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DESCRIPTION AND INITIAL CALIBRATION OF THE LANGLEY 20-INCH HYPERSONIC ARC-HEATED TUNNEL

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SUMMARY

The Langley 20-inch hypersonic arc-heated tunnel with water-cooled copper electrodes and a direct-current power supply was developed to investigate reentry types of thermal protective materials. During the initial operation of the arc heater, four different throat sizes (0.483, 0.680, 0.965, and 1.366 cm) were investigated to determine the effect of throat size on arc-heater performance. The 1.366-centimeter-diameter throat was found to be the most efficient. Also, three different center electrodes were evaluated, and electrode size and shape were found to have a large effect on arc-heater performance.

At the present time, this tunnel has an enthalpy range from 2790 to 27 900 kJ/kg. Four interchangeable nozzles (5.08-, 8.39-, 16.75-, and 50.80-cm exits) are used to vary heating rate and model stagnation pressure at fixed arc-heater conditions. With these four nozzles the heating rate can be varied from 17 to 1700 W/cm^2 (on a 3.81-cm-diameter hemisphere-cylinder model), and the model stagnation pressure can be varied from 0.01 to 2.7 atmospheres. Hemisphere-cylinder models up to 10.15 centimeters in diameter have been tested in the 50.80-centimeter nozzle exit, and models up to 6.35 centimeters in diameter have been tested in the 16.75-centimeter nozzle exit.

INTRODUCTION

The continuing need to improve and optimize vehicles for reentry and hypersonic flight requires more refined ground test facilities capable of producing high-enthalpy hypersonic airstreams suitable for research on problems resulting from aerodynamic heating in the oxidizing reentry environment. Because the attainment of this goal requires an effective system for heating air, a general research program to develop electric arc heaters suitable for hypersonic tunnel operation has been underway for some time at the Langley Research Center. Under this program a prototype magnetically stabilized rotating-arc air heater was developed and operated very successfully with very little stream contamination. (See ref. 1.)

On the basis of the prototype system presented in reference 1, a larger arc-heater system was designed for operation with up to 2.1 megawatts of arc power and at stagnation pressures suitable for hypersonic tunnel operation. This heater provided the basis for the development of a hypersonic tunnel system designated as the Langley 20-inch hypersonic arc-heated tunnel. This tunnel has been designed to operate with variation in nozzle throat size and nozzle exit diameter to provide the wide range of test environments desired for reentry simulations. The present report describes the main mechanical components of this arc heater and hypersonic tunnel. The basic arc-heater performance was measured over a pressure range from 6.8 to 66.0 atmospheres with variable nozzle throat sizes and three electrode configurations with arc input power in the 1.8- to 2.1-megawatt range. This report also presents the range of model test conditions attainable in this tunnel with the four different nozzle configurations presently available for research on thermal protective materials for hypersonic flight.

SYMBOLS

A	cross-sectional area of nozzle, square centimeters (cm^2)
B	magnetic field intensity, teslas (T)
d	diameter, centimeters (cm)
H	enthalpy, kilojoules per kilogram (kJ/kg)
I	current, amperes (A)
M	Mach number
N_{Re}	unit Reynolds number, per meter
p	pressure, atmospheres (1 atm = 101.325 kN/m^2)
$\dot{q}$	heating rate, watts per square centimeter (W/cm^2)
R	electrical resistance, ohms (Ω)
r	radius, centimeters (cm)
s	distance along surface, measured from center line of model, centimeters (cm)

T	temperature, degrees Kelvin ($^{\circ}K$)
u	velocity, meters per second (m/sec)
V	voltage, volts (V)
ρ	density, kilograms per cubic meter (kg/m^3)

Subscripts:

b	base
e	nozzle exit
ex	external
f	fixed
n	nose
t	total or stagnation conditions
2	behind normal shock
∞	free stream

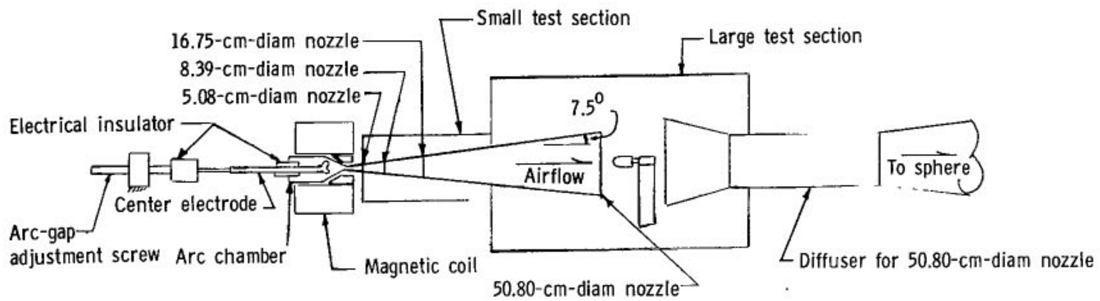
TUNNEL DESCRIPTION

The Langley 20-inch hypersonic arc-heated tunnel consists of an arc heater, four water-cooled conical nozzles, two free-jet test sections, and a fixed-geometry diffuser which exhausts through a heat exchanger to a vacuum sphere. A sketch of the general arrangements of these components is shown in figure 1 and a photograph of a general view of the tunnel is presented as figure 2. These components are described in the following sections.

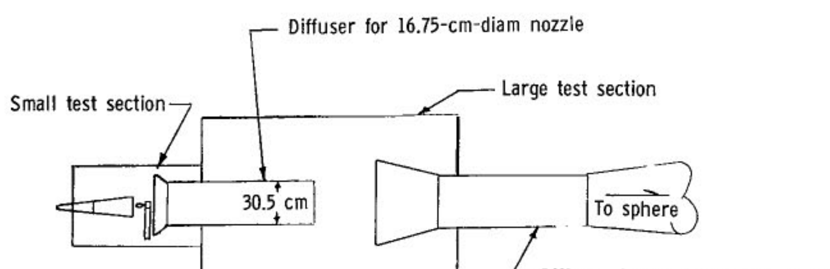
Arc Heater

The design of the arc heater was based on the data taken from a prototype arc heater which is described in reference 1. A drawing of the arc heater is shown in figure 3. The arc heater consists of a pressure vessel, a pressure-vessel liner (outer electrode), a center electrode, and magnetic coils. The pressure vessel is made of stainless steel and is designed to operate at arc-heater pressures up to 136 atmospheres. The pressure-vessel liner is made of oxygen-free copper and has ribs on the outside to support it against the pressure vessel and to form the water passages. This liner also includes the throat section and the first expansion section of the nozzle.

Two liner designs have been used in tests of the arc heater. The first design, illustrated in figure 3, incorporates interchangeable copper throat inserts soldered in place to permit studies of throat size (0.483-, 0.680-, 0.965-, and 1.366-cm-diameter) effects on arc-heater performance. The second liner design, which is used for the research on materials for normal operation at the tunnel, has an integral fixed contour throat to insure consistent flow development in the test nozzles. The center electrodes are constructed of oxygen-free copper and are cooled with high-velocity water. The arc gap between the center and outer electrodes can be changed by moving the center electrode along its longitudinal axis by means of a mechanical adjustment screw. This ability to vary arc gap permits control of the impedance required for operation of the arc heater over a wide range of arc chamber pressures and arc input powers.

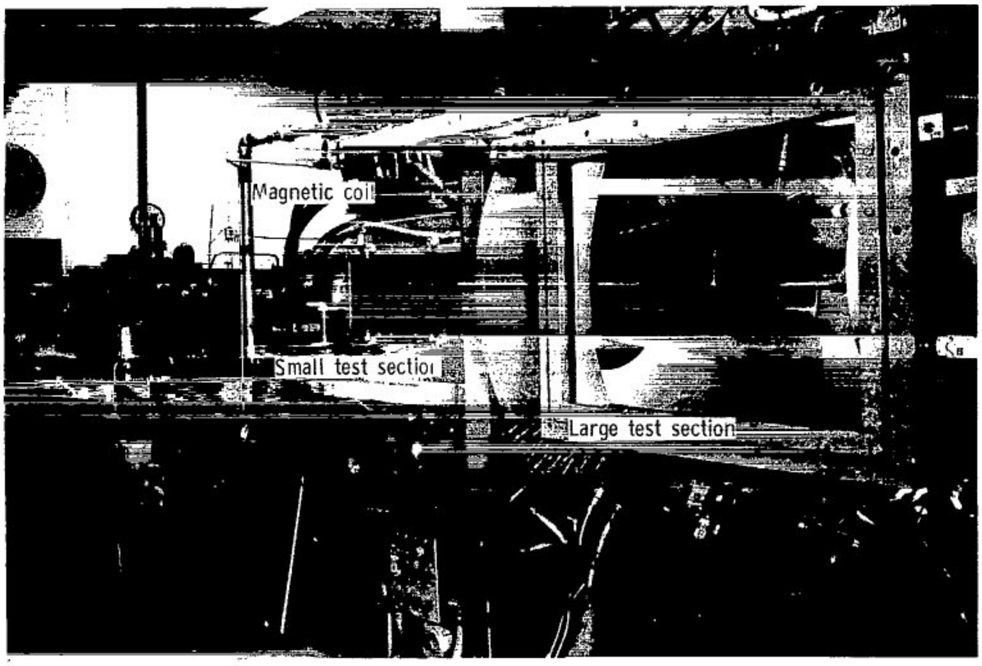


(a) 50.80-centimeter-diameter nozzle installed.

