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PHOTOGRAPHIC, PRESSURE, AND VOLTAGE MEASUREMENTS ON AN ARC BURNING COAXIALLY IN A SUPERSONIC NOZZLE*

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Abstract

A cascade nozzle experiment has been developed to study arc-gas flow interactions. The hyperbolic nozzle has a 45° inlet and a 5° exit asymptote matched at the throat whose diameter is 1 cm. The nozzle flow is underexpanded. Measurements were made with air for DC currents from 100-300 amperes and nozzle reservoir pressures from 1-10 atmospheres. Heat addition from the arc lowers the mass flow and raises the level of the axial pressure distribution. Fastax photographs show the arc to be stable upstream of the throat while becoming more diffuse and fluctuating in the expanding portion of the nozzle.

1. Introduction

The study of arcs burning in a coaxial flow has long been of interest. Early experimental work showed that an arc burning coaxially in a converging-diverging nozzle with an elongated, constant diameter, throat section produced a supersonic flow of high enthalpy at the nozzle exit in which high velocity aerothermodynamic tests could be made[2-7]. In most instances, however, the elongated throat section was so long that the mass flow through the nozzle was controlled by choking effects in this one dimensional region. Because of the high amount of heat addition per unit mass, the low upstream stagnation pressure and subsequent low mass flow in the nozzle allowed the arc to control the flow rather than interact with it.

If one removes the constant diameter section from the above experiment, the arc is left to burn in a converging-diverging nozzle. The mass flow will now be predominantly determined by the amount of heat addition upstream of the throat, the upstream stagnation pressure of the nozzle, and the area of the nozzle throat. In addition, the arc will now be interacting with the strong gas flow. Conditions do exist, however, whereby the amount of energy addition upstream of the throat can be great enough to allow the arc to control the flow.

This paper describes an experiment which is designed to permit a fundamental study of arc-gas flow interaction in a converging-diverging nozzle. Results of preliminary runs are also presented. Until recently[8-12], few experimental results have been available for this type of experiment.

2. Experimental Facility

Nozzle Assembly

A schematic of the nozzle assembly is shown in Fig. 1. This assembly consists of three parts: a high pressure reservoir, the segmented nozzle, and a low pressure receiver.

The reservoir is designed for a maximum working pressure of 34 atm. It is constructed of type 316 stainless steel for its good resistance to corrosive gases. Flow stabilizing screens are positioned near the entrance to the reservoir to eliminate turbulence in the flow by the time it reaches the nozzle entrance. The cathode is positioned along the axis of the reservoir and supported with a tripod holder. The cathode can be moved axially to achieve the most stable arc emission. The inner diameter of the reservoir is 20.32 cm while its length is 81.28 cm. The segmented nozzle assembly consists of a series of water-cooled copper disks separated from each other by dielectrically anodized aluminum spacers. Each copper disk has a concentric inner contour. O-rings provide seals between the copper disks and spacers. When these disks are sandwiched together, a nozzle is formed by the inner contour of the copper disks utilizing the cascade principle[1]. The water-cooled, axially nonconducting, inner contour of the nozzle forces the arc to burn along its axis when a gas flow is imposed.

The copper disks are 1.27 cm thick and are separated from each other by 0.16 cm. The inner contour of the nozzle is formed by two hyperbolae matched at the throat. The asymptote for the inlet hyperbola is 45° while that of the exit is 5°. The throat diameter is 1.0 cm.

Flanges constructed of 316 stainless steel mate to each end of the nozzle. These flanges are

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compressed towards each other by four equally-spaced threaded rods which are electrically isolated from the flanges. The inner contour of the flange at the nozzle inlet is mated with the contour of the first nozzle disk. The flange at the nozzle exit has a larger inner diameter than the exit diameter of the nozzle and expands at a 45^{o} angle to alleviate any flow obstruction caused by the anode.

Each cascade spacer is equipped with four window slots to allow viewing of the arc from two mutually perpendicular paths. Each set of windows is inclined to the viewing path to minimize reflected radiation. Each spacer also has two ports, from which the axial pressure can be measured or the insertion of a probe into the flow can be accomplished.

This type of nozzle arrangement allows one to easily alter its length by removing disks from the exit end. This becomes necessary when operating with a power supply with a fixed maximum output voltage if one desires to run at higher currents and reservoir pressures.

