of the tunnel.

On the basis of these tests no further attempts were made to obtain a lower density by increasing the Mach number. For these experiments, it did not appear feasible to expand beyond a Mach number of about 4 since the boundary layer begins to occupy an objectionably large percentage of the flow. A thick boundary layer is very undesirable in this application since a d-c discharge has such a strong tendency to localize in this region. Further, the decrease in gas density which is obtained by increasing the Mach number becomes less pronounced, since the rate of change of density with Mach number becomes lower for Mach numbers above about 4.5.

Decrease in Initial Density - Tests were made in which the gas density in the working section of the tunnel was reduced both by decreasing the initial pressure (p_o) and increasing the initial temperature (T_o). Pressure measurements, without the discharge running, again were used for determining the flow conditions, and a throat width of 0.080" was employed in most cases.

The initial pressure in the settling chamber could be reduced by throttling the inlet valve of the tunnel. It could be lowered to about half an atmosphere before the running time became excessively short.

A small electric furnace was used to heat the air entering the tunnel. It was constructed from heating elements taken from an electric range and placed in a large ceramic cylinder about 10 inches in diameter and two feet long. Small bricks and pieces of brass were also placed in the furnace to help increase the thermal capacity and to baffle the air around the heaters. A small iron-constantan thermocouple was used to measure the temperature in the settling chamber of the tunnel. Very fine wire (3-mill) and a sensitive millivoltmeter provided a rapid response. This arrangement was calibrated with a conventional potentiometer bridge in order to compensate for the current drawn by the millivoltmeter. With this arrangement it was possible to double approximately the absolute temperature of the gas in the settling chamber.

The essential results of these tests are summarized in Table B. It is interesting to note that, based upon pressure measurements, the measured Mach number was not significantly affected by these changes in density.

TABLE B

Throat width = 0.080"
Calculated Mach No. = 4.2

Initial Conditions			
Pressure mm of Hg	Temperature °K	Measured Mach No.	Calculated Stream Density g/cc
740	300	3.9	3.5×10^{-5}
300	300	3.7	1.7×10^{-5}
740	545	3.8	1.8×10^{-5}

At these reduced densities, the discharge was noticeably more diffuse, and appeared to occupy more of the tunnel cross section for the same current. However, the arc always clung to the dielectric boundaries and spread upstream and downstream to a much greater extent than at the higher densities. It still showed very little tendency to move into regions of higher velocity flow.

At the lower densities the arc column was not as bright, and apparently had a much lower current density. It was possible to use a stronger magnetic field and there was less tendency to localize near small imperfections in the walls. The voltage drop across the arc was also lower. Thus, the energy input per unit-volume was considerably less than at higher densities. This was desirable, since it tended to produce a less abrupt change in the stream properties and thereby reduced turbulence effects and the tendency toward flow-choking. Just as at higher densities, the arc became unstable as the current was increased beyond a certain value. The arc column also had the same slantwise orientation; however, this was less noticeable since the arc extended farther along the length of the tunnel.

Nitrogen Afterglow Considerations

An important factor to be considered when operating an arc in low density air or nitrogen is the formation of excited or ionized molecules that persist for long intervals of time.

At a fairly high pressure (a substantial part of an atmosphere), the percentage of ionized and excited atoms, for a given gas, is a function of temperature and pressure only, as given by Saha's equation. There is no significant persistance of ionized or excited states after the temperature has decreased, while at lower densities a discharge in nitrogen results in energy absorption in various metastable states. These excited molecules can persist for objectionably long intervals before the energy appears as thermal energy, or is radiated as afterglow.

Appendix II is a copy of a letter from Dr. W. B. Kunkel of the University of California which gives some idea of the complex situation encountered in connection with afterglow effects. Dr. Kunkel has studied activated low pressure gas streams as a means of "flow visualization" at very low densities.

In the air heating tests made on this project there was a pronounced increase in the amount of afterglow which could be noticed at the lower densities. Under some conditions a trail of reddish-brown afterglow could be seen blowing out downstream from the discharge. The ease with which it could be observed even though next to a highly luminous plasma was a good indication of its strong intensity. On one occasion, the laboratory was darkened and the interior of the vacuum tank was observed through the plate glass window which covered one end of it. With the discharge running, a jet of greenish-brown afterglow could be seen entering the tank and diffusing throughout the interior.

The effects of an activated gas in a wind tunnel situation have yet to be evaluated. Experiments by Rayleigh and others have shown that the energy which an excited gas can deliver to a metal surface may be as high as 22 calories per gram of the gas. (5)(6) It is not known how serious this delayed heating may be or how long it will persist in the airstream.

Experiments to Control Orientation of Arc

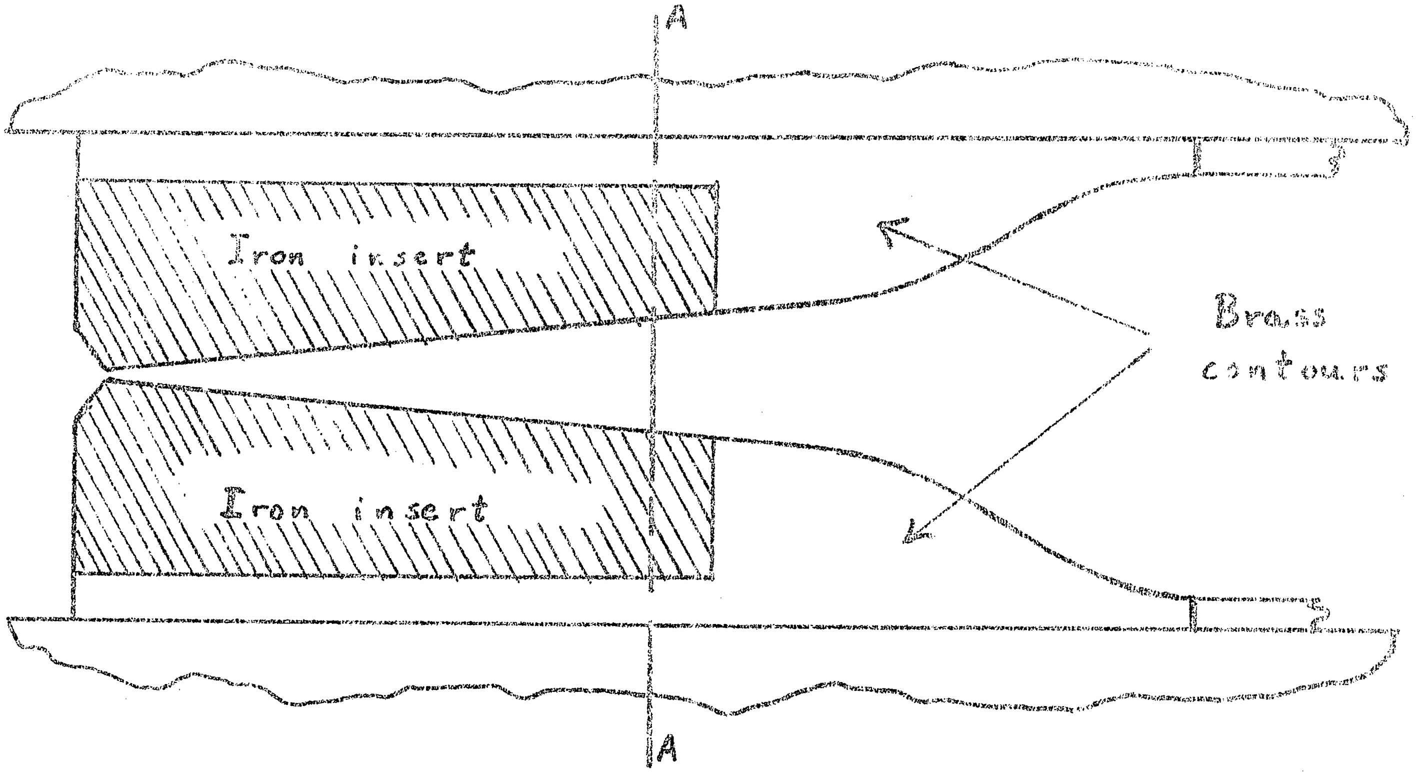
Different techniques were employed to improve the stability and to correct the skewed orientation of the d-c arc in the contour electrode tunnel. From visual observations, the discharge appeared to cross the tunnel at an angle of 20° to 70°, and the problem of establishing the correct orientation at first seemed to be one of controlling the locations of the cathode and anode ends of the arc column. The best way to accomplish this was by proper manipulation of the magnetic forces on the arc, although dielectric barriers and other devices were also used.

In a number of experiments the magnetic field was made more than twice as strong on the cathode side of the tunnel. Even with this increased magnetic force on the cathode end of the arc, there was virtually no change in the slantwise position of the discharge.