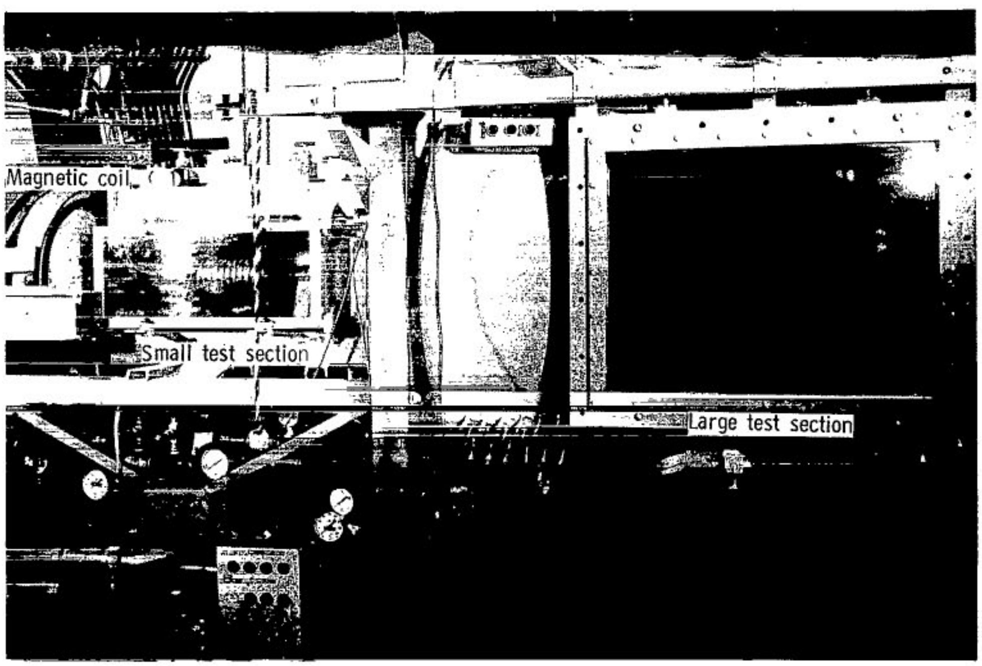


(b) 16.75-centimeter-diameter nozzle installed.

Figure 1.- Schematic drawing of significant tunnel components.



(a) 50.80-centimeter-diameter nozzle installed. L-66-6511.1



(b) 16.75-centimeter-diameter nozzle installed. L-65-8016.1

Figure 2.- The Langley 20-inch hypersonic arc-heated tunnel.

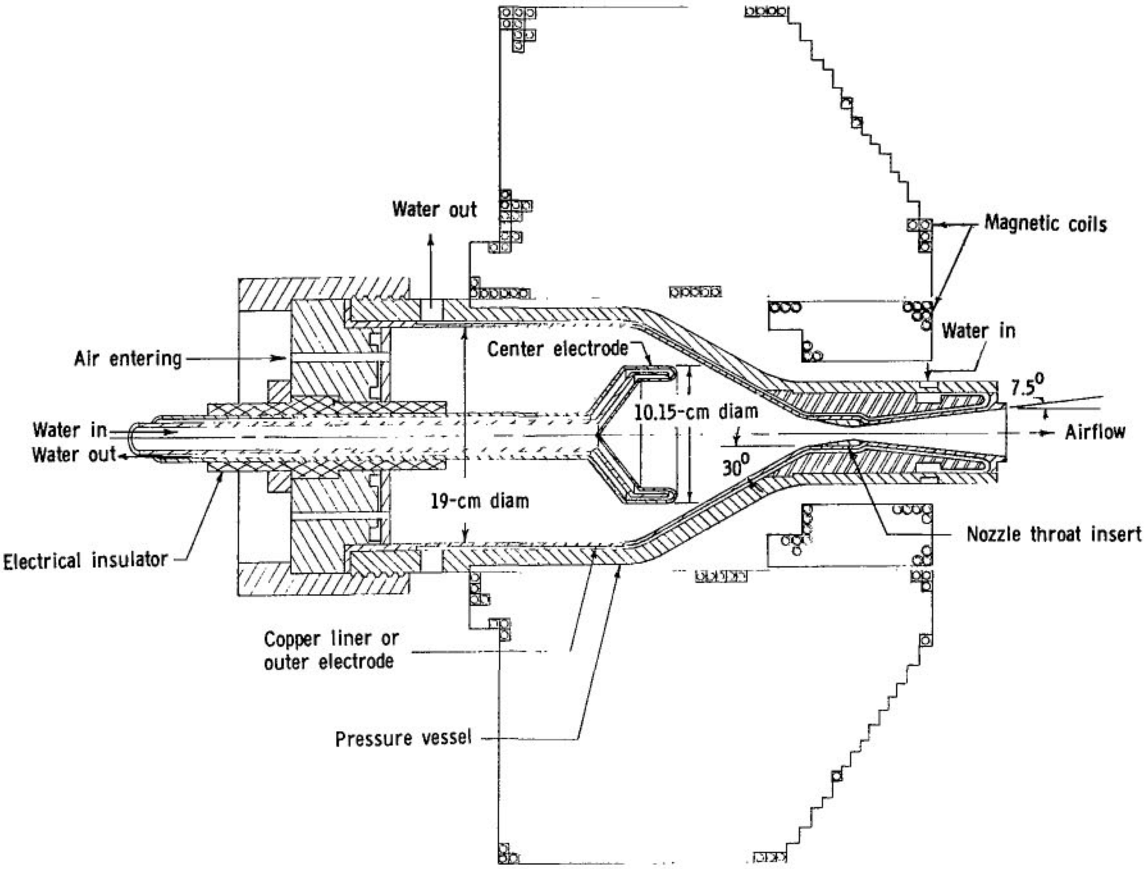


Figure 3.- Drawing of general arc-heater configuration.

A specially constructed water-cooled magnetic coil is fitted around the outer radius of the pressure vessel (fig. 3). This coil has a B/I ratio of approximately 0.001 tesla per ampere and is connected in series with the arc to provide increased arc stability. The magnetic field produced by this coil is used to rotate the arc at high speeds to reduce the erosion rates of the electrodes. The basic design concepts are discussed in reference 1.

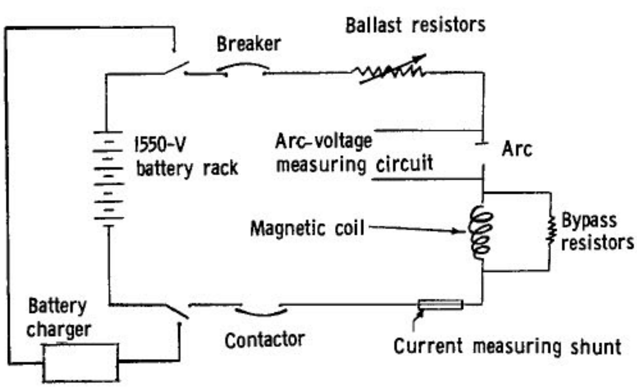


Figure 4.- Schematic drawing of electrical circuit.

The power supply consists of 1440 lead-acid batteries connected in a series parallel circuit to produce a power supply rated at 3000 amperes. Open circuit voltage of this power supply is 1500 volts. The power to the arc can be varied from approximately 1/2 to 2 megawatts by using variable water-cooled resistors. The electrical power circuit for the arc heater is shown schematically in figure 4.

Nozzle Test Section

The pressure-vessel liner (outer electrode) includes the throat section and the first expansion section of the nozzle. As shown in figure 1, in addition to the 50.80-centimeter-diameter nozzle, there are three other nozzle sections. Therefore, models can be tested at four different nozzle expansion ratios for any given throat area. The purpose of these four nozzle expansion ratios is to obtain a wider range of environmental test conditions at fixed conditions in the arc chamber. The two test sections used to accommodate the four nozzles can be seen in figures 1 and 2. The small test section provides the testing region with the 5.08-, 8.39-, and 16.75-centimeter-diameter exit nozzles (nominal Mach numbers of 3, 4, and 5.5, respectively). The large test section provides the testing region with the 50.80-centimeter-diameter exit nozzle (nominal Mach number of 8). Each test section is equipped with windows on three sides for visual observation of the models and flow fields. Each test section is also equipped with two mechanisms for inserting and retracting the model and the survey equipment from the airstream. Photographs showing typical model installations in the small test section are presented as figure 5.