The low pressure receiver is designed to withstand a maximum pressure of 14 atm. It is also constructed of 316 stainless steel. The inner diameter of the receiver is 25.4 cm while its length is 91.44 cm. The outer surface of the receiver is wrapped with a water-cooled heat exchanger tube. In addition, an inner water-cooled coil is inserted within the receiver to extract heat from the hot exhaust flow of the nozzle. A baffle is inserted near the end of the receiver to help make the flow within one dimensional. The partially cooled exhaust is drawn from the receiver by the house vacuum system.

The anode is positioned on the nozzle-receiver axis and is fed by an electrically isolated tube which extends along the receiver axis. The copper tube which supplies cooling water and current to the anode is shrouded by a stainless steel tube to provide extra rigidity. The shroud is supported near the anode by a tripod holder which clamps to the shroud. This prevents axial movement of the anode while the experiment is operating.

Both the anode and cathode are water-cooled. The cooling water impinges on the tip through an inner cooling tube and exits through the annulus created by an outer concentric tube. The cathode is a piece of 2% thoriated tungsten pressed into a water cooled copper holder. Its diameter is 7.7 mm and extends 15.2 mm beyond the end of its holder. Its tip has the shape of a truncated cone. Presently the anode is water cooled copper which also has the shape of a truncated cone. The tip of the anode has a diameter of 1.0 cm.

Possible Measurements

The measurements which can be made on this experiment are: arc current, arc voltage, axial voltage distribution, axial pressure distribution, mass flow, and optical measurements. The first two measurements are straightforward. The axial voltage distribution can be found with the aid of the water-cooled copper disks of the nozzle. The characteristics of these disks as electrical probes have been studied quite thoroughly for constant diameter cascade arcs[13, 14]. The disks have been found to measure the potential of the plasma (arc column) adjacent to their geometrically lower potential edges if the interdisk impedance is high and the input impedance of the measuring device is high. The interdisk impedance of this device is on the order of 2.0 megohms.

The axial pressure distribution is measured with the aid of the ports in the cascade spacers. Since the slot separating any two copper disks is finite compared to the nozzle dimensions, a computer analysis was undertaken to determine the point of pressure measurement for the slots using the isentropic pressure distribution for the nozzle. The point of pressure measurement turned out to be the midpoint between the disks for all of the slots of interest. A one dimensional analysis for the response of the pressure ports to a step increase in pressure at the centerline of the nozzle yielded a frequency of response for this pressure transducer geometry of approximately 10 kilohertz.

The mass flow through the nozzle is measured with a turbine flowmeter. The two mutually perpendicular viewing paths through each spacer allows one to make simultaneous photographic and spectral measurements of the arc. One could also take either streak, schlieren, or shadowgraph pictures of the temporal behavior of the arc. Events at any single spacer or at all the axial locations of the spacers could be recorded depending on the spatial resolution necessary to capture the event.

Support Facilities

A high pressure air supply can give approximately 20 minutes of service of dried, filtered air at the maximum operating pressure of 34 atm.

The receiver exhausts to the house vacuum system which has a volume of 368 cubic meters and is initially evacuated to 0.03 atm. The pressure in the receiver is maintained low enough so the flow at the nozzle exit is underexpanded.

The power supply is a General Electric Silcomatic DC supply with an output capacity of 1100 amperes and 865 volts.

Method of Operation

The nozzle is designed for a vacuum startup. The reservoir and receiver assemblies are isolated from the high pressure air supply and vacuum system by solenoid valves. All of the nozzle components and attached measurement devices, with the exception of the cathode, are electrically isolated from ground potential. The nozzle is pumped down to a pressure on the order of 200 microns (depending on the electrode separation). Upon application of the maximum open circuit power supply voltage, the gap between the electrodes breakds down according to Paschen's Law and quickly transforms to an arc discharge. The gas flow is initiated by the maximum power supply voltage on the anode and is established in the nozzle within a half second after the arc discharge has formed. The reservoir pressure is continuously adjustable with a dome loading regulator.

3. Initial Checkout Runs

Cold Flow

The nozzle was operated up to the maximum reservoir pressure. The level of the pressure distributions at intermediate values of reservoir pressure up to the maximum value were found to be slightly greater than predicted by isentropic one dimensional flow theory. The values measured, however, were within experimental error of the isentropic values.

The mass flow measured by the turbine flowmeter was found to be within experimental error of that predicted by isentropic one dimensional theory.

The electrodes were moved axially to see if their range of potential operating positions have any effect on the pressure distribution or mass flow. No influence was measurable within their range of operating positions.

