AIR ARC SIMULATION OF HYPERSONIC ENVIRONMENTS

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ABSTRACT

For the past five years the air arc, or plasma generator, has found an important use in the laboratory simulation of environments encountered by vehicles flying at hypersonic velocities through the atmosphere. One purpose of this paper is to outline the re-entry requirements of ballistic, satellite, glide and space vehicles and to show the usefulness of various air arc test configurations in providing the appropriate simulation of flight conditions.

To illustrate the capabilities of current arc facilities, the results of recent development studies with a hypersonic wind tunnel are presented. Measured expanded flow properties are discussed in terms of effective area ratio, boundary layer growth and state of the gas.

INTRODUCTION

When vehicles re-enter the atmosphere they are subjected to wide ranges of pressure, heat transfer and shear levels, and to other aerodynamic properties which influence their performance and strongly determine their design. On a relative basis, some of these environments are quite severe in terms of instantaneous combinations of thermodynamic properties (for example, high performance ballistic missiles), whereas some are mild in terms of thermodynamic properties but severe in terms of time duration and integrated effects (for example, manned glide vehicles). In Fig 1a are plotted the blunt body stagnation region enthalpy and pressure values for wide ranges of flight altitudes and velocities. Also shown in the figure are the general operating

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Presented at ARS International Hypersonics Conference, Cambridge, Massachusetts, August 16-18, 1961; this work was sponsored by the United States Air Force Ballistic Systems Division, Contract no. AF 04(647)-269.

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regimes for several classes of re-entry vehicles. We have attempted to indicate the regions of interest for future superorbital vehicles as well as for those of vehicles of current interest. Fig. 1b has been included to illustrate the heating rate and time characteristics of some typical re-entry vehicles.

The designer is interested in complete re-entry simulation. Since this appears to be an impossible or at best an impractical task in the laboratory, the experimentalist is faced with the job of providing sufficient simulation for the study of various aspects of the re-entry problem. In general, he has turned to two approaches. In the first, he takes advantage of both short time flow duration hypervelocity facilities, such as the shock tunnel, hot shot tunnel, and aerodynamics range, and of more conventional long time flow duration wind tunnels. With these tools he can study the aerodynamic or "external" problems of re-entry. In the second approach, he utilizes long time flow duration hot flow facilities, such as the rocket motor and the plasma generator (or air arc), to study the response of materials and structures to re-entry environments in the time scale typical of the re-entry mission in which he is interested. At present it appears that the air arc heater is the most attractive long time test facility. However, because of the restrictions in its operation which prevent it from being used to provide complete aerothermodynamic simulation of re-entry flight, it has been found necessary to "tailor" the flows in tools of this type to meet the requirements of particular studies; thus, these two approaches have been found to be complementary. This general approach to re-entry testing is presented in some detail in Ref. 1.

The purpose of this paper is to describe the use of air arc facilities in the study of atmospheric re-entry problems. The discussion is restricted to the facilities in which the simulation of the thermodynamic properties of flight in the model flow field is the basic concern; that is, the authors will not consider except in passing the application of electric arcs to heaters for high Mach number, continuous flow wind tunnels which have the express purpose of investigating aerodynamic problems. Because of the pressure requirements on such facilities, these cannot, at least at present, reach the enthalpy levels required for the complete simulation of re-entry flight. Examples of the work being done in this field are given in Refs. 2 and 3. The paper is divided into two main sections. The first is a general discussion of arc heaters, test configurations and restrictions; in the second, a detailed description is given of the operational characteristics of a recently developed air arc wind tunnel.

First, consider the flight problems of interest. Table 1 presents a generalized list of the characteristics of flight problems that may be studied in arc heated facilities. As mentioned before, the primary effort here is to investigate the behavior of heat protection systems in environments that simulate the re-entry flight. Two heat protection systems are of general interest: ablation, where the heat is absorbed and blocked by the removal of mass from the surface; and re-radiation, where the surface temperature and emissivity of the structure are sufficiently high to radiate heat to space at about the rate at which it is put into the body. Ablation is most satisfactory for short time, high heating rate, low total heating missions, such as the ballistic missile, whereas re-radiation is attractive for long time, moderate heating rate and high total aerodynamic heating applications, such as a glide vehicle. Of course, this is a simplified presentation of heat protection system concepts, since they can be combined and since there are other types of systems; however, these usually have the main features of either or both of the two mentioned (for example, a transpiration cooling system). The main test objectives for air arc studies or re-entry problems can be categorized as shown in Table 1. These are again quite general and several subheadings could be listed; for example, under material performance one could be interested in shape changes with time, heat of ablation with and without appreciable radiative contributions, oxidation resistance of re-radiating materials, surface temperature response, and several other materials properties. Several objectives can often be investigated in the same test program. Note that although the authors are not considering the class of arc facility designed to conduct basic aerodynamic studies, relative aerodynamic effects have been included as a test objective. This refers to flow situations, generally associated with slender bodies, in which the response of the heat protection system (thick boundary layers, time and space varying mass transfer and surface temperature, surface roughness) can affect the pressure distribution and forces on a vehicle shape. The basic approaches here in arc wind tunnel tests are to compare results with theory and to use theory in interpreting the results obtained with different heat protection systems.

It is necessary to consider local flow conditions when specifying a re-entry test. The items shown in Table 1 must be taken into account when tailoring an arc test to meet re-entry conditions. As examples: under body station one must consider stagnation and body regions, swept surfaces, protuberances, interference regions, and separated regions; under local free stream conditions are such items as total enthalpy, state of the gas (equilibrium or nonequilibrium) and vorticity gradients. It is interesting to note that radiative heating, caused by the shock heated air ground the vehicle, can be important in determining the response of heat protection systems. To the first order, the primary convective heat blockage mechanism for an ablation system, that is, the blowing of gases into the boundary layer, will not reduce the radiative heat transfer; thus, the effective heat absorbing properties of a material can be markedly reduced when subjected to a large percentage of radiative heating (Ref. 4). This problem will be of particular importance to vehicles re-entering at superorbital velocities.

The type of response expected from the heat protection system is also of key importance in planning an arc facility test. Actually this can be divided into the two headings shown in Table 1: a steady state response implying a rapid approach to equilibrium conditions (mass loss rate, surface temperature, sub-surface temperature distribution, etc.) in relation to some characteristic time scale describing the change of re-entry conditions. A nonsteady response experienced with an ablating system will cause performance predictions, based upon a steady state response, to be nonconservative (Ref. 5).

Note that the test time requirements can vary widely. For example, if interested in investigating an ablation material for application to a high performance ballistic missile, one needs only of the order of 10 seconds test time, since most materials of interest will come to an equilibrium ablation state during that period. A high heating rate (several hundred to several thousand Btu/ft^2-sec) is associated with this type of response. However, for long time missions, such as those that are several minutes to an hour or more, characteristic heating rates are low and materials response can exhibit a strong nonsteady behavior particularly for varying trajectory conditions. Here, long time testing and, in some cases, variable test conditions are required to obtain the simulated re-entry response. The general rule is reached, then, that high heating rate facilities can be of relatively short duration whereas long time flows are required for low heating rate environment simulation.

This discussion has been necessarily nondetailed because of the wide spectrum of conditions that can be encountered for the many different types of re-entry vehicles of interest. The authors have attempted, however, to present some general concepts against which the usefulness of the air arc facilities discussed next can be judged.

GENERAL PROPERTIES OF AIR ARC FACILITIES

Arc Heater Design

The air arc by its nature is an attractive tool for re-entry studies. It provides a heat exchange mechanism whereby gases are mixed with an electric arc column, which is capable of transferring electrical energy to gaseous energy at extremely high rates and without the use of solid heat transferring surfaces. Because of these properties, it is immediately attractive as a wind tunnel device for the study of problems in which the gas temperatures are much higher than those obtainable with the classical wind tunnel facility. (The air arc, of course, has many limitations; these will be discussed in a later section.) It is not the intent of this paper to trace the history of arc usage in flow processes, which dates back to the early part of this century (Ref. 6); a relatively complete coverage of the arc literature is given in Ref. 7. The authors will, however, discuss briefly several types of arc configurations that have been used to produce heated gases for re-entry testing. Perhaps the first arc unit used for this purpose was the water arc, shown schematically in Fig. 2c, the design of which was based largely on the work of Maecker (Ref. 8) and Weiss (Ref. 9). References 10 and 11 report some of the early work done on water arc development in this country. This unit provided a very high energy stream of gases (temperatures of greater than 25,000 K have been reported) in which relative materials ablation properties were evaluated. It soon became apparent, however, that to provide environments similar to re-entry and, therefore, from which design information could be obtained, air was more attractive as the working fluid.

The several arc configurations shown in Fig. 2 are representative of the designs that have been used by various investigators in re-entry studies. These are simple representations of classes of arcs and many modifications have appeared, each having particular advantages and disadvantages. The simplest configurations are the free arcs shown in Figs. 2a and 2b. To our knowledge, no extensive testing has been done with configuration 2a although it has been used for a significant amount of arc research. The development and use in re-entry studies of Fig. 2b at high power levels is discussed in Ref. 12. One major difficulty with the free arcs is the large amount of eroded electrode material that mixes with the test gas at high current densities. This tends to cause poor re-entry simulation in the chemical behavior of the test gas, an important factor in many materials studies. To eliminate this problem, several investigators have turned to the use of arc systems that are driven by the interaction of the arc column with a magnetic field. Fig. 2e and 2f show typical magnetically driven configurations, where the d-c system is driven by an external field and the a-c configuration is driven by the fields generated by the ring electrode configuration. The electrodes are usually made of water cooled copper and the arc motion reduces electrode material loss to a small amount. It has been found possible with these modifications to go to fairly high performance figures; for example, power levels of approximately 2 mw (11,000 rms amps) at a pressure level of 12 atm and an enthalpy level of 5000 Btu/lb have been obtained in configuration Fig. 2f (Ref. 13). Configuration 2d has also been used to reduce the contamination level. Since it was observed that the cathode material loss was approximately one half of the anode loss, the use of a water cooled anode sharply reduces the electrode material loss (Ref. 14). This type of design has also been used in a multiple unit with common plenum chamber to provide a high powered arc facility (Ref. 15). Other modifications of configuration 2d involve the separation of the anode and cathode over relatively long distances. In such a case the voltage is increased and current reduced and, thus, the electrode loss, strongly a function of arc current, is reduced. Here it is also possible to bring the cathode to the wall and rotate the arc column with an external magnetic field (Ref. 3). Such modifications, however, are associated with large chamber surface areas and attendant increases in energy losses to the cooling system. Fig. 2g is a sketch of an arc configuration which was developed by McGinn and is designed to provide both the elimination of electrode material and arc constriction for high temperature plasma generation (Ref. 16). The inlet flows on either side of the plenum are divided, a portion blowing back the electrode materials in a mixture that is exhausted from the system. The arc column passes through the plenum chamber, mixing with the pure test gas that then exhausts through the nozzle. This design, called the tandem Gerdien arc, is an extension of an arc described by Gerdien and Lotz (Ref. 17). Another type of electric heater not shown in Fig. 2 is the high frequency induction heater in which energy is transferred to the test gas from a rapidly alternating magnetic field. This system is not strictly an arc heater because of the lack of electrodes in the system. The concept is attractive, however, because of this fact.

