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ANODE NOZZLE EFFECTS ON THE BULK PROPERTIES OF ARC-HEATED ARGON

R. J. Bryson

ARO, Inc.

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June 1968

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FOREWORD

The work reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 6140501F, Project 8951, Task 895107.

The research was conducted by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract AF40(600)-1200. The work was conducted under ARO Project No. RW5716 and RW5806 in the Propulsion Research Area (R-2E-2) of the Rocket Test Facility (RTF) from June 1966 to December 1967, and the manuscript was submitted for publication as partial results of these research efforts on April 17, 1968.

The author wishes to acknowledge the late Jürgen Fröhlich for suggesting portions of this study and W. K. McGregor, Jr., for suggestions which added materially to the work.

This technical report has been reviewed and is approved.

Terry L. Hershey Captain, USAF Research Division Directorate of Plans and Technology	Edward R. Feicht Colonel, USAF Director of Plans and Technology

ABSTRACT

The thrust produced by a Gerdien-type d-c arc-jet using argon gas and exhausting into a low-pressure (approximately 2 mm Hg) test cell was measured and used to determine the momentum losses which occurred in the constant area anode nozzle. From these losses, a loss coefficient is defined which will yield good approximations for the gas total temperature and total pressure at the anode nozzle exit when applied to the standard constant area heat addition equations. The investigation was carried out for anode nozzles of different lengths and led to the fact that nozzle length was not a great contributor to these losses for relatively short nozzles (1.25 to 2.00 in.). Nozzle length was also found to play a very minor role in relation to the other contributing factors in determining the efficiency of the arc-heating process. The arc-jet was operated with gas flow rates of approximately 0.0034, 0.0042, and 0.005 lb/sec, electrical power input levels ranging from 2.7 to 5.8 kw, chamber pressures ranging from 6.7 to 11.7 psia, and gas inlet temperatures of approximately 530°R.

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NOMENCLATURE

A	Anode nozzle cross-sectional area
a	Intercept on ideal thrust axis
b	Intercept on measured thrust axis
C_ℓ	Loss coefficient (defined by Eq. (12))
c_p	Specific heat at constant pressure
F	Thrust produced by arc-jet
ℓ	Nozzle length
M	Mach number
m	Slope of straight-line approximation for ideal thrust
$\dot{m}$	Mass flow rate
n	Slope of straight-line approximation for measured thrust
p	Static pressure
p_o	Stagnation or total pressure
Q	Energy
R	Specific gas constant
T	Static temperature
T_o	Stagnation or total temperature
v	Velocity
z	Flow parameter (defined by Eq. (18))
γ	Ratio of specific heats
ρ	Density

SUBSCRIPTS

1	Station at entrance to anode nozzle
2	Station at exit of anode nozzle
a	Determined by using Eq. (12a)
c	Test cell
e	Input power

g	Gas
i	Ideal values
m	Measured values
RH	Obtained by Rayleigh heating analysis
tr	Translational mode

SECTION I
INTRODUCTION

To define the flow properties of the gas stream produced by an arc-jet heater, the temperature and pressure of the gas at the anode nozzle exit must be known. Because of the complex nature of the energy transfer process in such heaters, any theory used to determine these properties must be supported by experiment. A particular class of Gerdien-type, d-c arc-jet heaters having constant area anode nozzles was investigated by Bryson and Fröhlich (Ref. 1) and Fröhlich, Staats, and McGregor (Ref. 2). These studies indicated that a first approximation to the gas temperature and pressure at the nozzle exit for argon gas could be obtained through use of the Rayleigh heating analysis. Since this analysis is applicable only when heat is added to a one-dimensional, frictionless flow in a constant area duct, it cannot account for momentum losses in the nozzle without modification. To improve the accuracy of the values of gas temperature and pressure, the approach taken in this work was to define a simple correction to the Rayleigh heating analysis which would account for the nozzle losses and to experimentally verify its applicability.

The gas temperature and pressure at the nozzle exit are related to the thrust produced by the arc-jet. If the arc-jet thrust were measured, then the actual values of the gas temperature and pressure could be obtained. These values could then be compared with those given by the Rayleigh heating analysis, and the magnitudes of the errors in the ideal values caused by nozzle losses could be determined. This would then form a basis for correcting the ideal values to make them coincide with the actual values.

The losses which occur in the nozzle are caused by several mechanisms (e.g., friction, field effects, etc.), and this method of approach will not determine the various components. However, the frictional losses should be a function of nozzle length. The amount of energy transferred from the arc to the gas should also be a function of nozzle length because of the time the gas remains in the arc region (Ref. 3). Thus, it is desirable to obtain data from the arc-jet using nozzles of different lengths in order to investigate the effects of this parameter. An upper limit to nozzle lengths existed for the arc-jet used in these experiments because of cooling problems; however, a small range of lengths was investigated.

SECTION II
APPARATUS AND PROCEDURE

2.1 APPARATUS

The arc-jet used in these experiments was of the Gerdien type with a constant area, sonic nozzle anode (Fig. 1, Appendix I). This nozzle could be conveniently replaced to facilitate testing of various length throat sections. The arc-jet was operated in a vertical position inside a test cell (Fig. 2), which could be maintained at a pressure of approximately 2 mm Hg over the range of flow rates involved. The arc-jet operating parameters which were measured and the instruments used for the measurements are as follows:

		Accuracy of Measurements, percent
Gas supply pressure	Bourdon gage, 0 to 200 in. Hg (Absolute)	2.0
Gas flow rate	Brooks rotameter, 0 to 10 scfm	2.0
Gas inlet temperature	Copper-constantan thermocouple	1.0
Arc-jet chamber pressure	0- to 100-psid transducer strip-chart recorder	0.5
Arc voltage	Strip-chart recorder	1.0
Arc current	Shunt and strip-chart recorder	1.0
Cooling water flow rate	Time required to fill a given volume	2.0
Cooling water inlet and outlet temperature	Copper-constantan thermocouples	1.0
Cell pressure	McLeod gage	4.0

The thrust produced by the arc-jet was detected by letting it induce a torque in a rotating shaft and then using this torque to deflect a cantilever beam with a strain gage attached. This method allowed the strain gage to remain outside the test cell so that it was not subjected to low pressures or heat transfer. The maximum error of this system over the range of forces measured was ±3 percent. A more detailed description of the apparatus is included in Ref. 1.

2.2 PROCEDURE

The operating characteristics of the arc-jet are obtained as follows: The arc-jet is started, and the gas flow rate and power input are set. After steady-state operation is reached (about 1 min), the operating parameters are measured. This process is followed until the desired range of input conditions is covered for a specific anode nozzle. The nozzle is then replaced by one of different length, and the procedure is repeated. The anode nozzle entrance and the cathode tip were separated enough so that the flow did not choke at the entrance plane. For these experiments, the gas flow rate ranged from approximately 0.0034 to 0.005 lb/sec. The input power was varied in a range from 2.7 to 5.8 kw. The anode nozzles used had a diameter of 0.250 in. and lengths of 1.25, 1.50, 1.75, and 2.00 in.