A shadowgraph picture of the nozzle flow at a reservoir pressure of 3.84 atm is shown in Fig. 2. The picture shows Mach waves which originate slightly downstream of the nozzle throat (second slot from left). The waves subsequently reflect in a continuing downstream pattern with each reflection occurring at the approximate local Mach angle predicted by isentropic 1-D flow theory. A reconstruction of these waves shows the flow to be approximately symmetrical about the centerline of the nozzle. These Mach waves are always present in an expanding supersonic flow. No additional disturbances appear to be generated by the discontinuities in the nozzle wall which are created by the finite disk separation.

Hot Flow

The position of the cathode was found to be very important for arc stability. The tip of the cathode was originally positioned at the entrance plane of the inlet flange. At this position the arc was extremely unstable, having no preferred direction and periodically striking the flange. As the cathode was moved towards the nozzle throat, the arc gained stability. Good stability was attained when the cathode tip reached the point where the inlet to throat area ratio was approximately eight. This corresponds to an arc length upstream of the throat of approximately 1.59 cm.

A sintered copper-tungsten rod (40 Cu:60W) of 7.7 mm diameter was initially tried as the cathode. Its emission was stable, but there was considerable erosion from the tip. The eroded material deposited on the nozzle wall and changed the surface finish. This effect was judged undesirable because of possible temporal changes in the flow boundary layer. A 2% thoriated tungsten cathode of the same diameter was then tried. Its tip had the shape of a truncated cone. This cathode performed very well with little erosion for currents below approximately 200 amperes.

The anode was initially positioned midway in the flange which mates with the nozzle exit. At this position the arc was blown off of the anode tip at a mass flow below 50 gm/sec. Neither dishing out the tip of the anode nor providing gas flow through its tip solved this problem. Finally, the arrangement shown in Fig. 1 was tried with much success. This arrangement exposes the anode to a less severely expanded flow at tis tip, which subsequently lowers the transverse aerodynamic forces on the arc attachment point. The flow area of the annulus around the outside of the anode is approximately twice that of the nozzle exit area.

Both standard purity copper and oxygen-free high conductivity copper have been used as the anode material. The amount of erosion of these materials appears to be caused by both ablation of the molten anode spot and the impingement of hot tungsten particles from the cathode onto the anode tip. The particles are believed to cause localized melting and subsequent ablation of the copper due to their large difference in melting temperature. A grey metallic coating on the anode tip at the end of each run is evidence of the above phenomenon.

The arc was also discovered to be wandering into the separation between the nozzle disks before the gas flow was established. This problem was eliminated by covering the opposing disk surfaces (i.e. the surfaces that do not form the inner contour of the nozzle but between which the arc could burn) with pressure sensitive teflon tape. This tape is nonporous and has a very high dielectric strength.

4. Preliminary Results and Discussion

A plot of arc voltage versus reservoir pressure for the runs made to date is shown on Fig. 3. The points are shown for an electrode separation of 9.37 cm. It proved necessary to calculate the arc voltage for the 205 ampere arc with an electrode separation of 9.37 cm, since the actual data was recorded at an electrode separation of 7.94 cm. The actual data for the 205 ampere arc is also shown.

The values of arc voltage for the electrode separation of 9.37 cm were found by assuming a linear voltage distribution between the nozzle throat and the anode for the actual data. This linear distribution is then extrapolated to the new arc length of 9.37 cm, since the change in electrode separation occurred downstream of the throat disk. The anode voltage is then either graphically measured or calculated. These new values of anode voltage undoubtedly overpredict the arc voltage because the average pressure in the calculated section is less than the average pressure in the section over which the voltage distribution is assumed linear. The data clearly show that at constant current the arc voltage increases as the reservoir pressure increases.

Also shown on Fig. 3 is the voltage which was measured at the throat disk for different currents and reservoir pressures. The distance between the cathode and the throat disk is 1.59 cm for all of the data points. The values were measured with a 100:1 voltage divider circuit which has an impedance of 1.01 megohm connected to ground potential. This circuit draws an ion current from the probes equal to the measured voltage divided by its input impedance. This ion current will cause the measured probe voltage to be slightly lower than its actual floating potential value[13,14] (i.e. the value of voltage the probe assumes when no current is drawn from it). However, the large thickness of these probes should cause the knee in the ion current portion of the probe characteristic to shift further below the zero current axis[15] and thereby minimize the voltage error at the low ion currents which were drawn (i.e. of the order of 100 μamp).