Broadly speaking there are several properties that appear to be important in an arc design. First, constriction of the arc along the flow direction tends to increase the temperature of the column as well as increase the mixing of the cool gas with the hot column. In some cases, constriction also allows operation with a stable voltage-current characteristic. The free burning and magnetically driven arcs shown in Fig. 2 do not accomplish this (arc constriction) as well as do the vortex and divided flow units and, therefore, do not reach as high an enthalpy level as these systems. Second, electrode contamination, generally undesirable, can be reduced to small amounts by magnetically driving the arc column or essentially eliminated by dividing the gas flow as shown in Fig. 2g. Third, since uniformity and steadiness of the test gas are desirable features in a test flow, plenum chambers are often used downstream of the arc station at the expense of a reduction in enthalpy and efficiency. All configurations shown in Fig. 2 except 2c and 2d have plenums inherent in their design. Configurations 2e and 2f can be quite flexible in operation, since their designs can be earily accommodated to include a varying plenum volume. It is interesting to note that swirl introduced by a rotating arc or by a vortical entrance flow can be eliminated in configuration 2g, or when multiple units are connected to a single plenum chamber, simply by bucking the tangential components in the opposite entrance sections. This also improves mixing in the plenum chamber.

Input pressure levels for typical arc units are from less than 100 kw to more than 10 mw and facilities have been contemplated at several times this latter value. At present the largest units (Refs. 12, 13 and 15) put from 2 to 3 mw into the test gas and run for the order of 30 sec. Maximum current and voltage levels for existing facilities are of the order of 10,000 amp and 2000 v, respectively. Large continuous arcs have also operated successfully to the order of 1500 psi, at enthalpy levels of below 5000 Btu/lb (Ref. 18); however, at higher enthalpy levels to the order of 20,000 Btu/lb operation to date has been restricted to the order of 2 atm (Ref. 16).

Electrode materials are generally carbon or water cooled copper although thoriated tunsten has also been used extensively in smaller units. Some systems have also been developed to reduce electrode contamination by sheathing the electrodes in argon. In most units capable of long time operation the arc chambers, plenum chambers, nozzles, etc. are made of water cooled copper.

Test Flow Configurations

Since the arc unit is essentially a gas heater, any may be used in conjunction with several types of test flows, each of which has certain advantages in re-entry studies. Six of these test configurations are shown in Fig. 3. In these, it is assumed that the power E has been added to the gas flow $\dot{m}$ upstream of the plenum chamber through a continuous arc discharge.

Fig. 3a shows a sketch of a configuration in which the heated gas is expanded only to subsonic velocities. Such a device has been used generally for stagnation point testing and as a screening tool for materials studies (Refs. 10,11 and 19). In Fig. 3b it is assumed that the plenum pressure P_p is greater than about twice the ambient pressure and reaches a moderate supersonic free stream test flow (Ref. 12). Fig. 3c is a representation of a supersonic tunnel. Here, relatively large models may be tested for a given arc heater with some simulation of atmospheric flight conditions (Refs. 5,14,20 and 21). The shroud nozzle flow configuration shown in Fig. 3d is an adaptation of the wind tunnel test technique suggested by Ferri and Libby (Ref. 22). It has several advantages in the materials testing area: it allows a large percentage of the heated gas to interact with the model and, therefore, allows the testing of a large model; there is an appreciable latitude in the selection of the model and nozzle shapes; and it is not necessary to experience a total pressure loss through a bow shock wave in front of the model (Ref. 1). The final two configurations, the straight and the contoured pipe models in Figs. 3e and 3f are included to illustrate how an arc heated facility may be tailored to the study of special problems; in this case, turbulent boundary layer flow.

This spectrum of test configurations illustrates the principle of tailoring test flows to meet the requirements of particular reentry studies. The shroud test unit is attractive as a high heating rate facility; that is, it can be used for the study of problems of vehicles that re-enter at high speeds at relatively low altitude A typical approach taken to the design of a shroud unit is shown in Fig. 4. Here the nozzle entrance section has been contoured to match a potential flow stream tube for subsonic spherical flow. Thus, the velocity gradients in the vicinity of the stagnation region are reasonably well known. Experimental pressure distributions in the vicinity of the stagnation point in a 200 kw shroud unit have verified that the potential flow velocity gradient is closely approximated in the stagnation region. Although this is not essential for the use of such a tool, it provides an additional control from which test flow properties can be determined. Standard calibration procedure for the shroud unit is also indicated in Fig. 4. Here, simple throats are inserted into the plenum chamber and the facility is calibrated over a range of throat diameters and pressure, mass flow and power levels according to a technique which requires simply a knowledge of P_p, $\dot{m}$ and d_* (Ref. 23). When model tests are conducted, mass flow and input power levels are set before the model is inserted. The test P_p level, established after insertion of the model, indicates the effective d_* represented by the blockage of the complex test flow. For ablation studies, the model is moved into the nozzle during a test so that P_p and, thus, the effective throat area remains constant. This has proven to be a reliable and repeatable technique.

A photograph of a 200 kw shroud unit in operation is shown in Fig. 5. For this power level, it has been possible to test models up to 2 in. in diam; however, this dimension depends critically upon the pressure level, since the throat clearances become quite small at high pressures. Tests have been conducted in the shroud unit shown in Fig. 5 up to the order of 5 atm. Of course, as the power available goes up, higher pressure levels can be used; however, the model size remains small.

The smaller power level shroud is most practical for use in stagnation region testing; however, for larger power levels it is possible to consider testing away from the stagnation region and possibly into turbulent boundary layer flow regions. Here, when testing ablation systems, the change in shape of the model during a test must be considered.

The instrumentation techniques available for the shroud unit shown in Fig. 5 are listed in Fig. 4.

In Fig. 6, a schematic diagram of a supersonic arc wind tunnel is shown. The main purpose for such a test configuration is to provide a low heating rate environment; that is, the flow is expanded to a Mach number sufficient to reduce the total head in the stagnation region of the model to a level required by simulation considerations. At present, this test philosophy must be followed with arc wind tunnels if it is desired to simulate the stagnation enthalpy of flight. If one attempted to simulate both Mach number and enthalpy at reasonable flight altitudes, the pressure requirements near the orbital velocity would probably be impossible to achieve, since the order of 100,000 psi and the throat cooling problem would be enormously difficult to solve. Mach number levels of usual interest for this type of facility are from 3 to 10 (assuming an equilibrium expansion process; this will be discussed in a later section).

The various sections shown in Fig. 6 are self - explanatory. Usual operation involves the starting of the flow and the coming to equilibrium facility conditions before the model is inserted into the flow. Facilities of this type usually run for long time periods greater than 10 minutes, so that a continuous pumping system is required. For small scale units of the order of 200 kw diffusion and backing pumps are adequate; however, for larger tunnels, ejector systems are generally most practical. A photograph of an early laboratory scale tunnel, Mach 5, is shown in Fig. 7. A more recent design is discussed in detail later in this paper. Typical model measurements for such a tunnel are listed in Fig. 6.

Fig. 8 is a photograph of a large AC air arc facility located at the General Electric Switchgear Development Laboratory in Philadelphia. This facility was developed for the conduction of re-entry studies requiring large model scale, particularly turbulent ablation studies. The insert in Fig. 8 shows the turbulent test configuration used in several test programs; this is the test configuration shown schematically in Fig. 3e. Here, a subsonic pipe model is used to provide a flow of sufficiently high Reynolds number to cause boundary layer transition before fully developed pipe flow is experienced; thus, an essentially constant pressure or flat plate test configuration is produced (Refs. 1, 7 and 15). Several properties of the turbulent ablation configuration and test procedure should be pointed out. First, there is a bypass port through which the heated gases are exhausted until the unit comes to full operating temperature. A quick opening valve is then actuated to divert the hot flow through the model. Valid test times for as short as 1 sec are thus available. Second, the model is sectioned so that local test data can be obtained. The entrance section is made of the test material and it extends into the plenum chamber of the arc unit. This section is only used to establish the flow; data are not taken from it. Third, ablation tests are conducted for various flow time durations. Since the model area is varying during a test, data for each station of the model must be interpreted on a rate basis (mass loss, area change and nonablating heating rate). Fourth, facility calibration is accomplished in the same manner as for the shroud (Fig. 4); i.e., a series of short calibrator nozzles are substituted for the turbulent flow equipment. The blockage from the test set-up is then correlated with the calibrator exit diameter data to give the proper entrance flow conditions to the pipe models. It is to be noted that this approach to calibration eliminates the need for estimating the exit area reducing effect of boundary layer growth through the model and nozzle; if this effect is neglected, an overestimate of the test gas stagnation enthalpy will result. Fifth, nonablating calorimeter data is obtained through the use of highly cooled copper models in place of the test model. Sixth, heat transfer rate and shear stress can be varied independently to some extent by using models of various internal diameter. This provides a degree of flexibility in the test procedure and allows the investigation of the effects of these two parameters which are important in the performance of many ablation materials.

Turbulent ablation data have been obtained with the arc unit and test configuration equipment shown in Fig. 8 at power levels of up to about 2 mw (in the air), at enthalpy levels of up to 5000 Btu/lb and at plenum pressure levels to 12 atm. The model is 1 ft long and has an inner diameter of approximately 1 in.

It is interesting to relate the performance of various test configurations to flight conditions. Fig. 9 is a stagnation enthalpy-stagnation pressure map upon which are given the performance characteristics of a typical arc wind tunnel. The coordinate scales in Fig. 9 are the same as for the re-entry flight spectrum shown in Fig. 1a, so that an estimate of facility simulation of flight conditions can be obtained by comparing these two figures. The assumed arc operation limit is, the authors believe, a reasonable estimate of what will be available in the near future. In the higher enthalpy regions this estimate is based upon the results of air arc development work that has been conducted by McGinn at the General Electric Space Sciences Laboratory in Philadelphia (Ref. 16). At the higher pressure levels the limit is estimated considering gaseous radiation losses and practical efficiency ranges.