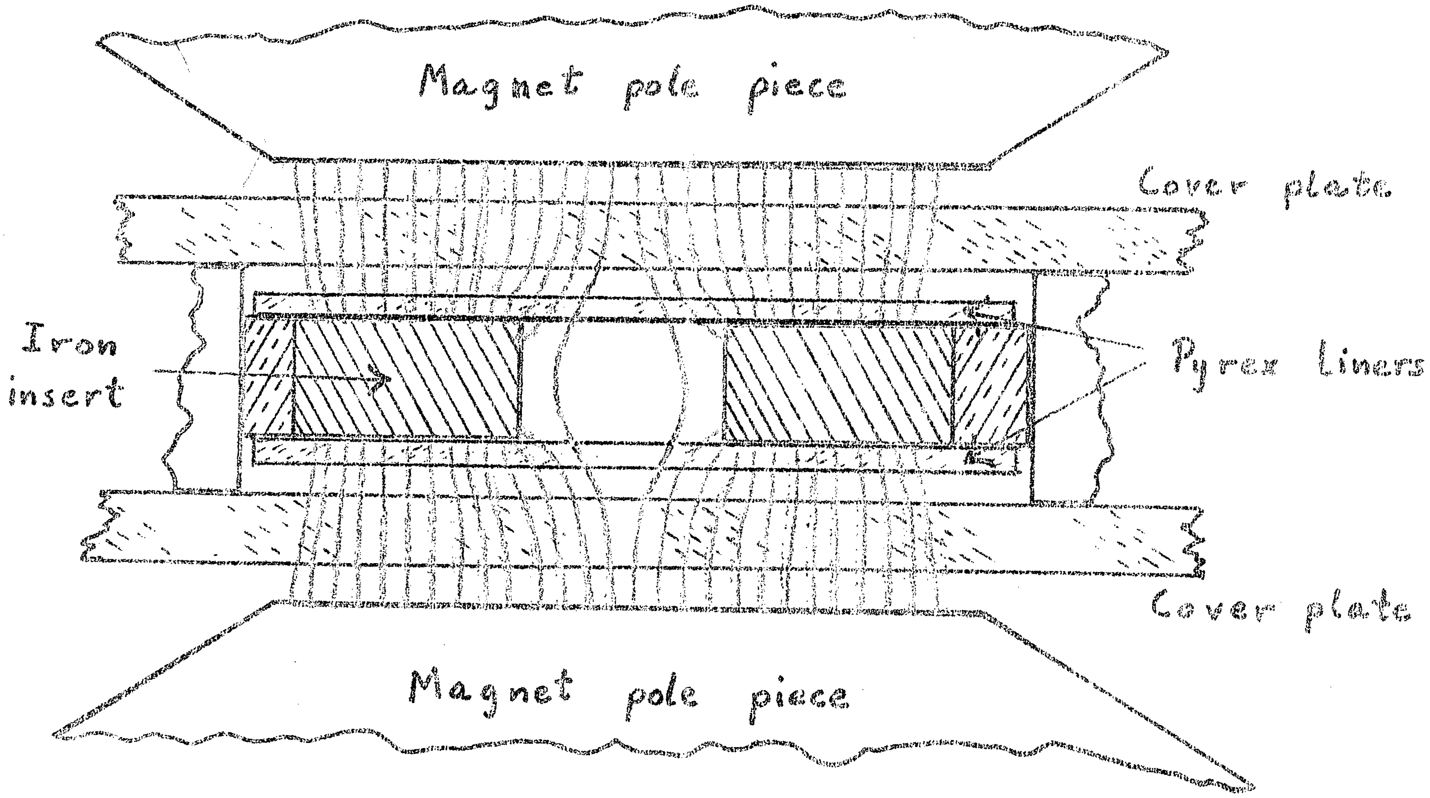
In other experiments, the magnetic field adjacent to the anode surface was decreased by means of an iron insert, fitted into the electrode as can be seen in the lower contour in Fig. 3. The iron had the effect of by-passing magnetic flux which otherwise would be present near the anode surface. Although the iron produced only a moderate improvement in the skewed orientation of the arc, it was quite effective in preventing the discharge from running too far upstream. Thus, it was possible to use a stronger magnetic field and higher currents, and to fill a larger cross section of the tunnel without having the discharge move up into the throat. Larger inserts than shown in Fig. 3 were also used, but there was no noticeable difference between the various sizes.

In general, a stronger magnetic field tends to increase the diffusivity of the arc, and also helps to straighten out the angle at which the arc crosses the tunnel. Since the reduction in magnetic field due to the iron inserts tended to limit the arc from running too far upstream, it appeared that a properly tapered magnetic field would stabilize the arc in the nozzle exit.

This approach was tested with the arrangement illustrated in Fig. 5. Large iron inserts were placed in the brass contour blocks so that forward of a point about 1 1/2 inches from the nozzle exit the contours were essentially all iron. This iron short-circuited the magnetic field around the tunnel opening and thus effectively removed the magnetic force from the arc column when it moved upstream into the region of the iron contours. Fig. 5 (b) is a sketch of the



(a) Top View

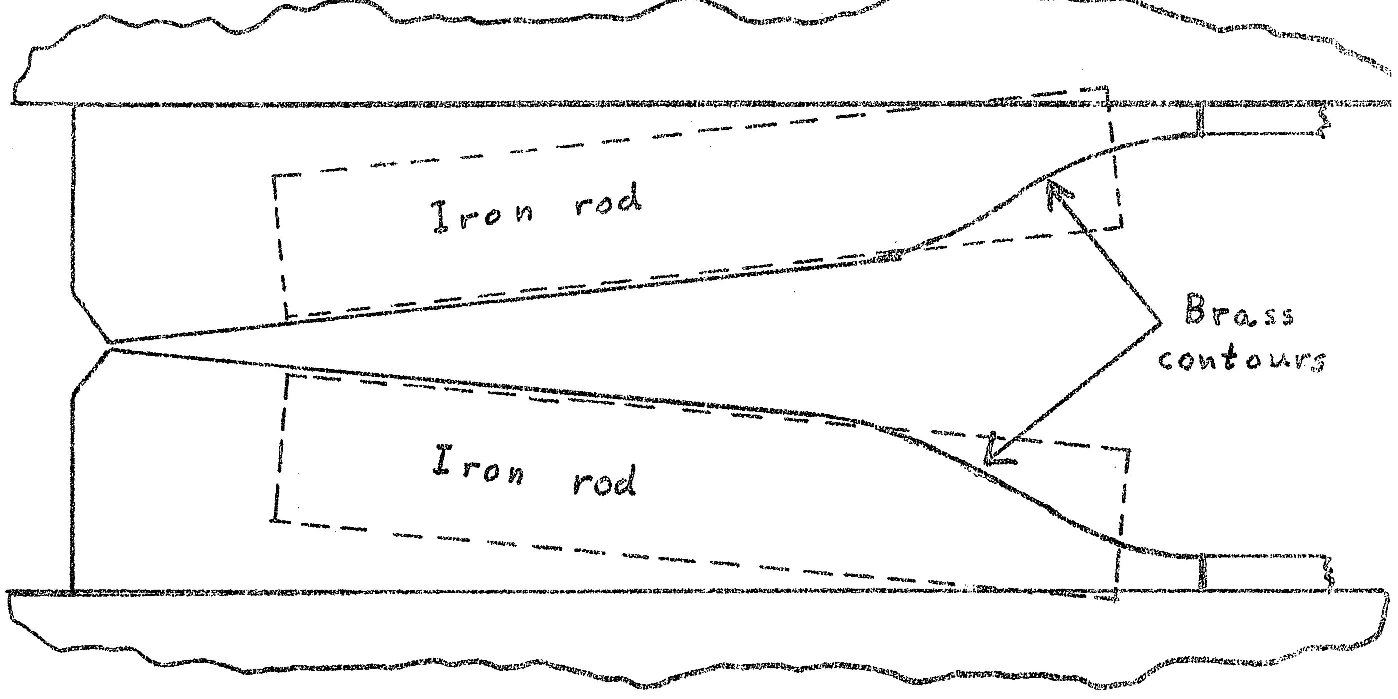


(b) Section Through A-A

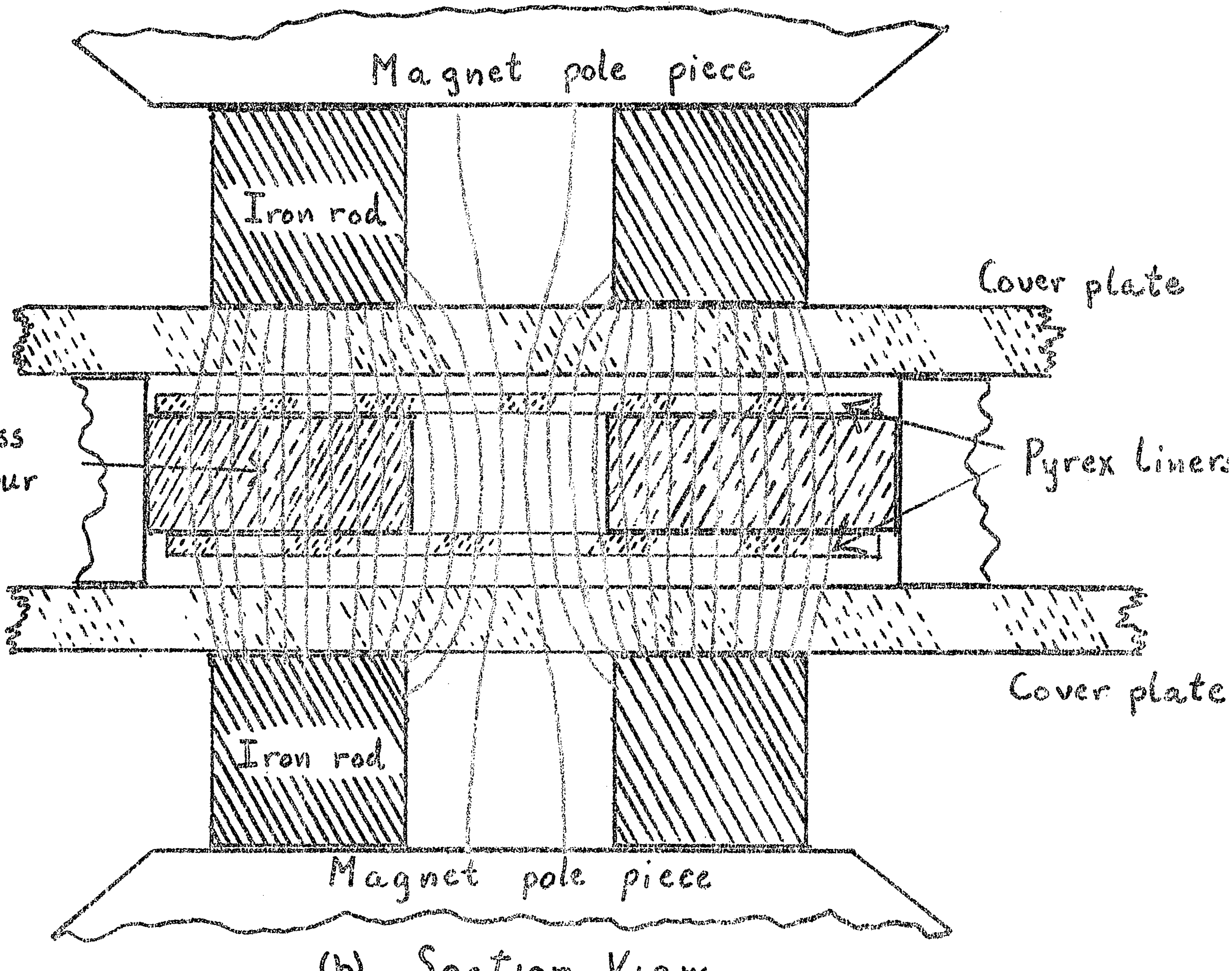
Fig 5 - Reduction of Magnetic Field in Contour Electrode Tunnel section through the tunnel at A-A and shows the relation of the iron inserts to the tunnel opening and magnet pole pieces. The approximate configuration of the magnetic flux lines is also shown in red. For these tests the separation between the parallel glass tunnel walls was 1/2 inch.