The results indicate that the arc voltage (and impedance) decreases as the current increases at constant reservoir pressure. The larger part of the voltage decrease appears to occur in the expanding portion of the nozzle downstream of the throat. The above trend is in agreement with the results of the Brown-Boveri experiment[8-12] which has an arc voltage of approximately 1000 volts for a nitrogen arc of 2000 amperes burning in a converging-diverging nozzle of 10 cm in length, 1.2 cm throat diameter, and a reservoir pressure of 23 atm. The results also indicate that the experiment may be operating on the falling portion of the arc current-voltage characteristic, if such a characteristic does exist for this type of arc for a constant reservoir pressure.

The throat voltages indicate an electric field strength greater than 100 v/cm exists in the converging section of the nozzle for reservoir pressures greater than 2.38 atm. It also appears that the voltage drop from the throat to the cathode is slightly greater for lower currents at the same reservoir pressure.

The nozzle pressure and voltage distribution for three different run conditions are shown in Figs. 4, 5, and 6. Also shown on each graph is the isentropic pressure distribution and the distribution measured for the same upstream cold flow conditions. One should note that the data of Figs. 5 and 6 are for a shorter electrode separation and nozzle length than that of Fig. 4.

For these results, the effect of the heat addition caused by the arc is to lower the mass flow and drive the sonic point downstream of the throat. This results in the overall level of the pressure distribution being significantly higher than that measured for identical upstream cold flow conditions. The results also show that the ratio of hot mass flow to cold mass flow at a given reservoir pressure increases as the heat addition per unit mass decreases.

Some frames of a Fastax movie of the arc of Fig. 5 are shown in Fig. 7. For these photographs, the framing rate is 7,800 frames per sec, the exposure time is approximately 25 μsec, and the time between frames is approximately 128 μsec. The fluctuations in the arc diameter appear to be random at all of the spacers. The fluctuations in the diameter grow as the arc traverses downstream, being quite small at the first two positions—the second position being at the nozzle throat. An average diameter of the arc was calculated for 21 frames of the movie including those shown in Fig. 7. The average diameters measured from left to right were 5.6 mm, 3.1 mm, 4.3 mm, 4.4 mm, 4.0 mm, and 4.4 mm.

The amount of cathode erosion was also measured for the run during which the data for Fig. 5 and 6 were recorded. The weight of the eroded cathode material was 0.80 grams which represents a percentage of 0.21% of the total mass which flowed through the nozzle during the run.

5. Conclusions

Preliminary results for an arc burning coaxially in a converging-diverging nozzle with air as the medium have been presented. The mass flow through the nozzle was found to decrease as the rate of heat addition per unit mass increased. The overall level of the pressure distribution for hot flow in the nozzle was found to substantially increase over the level of the cold flow distribution.

One should be able to increase the mass flow and decrease the level of the pressure distribution towards its isentropic distribution by moving the cathode towards the nozzle throat while the current and reservoir pressure are held constant. This is because the largest amount of heat addition/unit length occurs upstream of the throat in the high pressure region of the nozzle.

For the conditions tested, the arc voltage was also found to decrease as the current increased at constant reservoir pressure. The possibility of operation only on the LHS of the arc current-voltage characteristic was discussed. Further experimental results should clarify this observation.

The Fastax pictures failed to show whether the fluctuations in the arc diameter were generated either up or downstream of the point where they were recorded or if they were random. Results of streak photographs, which will be available soon, should provide a better understanding of this phenomenon. These streak photographs should also yield a better measurement of the arc diameter, since their exposure time will be much shorter.

A design requirement for cascade arcs is that the voltage drop across the distance separating the lower potential edges of any two adjacent disks must be less than the sum of the combined anode and cathode fall voltages. In this experiment the separation between the lower potential edges of any two adjacent disks is 1.43 cm. This would give a 143 volt drop at 100 v/cm (conditions of Fig. 6) across two adjacent disks. Although the combined anode and cathode fall voltage for this experiment is unknown, it is believed to be less than 143 volts (i.e. the combined anode and cathode fall is on the order of 40 volts for an atmospheric pressure nitrogen arc). It appears that the design criteria for the disk thickness of a constant diameter cascade does not carry over to a variable area cascade nozzle. One should note, however, that the arc in this experiment is isolated from the nozzle wall by the cold gas flow except when the experiment is operating near "clogging" conditions. The arc is most likely in poorer electrical contact with the wall than an arc in a constant diameter cascade. Therefore, a comparison between the two experiments may not be justified.