A probable shroud operating range for such an arc heater capability is indicated in Fig. 9. As discussed earlier, the choice of shroud test conditions depends upon several items (e.g., test objectives and power level) and, therefore, the limits shown are somewhat arbitrary. Pipe model testing of the type discussed (subsonic pipe) would be obtained with a maximum test condition a few atmospheres lower than the estimated plenum conditions. The wide property coverage of the arc wind tunnel is obtained through the use of a wide range of test section effective area ratios. High performance, in terms of high pressure levels, can be obtained at small area ratios; however, the test section size, as indicated by the $d_e/\sqrt{E}$ lines on Fig. 9 is quite small in these regimes unless a large amount of test gas power E is available. It can be seen that large test sections of the type with which the investigators are familiar in lower temperature wind tunnels will require the development of significantly higher power arcs than those now existing. The equilibrium flow Mach number for various points on the operation map are also shown in Fig. 9. Since the assumption of equilibrium expansion through the nozzle is questionable, particularly in the low plenum pressure regions, these numbers have only a qualitative value at best.

Air Arc Facility Limitations

During the previous discussions a number of arc problems have been mentioned. These will now be discussed briefly.

Electrode material contamination is detrimental to the conduction of re-entry tests in arc facilities in several respects. First, if the electrode material is present in reasonable quantities and is in the gaseous state, the chemical composition of the test gas will be different from that encountered in flight.

This can be particularly important for arcs with carbon electrodes and in tests in which the behavior of the material depends upon the oxidation of its surface, since a relatively small contamination level will deplete a much larger percentage of the available oxygen in the test gas. Second, the contamination in the form of large particles can have an adverse effect upon test results, and it is difficult to estimate the importance of this effect. Third, the presence of strongly radiating contaminants in the test gas can reduce the efficiency of an arc unit particularly at the higher pressure levels. It can also cause variable test conditions in internal flow systems such as the pipe test system discussed earlier. Fortunately, it is now possible to reduce contamination levels to negligible amounts through the use of specially designed arc heaters such as that shown in Fig. 2g. References 24 and 25 describe some of the work that has been done on this problem.

Radiation losses limit the performance of arc heaters in a manner similar to that shown in Fig. 9; i.e., at high pressures lower enthalpies are available. These limits can be extended somewhat at the expense of very low efficiency or through the elimination or reduction in size of the plenum chambers (increase in flow non-uniformity). Radiation loss intensities and characteristic time estimates for pure optically thin air are given in Ref. 7. For contaminated arcs and at pressure levels where the gas is no longer optically thin, however, these estimates are probably nonconservative.

In high enthalpy and associated low plenum pressure operation of an arc wind tunnel, the gas will undoubtedly be far from its equilibrium composition and energy partition levels during expansion from the nozzle to the test section at any appreciable area ratio, even if in equilibrium in the plenum chamber. This conclusion is based upon analytical (Refs. 26 and 27) and experimental (Ref. 28) investigations of similar flows and upon data presented later in this paper. This raises several questions concerning the usefulness of such a facility for aerodynamic studies although it has been suggested, for example by Whalen (Ref. 29), that the resultant high frozen "Mach" number flows might be useful with the proper interpretation in terms of classical hypersonic parameters. It is also possible that the availability of nonequilibrium analyses, such as those described by Langelo (Ref. 30), will provide us with a powerful experimental tool through which both the kinetics of reacting and flowing gases and the effects of nonequilibrium flows on complex shapes may be studied. This suggests that a considerable amount of effort must still be expended in this area of arc facility research.

Another serious problem associated with high enthalpy, low pressure wind tunnel operation is the rapid growth of nozzle boundary layers at relatively low nozzle Reynolds numbers. Data presented in a later section of this paper illustrate this problem.

A final difficulty with air arc test facilities is the existence of property nonuniformities and gradients in the test flow. These are presumably caused both by the oscillations of the arc column and by the strong cooling requirements in the upstream plenum chamber and nozzle sections. Photocell observations of test flows show as much as a 50% high frequency (order of 1000 cps) fluctuation in light intensity in facilities that are believed to be relatively steady. Although the variation in properties, such as stagnation enthalpy, is by no means of the same order of magnitude (as interpreted from simultaneous measurements of power fluctuations), it is difficult to estimate the effects of such random fluctuations, particularly in aerodynamic applications.

PERFORMANCE OF AN ARC HEATED WIND TUNNEL

Facility Description

The remainder of the paper will be concerned with studies conducted in a moderately high Mach number air arc wind tunnel developed recently at the General Electric Space Sciences Laboratory. Fig. 10 is a photograph of the tunnel; the arc heater is of the tandem Gerdien or divided flow (Fig. 2g) type and is mounted in the vertical position. The vertical orientation was chosen in order to minimize space and because of certain conveniences in operation of the unit. A close-up of the heater itself is shown in Fig. 11. As would be expected in any continuous flow arc heater design, the necessary water lines tend to mask the actual hardware. The upper and lower chambers are the anode and cathode housings, respectively. A portion of the entering air flows through these housings, mixes with the carbon eroded from the electrodes, and exhausts from the system. The test air is heated in the arc column and collected in the plenum located at the center of the unit. The gas is then expanded through the sonic throat and a conical nozzle to the test section. It next passes through a diffuser, heat exchanger and finally a two stage mechanical vacuum pumping system. The test section is of the free jet type with the models mounted downstream and just ahead of the diffuser inlet. The nozzle is conical (21-1/4 deg included angle) and can be shortened from its usual length (4-7/8 in. exit diam) to a point where the exit diam is 1-3/16 in. Tests can be run in the large and small test sections, geometric A/A* values of 1000 and 58, respectively, and at intermediate area ratios by moving the model into the large nozzle. Fig. 12 shows a typical model in the flow of the large nozzle photographed through the test section windows.

The tandem Gerdien arc heater provides clean flows of air at high stagnation enthalpy levels for long running times. Spectroscopic studies performed on the gas exiting from the plenum have shown it to be free of contamination to the order of 100 ppm at stagnation enthalpy values (h_s/RT_0) of the order of 400. At these conditions running times up to 15 min duration have been obtained, although modifications are now being planned to permit continuous operation in excess of 1 hr.

Test Flow Calibration

In order to establish the flow properties at the various operating conditions, it is necessary to examine the flow in detail. The following measurements have been made at a relatively high enthalpy test condition: impact pressure and stagnation point heat transfer profiles across several nozzle stations, nozzle wall static pressure distributions and test gas stagnation enthalpy. Conclusions drawn from these data are discussed in this section. Some of the equipment used in the calibration study is shown in Fig. 13. Included in this figure is a photograph of a model balance which has been developed for the measurement of model forces (three component).

As with all arc test facilities, an important measurement is the stagnation enthalpy level of the test gas. It is possible to do this in a number of ways. For example, the following measurements will give or lead to the total enthalpy: power to the unit and losses from it; local gas temperature spectrographically and local pressure; energy in test gas, locally and totally; heat transfer to a model and local velocity gradient; mass flow through sonic restriction from known plenum pressure level; and free stream velocity measurements in a highly expanded flow. Although each of these will give the correct information if the measurements are exacting, some approaches appear to be less difficult and more probable of supplying the correct information. Also, the design and operation of this particular arc heater influences the choice of methods.

Owing to the inherent difficulties in measuring heat losses in the test hardware and the uncertainties of flow equilibrium associated with nozzle flows, the authors have concentrated on two stagnation enthalpy measurements. These are gas temperature obtained spectroscopically at the choken throat, and total calorimetry of the gas exiting from the plenum chamber. A special nozzle terminating at the throat is used for these measurements. Provision is made for observation of the gas at the throat through a window slit arrangement from the side. The spectroscopic temperature measurement is made by ratioing the intensities of two atomic oxygen lines, 7947/7774A (Ref. 31). This procedure leads to an exitation temperature. The accuracy of the measurement in the vicinity of 8000 K is estimated to be ± 200 K. Assuming flow equilibrium, this implies an accuracy of ± 5% in stagnation enthalpy. The instrument used in this work is a Jarrell-Ash F6.3 spectrograph. Simultaneously with the spectroscopic measurement, a total calorimeter is fastened to the unit so that it can accept the hot gas emerging from the throat, extract the heat from it, and measure its flow rate; this permits calculation of the heat content of the gas. Care was taken to minimize the losses that could occur in such an arrangement by keeping the contact between the calorimeter and the arc or tunnel hardware to a minimum (wherever necessary line contact was used). To minimize gaseous radiation losses, the distance between the two pieces is limited to the optical slit width for spectrographic requirements. A photograph and a schematic drawing of the calorimeter are shown in Fig. 14. Because of the high temperature of the flow, it was decided to investigate the radiative loss from the gas as the flow expanded downstream of the throat in the test nozzle. Another calorimeter was built which connected to the short nozzle (A/A^* 58) and allowed a stagnation enthalpy measurement at that station.

The results of the stagnation enthalpy measurements at the nominal test point were as follows:

Spectrographic	$h_s/RT_o = 400 \pm 5\%$
Calorimeter (throat)	$h_s/RT_o = 355 \pm 3\%$
Calorimeter ($A/A^* = 58$)	$h_s/RT_o = 335 \pm 3\%$

These data were obtained for an average of five runs per measurement. The differences in levels are expected. As shown in Fig. 16, the stagnation enthalpy varies across the flow; this is undoubtedly caused by the strong upstream cooling experienced by the test gas as well as by boundary layer cooling. An integrated total enthalpy measurement gives a weighted average and does not specify the value higher than the average near the axis of the flow. Since the spectroscopic measurement responds primarily to the maximum temperature regions of the jet, it will give a stagnation enthalpy somewhat higher than the average value. Also, any losses in the calorimeter system will tend to reduce the apparent average enthalpy. The mass flux distribution at the downstream stations has not yet been measured and therefore, absolute values cannot be assigned of enthalpy level to the distributions shown in Fig. 16. The calorimeter measurement downstream is approximately five percent below the throat calorimeter value. When one considers the boundary layer losses in the nozzle section, it may be concluded that the radiative losses from the gases expanding downstream of the throat are negligible. One other point should be mentioned. The spectroscopic enthalpy measurement is actually based upon an electronic temperature. The relatively good agreement, therefore, between this measurement and the calorimeter data indicates that the throat flow is in thermodynamic and chemical equilibrium. From these studies, it may be concluded that the stagnation enthalpy of the test gas in the useful center core region is bracketed by the throat measurements and, therefore, is reasonably well known. It is probably closer to the spectroscopic than to the calorimeter value because of the profile considerations and possibilities of unaccounted-for losses that have been discussed.