Electrical tests with the tunnel shown in Fig. 5 were very unsatisfactory. The discharge pressed very hard against the dielectric walls of the tunnel and formed an exceedingly intense hot channel. For the same power input it tended to burn the Pyrex glass much more quickly, and as the current increased, it showed no tendency to extend into the flow. Even at lower gas densities the discharge was very bright and hugged the walls. At no time did it occupy more than about 1/4 to 1/3 of the tunnel cross section, even with currents up to 15 amperes. Any effectiveness of the magnetic barrier was lost in this strong tendency to cling to the sides of the tunnel.

A probable explanation of this behavior can be described most easily by comparing it to the situation sketched in Fig. 6. In this case, the contour electrodes were made entirely from brass, and iron rods 1" x 1" x 4" were placed above and below the tunnel as shown. The approximate shape of flux lines is sketched in red in Fig. 6 (b). A comparison of Fig. 5 (b) and Fig. 6 (b) shows that the fringing of the magnetic field <u>inside of the tunnel</u> is essentially opposite for these two cases.



(a) Top View



(b) Section View

Fig.6 — Fringing Magnetic Field in Contour Electrode Tunnel

The behavior of the discharge in the tunnel sketched in Fig. 6 was moderately good. Most important, it did not press against the glass walls and in some instances it even appeared to be a short distance out into the tunnel. With 5 amperes the arc column appeared to be about 1/4 inch in diameter and had a smoothy cylindrical appearance. It was not excessively bright and appeared very steady and uniform. Although it was always near the top or bottom, it appeared to be pushing out away from the boundary layer and into the center of the flow. The position of the arc column along the length of the tunnel, however, was quite sensitive to small changes in the magnetic field. This situation made it impossible to increase the current beyond the 10 ampere level and consequently the tunnel was never more than 2/3 filled.

The difference in the behavior of these two arrangements is a consequence of the shape of the magnetic fields. For the tunnel sketched in Fig. 5, the field is generally weak, but has its greatest value next to the two glass walls because of the fringing effects at the edges of the iron inserts. For the tunnel in Fig. 6, however, the field is slightly stronger at the center than at the top or bottom of the tunnel since the field is fringing in the opposite direction.

In Fig. 5, the magnetic force on the discharge is strongest next to the walls. If the column moves toward the center of the tunnel, the magnetic force becomes less and the ability to counteract the wind decreases. The most stable position in Fig. 5 is, therefore, immediately adjacent to the dielectric walls. In Fig. 6, on the other hand, the magnetic force on the plasma is slightly stronger in the center of the tunnel, so that the wind forces can be counteracted more effectively in this region than near the top or bottom.

This simple explanation does not account for the variation of stream velocity and gas density through the boundary layer. If these factors are taken into consideration, the situation in Fig. 5 is made even worse, while in Fig. 6 the stronger magnetic force at the center of the tunnel is offset by both the higher stream velocity and increased gas density. Thus, for the situation in Fig. 6, the discharge probably initiates in the boundary layer and grows out toward the center of the stream, but is only able to push out a short distance before the factors af increased density and wind dominate over the slight increase of magnetic field strength. This explanation is only approximate, but appears to provide at least a qualitative interpretation of the observed behavior.

Another method which was used for correcting the orientation of the discharge was to place a dielectric section in the electrode. An insert of silicon carbide was placed in the anode contour in the same position as the iron insert shown in Fig. 3. It prevented the anode end of the arc from moving upstream and when combined with a strong magnetic field was moderately effective in straightening out the orientation of the arc. The difficulty with any such dielectric barrier is that the arc presses very hard against the junction between the metal and dielectric, and forms a very hot concentrated spot which will quickly erode even the most refractory materials. This hot spot also forms a highly concentrated region in the discharge which detracts from the uniformity of the heating.

A third device which was used in an attempt to correct the skewed position of the arc was to place either slots or fins in the cathode contour. From early observation, it appeared that one of the reasons for the slantwise orientation was that the processes at the cathode were more sensitive to the wind than those at the anode. It was reasoned that a suitably placed slot on the cathode contour would provide a sheltered place in which the cathode spot could locate. A variety of both slots and fins was used without any apparent success. In most cases no conclusions could be drawn since the slot or fin was always placed midway between the two parallel glass walls, while the discharge was always adjacent to one or the other of the glass walls.

VII - HIGH SPEED MOTION PICTURES

High speed motion pictures were taken of the discharge in the contour electrode tunnel, using an eight millimeter Fastax camera which had a maximum speed of about 8,000 frames per second. Fig. 8 is an enlargement made from a selected section of these films. This figure is a negative print; therefore, the arc appears black against a white background. Four consecutive frames are shown. This enlargement was printed so as to bring out the details in the arc and thus is considerably underexposed, and consequently, the outline of the tunnel cannot be seen in this print. Fig. 7 is a diagrammatic sketch of the tunnel as viewed from the same position as the Fastax camera and should help to orient the reader as to what is portrayed. All that is visible in the enlargement in Fig. 8 is the arc and part of the reflection in the brass cathode contour.

These high speed pictures brought out several aspects of the discharge which could not be observed otherwise. The general shape and appearance of the arc and the formation of a pronounced cathode spot can clearly be seen. Although it is not evident in the four frames shown in the enlargement in Fig. 8, the arc spot was dancing rapidly over the cathode surface. Under some conditions it see-sawed back and forth in a periodic fashion, gradually working downstream and then jumping upstream abruptly before working back again. From the previous visual observations, this

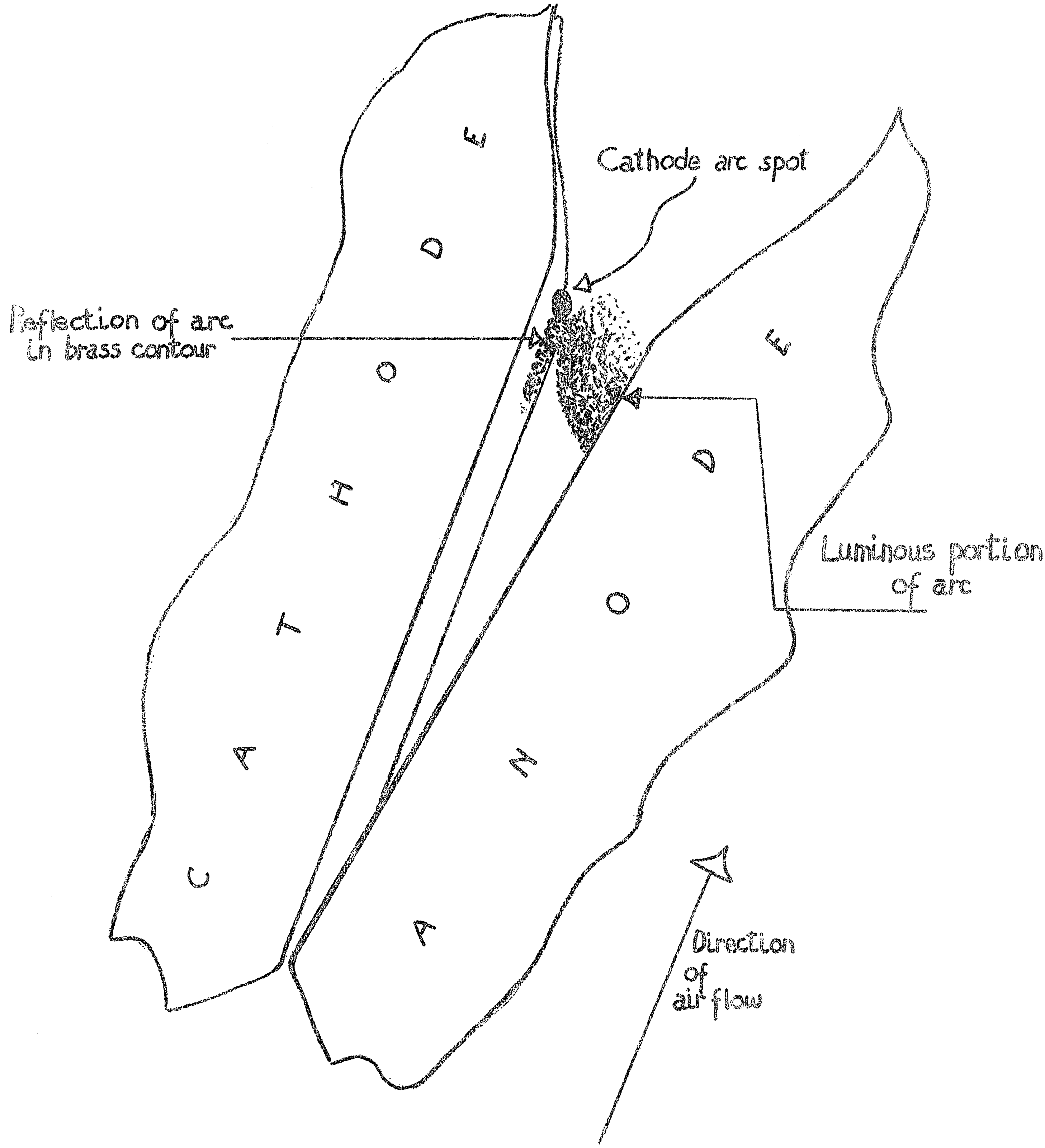


Fig. 7 Perspective Sketch of Fig. 8

Fig. 8

rapid motion of the cathode spot had given the impression of a sheet of uniform width extending straight across the tunnel in a slantwise direction. In these pictures the leading edge of the arc column has a distinct curvature and is somewhat brighter than the trailing portions. Under some conditions this curvature became so great that a new cathode spot would form upstream and the arc would progress stepwise up the tunnel. All of these observations of the high speed motion pictures only served to bring out the non-uniform nature of the discharge under the present experimental conditions.

VIII - "ROD ELECTRODE" TUNNEL

Description

All of the experiments in the contour electrode tunnel strongly indicated that some form of restricted electrode was necessary in order to anchor the arc in the nozzle exit. In order to accomplish this, a new tunnel was constructed in which two copper posts served as the electrodes. The nozzle in this tunnel discharged directly into a large chamber forming an open jet. The electrode posts which were isolated electrically from the rest of the tunnel were located immediately downstream from the nozzle exit, just at the edge of the supersonic jet from the nozzle.