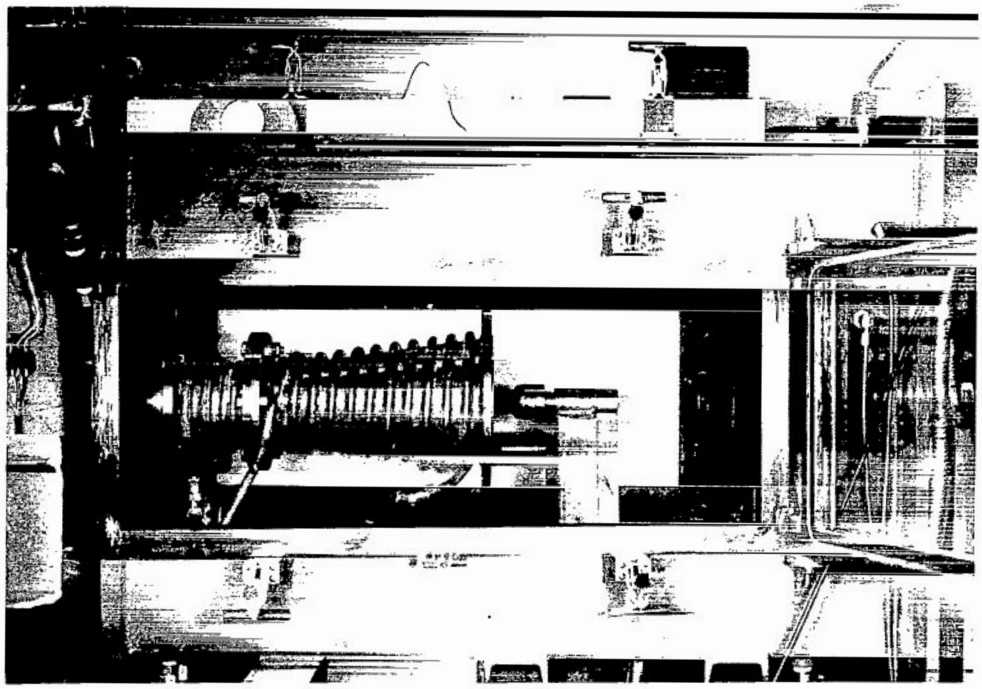
Diffuser and Vacuum System

With the vacuum supply available, the hypersonic 50.80-centimeter-diameter nozzle requires a diffuser for maintaining a sufficient pressure ratio across the nozzle to operate at useful testing times. The diffuser (fig. 1(a)) for this nozzle was designed with the use of data from reference 2. It consists of a 15° inlet scoop, a long constant diameter section with an area ratio A/A_e of 0.7, and a divergent section which exhausts into the heat exchanger and vacuum sphere.

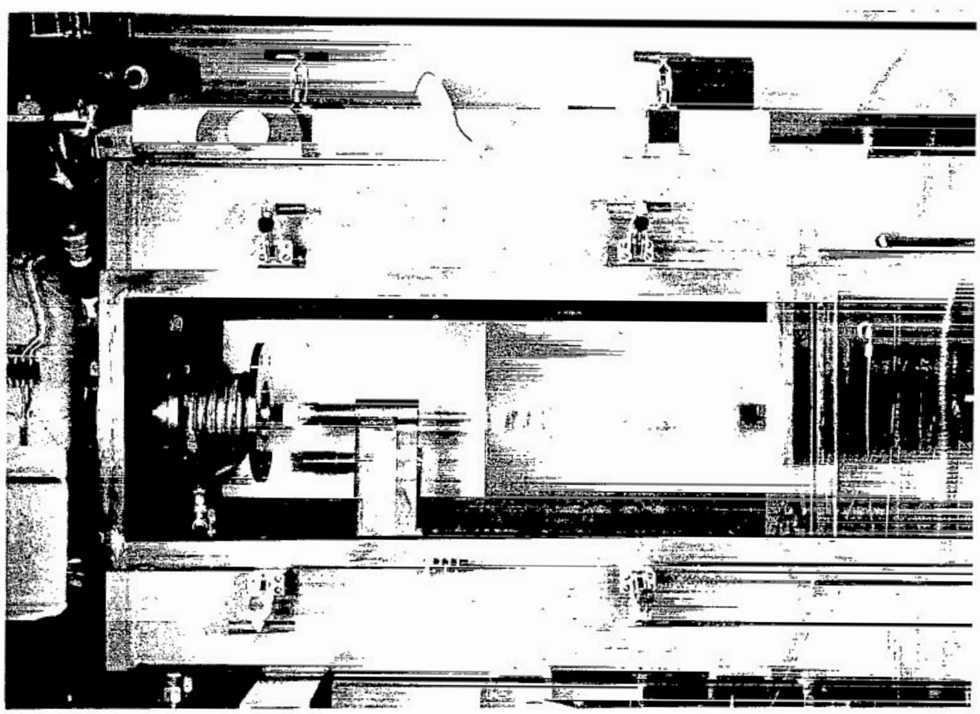
The lower Mach number 16.75-centimeter-diameter exit nozzle (nominal Mach number of 5.5) requires only about 25 percent of normal-shock recovery from a diffuser to operate with the vacuum supply available. For this nozzle a 30.5-centimeter-diameter straight exit pipe (fig. 1(b)) is used, and although the straight pipe is an inefficient diffuser, it does give sufficient pressure recovery to operate the nozzle and allows it to operate with large models installed.

With the vacuum supply available, the 5.08- and 8.39-centimeter-diameter nozzles do not require a diffuser for maintaining a sufficient pressure ratio across these nozzles to operate. In fact, since the pressure in the vacuum system is normally lower than that in the nozzle exit for these two nozzles, a pressure control valve – located downstream of the heat exchanger – is used to match the test-section pressure to the stream pressure.

The vacuum system consists of three spheres and three vacuum pumps. The spheres have a volume of 2180 cubic meters, and they are normally pumped down to approximately 70 newtons per square meter before each test run.



(a) 16.75-centimeter-diameter nozzle installed. L-65-8015



(b) 8.39-centimeter-diameter nozzle installed. L-65-8014

Figure 5.- Typical model installations in small test section.

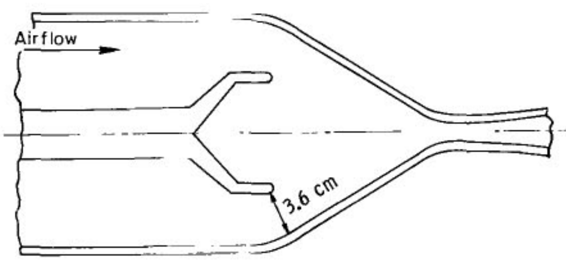
TEST METHODS

Arc-Heater Performance

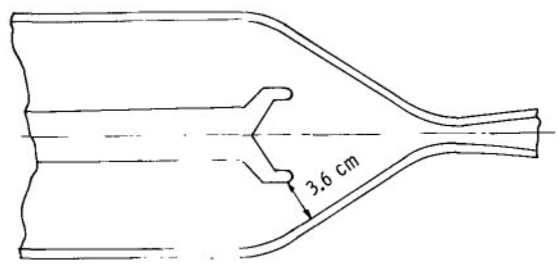
Arc-impedance determination.- The initial performance tests on the arc-heater system were designed to define the impedance characteristics of the arc as well as the fixed impedance of the complete system. Tests were made for a range of arc gaps at several arc chamber pressures, with arc power gradually increased from low levels to maximum levels available for the system. Impedance curves obtained in these tests provided the basis for setting arc conditions in the remainder of the program.

Effect of nozzle throat size.- Upon completion of the initial performance tests on the arc heater with a 0.680-centimeter-diameter nozzle throat, a test series using three additional nozzle throat sizes was initiated to define the effects of mass flow on the arc-heater performance. In these tests, heater efficiency and arc-system characteristics were studied over a range of arc chamber pressures for full-power operating conditions with the use of the 10.15-centimeter-diameter cup electrode (initial design) shown in figure 3. Throat inserts were used in this program to give throat sizes of 0.483, 0.680, 0.965, and 1.366 centimeters in diameter. Minimum pressures were fixed by arc instability or high current levels (maximum of 3000 amperes) and maximum pressures were determined by arc blowout or maximum design pressure of the electrodes (66.0 atm). These tests provided the basis for selecting a throat diameter most acceptable for general operation with the nozzle system under development for use in a materials-research facility. As pointed out subsequently in the discussion of the arc-heater performance, the 1.366-centimeter-diameter nozzle throat was selected for general use, and all remaining tests were made with an arc chamber having a fixed throat of this dimension.

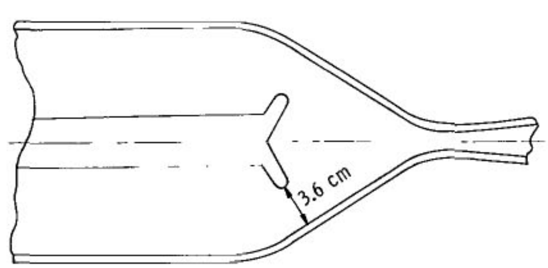
Effect of electrode configuration.- As previously noted, initial arc-heater performance tests were made with the 10.15-centimeter-diameter cup-shaped center electrode shown in figure 3. This electrode was a scaled-up version of the center electrode of the arc heater described in reference 1. Because no experience existed from the prototype heater for arc operation in the conical portion of the arc chamber, a conservative approach was taken, and the 10.15-centimeter deep-cup design was chosen for initial operation. This design permitted operation for the desired range of arc gaps (up to 3.81 cm) and arc currents with the arc region maintained in the transition and first stage of the conical nozzle approach section of the arc chamber. Since experiences with arc-heater systems have pointed to improved performance (efficiency) for configurations exposing the smallest cooled wall area to the heated gases, two additional electrode configurations were designed for operations over the same arc-gap range (up to 3.81 cm) but with a smaller diameter (7.61 cm) to permit operation deeper in the conical section. (See fig. 6.) The cup shape was retained in the design of one of these electrodes whereas a dish shape (with reduced surface area) was utilized in the alternate 7.61-centimeter-diameter-electrode design. Arc-heater performance tests were carried out for each of these electrodes to establish arc operating characteristics and system efficiency over the pressure range available with this system at a fixed power of approximately 1.8 to 2.1 megawatts.