The nozzle flow was examined in some detail through the use of impact probe and stagnation point heat transfer probe rakes and through the measurement of wall static pressure distribution. The results of these studies are shown in Figs. 15, 16 and 17.

In Fig. 15, the effective area ratio as a function of nozzle axial length is shown. The experimental band was determined as shown in Fig. 17a. In this figure it is seen that the spread of area ratio for different constant γ (and equilibrium) expansions is relatively small for a measured P_{s_o} value. This is expected, since the impact probe provides essentially a measurement of momentum flux. The various γ values are used primarily for illustrative purposes, although the $\gamma = 1.58$ curve (see Fig. 17) has a significant physical interpretation: it refers to a frozen expansion from throat conditions in which only the translational and rotational degrees of freedom are involved. The wide spread in static pressure for expansions in various degrees of nonequilibrium is pointed out in Ref. 28 and used there to investigate expansion processes in shock tunnel nozzle flows. The impact pressures, measured at several X/L stations in the nozzle, are plotted in Fig. 17. Since the flow properties will be somewhere between the frozen and equilibrium conditions, the level of possible effective area ratios for each measured pressure level is bound by these calculated values. These levels are plotted in Fig. 15. An effective boundary layer thickness distribution, based upon this area ratio measurement, is shown in this figure.

It is interesting to compare the effective area ratio distribution with several prediction techniques. Boundary layer displacement thickness based upon the prediction of Lee (Ref. 32) and upon an approximate laminar calculation are shown in Fig. 15. The Lee prediction is for a turbulent boundary layer. The laminar analysis involved a step by step calculation down the nozzle in which flat plate solutions were matched for each section by matching displacement thickness. The results of Van Driest (Ref. 33), Chapman and Rubesin (Ref. 34) and Low (Ref. 35) were used to calculate the displacement thickness for each step. The data in Fig. 15 obviously compare better with the laminar prediction band indicated by the $\gamma = 1.1$ and $\gamma = 1.6$ curves than with the turbulent calculation. Thus, the conclusion is drawn that the nozzle boundary layer is laminar. This might be expected, since the local Reynolds number based upon distance from the throat is always less than 10^4. The relatively good agreement between the data and the $\gamma = 1.1$ calculation (which is close in properties to the equilibrium case; see Fig. 17) is interesting; however, because of the many assumptions used in the analysis (constant γ, for example) it cannot be concluded at this time that this agreement provides any quantitative information on the state of the gas during nozzle expansion.

The profiles shown in Fig. 16 show conditions at two nozzle stations. Actually, one is slightly downstream of the nozzle exit. Here, the boundary layer appears to have merged as indicated by both the impact pressure and heat transfer profiles. This is also suggested by the axial impact pressure data as interpreted in terms of area ratio in Fig. 15. The generally smoothly rising A/A^* band is observed to droop just upstream of the $X/L = 1.02$ station. A small but definite core is seen to exist for the $X/L = 0.8$ station. The Mach number profile for the two stations are calculated from measured impact and static pressure data assuming a constant γ process. (The normalized profile is insensitive to the assumed γ value.) The stagnation enthalpy profile is based upon the assumption of Newtonian stagnation point velocity gradient and the measured impact pressure and heat transfer data.

Static pressure data along the nozzle wall are shown in Fig. 17, plotted against curves for various γ values and for equilibrium expansion. The spread of area ratio for each static pressure station is determined from the impact pressure data and calculated curves in Fig. 17. Thus, the intersection of the static pressure line with the dashed line indicates a particular area ratio and γ value for the expansion to different downstream nozzle stations. At present, it is difficult to attach any physical significance to these results, since they do not agree well with either the equilibrium or frozen expansion curves, other than the fact that the expansion process is somewhere between these two limits and probably dominated by neither. It is planned in the future to compare results of this type with nonequilibrium expansion calculations (Refs. 27 and 30) in an attempt to more clearly understand the expansion process.

Because of the present lack of knowledge of the detailed properties of the free stream flow in the arc tunnel, it is difficult to determine the actual flow Mach number in the test section. The indicated centerline Mach number specified in various ways is

$X/L = .80$

	P/P_p	P_s/P_p	P/P_s
Equil.	5.0	4.7	7.0
$\gamma = 1.4$	7.7	8.2	6.5
$\gamma = 1.58$	9.2	10.3	6.1

$X/L = 1.02$

	P/P_s
Equil.	7.8
$\gamma = 1.4$	7.1
$\gamma = 1.58$	6.7

This table shows an appreciable Mach number uncertainty. However, it is thought that this is not a serious restriction, since local model surface properties and stagnation enthalpy are the variables of primary importance for most current uses of arc wind tunnels. Also, it is again pointed out that a tool of this type can be used in helping to investigate high energy expansion processes and may be more useful in the future as an aerodynamic tool when these processes are understood.

CONCLUSIONS

The air arc heater in combination with various test flow configurations has proven to be a versatile tool for the simulation of many re-entry environments. At present, however, its use appears to be limited to heat protection system studies when stagnation enthalpy simulation is required. It may be possible, however, to extend its capabilities to aerodynamic studies through improvements in arc performance and through investigation of the details of nozzle expansion processes. Extensions that are indicated are, first, an incorporation of improved instrumentation techniques (such as are discussed in Ref. 36), so that local test section properties will be known in detail and, second, comparison with appropriate nonequilibrium theoretical predictions, so that an understanding of nonequilibrium expanding flows will be obtained.

The performance of a high purity air arc heated wind tunnel has been investigated at moderately high enthalpy test conditions. Several conclusions were reached:

1) The wall boundary layer merges near the end of the nozzle.

2) The nozzle boundary layer is laminar and its thickness is reasonably well predicted by a simplified analytical prediction.

3) The flow at the nozzle throat is in equilibrium.

4) The flow expanding through the nozzle is not in equilibrium. Also, it is not completely frozen. Although they do not properly predict all flow properties, it is convenient to use constant γ expansion processes for characterizing the flow in an arc tunnel.

ACKNOWLEDGMENT

The authors are indebted to several people for their assistance in the present study. In particular, thanks are given to W. Heard, J. Logan and G. Catalano, who operated the experimental facilities; H. Sadjian, R. Harner and their associates, who obtained the measurements of gas temperatures; R. Geiger, whose advice assisted in the interpretation of the experimental results; and J. McGinn, who provided continuous counsel on the design and operation of the tandem-Gerdien arc heater.

NOMENCLATURE

d = diameter
h = enthalpy
$\dot{m}$ = mass flow rate
q = heat transfer rate per ft^2
t = time
A = area
E = power added to the test gas
L = length
M = Mach number
P = pressure
Q = total heat transferred per ft^2
R = universal gas content
RT_o = 33.86 Btu/lb
T = temperature
U = velocity
X = axial length
γ = specific heat ratio
δ^* = boundary layer displacement thickness

Subscripts

s = stagnation region
p = plenum chamber
e = nozzle exit
$*$ = nozzle throat
o = nozzle axis
g = glide vehicle

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Table 1 Characteristics of re-entry problem areas - air arc facilities.

Heat protection systems	ablating re-radiating
Test objective	material performance structural response and performance structural integrity aerothermoelastic response fatigue and life performance relative aerodynamic effects
Local flow conditions	body station shear stress level pressure level and gradient convective heating level radiative heating level boundary layer (laminar, turbulent) local free stream conditions
Type of response	steady state transient

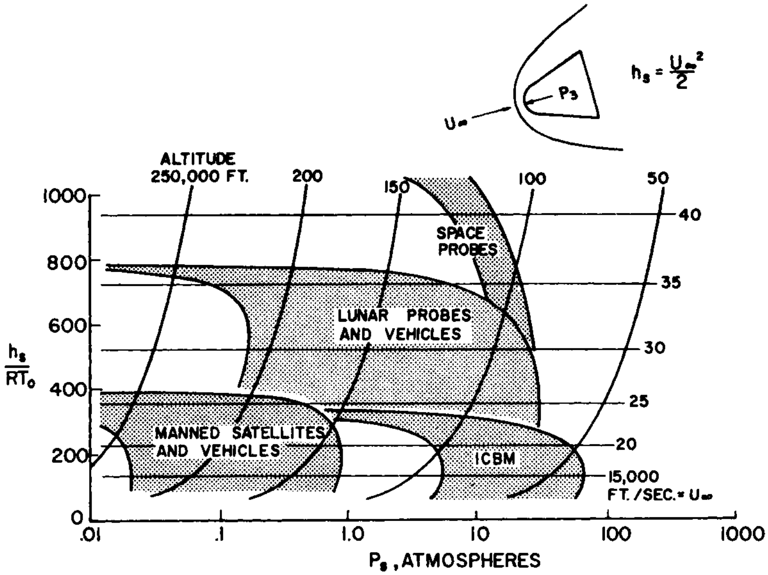


Fig. 1a Re-entry vehicle flight spectrum.

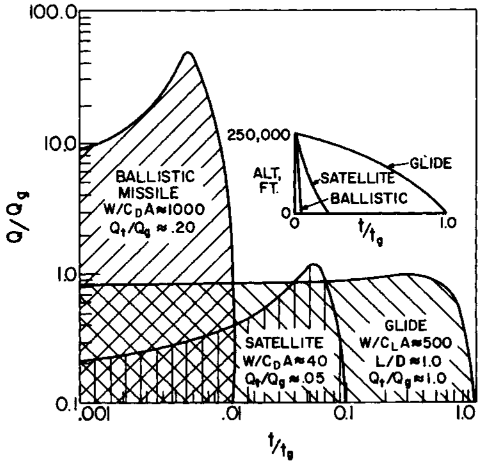


Fig. 1b Typical re-entry heating cycles.