Fig. 9 is a sketch which illustrates the essential features of this design and Fig. 10 is a photograph of this tunnel with the top cover removed. The settling chamber and forward portion of the nozzle are hidden under a lamacoid slab in these figures. (Lamacoid is a phenolic laminate which was used for the structural members.) Thin Teflon gaskets were used between the lamacoid covers and the brass nozzle blocks. The whole arrangement was clamped together very tightly by several screws (hidden under the black wax in the photograph). This arrangement provided an excellent seal around the throat of the tunnel and eliminated the leak problems which had been encountered in the contour electrode tunnel design. An 11° wedge nozzle was again used, and with a 0.065 inch throat, a Mach 4

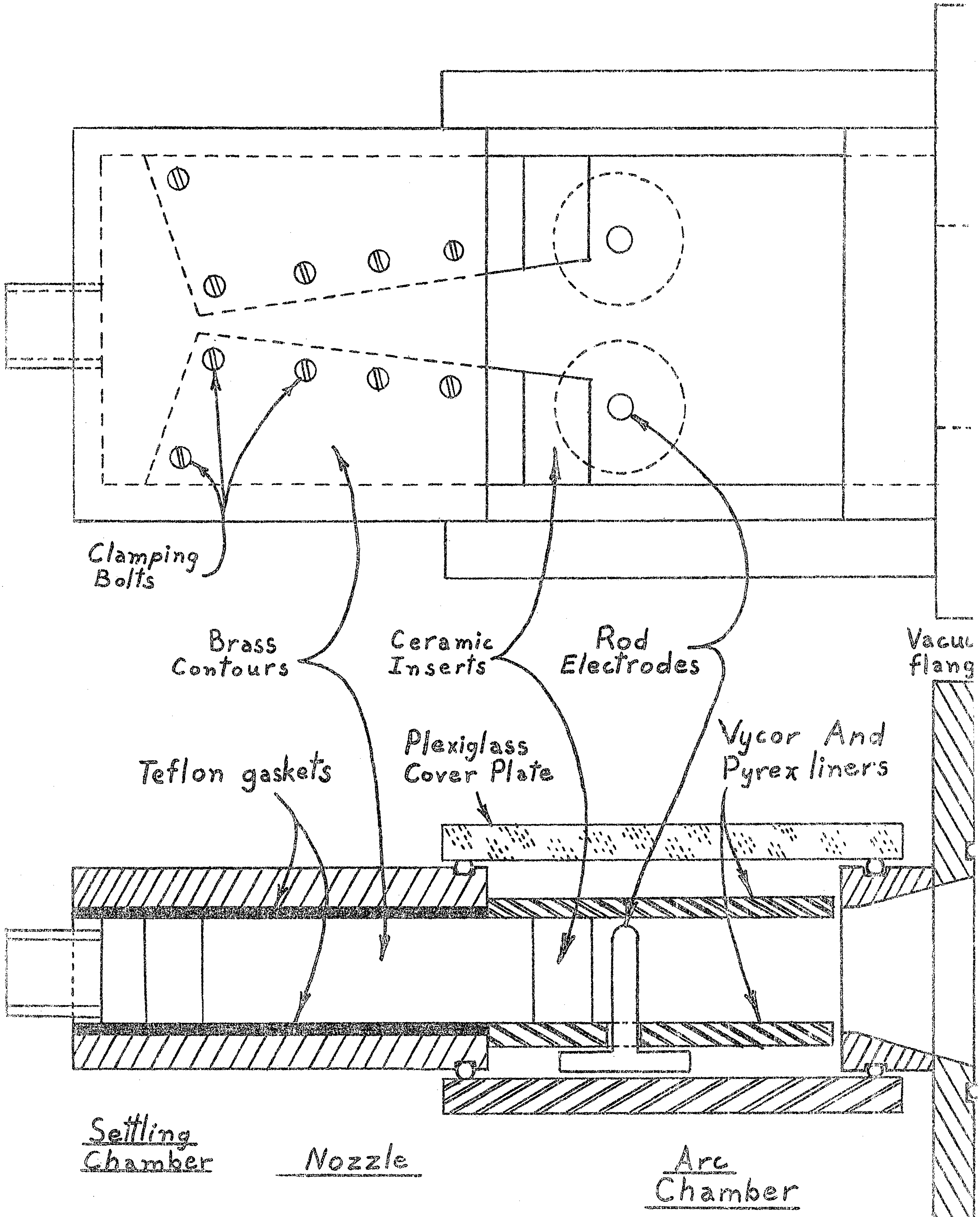
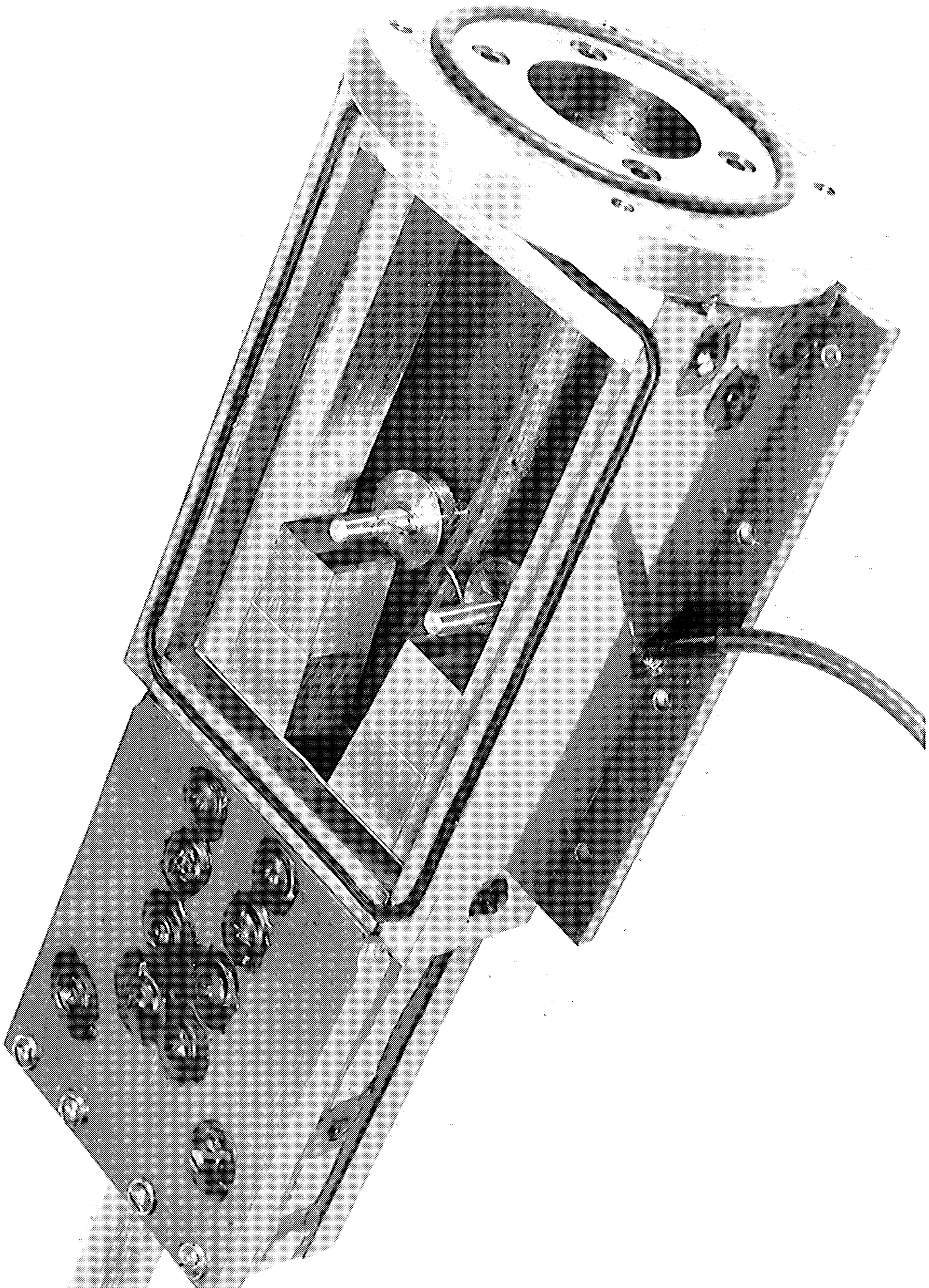


Fig. 9. "Rod Electrode" Tunnel



flow with a 1" x 1" cross section was obtained in the region of the electrodes.

Vycor or Pyrex glass liners were used as the parallel walls of the tunnel over the last two inches of the nozzle and for the chamber containint the discharge electrodes. These butted against the Teflon gaskets and formed a smooth continuation of the tunnel wall which could withstand the heat of the discharge and provide visual observation of the arc. In order to obtain a vacuum-tight structure, Plexiglass and Mycalex cover plates were fitted over the chamber containing the glass liners. These were clamped together outside of the tunnel in much the same manner as in Fig. 2. "O" ring stock was embedded in the lamacoid members as shown in Figs. 9 and 10 to provide a good seal with the covers. This arrangement made it very easy to open the tunnel for modifications and yet insured a vacuum-tight structure at all times.

For the photograph in Fig. 10, the top cover plate and glass liner were removed to show the interior of the tunnel more clearly. The copper rod electrodes projected through holes drilled in the bottom glass liner and were located about 1/4 inch downstream from the end of the nozzle blocks. In Fig. 10 the large circular bases of the electrodes are easily visible but were located below the bottom glass liner. Also visible, through the glass, are short pieces of rubber tubing which provided electrical insulation between the bases of the electrodes.

Behavior of a d-c Arc in the "Rod Electrode" Tunnel

A d-c arc was maintained between the rod electrodes by the action of a magnetic field in the same manner as in the contour electrode tunnel. The arc remained in the boundary layer region and clung very close to the glass liners just as in the contour electrode tunnel. There appeared to be even less tendency to spread out into the main flow; however, this may have been due to a thicker boundary layer.