SECTION III
ANALYSIS

It was shown in Refs. 1 and 2 that a one-dimensional constant area heat addition (Rayleigh heating) analysis of the gas flow through the arc in the anode nozzle section yields reasonable approximations for the gas properties at the exit plane since friction is neglected. These Rayleigh heating equations may be found in most fluid flow textbooks (cf., Ref. 4) and are reproduced here in the notation of Refs. 1 and 2 for convenience.

The change in the total temperature of the gas through the heating zone is given by

$$\left(\frac{T_{o2}}{T_{o1}}\right)_{RH} = \frac{M_2^2\,(1+\gamma M_1^2)^2\,\left(1+\frac{\gamma-1}{2}M_2^2\right)}{M_1^2\,(1+\gamma M_2^2)^2\,\left(1+\frac{\gamma-1}{2}M_1^2\right)} \tag{1}$$

where the subscript 2 denotes the exit plane of the nozzle and the subscript 1 denotes the entrance plane. The subscript RH refers to the values predicted by the Rayleigh heating process. Similarly, the change in total pressure is

$$\left(\frac{p_{o2}}{p_{o1}}\right)_{RH} = \frac{(1+\gamma M_1^2)\,\left(1-\frac{\gamma-1}{2}M_2^2\right)^{\gamma/\gamma-1}}{(1+\gamma M_2^2)\,\left(1+\frac{\gamma-1}{2}M_1^2\right)^{\gamma/\gamma-1}} \tag{2}$$

The Mach number at the entrance (M_1) may be found through use of the mass flow equation in the form

$$\frac{\dot{m}}{A} = \sqrt{\frac{\gamma}{R}}\,\frac{p_{o1}}{\sqrt{T_{o1}}}\,\frac{M_1}{\left(1+\frac{\gamma-1}{2}M_1^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \tag{3}$$

and the measured parameters ($\dot{m}$, A, p_{o1}, and T_{o1}). It was also shown in Ref. 1 that the degree of ionization for a similar arc-jet under similar operating conditions is quite small; therefore, using the ideal value of the ratio of specific heats ($\gamma = 5/3$) is justified. The flow through the nozzle is assumed to be choked at the nozzle exit (Ref. 2), and therefore $M_2 = 1$.

The thrust produced by the arc-jet may be written as

$$F = \dot{m}v_2 + A(p_2 - p_c) \tag{4}$$

With the use of the mass flow equation in the form,

$$\dot{m} = \rho A v \tag{5}$$

and the ideal gas relations,

$$v = M\sqrt{\gamma RT} \tag{6}$$

and

$$p = \rho RT \tag{7}$$

Equation (4) may be transformed into

$$F = p_2 A(1 + \gamma M_2^2) - Ap_c \tag{8}$$

If the isentropic relation at station 2,

$$\frac{p_{o2}}{p_2} = \left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{\gamma/\gamma-1} \tag{9}$$

is used, the equation for the thrust may be further transformed into

$$F = p_{o2} A \frac{(1 + \gamma M_2^2)}{\left(1 + \frac{\gamma-1}{2} M_2^2\right)^{\gamma/\gamma-1}} - Ap_c \tag{10}$$

Now if Eq. (2) is substituted into Eq. (10),

$$F = p_{o1} A \left[\frac{(1 + \gamma M_1^2)}{\left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\gamma/\gamma-1}}\right] - Ap_c \tag{11}$$

If the values of M_1 are small, the value of the bracketed quantity in Eq. (11) will approach unity. The more heat added to the gas in the anode nozzle, the smaller M_1 becomes, so that only at the lower power input conditions will the bracketed quantity be appreciably different from unity. (The largest value of M_1 encountered in these experiments was $M_1 = 0.22$. This will lead to a value of the bracketed quantity of 1.04. For cold flow, M_1 is considerably larger; therefore cold flow cannot be included in the same approximate analysis as hot flow.) If a constant value near unity is assumed, then an approximate linear form of Eq. (11) is

$$F \approx (\text{constant})\,(p_{o_1} - p_c) \tag{11a}$$

This indicates that the thrust produced by the arc-jet may be displayed to advantage as a function of the chamber pressure (p_{o_1}). Now a loss coefficient (referred to as resistance coefficient in Ref. 2) may be defined as

$$C_\ell = \frac{F_i - F_m}{F_i + Ap_c} \tag{12}$$

where the numerator is the difference between the ideal thrust and the measured thrust and is that portion of the impulse which is lost in the nozzle to friction and to interaction of the gas with the electric field in the nozzle. If Eq. (10) is substituted into Eq. (12), there will result

$$p_{o_2} = (1 - C_\ell)\,p_{o_{2_i}} \tag{13}$$

Dividing both sides of Eq. (13) by p_{o_1} gives

$$\frac{p_{o_2}}{p_{o_1}} = (1 - C_\ell)\left(\frac{p_{o_2}}{p_{o_1}}\right)_{RH} \tag{14}$$

which is the actual value of the total pressure ratio through the nozzle and is the value predicted by the Rayleigh heating analysis with a correction applied. Similarly, substitution of Eq. (8) into Eq. (12) and using Eqs. (5), (6), and (7) and the isentropic relation,

$$\frac{T_o}{T} = \left(1 + \frac{\gamma - 1}{2} M^2\right) \tag{15}$$

will lead to

$$T_{o_2} = (1 - C_\ell)^2\,T_{o_{2_i}} \tag{16}$$

and division by T_{o_1} gives

$$\frac{T_{o_2}}{T_{o_1}} = (1 - C_\ell)^2\left(\frac{T_{o_2}}{T_{o_1}}\right)_{RH} \tag{17}$$

This again gives the actual total temperature ratio through the nozzle as a corrected Rayleigh heating value.

Equation (11a) showed that the thrust (F) could be written as an approximate linear equation in (p_{o_1}). If such linear equations for the ideal thrust (F_i) and the measured thrust (F_m) are determined empirically, then they could be substituted into Eq. (12), and there would result an empirical equation for C_ℓ as a function of p_{o1}. This equation would take the form,

$$C_\ell = \frac{(m-n)\,p_{o1} + (a-b)}{m\,p_{o1} + (a + A p_c)} \tag{12a}$$

where m and n are the slopes of the lines representing the ideal thrust and the measured thrust, respectively, and a and b are the intercepts on the F axis.

An energy balance performed on the arc-jet should yield any nozzle length effects imposed on the efficiency of the energy addition process. This energy balance consists of two parts. First, the total amount of energy which goes into the gas (Q_g) is obtained by subtracting the cooling water losses from the total electrical power input (Q_e). Second, the amount of energy added to the gas as translational energy (Q_{tr}) is determined from the change in the total temperature through the nozzle. These two energy additions should reflect any dependence of the efficiency on nozzle length over the range investigated.