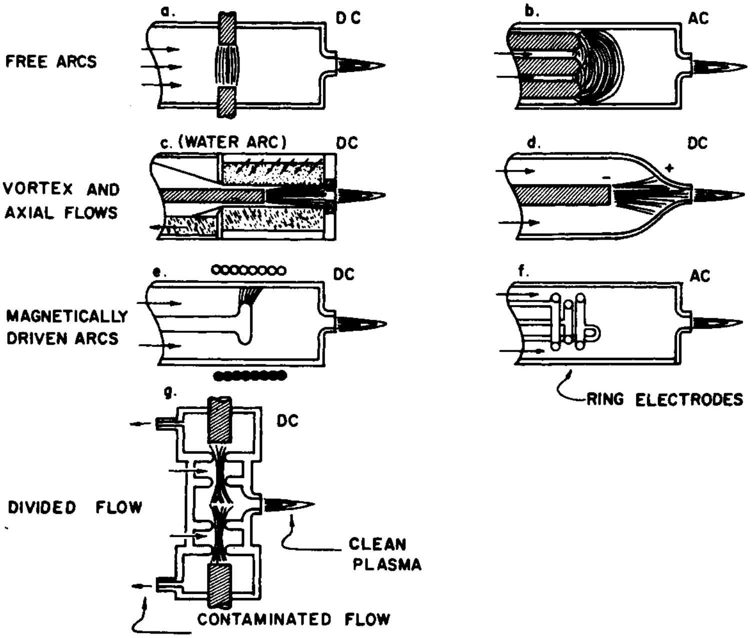
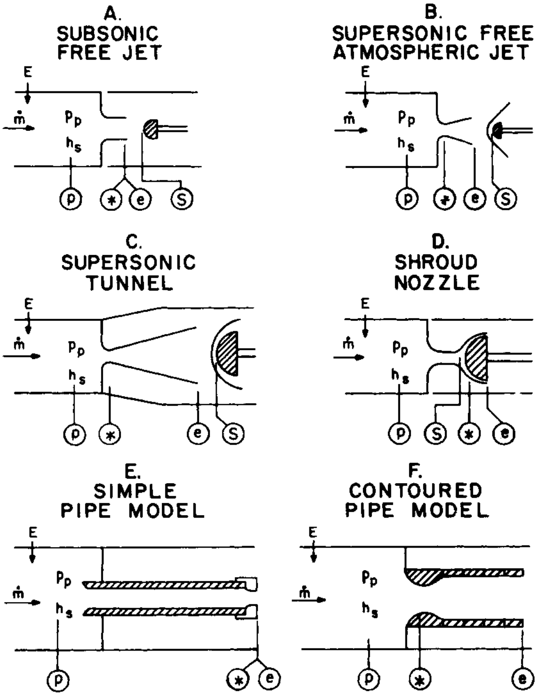


Fig. 2 Several types of arc heaters.


A. SUBSONIC FREE JET

B. SUPERSONIC FREE ATMOSPHERIC JET

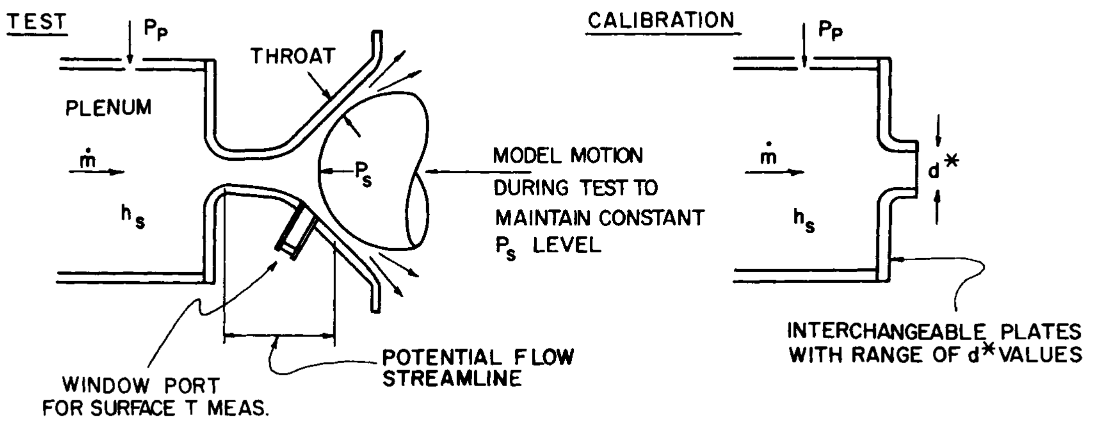
C. SUPERSONIC TUNNEL

D. SHROUD NOZZLE

E. SIMPLE PIPE MODEL

F. CONTOURED PIPE MODEL

Fig. 3 Test configurations for arc facilities.



TYPICAL TEST MEASUREMENTS

MODEL

1. SURFACE TEMPERATURE
2. SUB-SURFACE AND BACKWALL TEMPERATURE
3. SURFACE PRESSURE
4. SURFACE HEAT TRANSFER RATES-NON-ABLATING
5. ABLATION RATE-LOCAL AND TOTAL

FACILTY AND CALIBRATION

1. VOLTAGE
2. CURRENT
3. ELECTRODE EROSION RATE (IF APPROPRIATE)
4. AIR MASS FLOW RATE
5. PLENUM PRESSURE
6. GAS TEMPERATURE - THROAT
7. GAS TEMPERATURE - PLENUM

Fig. 4 Characteristics of shroud arc test facility.

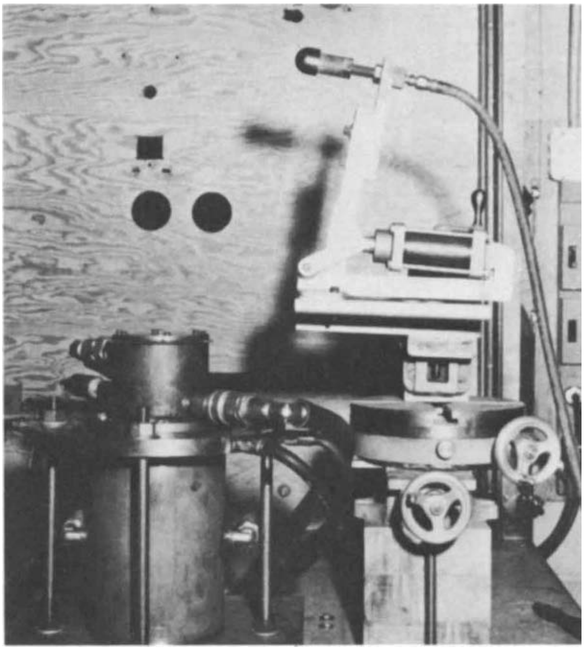
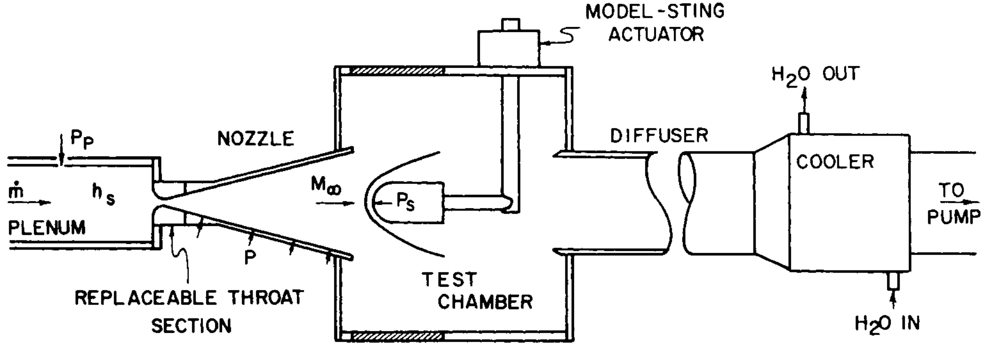


Fig. 5a Model out.

Fig. 5b Ablation test in shroud arc facility.



TYPICAL TEST MEASUREMENTS

MODEL

1. SURFACE T
2. SUB-SURFACE AND BACKWALL T
3. SURFACE P
4. SURFACE $\dot{q}_o$
5. ABLATION RATE - LOCAL AND TOTAL
6. FORCES - 3 COMPONENT
7. FLOW PHOTOGRAPHY

FACILITY AND CALIBRATION

1. VOLTAGE AND CURRENT
2. ELECTRODE EROSION RATE (IF APPROPRIATE)
3. AIR MASS FLOW RATE
4. P_P
5. GAS T - THROAT, PLENUM, TEST SECTION
6. h_s CALORIMETER - TEST GAS
7. NOZZLE STATIC PRESSURE - P
8. $\dot{q}_o$ PROFILES - TEST SECTION
9. P_s PROFILES - TEST SECTION
10. LUMINOSITY FLUCTUATIONS - TEST GAS

Fig. 6 Characteristics of supersonic arc wind tunnel.

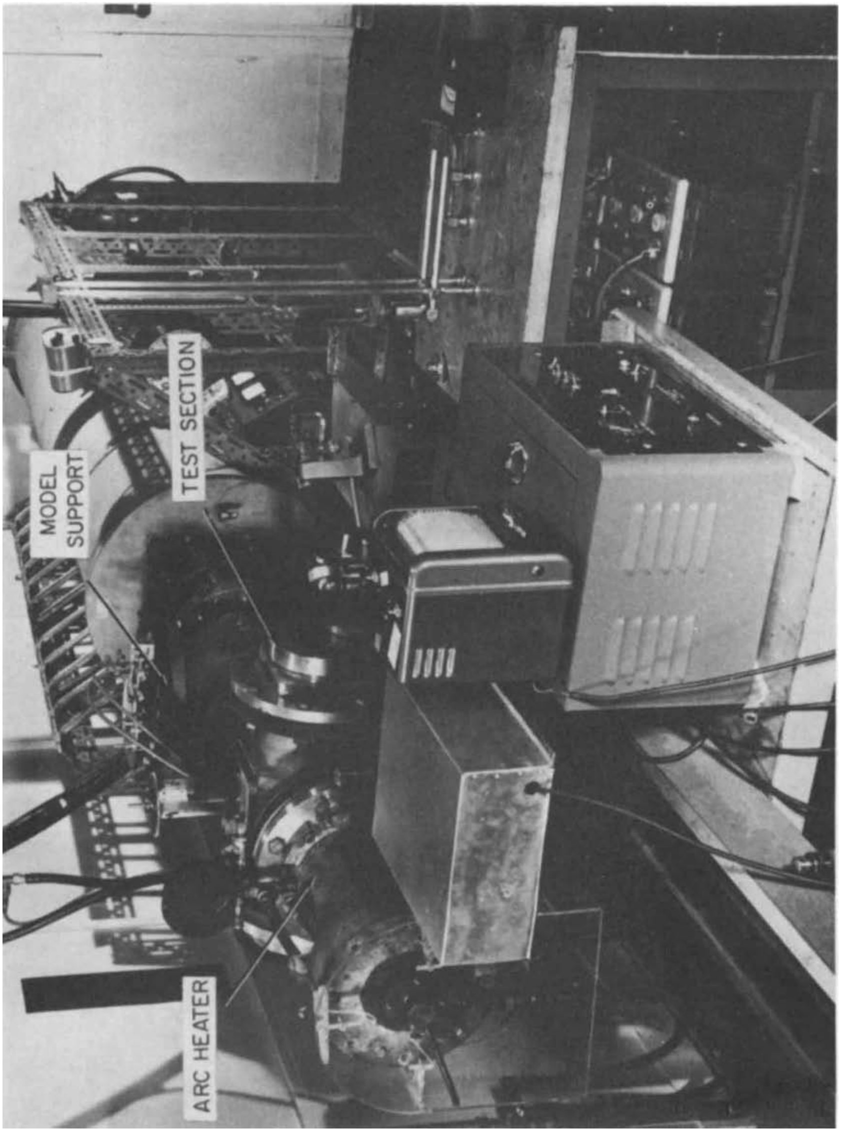


Fig. 7 Supersonic arc wind tunnel.