Most interesting of all, the arc column had the same slantwise orientation across the airstream, even though this required a considerably longer discharge path. The extent to which the arc went upstream depended upon the magnetic field, but the anode side was always farther upstream than the cathode side even though the two electrodes were directly across from each other. In preliminary tests the contours were made entirely from brass. If the magnetic field or current were made too strong, the discharge would go from one electrode to the bottom of the brass contour just upstream from it, then it would cross the tunnel to the other contour upstream under the lamacoid cover plate, and finally go to the other electrode, making three separate arcs in all. Ceramic inserts were later placed in the downstream portions of the contours as seen in Fig. 10 in order to eliminate this behavior.

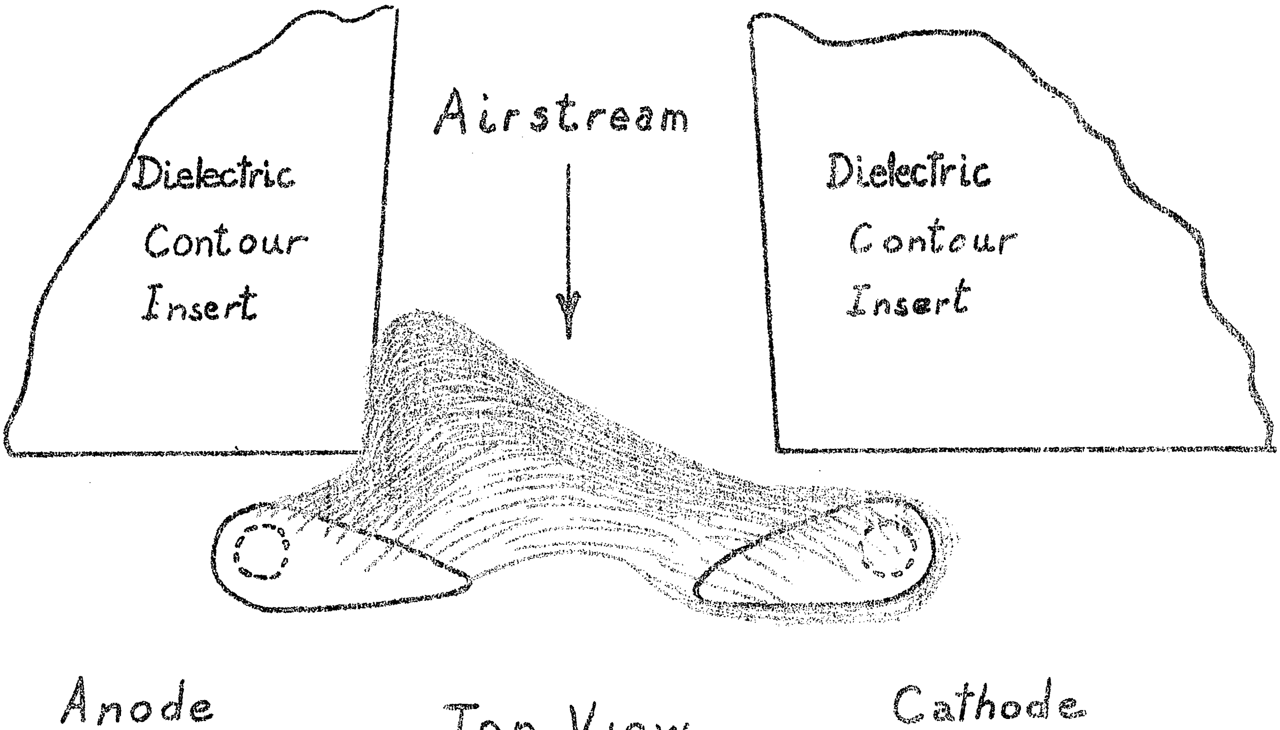
Even with the ceramic inserts, the arc went from the cathode post slantwise across the tunnel to a point on the anode contour which was upstream from the anode post, and then it passed along the surface of the contour to the anode post. With this particular configuration the magnetic force drove the arc very tightly against the surface of the anode contour; therefore, the insert had to be made of a highly refractory material in order to withstand this intense heating. Zirconium bonded silicon carbide was used, but even this showed some erosion after several seconds total running time. The insert on the cathode side, on the other hand, could be made of almost any convenient dielectric since it was not subjected to direct contact with the arc.

The rod electrodes appeared to be very desirable in one respect, however. Under some conditions a luminous cyclindrical sheath surrounded the cathode post. This is characteristic of a low density glow-type discharge in a strong magnetic field. "Magnetic trapping" of electrons in a cylindrical cathode sheath tends to replace the concentrated cathode spot at low enough densities. Further, when the discharge was observed to go to the brass contours, clearly visible arc tracks were formed on the flat ends of the contours, but no tracks could be noticed on the

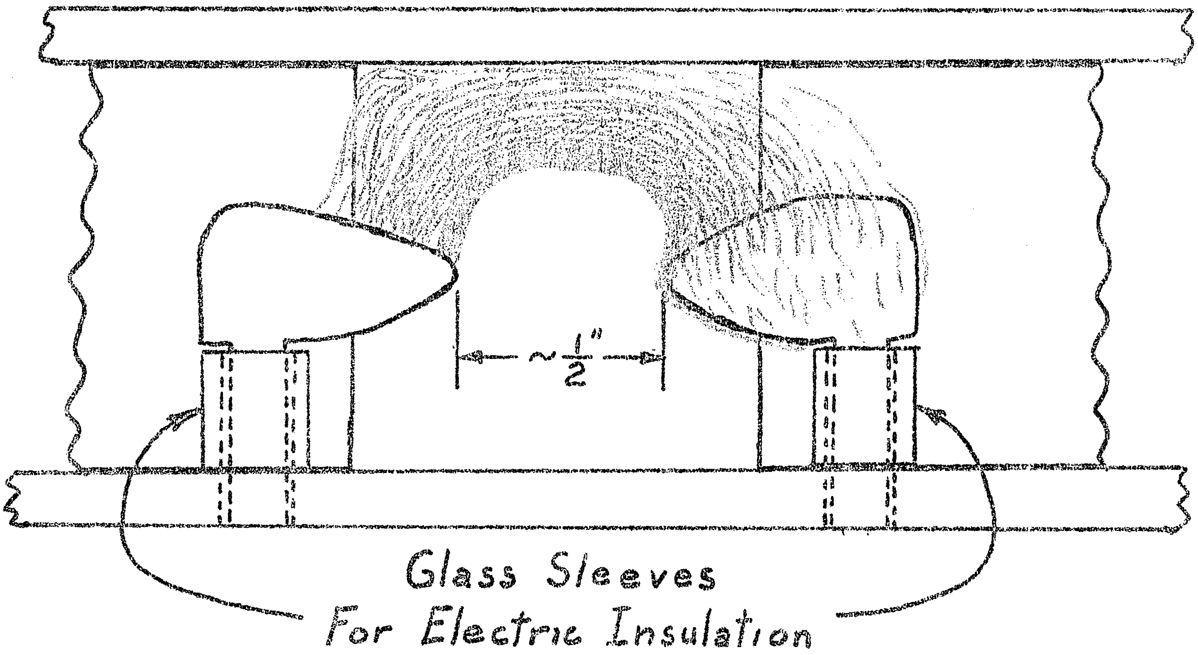
Several experiments were made in an effort to force the arc out of the boundary layer and into the center of the flow. The most successful approach was to use short "horn electrodes" which projected into the stream as shown in Fig. 11. In this arrangement the active portion of the electrode was restricted to the central one-third of the tunnel midway between the top and bottom. Thus, the discharge path through the boundary layer was about three times longer than the direct path across the tunnel between the horn tips.

With the horn electrodes in Fig. 11 the discharge tended to fill much more of the tunnel than when the post electrodes of Figs. 9 and 10 were used. With a power input of about two kilowatts the discharge appeared roughly as shown in Fig. 11. In some cases it was on the bottom of the tunnel instead of on the top, but it always avoided the center and always skewed upstream on the anode side. It was interesting to note that when the flow went subsonic, the arc immediately localized on the tips of the horns and went straight across the center of the tunnel. Further, in the subsonic situation, the arc as viewed from the top had an "S" shape with the anode end again upstream.

The strong tendency for the arc to assume a slantwise orientation across the tunnel is an inherent characteristic of this type of discharge. These experiments indicated quite conclusively that this behavior did not necessarily depend upon the processes at the anode or cathode, but was a consequence of the



Top View



End View

Fig. 11 "Horn Electrodes"

momentum transfer mechanism in the arc column itself. A very satisfactory explanation of the skewing tendency can be postulated, based upon the complex mobilities of ions and electrons in a magnetic field. However, a worthwhile method for correcting this condition has not yet been worked out.

IX - PULSED DISCHARGES

An entirely different approach was tried for obtaining an electrical discharge which would completely fill the tunnel cross section. It appeared reasonable that if a pulse of sufficiently high current were passed through the discharge it would at some point fill the whole flow. If this method were to produce approximately uniform heating, the repetition rate of the pulses would have to be high enough so that each volume element of the stream would be exposed to several pulses. The duration of each pulse would be very short in order to maintain a reasonable value of average power and still provide peak currents of a very high level.

Most types of electrical discharges have a tendency to produce relaxation oscillations when a capacitor is placed across the electrodes. When relaxations occur, the arc current flows in very short pulses, and in between these the arc extinguishes until the voltage across the capacitor becomes high enough to break down the gap.

Oscillograms were made of the voltage across the contour electrode tunnel to investigate relaxation effects. With no capacitor, and using the series resistance and inductance in the power supply, employed with most of the tests, the voltage was reasonably steady at a value between 350 and 500 volts, depending upon experimental conditions. "Noise" fluctuations of about 50 to 100 volts were superimposed upon this d-c value. As the amount of capacitance across the tunnel was increased, the amplitude of these fluctuations became greater until with 0.05 μfd of capacitance definite relaxations were present.

When relaxations occurred in the contour electrode tunnel, the arc was much brighter and hotter and had a stronger tendency to erode the glass walls. As the value of capacitance was increased, the arc moved upstream where it constricted into an intense, fine channel. Because of this behavior it was impossible to use a capacitor greater than 0.1 μfds. The peak current under these conditions was about 100 amperes.

The pulsed discharge technique was used more successfully in the rod electrode tunnel, shown in Figs. 9 and 10. With the discharge column anchored at the nozzle exit, much higher pulse currents could be used. In order to take full advantage of this characteristic, an additional modification was introduced into the circuit. An auxiliary air-blown spark gap was placed in series with the capacitor and the tunnel electrodes. This auxiliary gap could be adjusted to break down at any desired voltage so that for a given value of capacitance the maximum voltage and thus the peak currents could be greatly increased. The gap between the tunnel electrodes broke down at about 1,000 volts; however, with the external gap it was possible to charge the capacitor to as high as 10 kv before discharging it across the airstream.