10.15-cm cup center electrode



7.61-cm cup center electrode



7.61-cm dish-shaped center electrode

Figure 6.- Three center-electrode configurations.

Evaluation of Nozzle Flow Characteristics

After the study of arc-heater performance, the test environments available for materials research in the four nozzle systems of this test facility were determined in terms of the stagnation-point parameters considered most significant in the study of the response of materials to high-enthalpy entry environments (ref. 3). In the present tests, stagnation heating rates, model stagnation pressures, and stream enthalpy were measured at nominal model test positions in each nozzle for arc-heater pressures ranging from 6.8 to 34.0 atmospheres with the arc operating at full power. Thus, the maximum flow conditions attainable in each nozzle system would be defined. In conjunction with these tests, model blockage studies were also made to define maximum model sizes which could be tested in each nozzle.

Model stagnation pressures were measured with pressure probes on the center line in all nozzles, and heating rates were measured with both thin-shell and slug-type calorimeters. (See fig. 7.) The 2.54-centimeter flat-face thin-wall design and the slug-type (ref. 4) flat-face design were used for all primary calibrations and were compared with the other configurations to verify shape correction factors of reference 5 and allow application of these data to shapes of interest for materials research programs. Stream enthalpy was computed for each test point by use of Fay and Riddell heat-transfer equations (ref. 6) and measured values of pressure and heating rates for the test stream;

thus, a check on bulk enthalpy values computed from heat balance of the arc-heater system was provided.

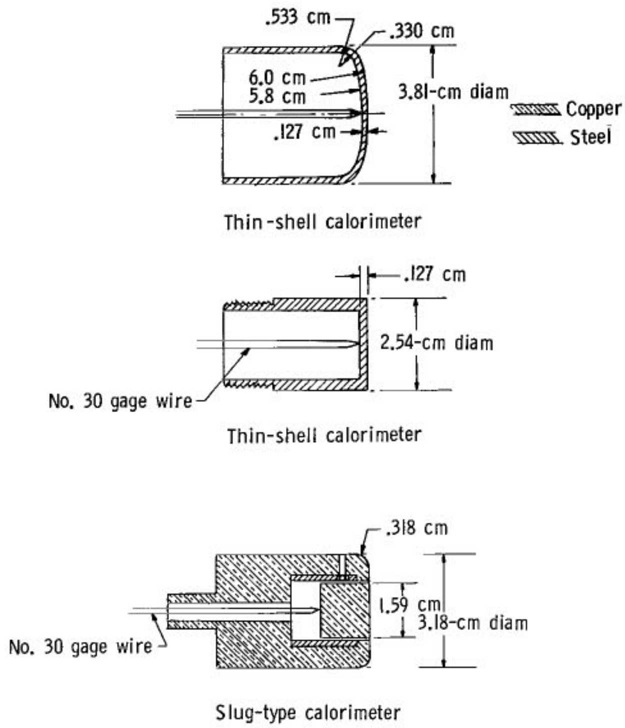


Figure 7.- Calorimeters used for flow evaluation.

Lateral pressure distributions were not measured for each nozzle; however, as a check on the suitability of the test streams for materials research, measurements of heating rates and pressure distributions on models typical of the ones used for materials research (fig. 8) were made and compared with theoretical values. The shape chosen is designed for essentially constant heating across the front face and is used as a basic configuration for studies of materials response.

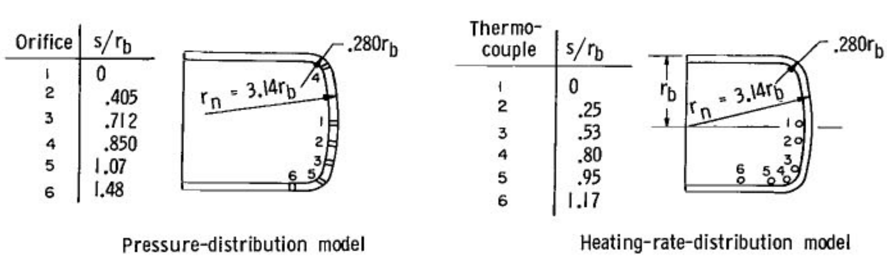


Figure 8.- Typical pressure-distribution and heating-rate-distribution models.

Instrumentation

The determination of arc-heater performance in this program was based on stream stagnation-point heating and pressure measurements as well as on heat-balance computations for the complete arc heater including the nozzle sections. This technique required measurements of arc current, arc voltage, airflow rate, cooling waterflow rates, and temperature rise in the cooling water passing through the system. These measurements were estimated to be accurate within 2 percent.

In the evaluation of the flow conditions produced by the four nozzles of the tunnel, the primary measurements required were pressure and temperature. For measurement of model stagnation pressures, strain-gage transducers with ranges from 0.034 to 3.4 atmospheres, as indicated by expansion ratios for the different nozzles, were used in all cases. Heat-transfer measurements were made with No. 30 gage chromel-alumel thermocouples to obtain temperature-time response for thin-shell or slug calorimeters, and these responses were recorded with a fast-response potentiometer.

Data from all instrumentation used in these studies were continuously recorded by high-response oscillographs.

RESULTS AND DISCUSSION

System Electrical Characteristics

Power supply.- The computed arc-current and arc-voltage relationship for the existing battery power supply is shown in figure 9. This power supply has an open circuit voltage of 1550 volts, but the effective voltage during operation is approximately 1350 volts. Figure 9 is based on the effective battery voltage and the measured value of the fixed resistance of the circuit. In this figure the range of operation for the tunnel is shown. The boundaries of this operational range are not completely defined because no attempt has been made to define the total operation range of the arc heater at the lower power levels; however, the two lower boundaries drawn do show where the arc heater has operated. At the lower power levels, there is a range of arc gaps and external electrical resistances that will produce a given power; therefore, the arc-gap and resistance settings that produce the lower currents are generally used because these limits keep the erosion rates on the electrodes to a minimum. The maximum power level and the maximum current have been defined. The maximum current was set at 3000 amperes to keep the erosion rates on the electrode to a minimum. The lower current, at full power, was set at 2000 amperes because for this configuration the arc would become unstable and would blow out if set below 2000 amperes.

Arc impedance.- Figure 10 shows typical values of arc chamber pressure plotted against arc impedance for the normal range of heater operating conditions with the three

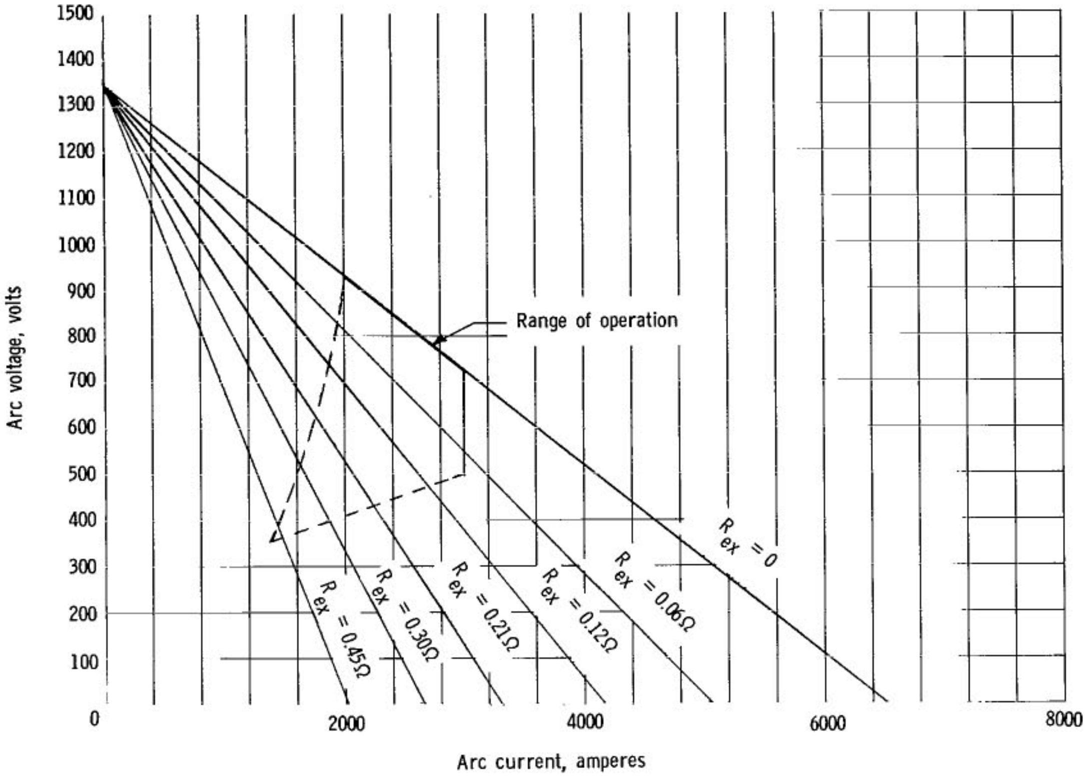


Figure 9.- Computed arc current and voltage for the battery power supply. $R_f = 0.2069\Omega$; $R_t = R_f + R_{ex}$.