SECTION IV
RESULTS AND DISCUSSION

The complete set of arc-jet operating characteristics is given in Table I (Appendix II).

The values of the measured thrust produced by the arc-jet are given as a function of the arc-jet chamber pressure in Fig. 3. The linear approximations (Eq. (11a)), determined by a least-squares fit of the individual points, are shown as the solid line for the ideal values and the dashed line for the measured values. It can be seen that the difference between the two values which constitutes the nozzle losses is, on the average, about 6 percent of the ideal value. The values of the measured thrust are given for all the different length nozzles; there is no apparent pattern in the scatter which would indicate greater differences for any nozzle over another. The scatter in the measured values is then considered to result mainly from errors in the force measuring system. The largest error involved in the force measuring system is a hysteresis effect caused by the many leads attached to the arc-jet to supply power, cooling water, gas, etc. However, this error is at most ±3 percent.

The values of the loss coefficient (C_ℓ) defined by Eq. (12) are shown in Fig. 4. The relation between C_ℓ and p_{o1} (Eq. (12a)) obtained from the linear approximations for the ideal and measured thrust is shown as the solid line in Fig. 4. The scatter of the points about this curve appears somewhat excessive. However, when the ±3-percent possible error of the thrust measuring system is accounted for, the scatter is brought more into perspective. This error introduced into Eq. (12a) produces the error bounds shown as dashed lines in Fig. 4. An improvement in the accuracy of the thrust measuring system would be required to reduce the scatter. If it is assumed that the least-squares fit of the linear equation to the values of the measured thrust is adequate to average out the errors in measurement, then Eq. (12a) yields very good values for the loss coefficient (C_ℓ).

The total temperature ratio through the nozzle is given in Fig. 5 as a function of the flow parameter,

$$z = \sqrt{\frac{R}{\gamma}}\;\frac{\dot{m}}{A}\;\frac{\sqrt{T_{o1}}}{p_{o1}} = \frac{M_1}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \tag{18}$$

obtained from the mass flow equation (Eq. 3)). The total pressure ratio through the nozzle is similarly displayed in Fig. 6. The solid lines indicate the values predicted by the Rayleigh heating analysis, and the experimental values are indicated by the different symbols. There is a considerable amount of scatter in the experimental points in both cases. Again, the scatter does not indicate any apparent dependence on nozzle length, and thrust measurement errors appear to dominate. Listed in Table I are the corrected values of T_{o2}/T_{o1} and p_{o2}/p_{o1} obtained from the Rayleigh heating theory by applying C_ℓ from Eq. (12a). These values exhibit some dependence on the mass flow rate, with the larger flow rates having the smaller losses. This trend is consistent with that expected of frictional losses in this range of Reynolds numbers ($\sim 10^4$ based on gas exit conditions and nozzle length) because the larger flow rates would be associated with larger Reynolds numbers, and the flat plate solution should be used because the flow is not fully developed (Ref. 5). The corrected values of T_{o2}/T_{o1} and p_{o2}/p_{o1} obtained by using C_ℓ from Eq. (12a) and associated with mass flow rates near 0.00410 lb/sec are indicated by the dashed lines in Figs. 5 and 6 for comparison with the experimental values.

The amount of energy absorbed by the gas while in the nozzle (Q_g) is shown in Fig. 7 as a function of the total electrical power supplied to the arc-jet (Q_e). There is no apparent trend in the amount of energy absorbed by the gas with the length of the nozzle. Neither is there any obvious pattern associated with the different gas flow rates. The efficiency indicated for this power transfer process is, on the average, about 66 percent.

In Fig. 8, the portion of the absorbed energy which serves to increase the translational energy of the gas (Q_{tr}) is given as a function of the total electrical power supplied to the arc-jet. This translational energy increase is calculated from the measured total temperature increase in the nozzle and a constant value of the specific heat at constant pressure (c_p) of 0.1243 Btu/lb-°R. Again, there is no obvious trend of the increase in translational energy with either the nozzle length or the gas flow rate. The scatter in the indicated points is considerably worse in this case than for that shown in Fig. 7, and on the average, the efficiency is about 32 percent.

The scatter in Figs. 7 and 8 is believed to be caused by two effects. First, even though the same gas flow rate and arc current could be accurately set each time, the arc voltage could not be regulated to any degree of accuracy because the arc gap distance could not be maintained at one value within the necessary tolerances. This was caused mainly by arc-jet assembly problems, but an additional difference was caused by the tip of the cathode becoming molten and changing shape to a small degree. (There was no apparent erosion of the anode nozzle.) The difference in voltage caused by this small gap change was superimposed on the normal voltage and apparently forced the heat addition to proceed in a different manner. The second effect is the mode of operation of the arc. These modes have been referred to as the laminar mode and the turbulent mode (Ref. 6). They are characterized by a constant, well-behaved arc voltage for the laminar mode and an arc voltage of a highly oscillatory nature for the turbulent mode. The change from laminar to turbulent mode occurs quite suddenly and is dependent on both the gas flow rate and the power input. It is quite possible that the mode of arc operation has an effect on the gas heating efficiency. However, a more complete investigation of the arc mode operation would be required to determine if it is important for this case. In view of these facts, it is fortuitous that the heat addition process is well behaved enough to enable the determination of the gas properties at the exit of the anode nozzle to be made with some degree of reliability.

SECTION V
CONCLUDING REMARKS

In the arc heating process described herein, the interaction of all the input conditions, such as gas flow rate, arc current, arc voltage, etc., results in the fact that no one input parameter can be used to correlate the gas exit conditions. However, the process is well behaved enough so that exit conditions may be predicted very well by a flow parameter obtained from the mass flow equation and an experimentally determined loss coefficient based on gas impulse losses in the nozzle. The flow parameter determines the ideal total temperature and total pressure ratios through the nozzle as given by the Rayleigh heating analysis. The loss coefficient then allows these values to be corrected to yield the actual values at the nozzle exit.

An effort to establish a well-defined nozzle length effect on the gas properties and arc-jet operating efficiency met with little success. The small range of nozzle lengths covered (1.25 to 2.00 in.) did not contain one long enough for this effect to overshadow those imposed by the variations in the heating process itself. This would seem to indicate that the loss coefficients listed herein may be applied to an arc-jet of similar design without considering the nozzle length if it is not extremely long. The diameters of the constant area sections of the nozzle used in this study were all 0.25 in. Since the frictional losses cannot be separated from the field effects, any attempt at scaling these results to nozzles with different diameters should be done with caution. The same note of caution should be observed if applying these results to gases other than argon.

The results obtained by this method should remain useful until the power input reaches the point where ionization becomes so large that the specific heat ratio (γ) cannot be considered a constant. However, if γ does change, the values of gas temperature and pressure will not be in error by a large amount. Typically, a decrease in γ of 30 percent will cause a decrease of about 13 percent in the calculated total temperature and an increase of about 5 percent in the calculated total pressure.

