The increasing speed requirements of aircraft and missiles have demanded rapid development of hypersonic propulsion tunnels for testing at simulated flight conditions. The need to provide flight temperatures in such tunnels has led to the development and use of split-ring, water-cooled plasma arc heaters to furnish heated air for propulsion research in the Mach 7 to 10 range.

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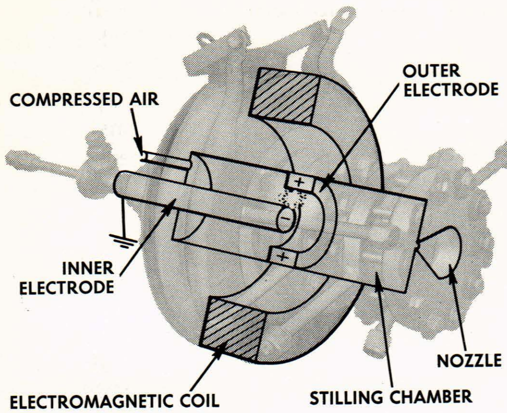
PLASMA ARC HEATING

for Hypersonic Wind Tunnels

The prevailing requirement for increasing flight speeds in the atmosphere has given rise to a corresponding evolution of wind tunnels for ground-testing of flight vehicles and power plants. A recent addition to this evolutionary series is the hypersonic tunnel in which the Mach number exceeds 5. Development of air-breathing engines imposes a special requirement on all such tunnels, namely, that the flows in the working sections correctly simulate in both temperature and pressure the conditions at various altitudes. For example, at Mach 8 and an altitude of 120,000 ft, the required stagnation pressure and temperature are 1000 psi and 5200°R. While stagnation pressures of this magnitude are easily obtained, prolonged operation of a propulsion tunnel at such temperatures is more difficult to accomplish; it appears to be most readily obtainable by use of the electric plasma arc as an air heater.

Application of the plasma arc to the heating of gases has a history dating back to the early years of the century when arcs were used in the production of nitric oxide for the making of fertilizer (Birkeland-Eyde process). However, its application to heating gases for expansion in hypersonic tunnels is a relatively recent development. Research work on this problem at APL has proceeded in collaboration with the General Electric Company, Cincinnati, and the joint program has borne fruit along the lines indicated below. One form of plasma arc heater utilizes a pair of coplanar ring electrodes made of copper tubing and located in a pressure chamber upstream of the throat of a hypersonic expansion nozzle. Compressed air enters the chamber at one end and is heated by being passed through the region occupied by the arc discharge struck between the electrodes; AC or DC operation is possible.

Water-cooled metal electrodes can be made to provide operation without excessive ablation, an effect which is a serious drawback of carbon electrodes. The large amount of heat flowing from the arc to the electrodes must be removed by intensive water cooling. Also, in order to minimize local melting of the electrodes, rapid movement of the arc attachment points over the electrode surfaces must be produced in order to distribute the heat load. Considerable ingenuity has been displayed in bringing about such movement. At low pressures (atmospheric) it is sufficient to make use of tangential gas entry to set up a vortex in the gas. Once struck, the arc tends to rotate with the vortex. At higher pressures, however, this arrangement is progressively less effective, and it becomes necessary to rotate the arc by applying an external magnetic field; a gas vortex, while still present, is the result, instead of the cause, of arc rotation.



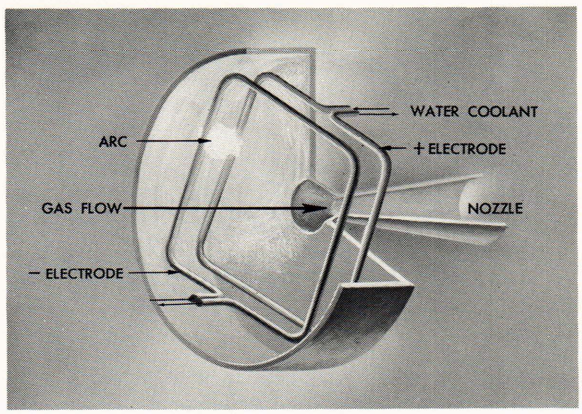
General arrangement of a coplanar electrode type of plasma arc heater in which arc rotation is induced by an externally applied magnetic field.