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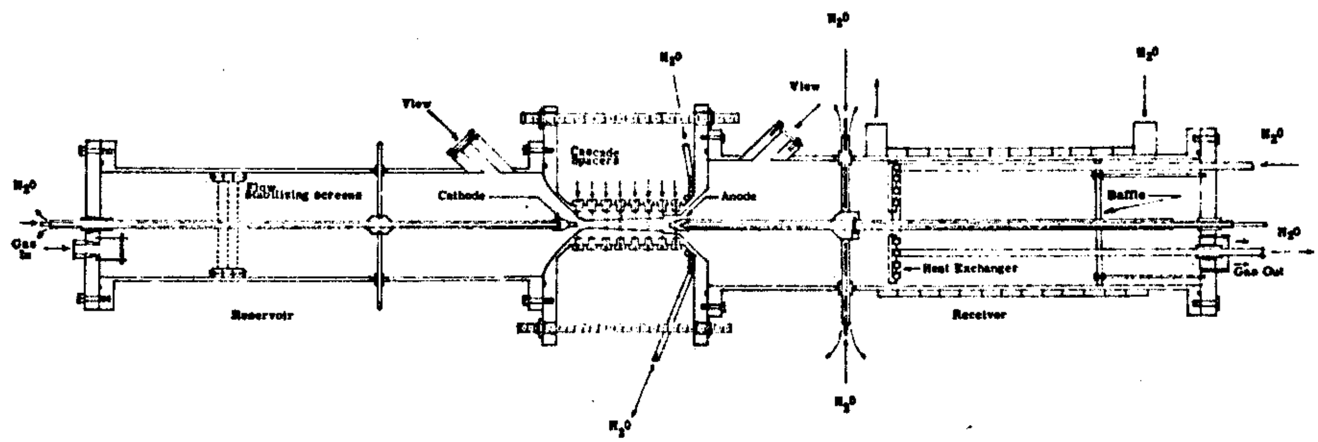

Figure 1. Schematic (not to scale) of Cascade Nozzle Assembly.

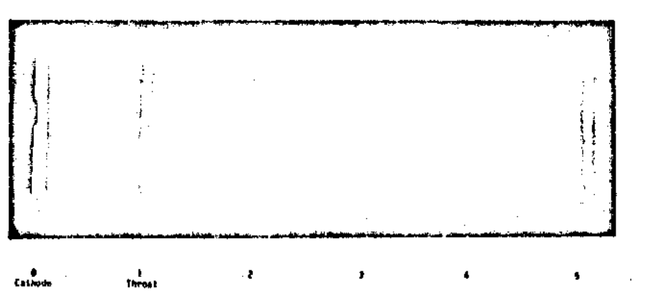

Figure 2. Shadowgraph of Nozzle Flow (P_o = 3.84 atm).

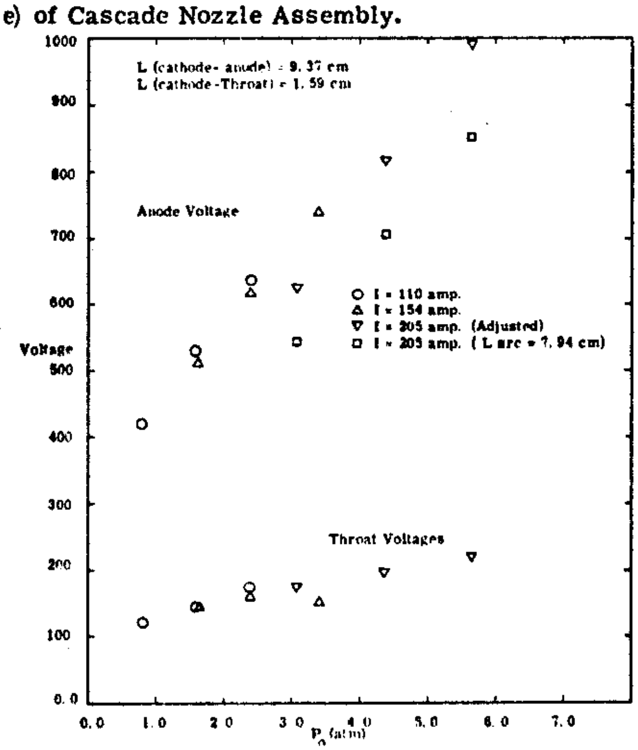

Figure 3. Arc and Throat Voltage vs Reservoir Pressure at Different Current Levels.