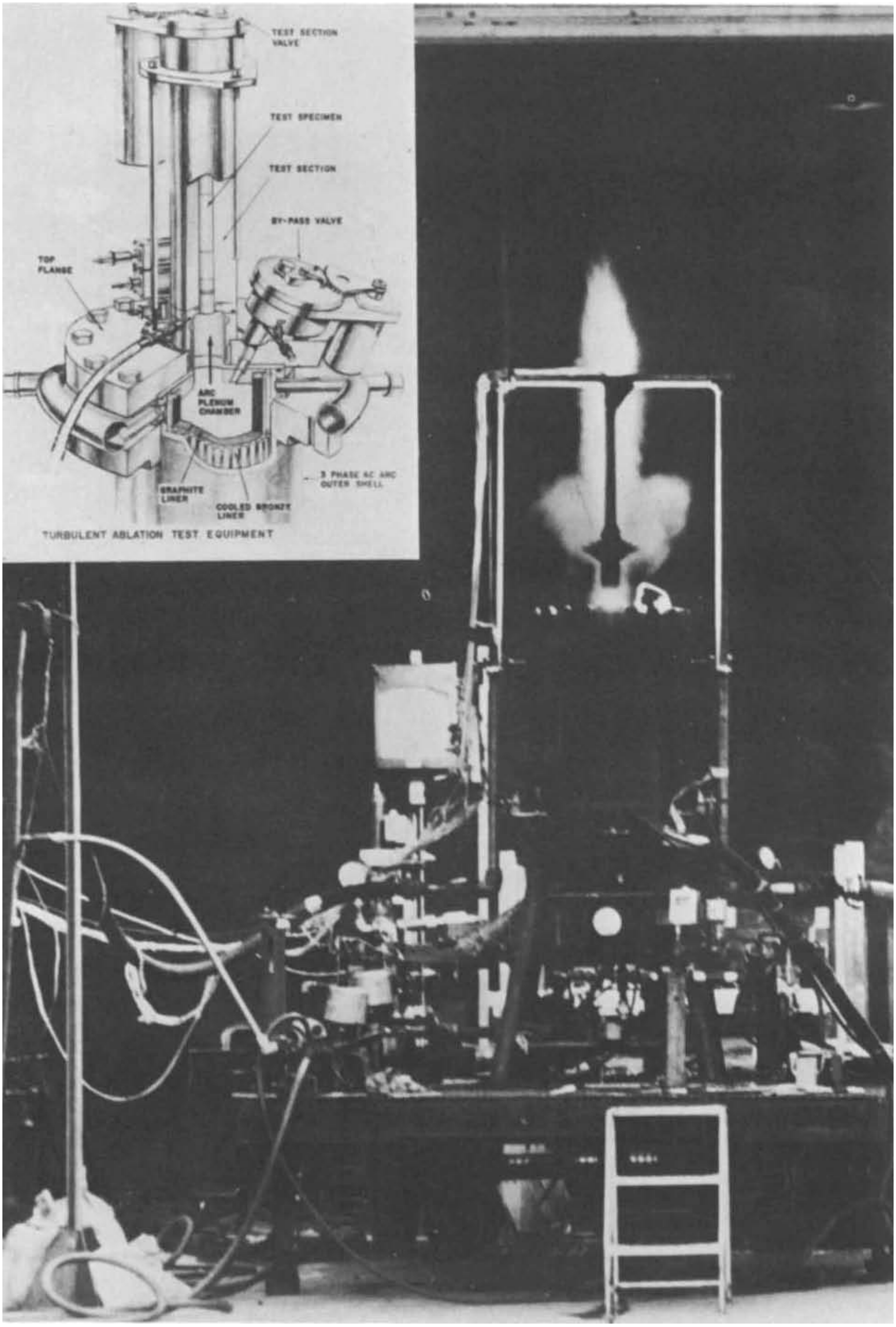
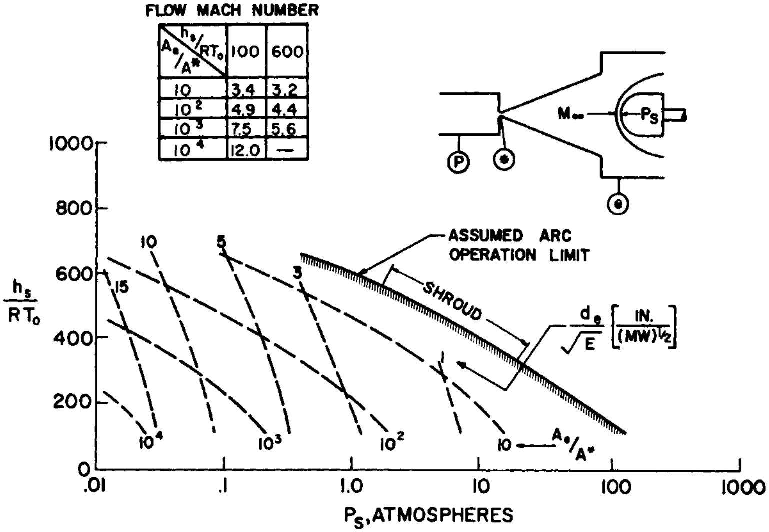


Fig. 8 Turbulent ablation facility.



FLOW MACH NUMBER

A_e/A^* \ h_s/RT_0	100	600
10	3.4	3.2
10^2	4.9	4.4
10^3	7.5	5.6
10^4	12.0	—

Fig. 9 Characteristics of arc wind tunnels.

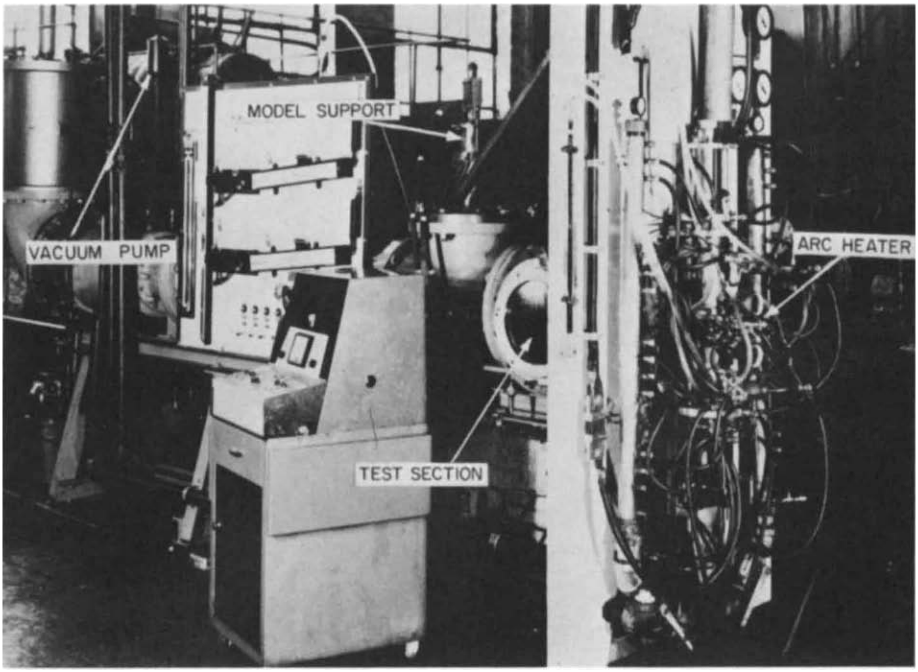


Fig. 10 Hypersonic air wind tunnel.