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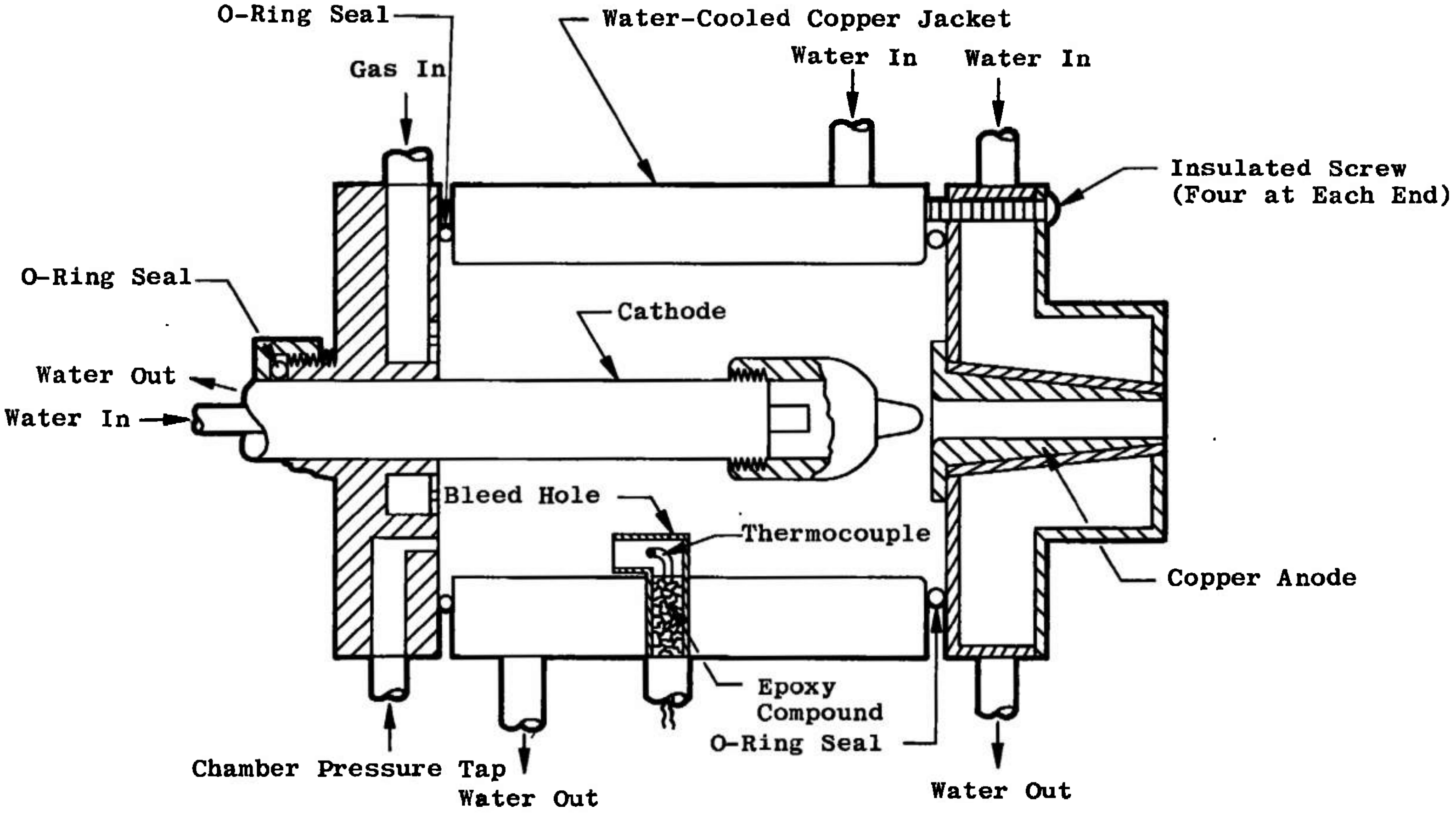
APPENDIXES

I. ILLUSTRATIONS
II. TABLE



(Not to Scale)