In all instances, the pulsed discharge was a very bright hot spark with an apparent diameter of between 1/16 and 1/4 inch. Various values of capacitance and voltage were used and the stored energy was raised as high as 15 watt-seconds per pulse. In one case a 0.04 μfd capacitor was charge to 10 kv. The peak current was calculated from oscillograms of the voltage waveforms to be 1,500 amperes. Even with this extremely large value of current, the discharge appeared a s an intensely bright channel about 1/4 inch in diameter.

With the auxiliary spark gap the discharges were oscillatory. (The stray lead inductance in the discharge circuit was about 0.7 μh.) Thus, the magnetic field made the spark column move upstream on the first half cycle and downstream the next half cycle. With a large value of capacitance, the "ringing frequency" was low, and the discharge appeared as a thin sheet extending an inch of so both upstream and downstream. With a smaller capacitor, the ringing frequency was higher and the column did not move as far during each half cycle, and the discharge went straight across the tunnel.

Just as with the magnetically stabilized d-c arc, the pulsed discharge occurred in the boundary layer next to the glass liners. A series of experiments was, therefore, conducted in which a pulsed discharge was initiated directly across the middle of the flow. This was accomplished with small wire tips or horns. Two of these tips can be seen in Fig. 10, projecting out into the tunnel from the middle of the electrode posts. Another initiation arrangement consisted of a glass thread coated with Aquadag and stretched across the middle of the tunnel between the two electrodes.

The same pulsing techniques were used with these "initiation" devices, and the same general behavior was observed. However, the discharge spread across the stream to a slightly greater extent than when it took place in the boundary layer. The spark through the center of the tunnel also was less oscillatory, indicating that there was greater damping here probably as the result of greater heat loss.

When the spacing between the wire tips shown in Fig. 10 was more than 5/8 inch, the discharge took place through the boundary layer rather than across the supersonic flow between the tips. The spacing between the rod electrodes was 1 1/4 inches. Based upon spark breakdown considerations, this evidence indicated that the gas density in the stream was about twice the mean boundary layer density.

In all of these experiments, the pulse repetition rate was so low that each discharge occurred as an isolated pulse. That is, there was more than sufficient time between sparks for the residual ionization to be blown downstream before the succeeding spark was initiated. The calculated stream velocity was 2100 ft/sec. Thus, a minimum repetition rate of one every 10 to 20 μ sec. would be required even to approximate uniform heating. The maximum repetition rate which could be obtained with an air-blown spark gap required at least 100 to 200 μ sec. between pulses in order for the gap to deionize sufficiently for consistent firing.

If the repetition rate were made sufficiently high some residual ionization would remain in the flow from the previous breakdown and this would tend to increase the diffusivity of the succeeding pulse. The repetition rate limitation of the air-blown spark gap was not fully appreciated when these experiments were undertaken. In order to obtain the desired pulse rate, an elaborate set-up involving several hydrogen thyratrons and switching circuits would have been necessary, and this appeared to be too extensive a program to undertake on the present contract.

X - ALTERNATIVE AIR HEATING METHODS

The experiments described in this report were limited to a specific type of electrical discharge and to a relatively small range of experimental conditions. This method of air heating was particularly attractive because of its simplicity. Based upon the results of this investigation, it does not appear likely that a simple system can be devised which could readily be incorporated into an existing wind tunnel. It is probably more realistic to think of designing a tunnel which would be compatible with the requirements of the heating system.

Several alternative schemes are outlined below which are somewhat more complicated than the magnetically stabilized arc, but they offer the promise of overcoming some of the difficulties which have been encountered, and indicate a variety of possible approaches.

High Frequency Corona

A corona discharge from small wires or points is much more diffuse than an arc column at the same pressure. The formation of space charge in a corona streamer tends to prevent it from growing too large. New streamers continually form giving rise to a region which is more or less uniformly filled with a myriad of tiny discharge paths.

The rate of power dissipation (and heat generation) of a d-c corona is very low and is limited by the sparking voltage between the electrodes. For d-c or 60 cycle power and a small wire in air, the maximum corona current amounts to a fraction of a milliampere per inch of wire and the power dissipated is of the order of a few watts per cubic inch. However, when a high-frequency voltage is used, the situation is theoretically much more favorable. It has been reported that up to a frequency of 100 kc, the corona power is proportional to (f + 25), where f is the frequency of the applied field. (11) This relation may laso hold at higher frequencies and the corona power could become quite large under the proper conditions.

In the presence of a supersonic airstream, the properties of a corona discharge would be modified considerably. If r-f power were used, the streamers which form during each half cycle would tend to be broken up by the airstream before the next half cycle, and thus they would never grow to an appreciable size. Even if some streamers did bridge the gap between the electrodes, the current probably would not grow to a significant value during one half cycle because of the high circuit reactance and the high initial resistance of the breakdown streamer.

In order to heat the whole tunnel cross section uniformly it probably would be necessary to use polyphase r-f power and a multiplicity of corona wires connected in such a manner that at any instant the discharge would tend to take place between wires on opposite sides of the flow. It may be necessary to use wires in the center of the airstream; however, there is a possibility that by properly phasing the r-f power, the use of many wires located along the tunnel walls and parallel to the flow might provide the required uniformity of heating.

Ionization by Electron Beam

There is considerable theoretical basis for predicting that the diffusivity of a discharge in an airstream could be greatly increased by means of an external source of ionizing radiation such as a high intensity beam of beta particles. If the airstream is uniformly ionized by such a means, it should be possible to pass an r-f current through the gas to generate heat. With an external source of ionization gaseous conduction could take place in relatively cool gas. There would be no need for the high gas temperature required to produce thermal ionization. The usual type of high temperature arc column would not be present provided the electron temperature were kept low enough so that essentially all of the ionization was produced by the beta beam. Under such conditions, the distribution of r-f current density and heating would be determined by the distribution of the ionizing radiation.

Rough calculations as to the order of magnitude of the quantities involved indicate that such a process looks quite feasible. An assumed ion density of 10^{12} per cm^3 would provide enough electrical conductivity to assure an effective rate of heat generation. For conditions comparable to those in the present experimental work, the volume recombination rate is slow enough so that 90 microseconds are required for the ion density to drop from 10^{12} to 10^{11} ions per cm^3. This corresponds to about two to three inches of stream motion. A high intensity electron beam could be produced by an "open window" type of electron gun such as that used by Karlovitz at Westinghouse. It would be desirable to use a magnetic field to curl up the beta beam into a spiral inside the wind tunnel in order to increase its ionizing effectiveness.

A thorough evaluation of this scheme would involve a fairly elaborate research program. However, if the principles are sound, it probably has greater potentialities than the other methods discussed in this section.

"Scanning" with an Ultra-fast Moving Arc Column

By the action of a magnetic field, a d-c arc column can be driven at very high speeds through essentially cold air. If one or more such arcs were made to traverse continuously a section of a wind tunnel at sufficiently rapid rates, it might be possible to approximate uniform heating, provided each volume element of the flow were "scanned" many times. As mentioned in Section II of this report, the gas is heated only a relatively small amount on each pass under these conditions. Radical changes, therefore, are not produced in the flow by a rapidly moving arc. The diffusivity of the discharge column would not be an important factor, and thus this method could be used at almost any desired gas density.

Experiments at atmospheric pressure have shown that a pulsed arc running along two parallel rod electrodes under the action of a magnetic field can be made to travel at 2000 feet per second. At lower pressures this speed could be increased considerably. High speed motion pictures have also been made of an arc at atmospheric pressure, revolving in the annular space between a central post and an outer ring electrode. The arc appeared as a spiral "spoke" and rotated at speeds up to 8000 rps. At lower pressures and higher currents, the velocity of this spoke would also be increased by a considerable amount. (2)

There are many possible ways to make an arc scan an airstream. For instance, if a central electrode could be tolerated in the flow, a radial discharge could be used in a circularly symmetrical tunnel. With an axial magnetic field, the arc column would spiral out from the central electrode to the walls of the tunnel, and revolve at very high speeds. Other possible arrangements might use a transverse arc column scanning back and forth across the flow, or a longitudinal arc which would move through the flow in a lateral fashion. This type of scanning might be best achieved with a d-c magnetic field and an r-f arc current.

The major problem encountered with scanning techniques is to obtain the desired uniformity of heating without creating excessive turbulence in the airstream. The amount of turbulence which would be generated by a scanning arc, and also the degree of turbulence which could be tolerated in a particular application would have to be determined. If these values were compatible, the scanning method of air heating would have many desirable features.

A High Frequency Electrodeless Discharge

Under the proper conditions, more diffuse heating could be obtained with a high frequency discharge than with a magnetically stabilized d-c arc. Previous experience of project personnel has shown that an electrodeless discharge at 500 mc and atmospheric pressure is not collimated, but tends to be ball-shaped.

If an electrodeless discharge were used, the walls of the tunnel would be made of a dielectric material, and the discharge current would flow through the dielectric as a capacitance or displacement current. If the capacitive reactance of this dielectric wall were sufficiently high, the arc could not concentrate at one spot (as it does on a metallic wall), but would spread out over all of the available area.

Further, the inductive reactance of a small concentrated arc column is much higher than for a column of larger cross section. At microwave frequencies, this results in a "skin effect" which causes the current to flow near the surface of the arc column and thereby tends to enlarge the diameter. Calculations show that this effect would be very significant at 1000 megacycles.

The use of a high frequency discharge appeared sufficiently promising to warrant further consideration, and a search was made of the literature on the subject. It can be shown that the conductivity of an ionized gas at high frequencies is complex (both real and imaginary components are present).(9) (10) Among other things it is proportional to $(\mu - j\omega)/(\mu^2 + \omega^2)$, where μ is the electron collision frequency, and ω is the frequency of the applied electric field. When the collision frequency is high (at high pressures) or for low frequency fields, $\mu > \omega$, and the conductivity is essentially the same as in the d-c case. On the other hand, for very low pressures or high frequency fields, $\mu < \omega$, and very little real power is transferred into the discharge.