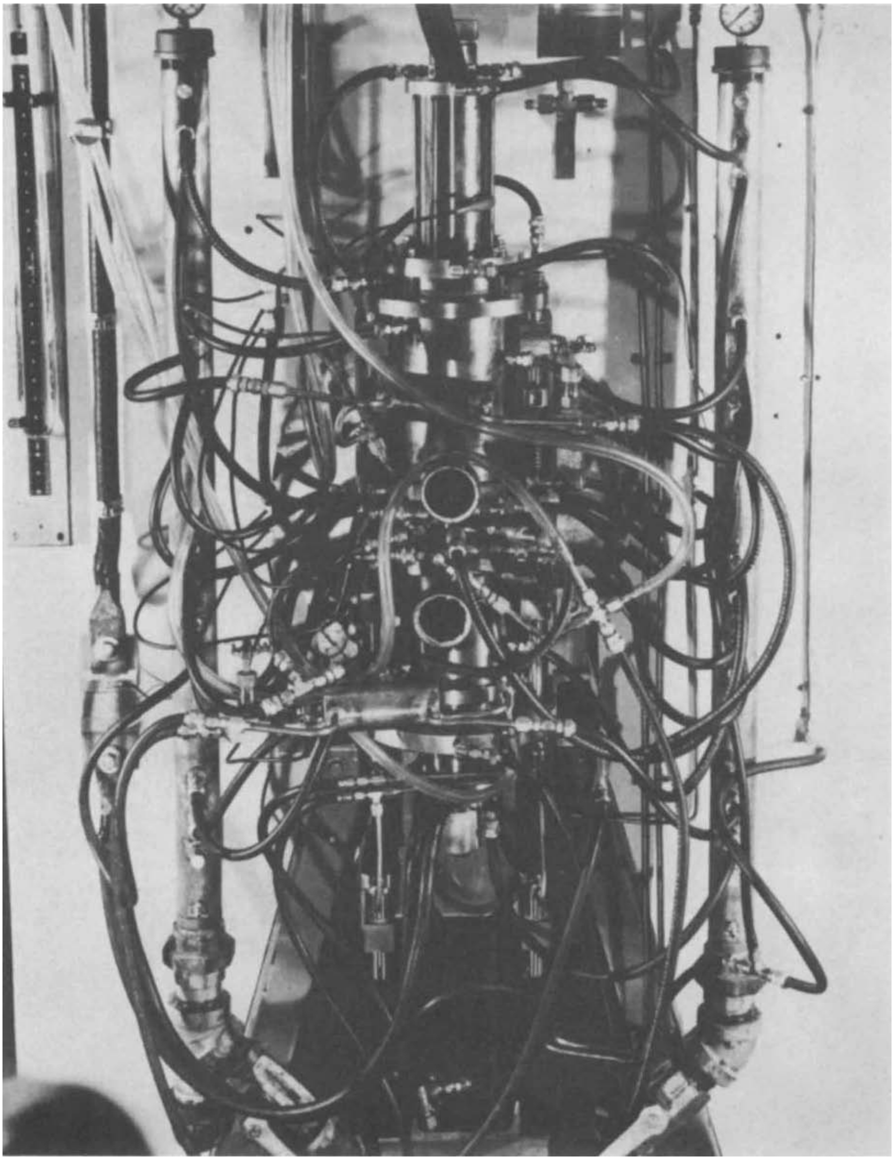


Fig. 11 Arc heater - hypersonic wind tunnel.

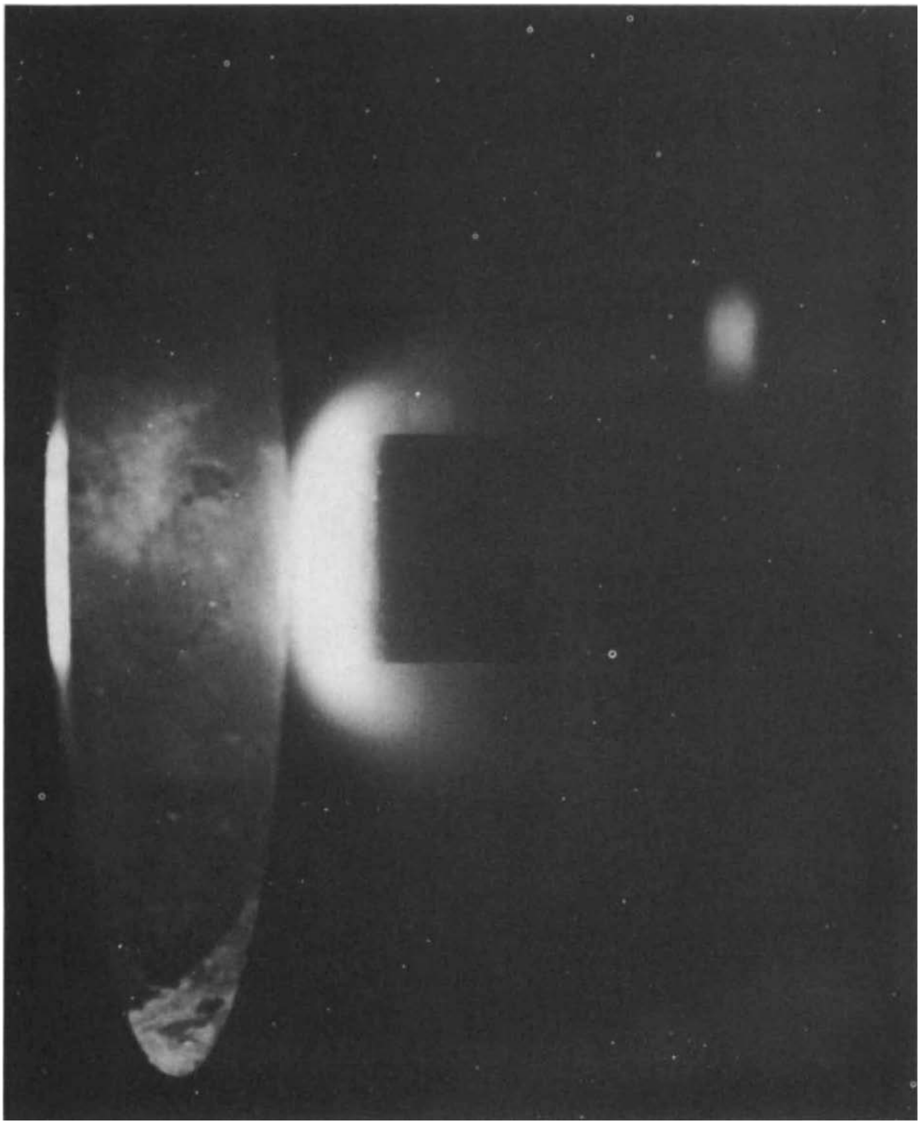


Fig. 12 Model in test flow - hypersonic arc tunnel. $d_m = 1$ in. and $h_s/RT_0 = 398$.

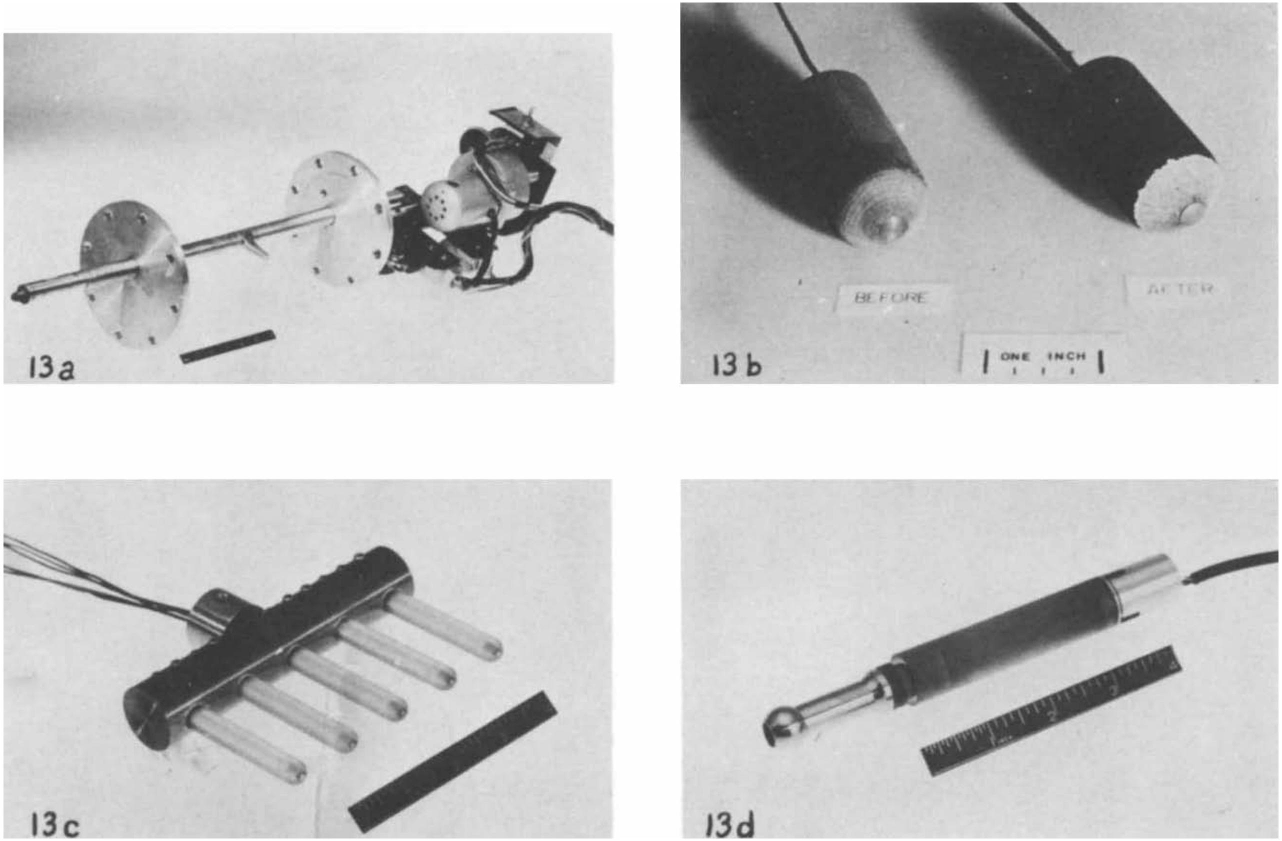


Fig. 13 Test instrumentation: a) pressure probe; b) model calorimeter; c) heat transfer rake; d) model force balance.

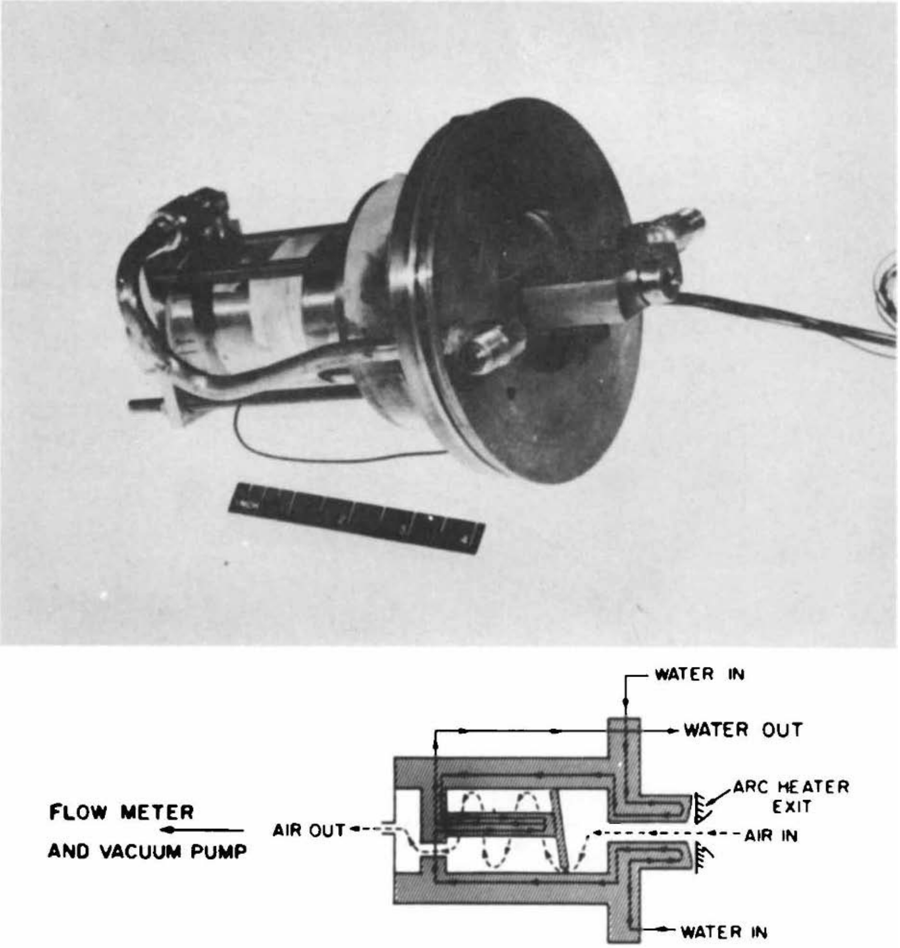


Fig. 14 Total enthalpy calorimeter.