Two methods of inducing rotation of the arc by magnetic fields are of interest. The first may be visualized by referring to the first diagram of an actual plasma arc configuration. The action of the electromagnetic coil upon the arc is analogous to that of field coils upon the current-carrying conductors in the armature of an electric motor. Movement of the arc occurs in a direction perpendicular to both the current flow and the lines of force of the magnetic field. The electrode configuration shown is not the only one possible; in fact, an arrangement in which electrodes of equal size are mounted side by side, with the arc struck between them, offers greater facility for gap adjustment and appears generally superior from the point of view of practical design. Considerable simplicity of operation may also be achieved by passing the electrode current through the field coils; greater flexibility of operation is possible, however, when separate power supplies are used.

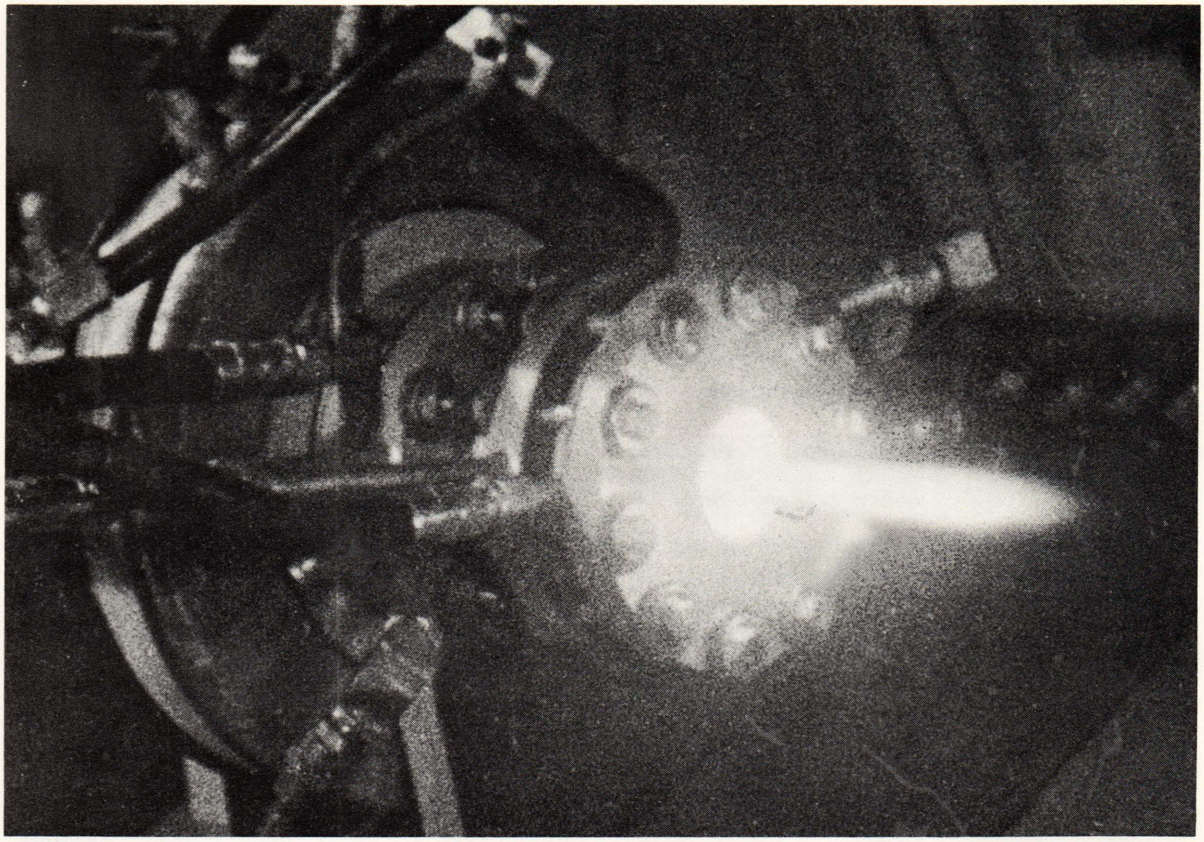
A second method of magnetically inducing rotation of an arc dispenses with an externally applied field. As illustrated in the second diagram, this method utilizes self-induced magnetic fields to rotate the arc around ring-type electrodes. This is accomplished by interrupting each of the electrodes at one point so that with a current connection on only one side of this electrode gap, the current always flows in the same direction around each electrode whatever the position of the arc may be. At high currents magnetic fields of considerable strength surround the conductors in which currents are flowing, and the interaction of these fields with that surrounding the arc struck between the electrodes induces a continuous movement of the arc. The direction of the currents in the two electrodes is so established that the magnetic fields of the two electrodes have the same effect on the movement of the arc within the arc gap. When the arc reaches the gap in the electrodes, the conducting path set up ahead of it by the movement of the ionized gas cloud enables the arc to bridge the gap and so continue its cyclical movement. Rotation rates of about 1100 per second (induced by arc currents of the order of 10,000 amp) have been observed at atmospheric pressure. This rate appears to be roughly proportional to the current and inversely proportional to some power, as yet not precisely known, of the chamber pressure.