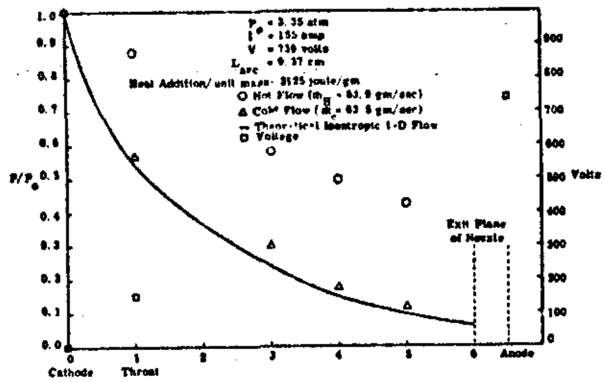

Figure 4. Nozzle Pressure and Voltage Distribution.

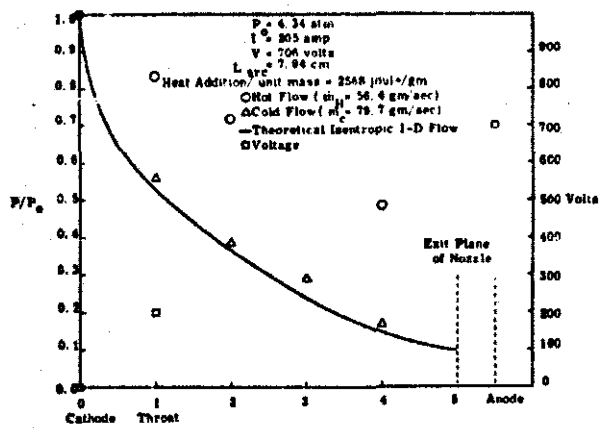

Figure 5. Nozzle Pressure and Voltage Distribution.

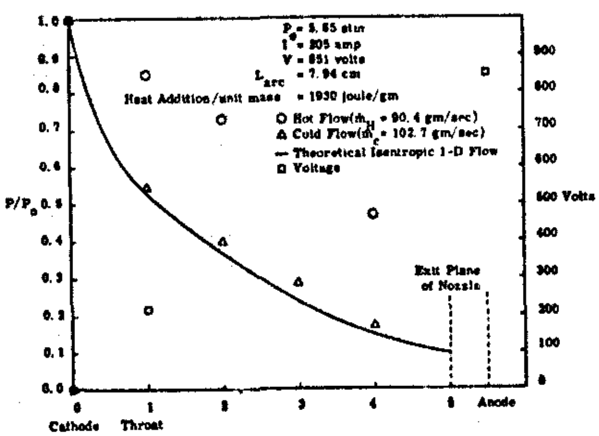

Figure 6. Nozzle Pressure and Voltage Distribution.

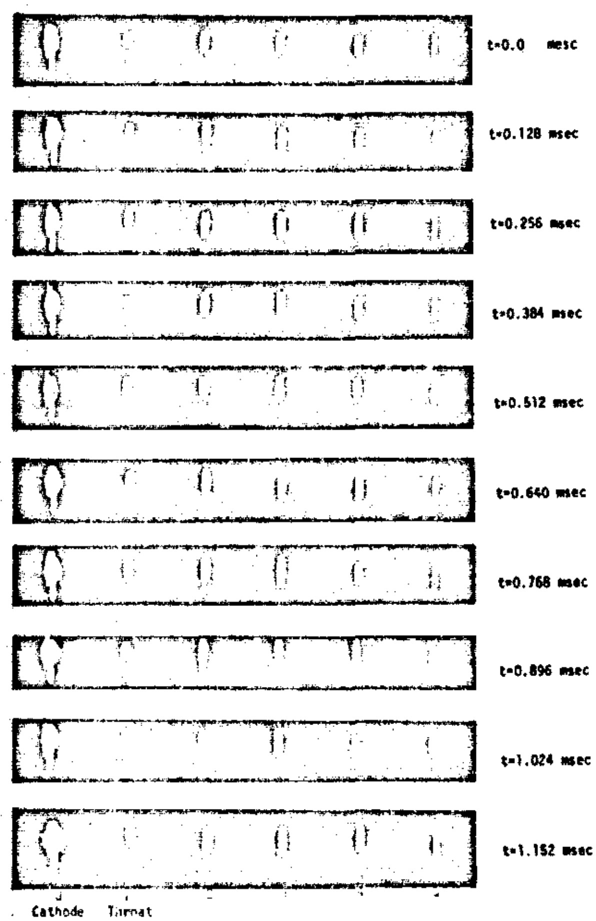

Figure 7. Sequence of Fastax Photographs of Arc of Figure 5.