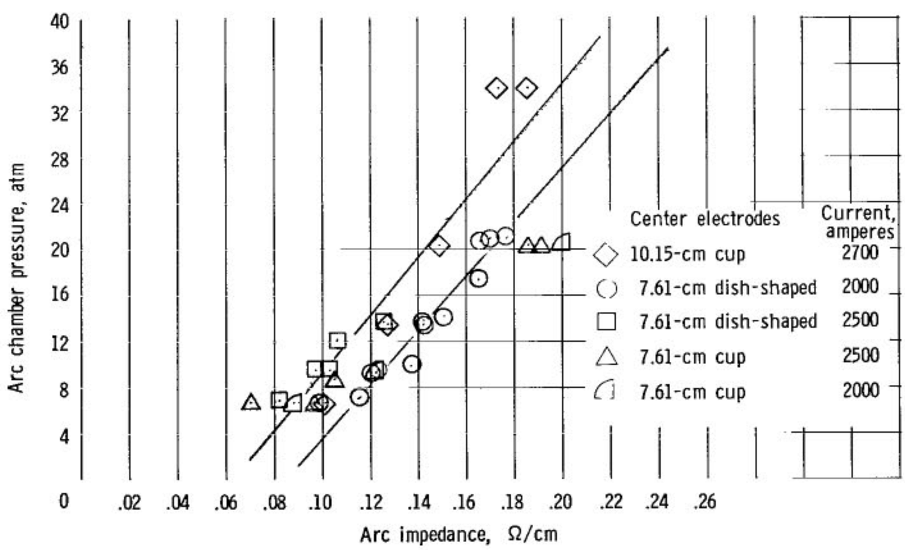


Figure 10.- Arc chamber pressure plotted against arc impedance for three center-electrode configurations with approximately full power. (Arc length assumed to be straight line distance between electrodes; throat size fixed at 1.366 cm.)

electrodes tested at a fixed throat size of 1.366 centimeters. The arc impedance increases as the pressure (or mass flow) increases, and it decreases as the arc current increases.

Arc-Heater Performance

Effect of nozzle throat size.- Data taken at approximately full power with the original 10.15-centimeter-diameter center electrode to determine the effect of arc-chamber nozzle throat size on arc-heater efficiency and maximum airstream enthalpy levels (computed from heat balance) are presented in figures 11 to 14. The results in figure 11 show conclusively that use of larger nozzle throat sizes produced a marked increase in arc-heater efficiency. As a result of this improved efficiency, the widest range of airstream

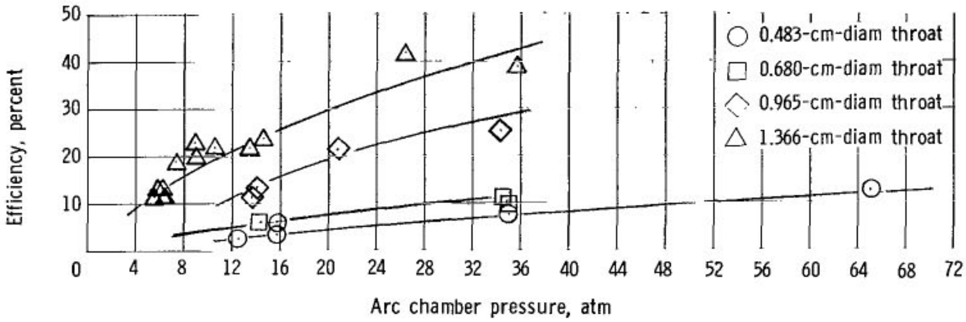


Figure 11.- Arc-heater efficiency plotted against arc chamber pressure for four throat sizes and the 10.15-centimeter-diameter center electrode at an arc power of approximately 1.8 megawatts.

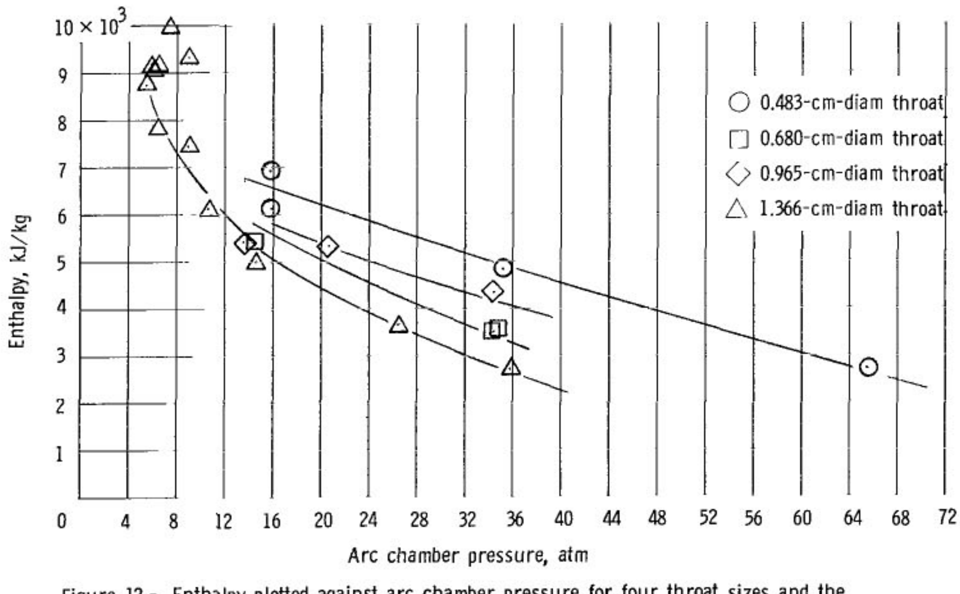


Figure 12.- Enthalpy plotted against arc chamber pressure for four throat sizes and the 10.15-centimeter-diameter center electrode at an arc power of approximately 1.8 megawatts.

enthalpy levels (see fig. 12) was attained with the 1.366-centimeter-diameter nozzle throat even though much higher mass-flow rates (see fig. 13) resulted with this nozzle throat, which represented an 8-to-1 area increase over the other throat sizes studied. Results of the enthalpy measurements for the four nozzle throats considered are shown in figure 14 plotted against arc-heater mass-flow rates.

The results were not unexpected as similar trends have been observed with the prototype heater and by other experimenters, and the increased efficiency is generally attributed to decreased dwell time (ref. 1) for the heated air in fixed-volume heaters. Although this simple concept accounts generally for the increase in efficiency, the effect involves pressure, mass flow, and arc phenomena; and the quantitative behavior of a particular arc system must be defined by calibration tests.

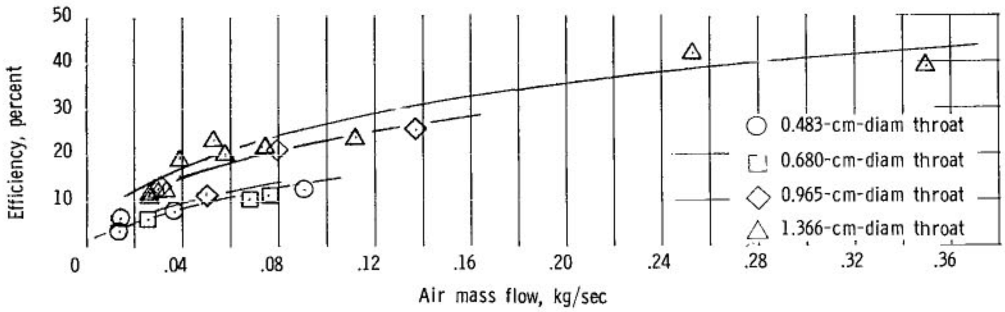


Figure 13.- Arc-heater efficiency plotted against air mass flow for four throat sizes and the 10.15-centimeter-diameter center electrode.

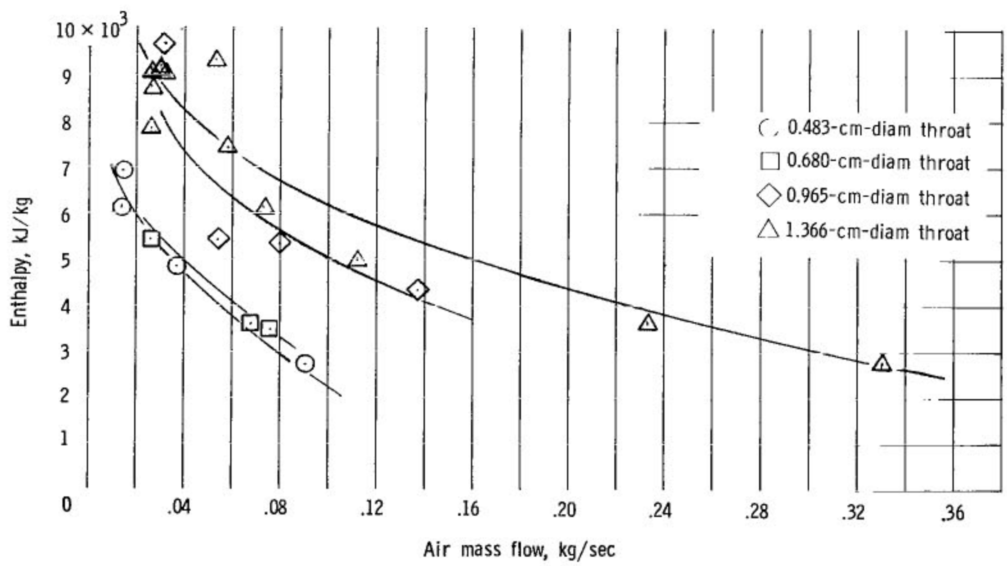


Figure 14.- Enthalpy plotted against air mass flow for four throat sizes and the 10.15-centimeter-diameter center electrode.