The arc heater constructed to drive the Mach 7 hypersonic tunnel at the APL Propulsion Research Laboratory (see *Digest,* September-October 1961) uses electrodes of this split-ring type. They are heavily water-cooled, as is the throat of the hypersonic nozzle. Power is supplied by a large battery which eventually will consist of a thousand submarine cells to provide an input to the arc of 15 megawatts at a current of about 13,000 amp. The associated test chamber will provide accommodation for various ramjet models of advanced design. This arc is capable of operation at a pressure of 1000 psi, and it is intended to increase this pressure capability as much as possible. When the continuing arc development is able to provide for arc operation at 2500 psi, testing facilities at Mach numbers as high as 10 or above will become available.

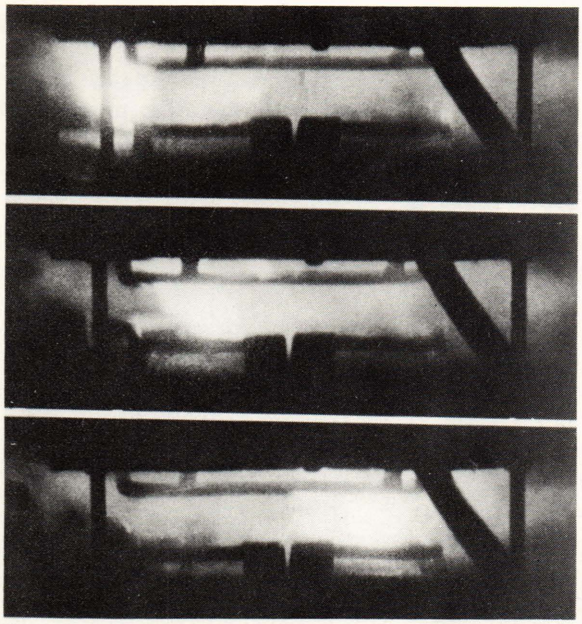
Final details regarding the performance of the arc heater to be used with the APL propulsion tunnel under operating conditions must await



General arrangement of a facing electrode type of plasma arc heater in which arc rotation around water-cooled metal electrodes is self-induced as a result of current connections made on only one side of each interrupted electrode.



In the Propulsion Research Laboratory a 350-kw plasma arc of the coplanar type is shown discharging into the atmosphere.



Movement of an arc around split-ring electrodes is seen in this sequence of three frames from a cine-photo film exposed at a rate of 6000 frames per second.

actual running; it has not been possible so far to test units of this size at sufficiently high simultaneous values of current, power input, voltage, and chamber pressure. However, values of heat flux to electrode coolant of up to 100 BTU/sec/in.^{2} of active electrode area have been measured. Split-ring electrodes have been run for as long as 40 seconds at chamber pressures of about 10 atmospheres and with a reduction in wall thickness during this period of about 25% at the point of maximum erosion. Though ablation rates of large electrodes are difficult to measure accurately, results obtained on small electrodes have shown that rates of contamination of the air stream, by weight of material, can be expected on the order of 4% for copper electrodes and 2% for silver. Since the arc vortex chamber acts as its own trap, however, most of the eroded material is expected to be retained. Power inputs of up to 3.2 megawatts have been achieved (limited only by existing facilities) and currents up to 16,000 amp have been run. The highest pressure of plasma arc operation so far attempted is 1200 psig.