Fig. 1 Arc-Jet

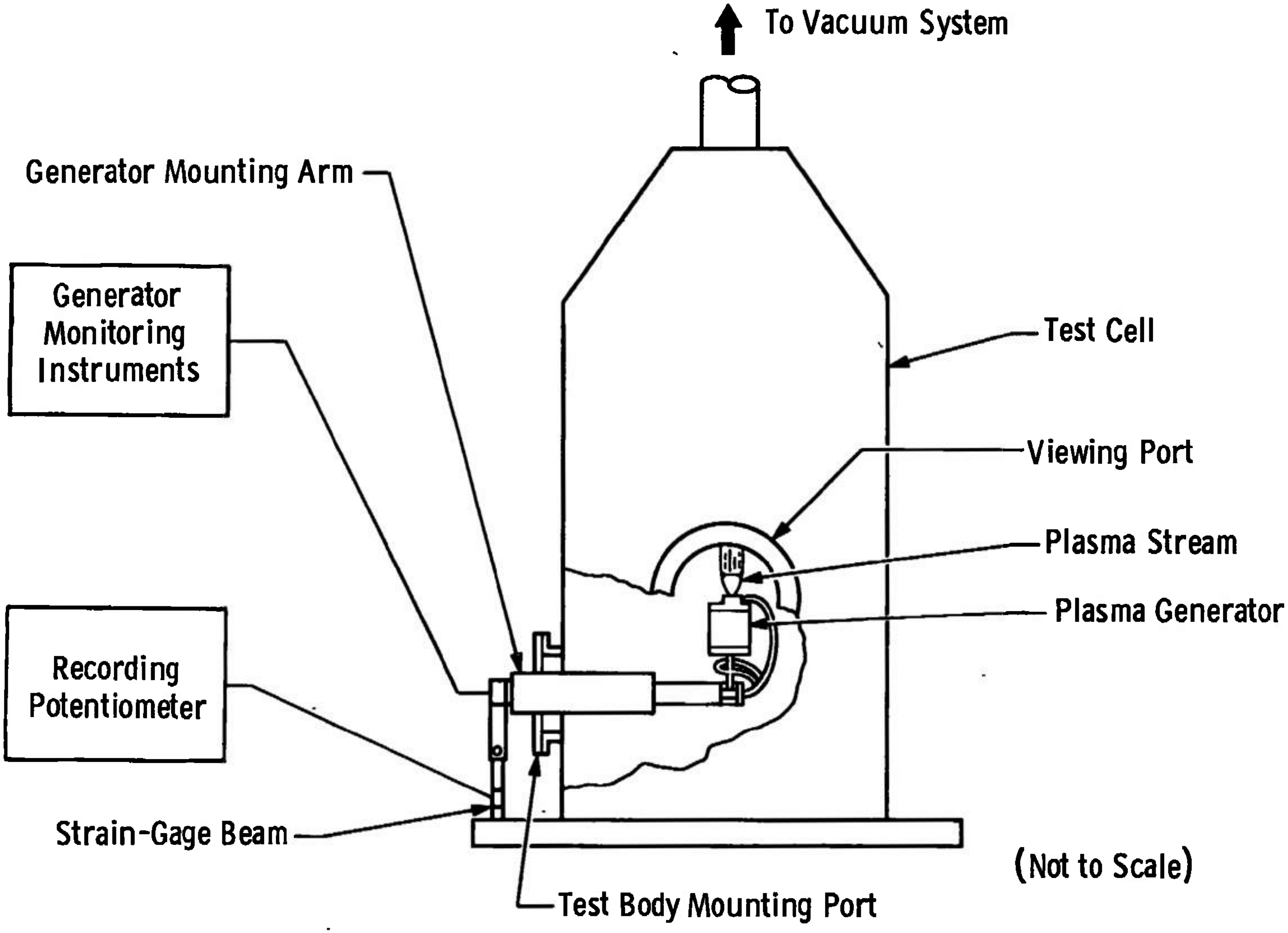


Fig. 2 Test Cell

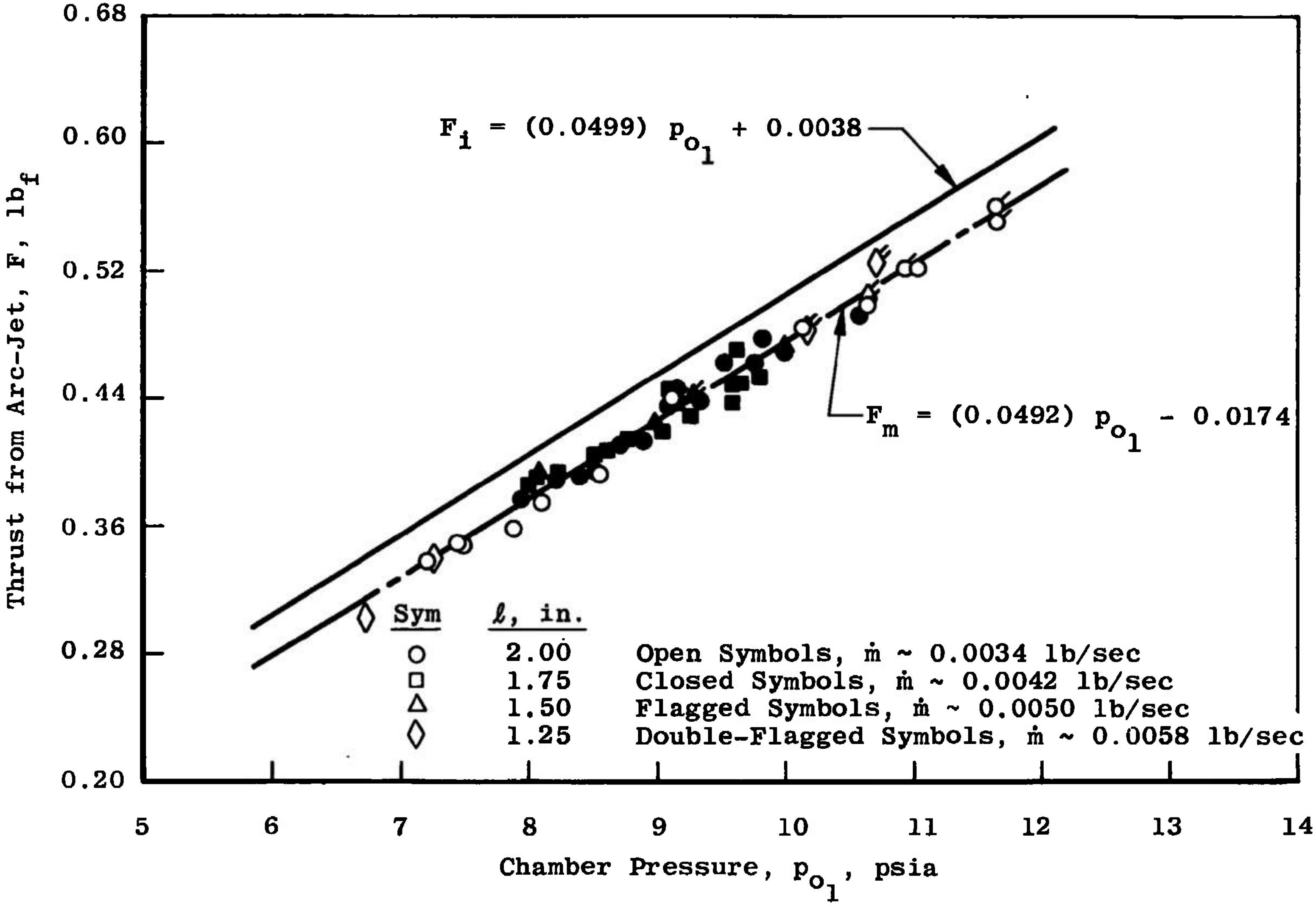


Fig. 3 Comparison of Ideal and Measured Thrust

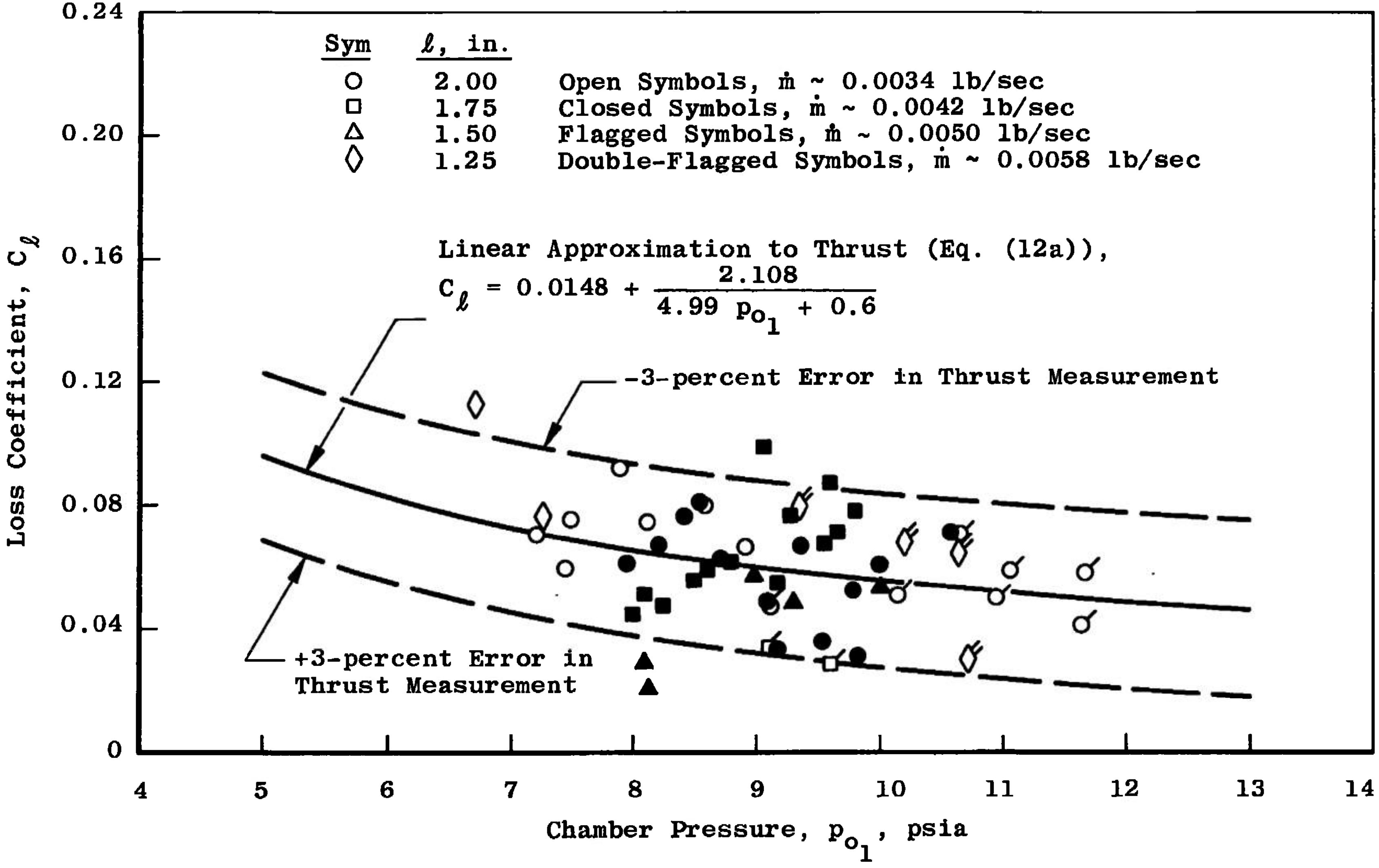