On the basis of the test results and a study of nozzle flow characteristics, the 1.366-centimeter-diameter throat size was chosen as the most acceptable for use with the hypersonic nozzles of this tunnel system. This configuration was considered the most desirable since the enthalpy, pressure, and nozzle mass-flow conditions, as well as the throat size, allowed expansion of the arc-heater flow to a range of hypersonic Mach numbers with model stagnation parameters $\left(\dot{q},\ p_{t,2},\ \text{and}\ H_t\right)$ and model size capability in the desired range for studies of the thermal and aerochemical response of ablation materials to reentry environments. Details of the four nozzle configurations used and the model flow environments produced are discussed in a subsequent section of this paper. (See section entitled "Nozzle Flow Characteristics.")

Effect of center electrode configuration.- The 10.15-centimeter-diameter deep-cup center electrode used in the initial arc-heater evaluation allowed operation over the pressure range from 6.8 to 34.0 atmospheres at maximum available power (1.8 to 2.1 megawatts) with heater efficiencies ranging from approximately 15 to 50 percent (fig. 15)

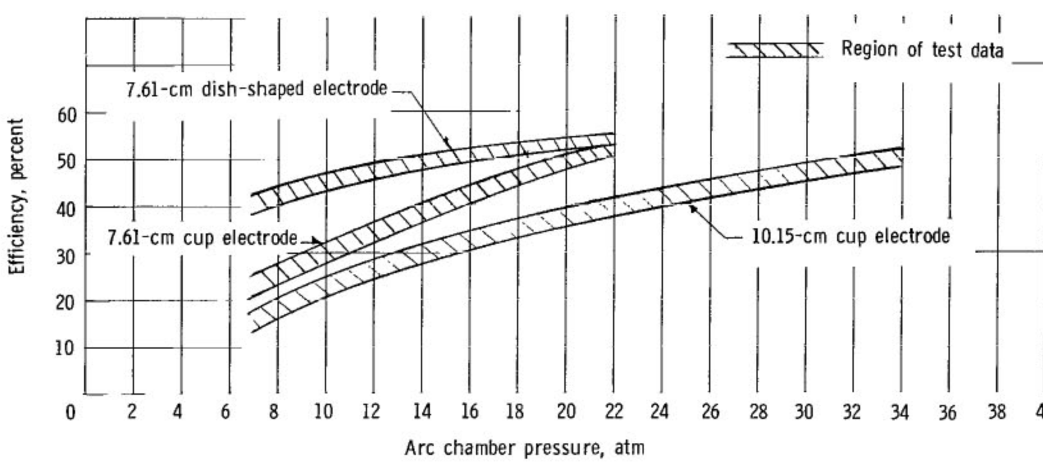


Figure 15.- Efficiency plotted against arc chamber pressure for the three center electrodes.

depending on pressure levels. Although the operation was successful over this range, the attainable enthalpy levels in the nozzle airstreams were somewhat disappointing with a maximum value of approximately 9450 kJ/kg measured at the lower operating pressures and values of approximately 2790 kJ/kg measured at the 34.0-atmosphere range (fig. 16). For this operating condition with the chosen 1.366-centimeter-diameter nozzle throat, enthalpy levels were primarily limited by available power for the high mass flows at the higher pressures and were further limited at the lower pressures by low heater efficiencies. Arc instability encountered with large arc gaps at the lower operating pressures (less than 6.8 atm) provided further restrictions.

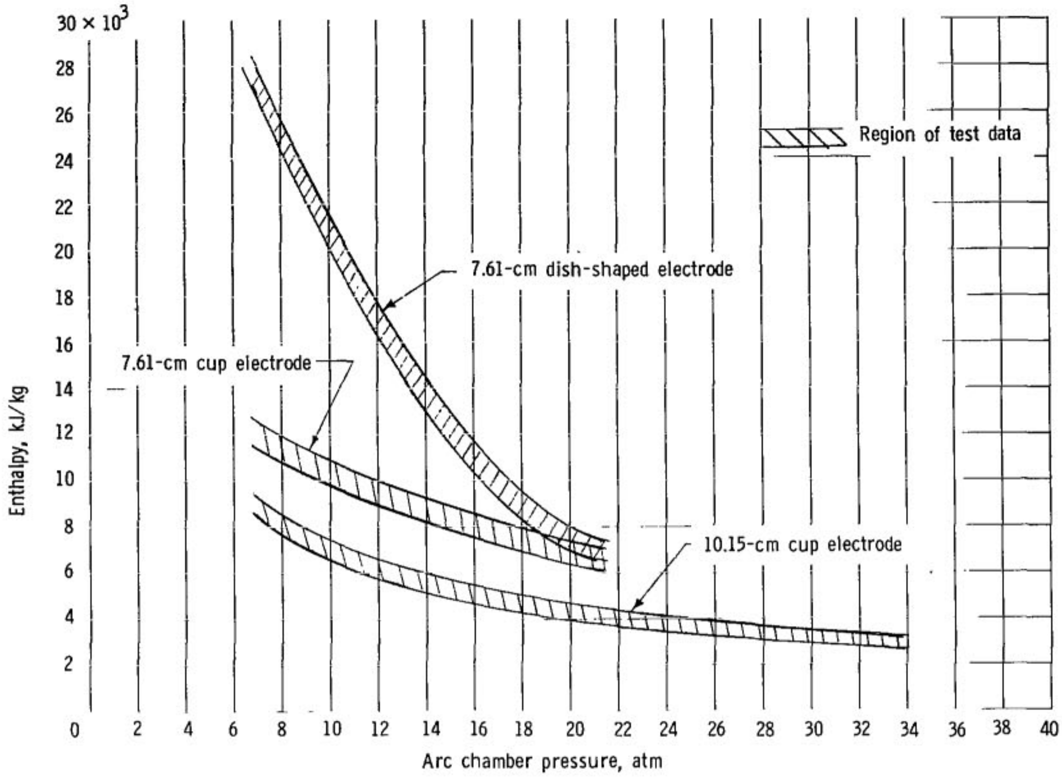


Figure 16.- Enthalpy plotted against arc chamber pressure for the three center electrodes used in this investigation.

In order to improve the arc-heater efficiency and arc stability at the lower operating pressures and thus attain higher enthalpy levels in the nozzle airstreams, tests were carried out to evaluate the two 7.61-centimeter-diameter center electrode configurations shown in figure 6. With these electrodes, the reduced diameter concept was expected to improve performance over that obtained with the 10.15-centimeter-diameter electrode in two ways. First, the smaller diameter was expected to improve efficiency by moving the arcing section closer to the heater throat (for any specific arc gap) and thereby reduce the area of cold wall available for heat loss. Second, the move into the cone was expected to improve arc stability by placing the arc in a stable region in the cone section rather than near the transition region as for the large arc gaps with the larger electrode.

With the reduced-diameter electrodes, marked improvements in arc-heater performance were obtained (figs. 15 and 16), although arc blowout at small arc gaps limited operation to pressures less than 21.4 atmospheres. The improved performance for the 7.61-centimeter cup electrode was generally as expected, and the arc behavior inferred from inspection of electrodes appeared similar to that for the 10.15-centimeter cup electrode, with the arc taking a path from the outer lip of the center electrode at all arc gaps, as illustrated in figure 17. For the modified 7.61-centimeter dish-shaped electrode, however, performance gains were realized (figs. 15 and 16) which were significantly larger than expected for the modest reduction in electrode surface area incorporated in this design.