In order to evaluate the r-f heating method, sample calculations were made based upon certain approximate assumptions. For conditions comparable with those existing in the tunnels described in this report, the collision frequency, μ, is of the order of 10^{11}. If frequencies of a reasonable value, from a practical standpoint, are considered, the electrons would experience a great many collisions during each half cycle and the mechanism for producing ionization would be essentially the same as in a d-c discharge. This implies that an objectionably high temperature arc column would be necessary to sustain the discharge. Based on this argument, very short wave-length microwave power would be required to obtain a situation appreciably different from the d-c case.

A Very Low Density Wind Tunnel

The evidence gained from the present investigation and from previous work at the University of Michigan indicates that at gas densities corresponding to a static pressure of 0.1 mm of Hg, a magnetically stabilized d-c arc would be sufficiently diffuse to provide uniform heating. In order to conduct tests at these low pressures, a fairly elaborate research program would be required. A very low density wind tunnel would have to be constructed, and a high speed vacuum system with enough capacity to provide continuous operating would be required since a "blow down" type of tunnel would not be feasible at these low densities. There would also be a variety of problems associated with the operation and instrumentation of a wind tunnel in the slip-flow region. (A suitable tunnel would be comparable to Tunnel #2 at the University of California at Berkeley.)

The problem of air afterglows would become much more severe at low densities. For certain applications the presence of these excited molecules might not be objectionable. However, their effect upon a supersonic flow would have to be evaluated before the usefulness of this method could be determined.

Longitudinal Arc in Throat

An arc column can be maintained in a stable fashion in an axial air flow. For certain processes in chemical engineering, a longitudinal arc is used in a gas stream to supply large amounts of energy for endothermic reactions. Also, certain types of European compressed air circuit breakers use air at sonic velocity passing through a nozzle surrounding the arc column. In these applications, the arc centers itself with respect to the air flow and constricts into a small diameter with a very high current density. (1)

In a similar manner a longitudinal arc might be used in the throat of a wind tunnel to heat the air passing through. The discharg e would center itself in the flow in a stable fashion. It would undoubtedly be very intense right in the throat, but as the flow expanded downstream, the gas density would become considerably reduced, due partly to the higher temperature, and the arc diameter would increase considerably. One of the limitations of this method would be the necessity of having an electrode in the center of the airstream.

Pre-Throat Heating

An electrical discharge could be used to heat the air entering the throat of a conventional wind tunnel. At the present time such a system does not offer any advantage over existing methods. If the severe problems of heat transfer in the throat can be solved and if very high temperatures are desired, an electrical method might ultimately be superior to present techniques.

APPENDIX I

THEROETICAL WIND TUNNEL POWER REQUIREMENTS WITH SUPERSONIC HEATING

1. A preliminary analysis has been made of the effect of heat addition at supersonic speeds on the power requiremens of a hypersonic wind tunnel. The analysis utilizes the one-dimenstional flow equations and numerical tables of Reference 7. In addition to the assumption of one-dimensional flow, it is assumed that the flow is inviscid, with isentropic expansion between reservoir and test section except in the region of heat addition. A schematic diagram of a hypersonic wind tunnel with supersonic heating is shown in Figure 12, on which also is illustrated the system of subscripts used.

2. The work done by an ideal compressor in compressing isentropically a volume of gas V at the final diffuser exit pressure p_f up to the initial upstream stagnation pressure p_o, is

$$W = V p_f \frac{\gamma}{\gamma-1}\left[\left(\frac{p_{o_1}}{p_f}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

This ideal compression process will be used as a standard for comparing the tunnel power requirements for various programs of heat addition. The power for continuous operation of the wind tunnel with supersonic heating (exclusive of the electrical power used in actual heating of the air by the electric discharge, and the power used to maintain any

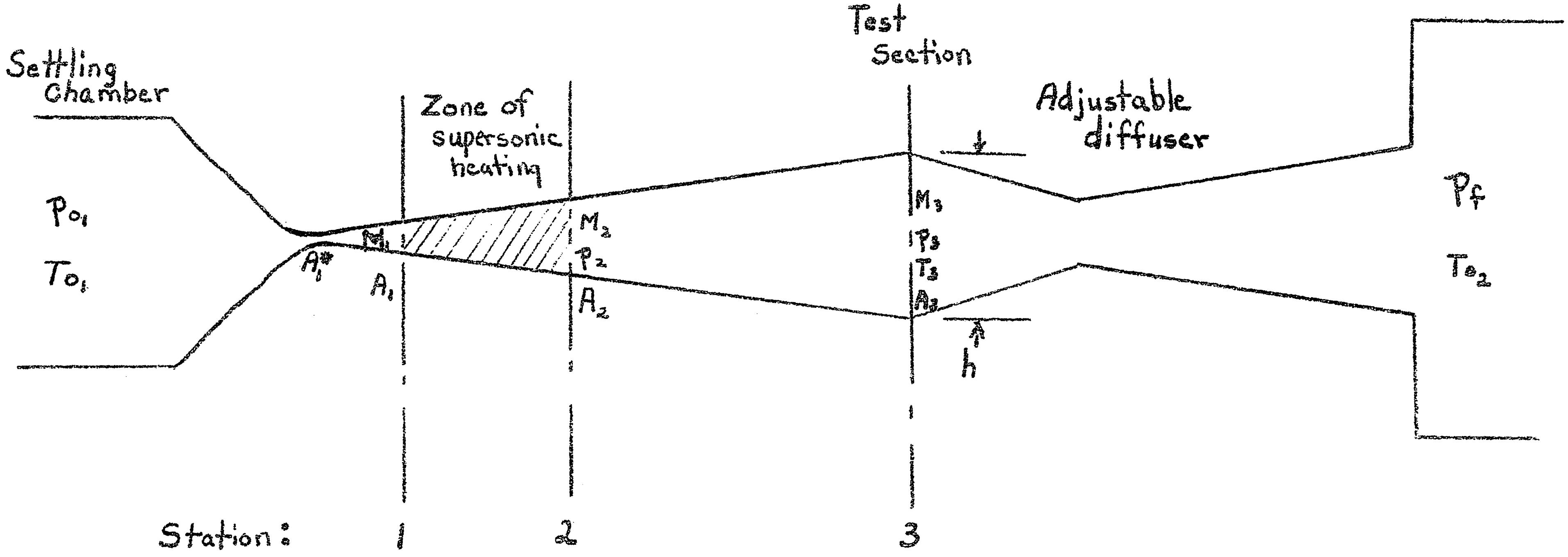


Fig. 12 -Schematic Diagram of Hypersonic Tunnel with Supersonic Heating

magnetic field that may be required to control the discharge) is then

$$H.P. = \frac{1}{550} m R T_{o_2} \frac{\gamma}{\gamma-1}\left[\left(\frac{p_{o_1}}{p_f}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

where m is the mass flow per second through the tunnel, T_{o2} is the stagnation temperature downstream of the region of supersonic heating, and R is the gas constant (all quantities are in the ft.-lb.-sec. units). Now with

$$m = \rho_3 A_3 v_3$$

the horsepower is given by

$$H.P. = \frac{1}{550} \rho_3 A_3 v_3 R T_{o_2} \frac{\gamma}{\gamma-1}\left[\left(\frac{p_{o_1}}{p_f}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

3. The comparison of various types of supersonic heating is aided by use of the ratio of Reynolds number based on tunnel height to horsepower required for continuous operation. The Reynolds number is defined as

$$Re = \frac{\rho v l}{\mu}$$

Where ρ is the mass density, v is the flow velocity, l is the characteristic length, and μ is the viscosity. Let the characteristic length be the tunnel height, h, and express the variation of μ with temperature by the empirical relation (for air)

$$\mu = \mu_a\left(\frac{T}{T_a}\right)^{.76}$$

Then,

$$Re = \frac{1}{\mu_a}\left(\frac{T_a}{T_3}\right)^{.76} \rho_3 v_3 h$$

The Reynolds number-horsepower ratio can now be expressed as

$$\frac{Re}{H.P.} = \frac{550}{h R T_{o_2}} \frac{\gamma-1}{\gamma}\left(\frac{T_a}{T_3}\right)^{.76} \frac{1}{\mu_a} \cdot \frac{1}{\left[\frac{p_{o_1}}{p_{o_2}} \frac{p_{o_2}}{p_f} - 1\right]}$$

where the test section is assumed square. In order to determine how supersonic heating affects the above ratio, two specific cases will be treated: (1) heat added in a diverging portion of the nozzle at such a rate that the Mach number remains constant, and (2) heat added in a constant area portion of the nozzle. In both cases an isentropic expansion occurs between the heating zone and the test section.

4. For constant Mach number heating, the analysis of Reference 7 gives

$$\frac{d p_o}{p_o} = -\frac{\gamma M^2}{2} \frac{d T_o}{T_o}$$

which integrates to

$$\frac{p_{o_2}}{p_{o_1}} = \left(\frac{T_{o_1}}{T_{o_2}}\right)^{\frac{\gamma M_1^2}{2}}$$

(It is of interest to note that the increase of area in the region of heating is, for this case

$$\frac{A_2}{A_1} = \left(\frac{T_{o_2}}{T_{o_1}}\right)^{\frac{1+\gamma M_1^2}{2}} \quad .)$$

The Reynolds number-horsepower equation becomes

$$\frac{R_e}{H.P.} = \frac{550}{hRT_{o_2}} \frac{\gamma-1}{\gamma} \left(\frac{T_a}{T_3}\right)^{.76} \frac{1}{\mu_a} \frac{1}{\left[\left(\frac{T_{o_2}}{T_{o_1}}\right)^{\frac{\gamma-1}{2}} M_1^2 \left(\frac{P_{o_2}}{P_f}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

The results for this case are plotted in Figure 13 as a function of M_1, for $M_3 = 5.0$, $\gamma = 1.4$, $h = 6''$, $T_3 = 400^\circ$ R ($T_{o2} = 2400^\circ$ R), and $T_{o1} = 1400^\circ$ R. It is assumed that the diffuser pressure recovery, $\frac{P_f}{P_{o_2}}$, is twice that of a normal shock at M = 5.0. (Pressure recoveries of this order were obtained with an adjustable diffuser in Reference 8.)