Fig. 4 Comparison of Measured Loss Coefficients and Those Obtained by Linear Approximations of Thrust

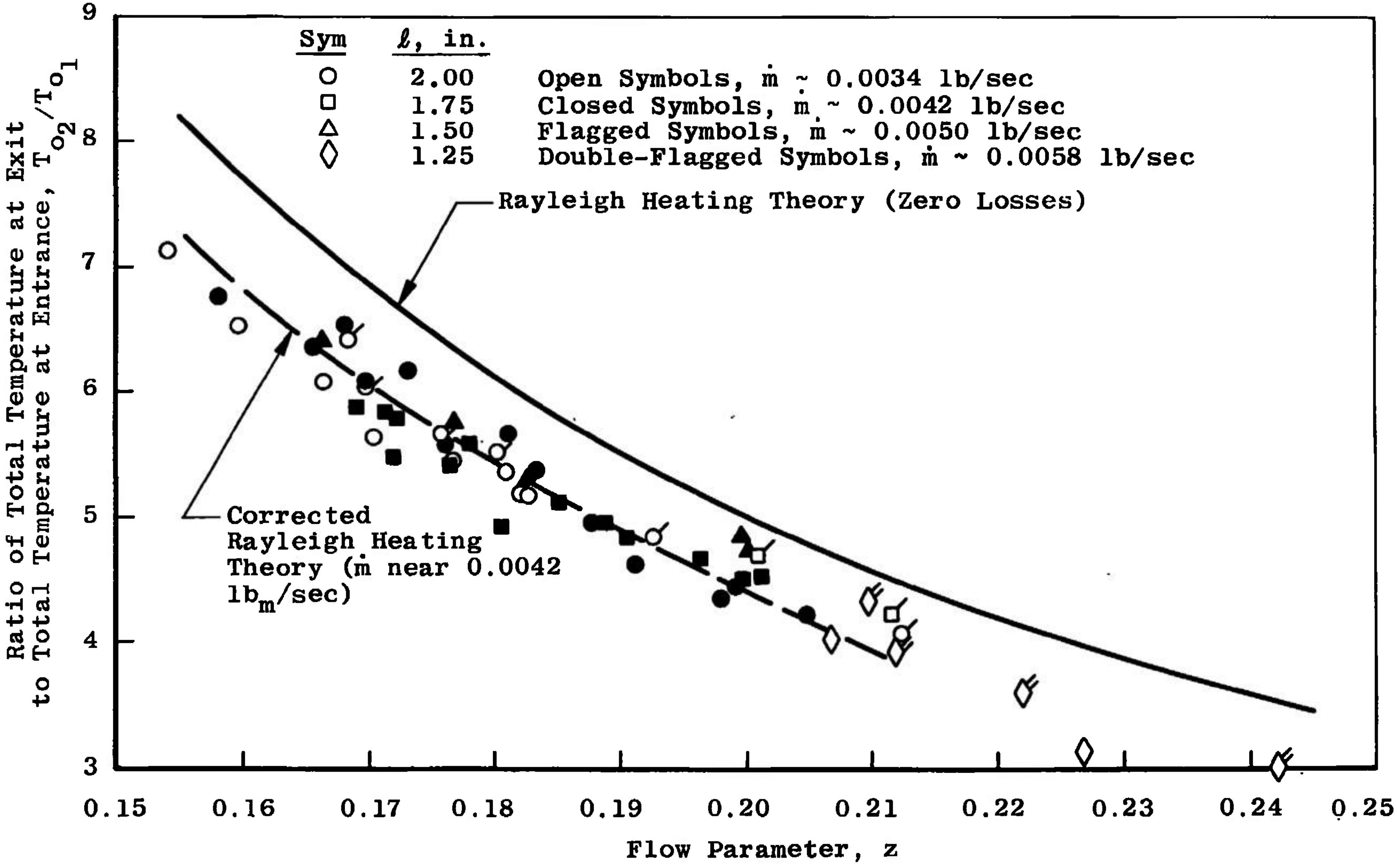


Fig. 5 Measured Total Temperature Increase in the Nozzle Compared with That Predicted by Rayleigh Heating Theory