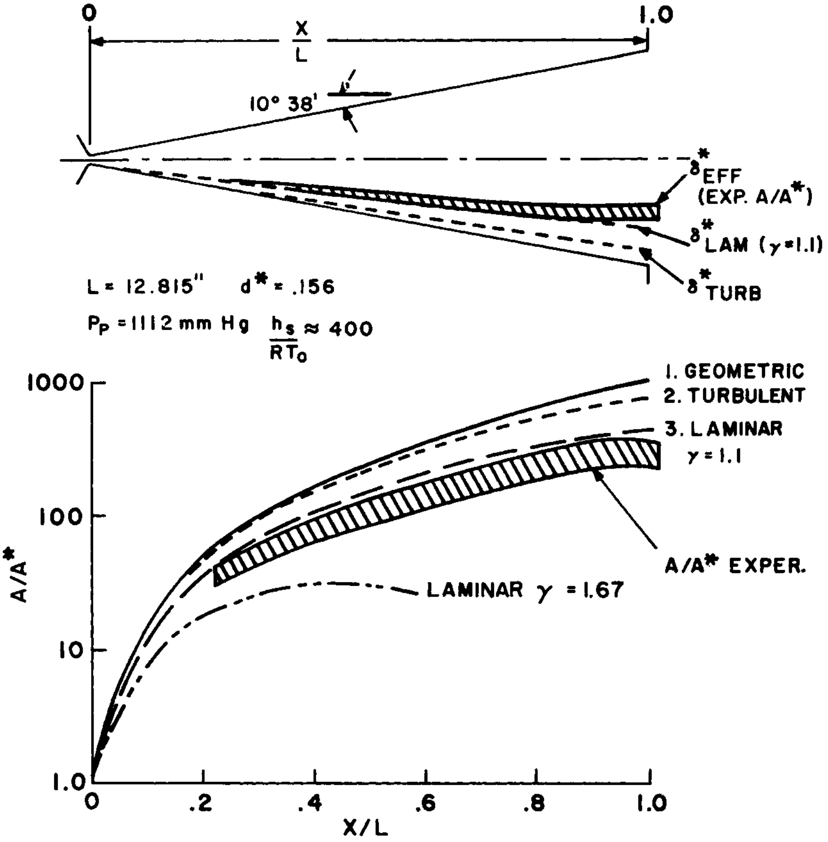


Fig. 15 Boundary layer development and effective area ratio in hypersonic air arc tunnel.

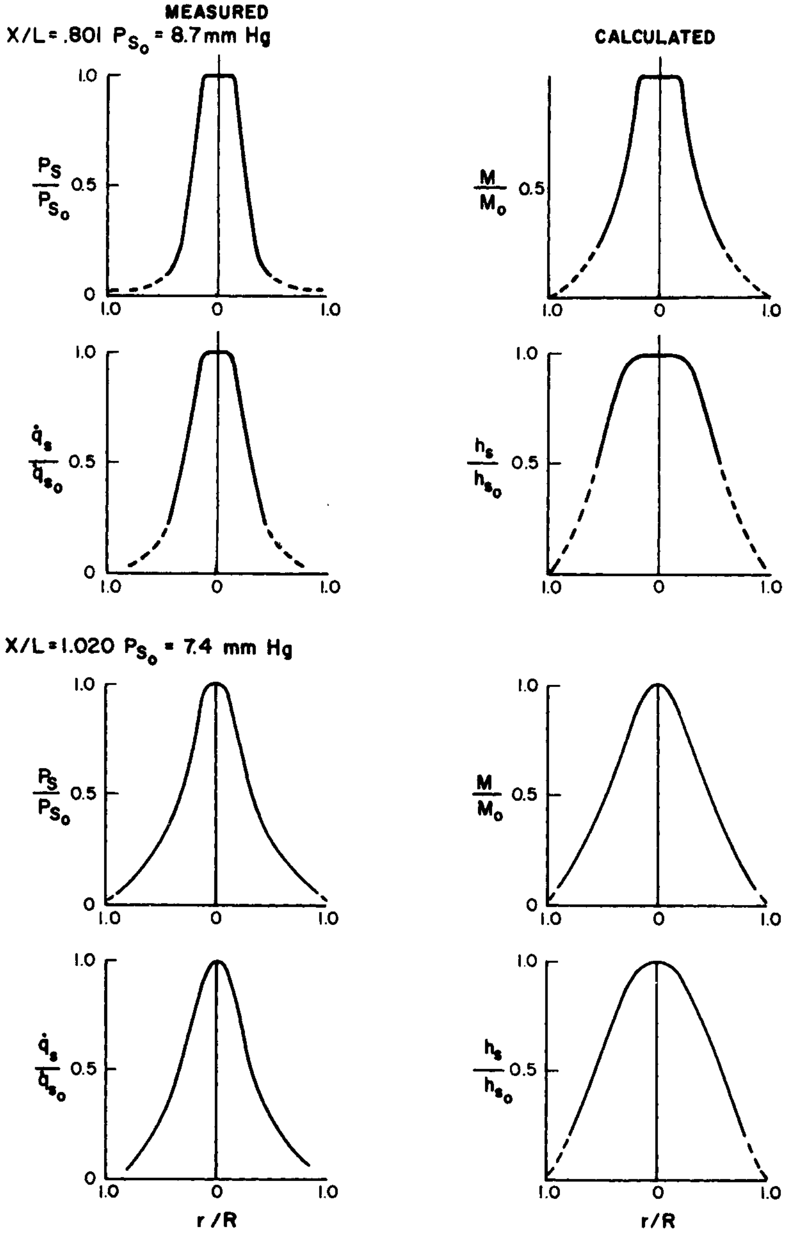


Fig. 16 Typical nozzle profiles of hypersonic arc tunnel; P_p = 1112 mm Hg $\frac{h_s}{RT_o} \approx 400$.

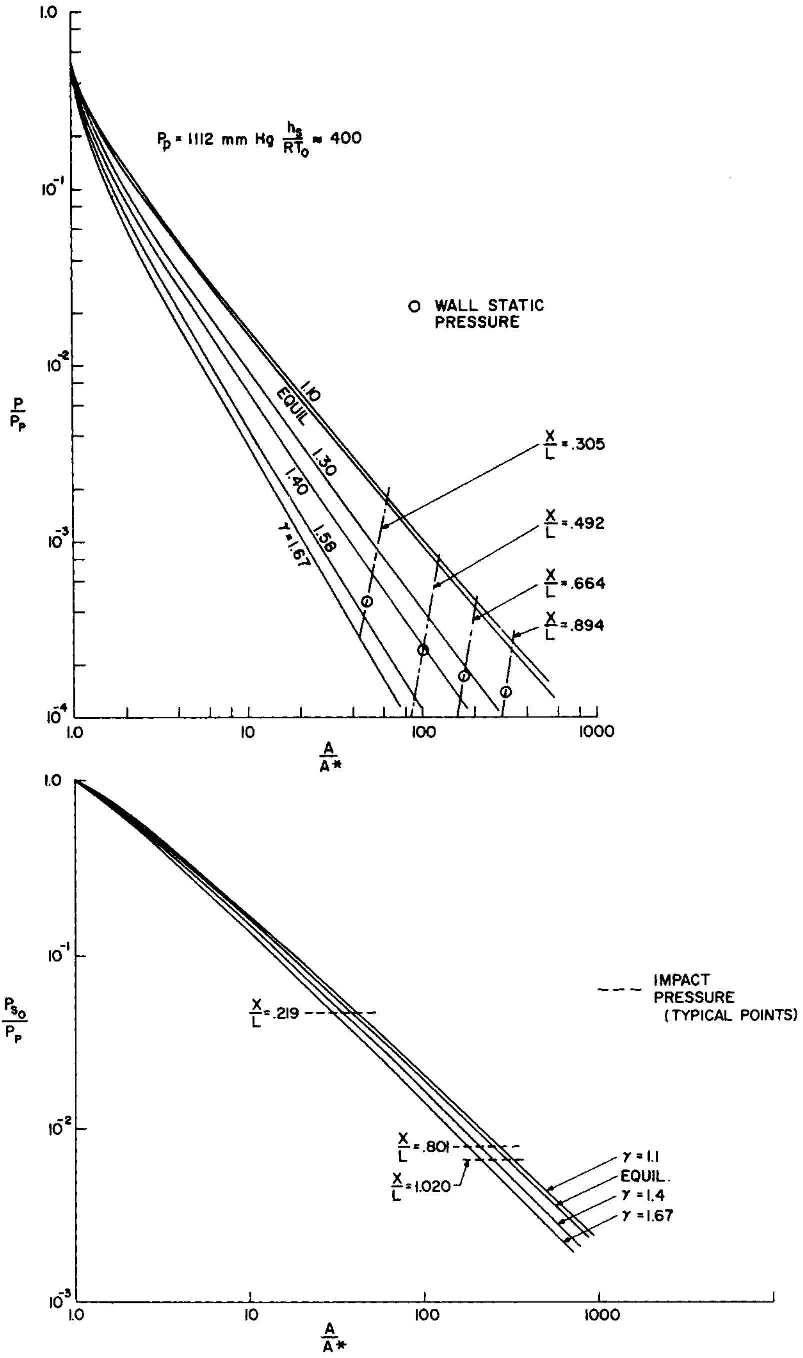


Fig. 17 Nozzle pressure measurements of hypersonic arc tunnel.