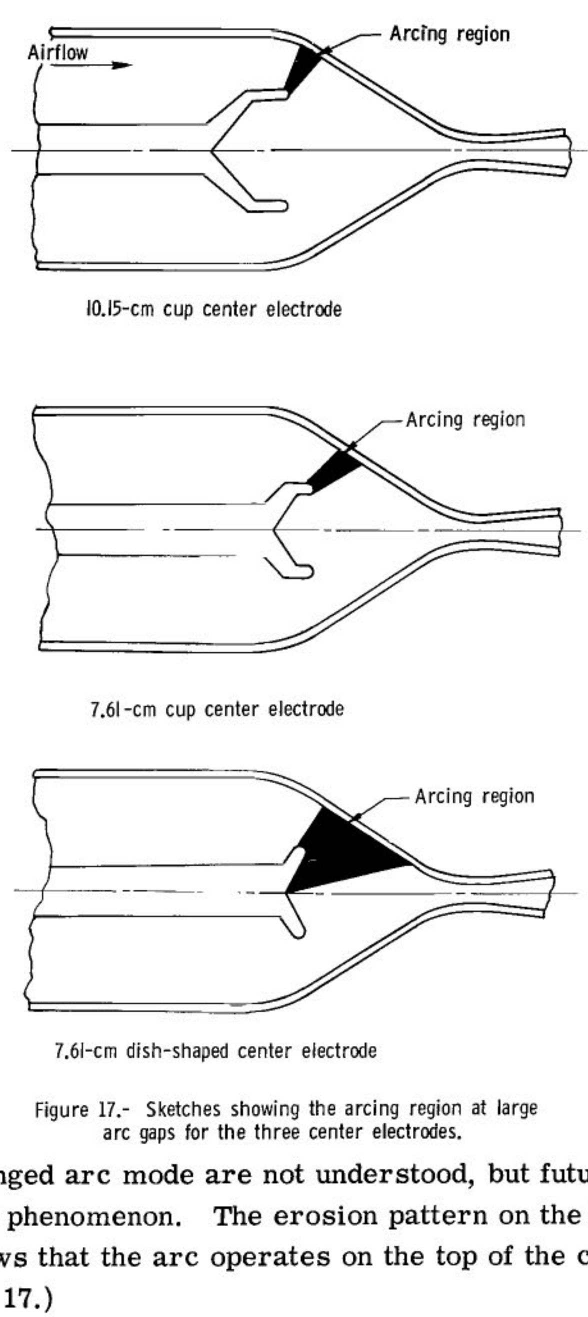
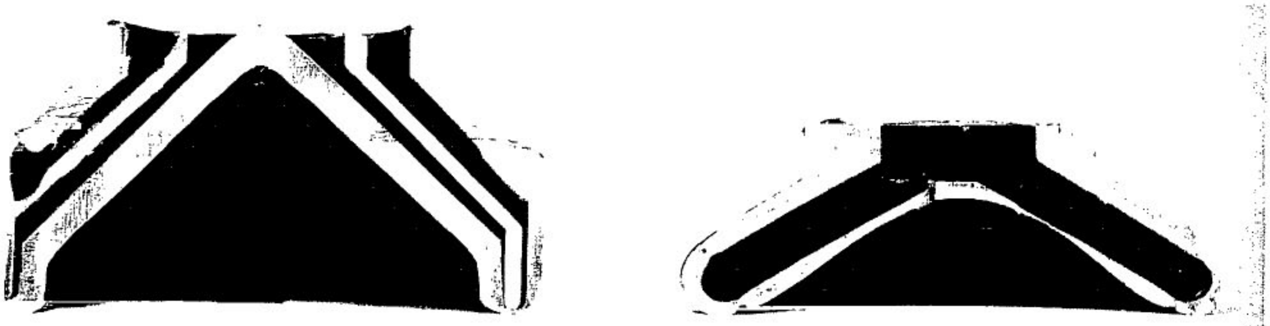


Figure 17.- Sketches showing the arcing region at large arc gaps for the three center electrodes.

Inspection of electrodes after operation indicates that a change in arc mode was experienced for the modified electrode when it was operated with large arc gaps in the lower pressure range. As can be seen from examination of the erosion pattern on electrodes sectioned after a number of tests (fig. 18), the arc on the 7.61-centimeter dish-shaped electrode operates over the complete front section in the manner illustrated in figure 17. In this mode of operation, which occurs only for large arc gaps (2.54 to 3.81 cm), the arc apparently operates over the complete electrode dish and takes a path toward the throat. This direction produces greatly increased efficiency and consequently higher enthalpy airflow. At present, the factors responsible for the changed arc mode are not understood, but future studies may provide an explanation of this phenomenon. The erosion pattern on the 7.61-centimeter cup-shaped electrode shows that the arc operates on the top of the cup and around the leading edge. (See fig. 17.)

On the basis of the studies completed to date, the arc-heater configuration chosen for the basic facility utilizes a fixed-throat nozzle of 1.366-centimeter diameter and makes use of both the 7.61-centimeter dish-shaped electrode and the original 10.15-centimeter cup electrode to obtain the widest range of operating conditions



(a) 7.61-centimeter cup electrode. (b) 7.61-centimeter dish-shaped electrode.

Figure 18.- Section view of two center electrodes after operation. L-67-4215

possible for the maximum power available with present battery power system. The 10.15-centimeter cup permits operation over a wide range of chamber pressures (fig. 16) with enthalpy levels of 2790 to 9450 kJ/kg in the supersonic nozzle sections. By using the 7.61-centimeter dish-shaped electrode, enthalpy levels from 27 900 to 7000 kJ/kg are available in the 6.8- to 21.4-atmosphere chamber-pressure range with full power. Intermediate pressure and enthalpy levels are obtained by variation in tunnel power and selection of the most appropriate electrode configuration to obtain a desired condition.

Nozzle Flow Characteristics

The primary purpose of the Langley 20-inch hypersonic arc-heated tunnel is to provide a range of model stagnation conditions suitable for studies of the response of ablation materials to reentry environments. Calibration tests in the nozzle flows have therefore been concentrated on defining the test boundaries for each nozzle configuration by measurement of center-line stagnation heating rates and pressures behind the normal shock. The results of these calibration tests are summarized in figure 19 with heating rates based on a hemisphere-cylinder model with a 3.81-centimeter diameter. Enthalpy values calculated from the measured heating rates and pressures by the method of reference 6 are also shown. In figure 19, the upper curved boundary for each nozzle is established by the full power limit of the battery power system and represents maximum performance for the arc-heater system over the full range of operating pressures (6.8 to 34.0 atm). The area to the left under each maximum power curve indicates the range of conditions made possible by reducing arc-heater power and varying chamber pressure. As a means of indicating the range of aerodynamic parameters available in the nozzle systems of this facility, table I was prepared to show nominal values of several parameters calculated for the range of arc chamber pressures at maximum operating conditions.

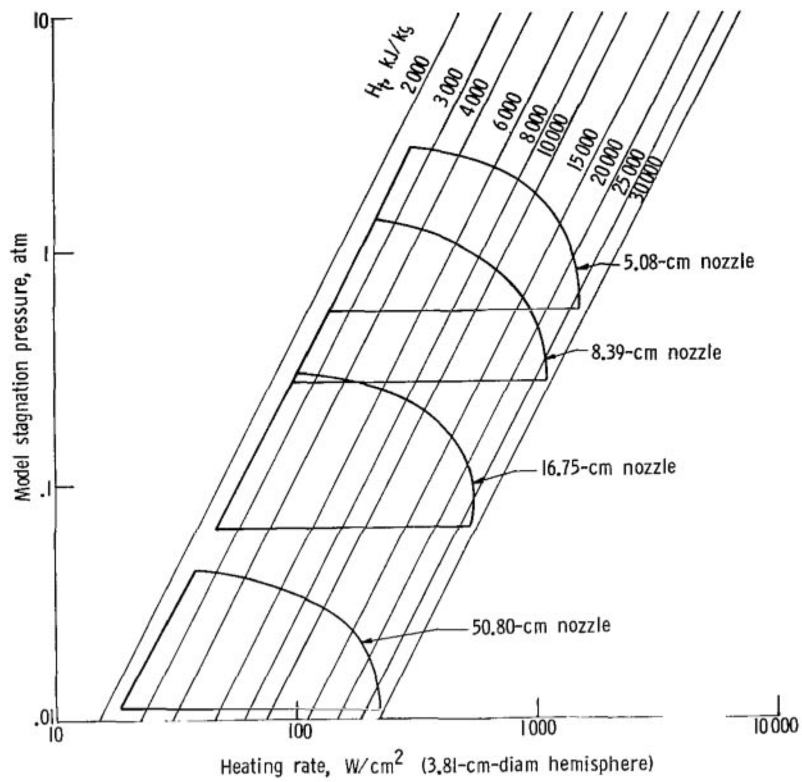


Figure 19.- Test conditions available in the Langley 20-inch hypersonic arc-heated tunnel.

Even though this table presents parameters that were calculated by assuming equilibrium flow conditions for each nozzle at an effective area ratio defined from measured model stagnation pressure, most of these conditions were probably not in equilibrium; however, the assumption had to be made for these parameters because, at this time, no other results were available.

From examination of figure 19 and table I, it is apparent that the arc heater with the four nozzle configurations of this tunnel system provides stagnation enthalpies (2790 to 27 900 kJ/kg), model stagnation pressures (0.01 to 2.7 atm), and stagnation convective heating rates (17 to 1700 W/cm^2 on a 3.81-centimeter-diameter hemisphere-cylinder model) typical of a wide range of reentry environments. With the 50.80-centimeter-diameter nozzle, stagnation pressures and heating rates typical of moderate-lift-drag-ratio lifting entry vehicles (HL-10 type) are available. The test conditions increase in severity as nozzle size decreases, so that with the 5.08-centimeter nozzle, heating rates and pressures typical of ballistic entry vehicles are possible. The heating-rate values shown in figure 19 are based on a model size (3.81-cm-diameter) which can be tested in all nozzle systems under hypersonic flow conditions.