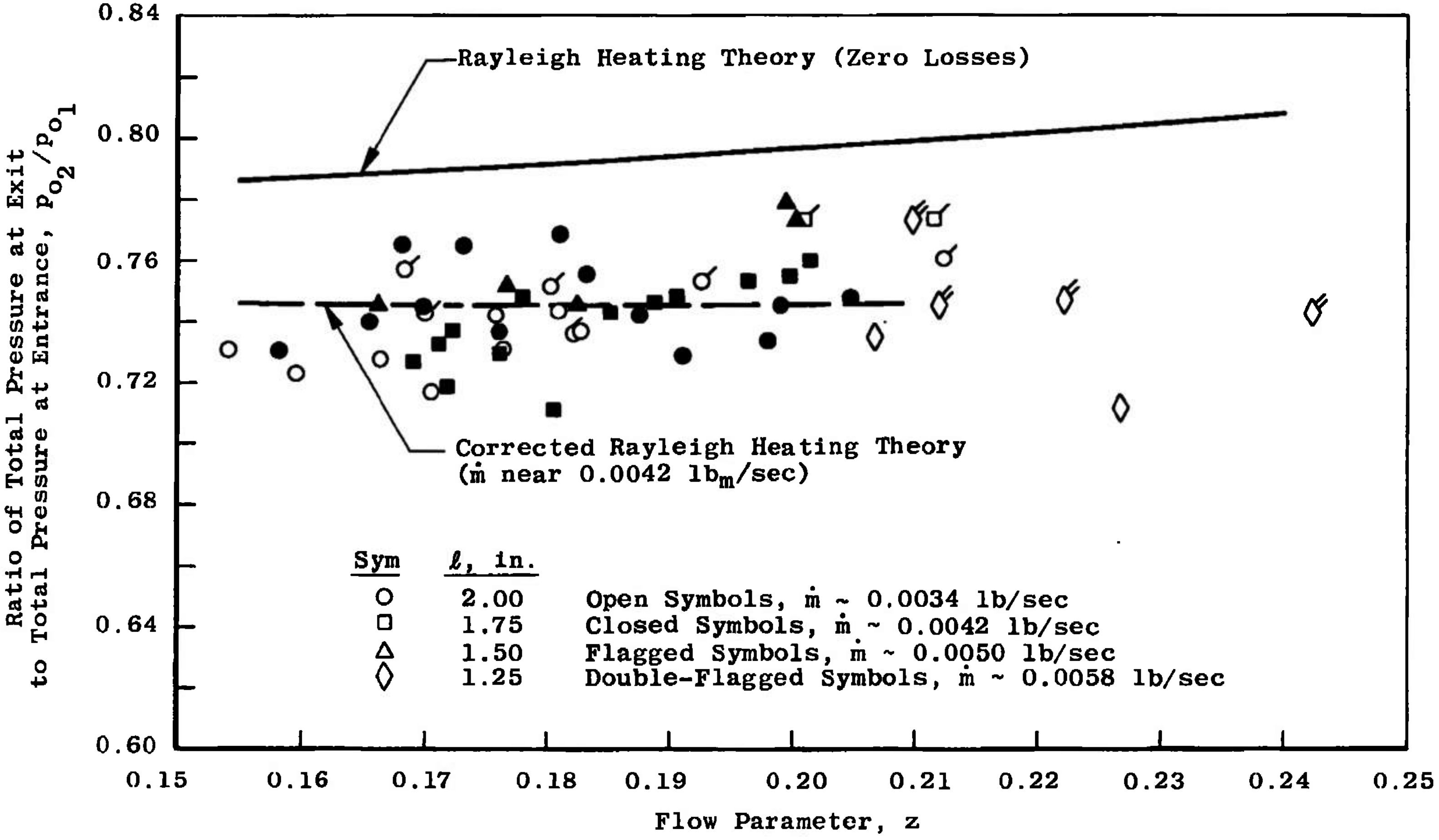


Fig. 6 Measured Total Pressure Drop in Nozzle Compared with That Predicted by Rayleigh Heating Theory

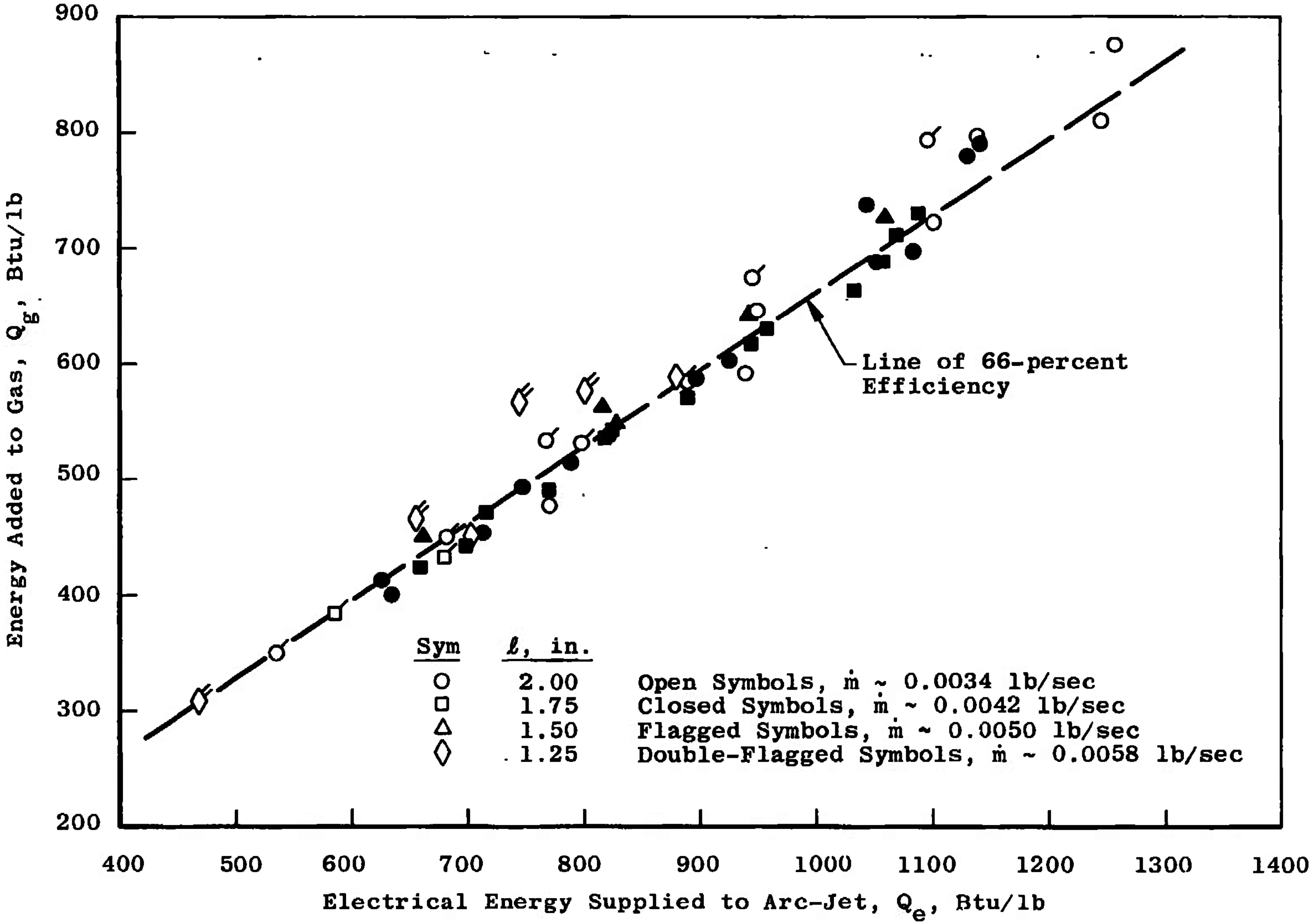


Fig. 7 Variation of the Energy Added to the Gas with Electrical Energy Supplied to the Arc-Jet