5. For constant area heating Reference 7 gives

$$\frac{P_{o_2}}{P_{o_1}} = \frac{1+\gamma M_1^2}{1+\gamma M_2^2} \left(\frac{1+\frac{\gamma-1}{2} M_2^2}{1+\frac{\gamma-1}{2} M_1^2}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{T_{o_2}}{T_{o_1}} = \frac{M_2^2}{M_1^2} \left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)^2 \frac{1+\frac{\gamma-1}{2} M_2^2}{1+\frac{\gamma-1}{2} M_1^2}$$

By use of the tables of Reference 7, the loss of stagnation pressure in the heating zone, and then the Reynolds number-horsepower ratio, were calculated for the same conditions as the constant Mach number case. The curve for constant area heating is terminated at $M_1 = 4.1$ since for lower values of M_1 the required temperature ratio $\frac{T_{o_2}}{T_{o_1}}$ cannot be obtained before M_2 becomes unity.

6. Shown on Figure 13 together with the above results is the value of $\frac{Re}{H.P.}$ for the case in which sufficient heat is added in the settling chamber (at $M = 0$) to bring the test section static temperature, T_3, to 100° R (representing approximately the heating required to prevent condensations of air). It is seen, by comparing this point to the point where $M_1 = 0$ on the constant Mach number curve, that a large portion of the increase in the power requirements with heating comes just from the fact that the test section stagnation temperature is increased.

The increase in power required due to loss in stagnation pressure is shown by the slope of the two curves in Figure 13. The loss in stagnation pressure increases with the Mach number at which the heat addition occurs. It is proved in Reference 8 that the rise in stagnation pressure loss with Mach number is a general result, independent of the programs of heat addition and/or area change.

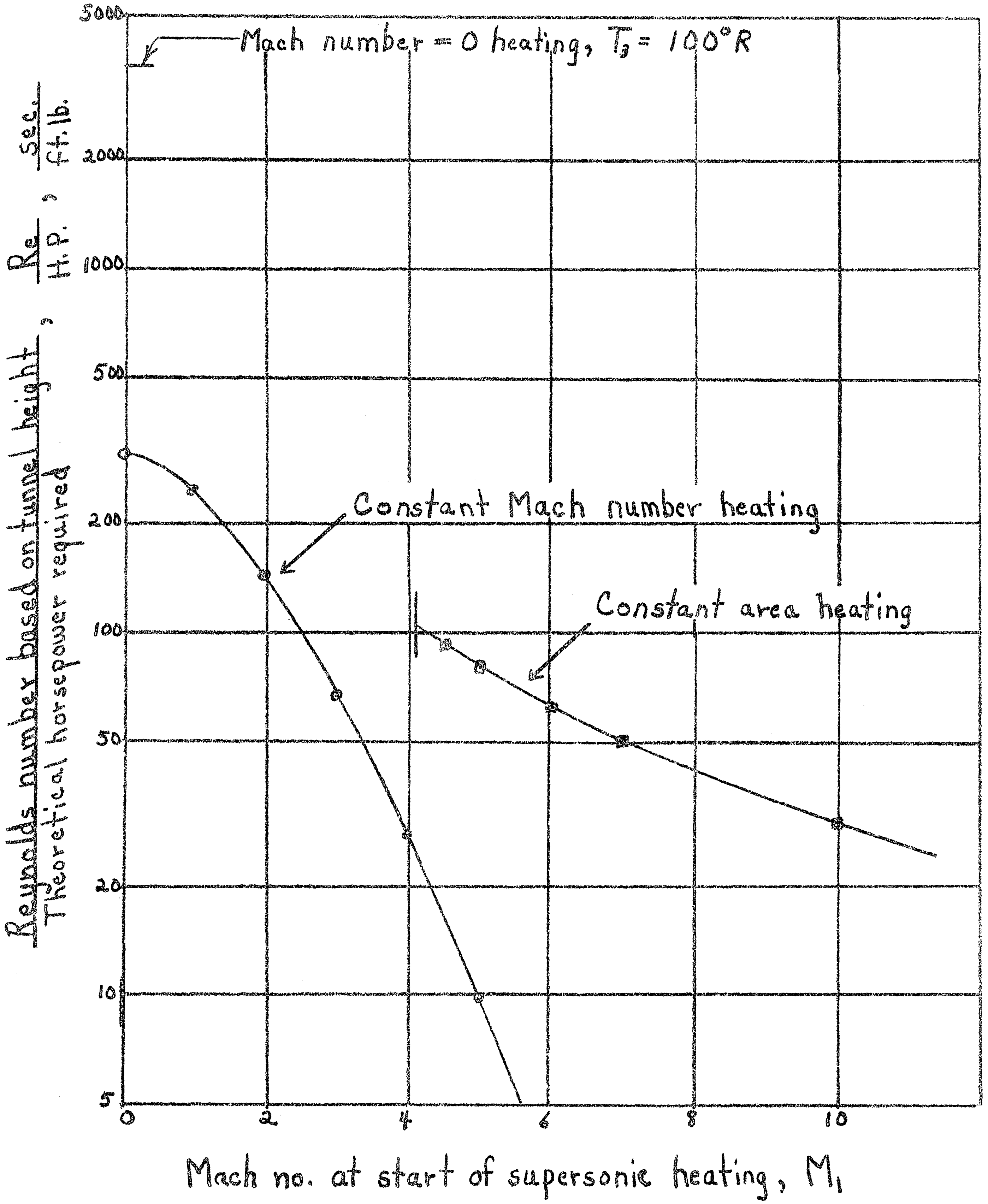


Figure 13 - Reynolds' number - horsepower ratio for 6" square wind tunnels with test section Mach no. $M_3 = 5.0$ — — — Upstream stag. temp. $T_{0_1} = 1400° R$, stag. temp. after supersonic heating $T_{0_3} = 2400° R (T_3 = 400° R)$.

APPENDIX II

(Copy)

Low Pressure Research
Engineering Field Station
301 64th Street
Richmond, California

April 9, 1954

Dr. H. C. Early
Research Engineer
University of Michigan
Ann Arbor, Michigan

Dear Dr. Early:

I am sorry I have postponed answering your letter for so long. The reason for my hesitation is the fear that what I have to say will not be of too much help to you. Your problem seems to be exactly the opposite of ours. We are dissatisfied because much of the energy put into the air stream goes to heat rather than potential energy, while you would like to suppress all forms of potential energy in order to get a maximum yield of heat.

At the present time it is our belief that the principal long lasting componenets carried by the activated low pressure gas streams are oxygen atoms in the case of air and nitrogen atoms in the case of relatively pure nitrogen. A powerful discharge may very well produce several percent dissociation. All other constituents like ions, electrons and metastable molecules decay to rather low concentrations within a few milliseconds. The nitrogen atoms produced in an air discharge are rapidly removed in reactions resulting in oxides of nitrogen, probably mostly nitric oxide. At higher pressures, perhaps above 100 mm Hg, the atomic oxygen tends to attach to oxygen molecules resulting in the well-known formation of ozone. The nitric oxide formed is not stable in the presence of air, being easily oxidized to yield nitrogen peroxide. If atomic oxygen is present simultaneously with the nitric oxide the resulting oxidation is accompanied by the emission of a greenish glow. This characteristic light emission is utilized as a test for the presence of free oxygen atoms (c.f. Gaydon "The Spectroscopy of Combustion ").

The rate at which the atomic constituents disappear depends very much on the gas pressure and the relative abundance of the various components. Polyatomic impurities in general "quench" the activity rather rapidly; e.g. water or organic vapors will reduce the duration or even completely inhibit the production of the afterglows. But whether this means that most of the energy is transformed into heat rather than into some other form of inert potential energy (endothermic reactions) is not really known. It will certainly depend on the details of the processes involved. Using merely a higher pressure to speed up the reactions, on the other hand, may not be sufficient since even at 50 mm Hg pressure, the air afterglow lasts at least 100 milliseconds and the excess free oxygen probably outlives the glow several times. In nitrogen the lifetimes are even longer. What is actually needed is a catalyst which, for full energy recovery, returns the gas to its original chemical composition before the flow enters the nozzle throat. Unfortunately no such gaseous substance is known to me; you would have to institute your own search for it. Partial recovery can, of course, be obtained easily if an adequate fraction of impurity may be added and if sufficient time can elapse between excitation and expansion of the gas.

The nearest thing to a catalyst is an inert metal surface. If it is possible to insert some sort of a filter, consisting perhaps of a tube section filled with platinum shavings, practically all energy will be converted into heat. The trouble here is, that primarily the temperature of the metal is raised so that the stream is heated again largely by heat transfer from the surfaces. In the last analysis, one wonders then whether it would not have been simpler to heat the metal parts directly by some electrical means. This, of course, you will be qualified to judge better than I.

I am sorry to have so few constructive suggestions. Your problem is not an easy one. I would be glad to help you if I could. If there is anything else in which I could be of assistance feel free to let me know. I wish you luck with your research.

Very sincerely,

W. B. Kunkel
Physicist

WBK:mr

APPENDIX III

THEORETICAL HEAT ADDITION IN A CONSTANT AREA SECTION TO CHOKE FLOW

Assume that heat is added in a constant area section of a wind tunnel to a gas having constant specific heat and composition. For a "simple T_0 change" the relation between the total temperature and Mach number is given by: (7)

$$\frac{T_{02}}{T_{01}} = \frac{M_2^2}{M_1^2}\left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)^2 \frac{1+\frac{\gamma-1}{2}M_2^2}{1+\frac{\gamma-1}{2}M_1^2}$$

If enough heat is added to bring the Mach number to unity, the flow will choke. Assume $T_{01} = 300^\circ K$, $M_1 = 4$, $\gamma = 1.4$, $M_2 = 1$, then $T_{02} = 515^\circ K$. Thus, a change in total temperature of 215° Centigrade reduces the flow from Mach 4 to Mach 1. If the mass flow is 10 gm/sec., and if $C_p = 0.24$ cal/gm/deg, the energy input to just choke the flow is 516 cal/sec or 2.16 kw.

VERY RECENT DEVELOPMENT

The high-frequency corona type of discharge, discussed on page 62 has been briefly tested, and the results look very encouraging. The corona was produced at atmospheric pressure, using r-f power from a 1 kw, 10 megacycle dielectric heating unit. In the presence of a stream of air from a 50 psi air hose, the discharge was not constricted or blown away by the wind. Instead, the region between the electrodes was filled with myriads of closely packed hair-like streamers. The corona power dissipation at r-f frequencies was two or three orders of magnitude larger than in a previous test where d-c power was used. Further tests are planned in the near future using a 5 kw, 400 kc induction heating oscillator which is available.

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