TABLE I.- CALCULATED CONDITIONS[a] FOR THE LANGLEY 20-INCH HYPERSONIC ARC-HEATED TUNNEL AT MAXIMUM POWER FOR FOUR DIFFERENT NOZZLES

p_t, atm	H_t, kJ/kg	T_t, °K	p_∞, atm	$p_{t,2}$, atm	ρ_∞, kg/m^3	u_∞, m/sec	$\dot{q}\sqrt{r}$, W/cm$^{3/2}$	M_∞	N_{Re}, per meter
					d_e = 50.80 cm				
6.8	28 980	7950	0.000387	0.015	0.355×10^{-10}	6560	401	5.6	340
9.5	23 890	7620	.000465	.020	.541	6090	382	6.2	428
13.6	16 690	6910	.000680	.028	1.056	5240	322	6.1	781
20.4	6 880	4250	.000430	.039	3.122	3580	150	8.1	3 920
34.0	2 950	2500	.000320	.048	9.120	2380	64	10.9	23 400
					d_e = 16.75 cm				
6.8	28 980	7950	0.002630	0.065	1.76×10^{-10}	6150	840	4.7	1 090
9.5	23 890	7620	.003660	.110	3.33	5730	890	5.0	2 190
13.6	16 690	6910	.004930	.150	6.13	4940	732	5.2	3 890
20.4	6 880	4250	.006560	.259	23.10	3420	389	5.6	17 500
34.0	2 950	2500	.005050	.288	56.20	2330	155	7.5	74 500
					d_e = 8.39 cm				
6.8	28 980	7950	0.01230	0.23	7.01×10^{-10}	5730	1565	4.1	3 740
9.5	23 890	7620	.01730	.34	11.64	5380	1571	4.0	6 230
13.6	16 690	6910	.02180	.50	22.77	4680	1334	4.4	12 700
20.4	6 880	4250	.03710	.87	86.06	3230	706	4.3	48 600
34.0	2 950	2500	.03880	1.38	292.21	2220	337	5.1	229 000
					d_e = 5.08 cm				
6.8	28 980	7950	0.03770	0.57	18.96×10^{-10}	5380	2420	3.6	9 080
9.5	23 890	7620	.05920	.86	34.11	5020	2510	3.5	15 800
13.6	16 690	6910	.06250	1.10	56.68	4450	2000	3.9	28 300
20.4	6 880	4250	.10300	1.79	195.81	3070	1010	3.7	91 700
34.0	2 950	2500	.12900	2.91	685.35	2130	494	4.1	414 000

[a]Conditions calculated by assuming equilibrium flow.

Maximum model sizes which can be tested in the various nozzles are dictated by the free jet diameter for the two lower Mach number nozzles and by diffuser blockage effects for the two larger nozzles. The maximum model diameters for the hemisphere-cylinder models found acceptable for the four nozzle exit diameters used in the tunnel system are as follows:

Nozzle exit diameter, cm	Maximum model diameter, cm
50.80	10.15
16.75	6.35
8.39	5.08
5.08	3.81

At present, maximum test times are limited by power decay characteristics of the facility battery power supply (approximately 3 percent per minute). Test periods up to 5 minutes are possible at full power.

Pressure-distribution and heating-rate-distribution measurements are taken on typical models in each nozzle system to define the suitability of the flow fields for studies of ablative materials and other high-temperature protective systems. Figures 20 and 21 show pressure and heating-rate distributions measured on 3.81- and 5.08-centimeter-diameter models of a typical materials model configuration designed to produce constant pressure and heating over the stagnation area in hypersonic flow. Comparison of the pressure data (fig. 20) with data from reference 7 taken in a conventional hypersonic tunnel shows generally good agreement in all nozzles evaluated. Further comparison of the measured heating distributions (fig. 21) with heating values calculated by the theory of reference 8 from the pressure distribution (ref. 7) shows fair agreement in all nozzles. The most significant differences are noted for the 5.08-centimeter nozzle where the maximum model diameter is three-fourths of the nozzle exit diameter. On the basis of these tests, it is concluded that models of 3.81-centimeter diameter can be tested in all nozzles. Larger models are acceptable in the larger nozzles.

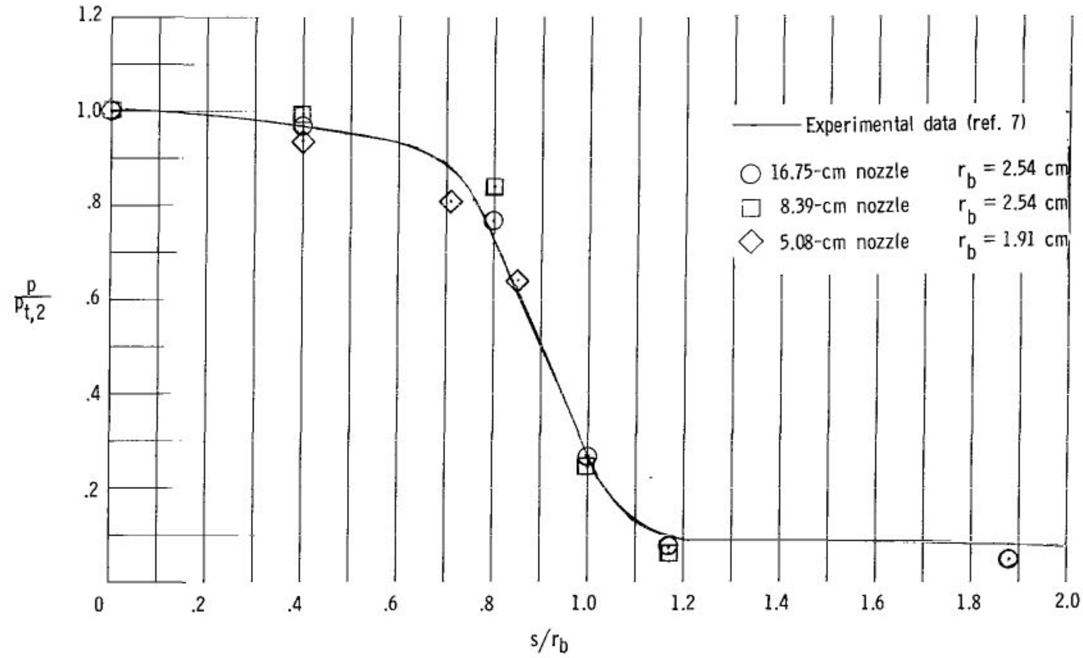


Figure 20.- Typical pressure distribution on models tested in three different nozzles.

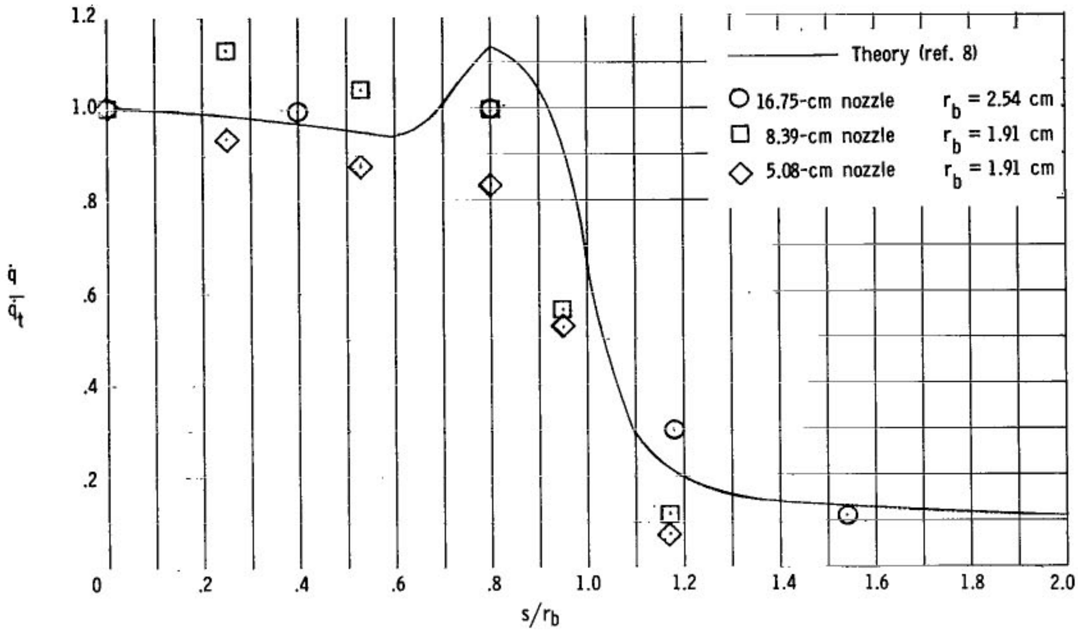


Figure 21.- Typical heating-rate distribution on models tested in three different nozzles.

SUMMARY OF RESULTS

The evaluation program carried out for the arc heater and test nozzles of the Langley 20-inch hypersonic arc-heated tunnel indicated the following results:

1. The arc heater developed for this system has been operated over a chamber-pressure range from 6.8 to 66.0 atmospheres at a power level to the arc of 2 megawatts.

2. Efficiency levels for this heater were observed to increase with increases in nozzle throat diameters between 0.483 and 1.366 centimeters.

3. Center electrode configuration has a strong effect on arc-heater performance. A 10.15-centimeter-diameter cup-shaped electrode proved best for higher pressure operation and a 7.61-centimeter dish-shaped electrode was markedly superior for lower pressures.

4. For the heater configuration with the 1.366-centimeter-diameter nozzle throat, operation at maximum available arc power of 2 megawatts produces airstream enthalpy levels ranging from 27 900 kJ/kg at the lowest operating pressure (6.8 atm) to 2790 kJ/kg at the maximum pressure (34.0 atm).

5. By varying arc input power, arc chamber pressure, and nozzle expansion ratio it was possible to produce stagnation heating rates ranging from 17 to 1700 W/cm^2 on a

3.81-centimeter-diameter hemisphere-cylinder model and stagnation pressures ranging from 0.01 to 2.7 atmospheres with pressure and heating-rate distributions on models representative of hypersonic flow.

6. Hemisphere-cylinder models up to 10.15 centimeters in diameter have been tested in the 50.80-centimeter nozzle exit, and models up to 6.35 centimeters in diameter have been tested in the 16.75-centimeter nozzle exit.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 31, 1968,
129-02-08-04-23.

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