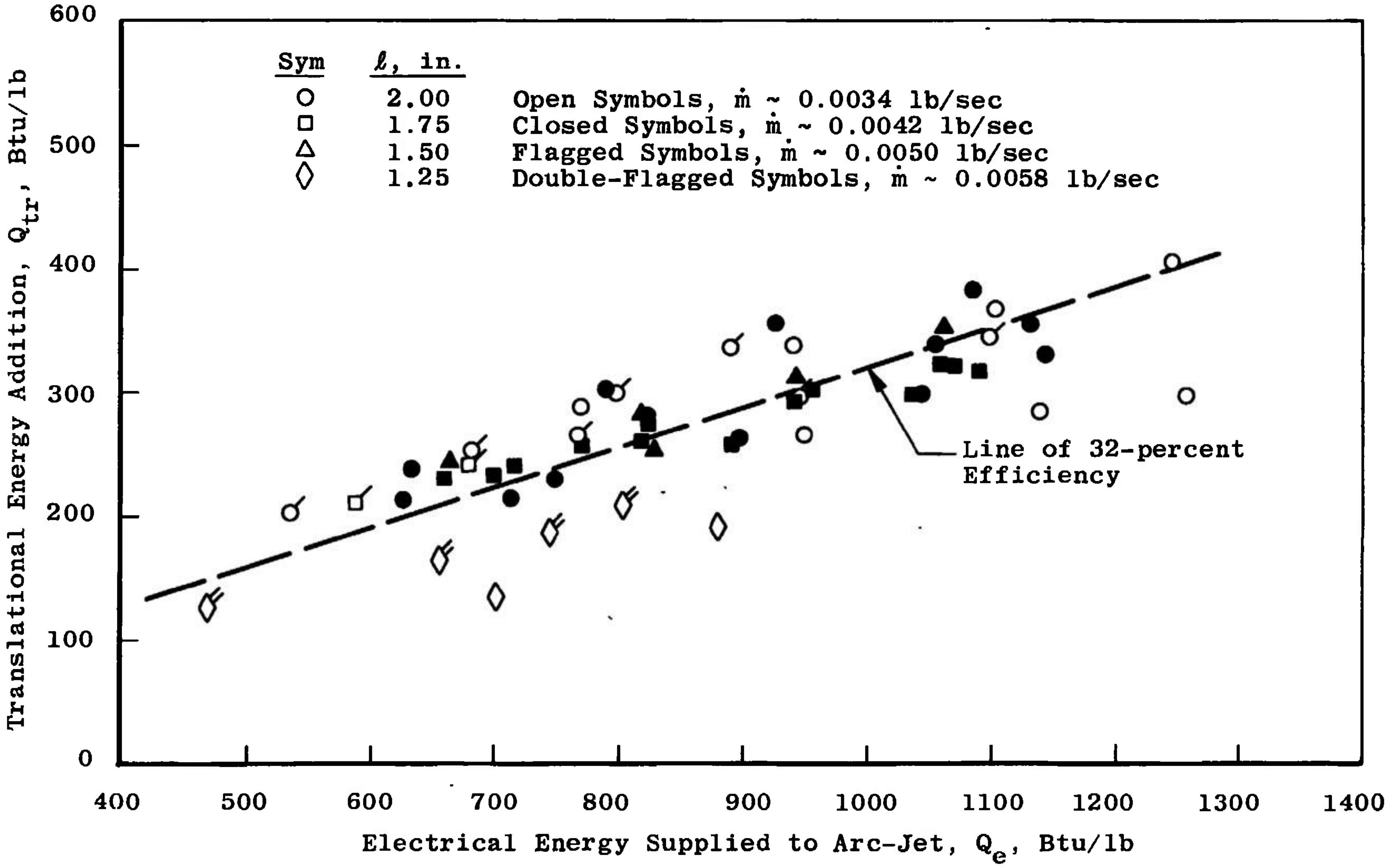


Fig. 8 Variation of the Translational Energy Addition with Electrical Energy Supplied to the Arc-Jet

TABLE I
ARC-JET OPERATING PARAMETERS

Symbol	ℓ, in.	$\dot{m}$, lb/sec	T_{o_1}, °R	p_{o_1}, psia	p_c, psia	F_m, lb$_f$	Q_e, Btu/lb	Q_g, Btu/lb	z	$(T_{o_2}/T_{o_1})_{RH}$	$(p_{o_2}/p_{o_1})_{RH}$	F_l, lb$_f$	$(T_{o_2}/T_{o_1})_m$	$(p_{o_2}/p_{o_1})_m$	Q_{tr}, Btu/lb	$(C_\ell)_m$	$(T_{o_2}/T_{o_1})_a$	$(p_{o_2}/p_{o_1})_a$
○	2.00	0.00342	510	7.68	0.035	0.358	1259	975	0.1705	0.81	0.7699	0.399	5.83	0.7170	297	0.0920	5.85	0.730
○		0.00337	514	7.49		0.549	1139	796	0.1700	6.37	0.7911	0.378	5.45	0.7512	295	0.0754	5.51	0.750
○		0.00337	611	7.22		0.336	949	645	0.1627	5.99	0.7923	0.304	5.17	0.7367	265	0.0704	0.19	0.736
ơ		0.00497	511	11.05	0.047	0.522	945	674	0.1759	0.40	0.7910	0.555	5.09	0.7422	290	0.0598	5.77	0.751
ơ		0.00497	509	10.05		0.498	706	553	0.1921	6.00	0.7923	0.538	5.19	0.7359	205	0.0706	5.40	0.751
ơ		0.00502	610	11.64		0.060	1090	793	0.1984	0.98	0.7695	0.5845	0.42	0.7509	343	0.0410	0.50	0.750
●		0.00413	054	9.99	0.048	0.470	920	003	0.1855	7.20	0.7886	0.500	8.35	0.7400	355	0.0910	0.47	0.747
●		0.00412	535	9.35		0.437	799	514	0.1791	0.50	0.7910	0.409	5.55	0.7362	502	0.0672	5.65	0.746
●		0.00419	534	10.57		0.490	1083	996	0.1592	7.00	0.7075	0.528	9.77	0.7302	394	0.0709	7.01	0.748
●		0.00408	532	8.52		0.594	833	400	0.1012	0.44	0.7945	0.428	4.81	0.7283	250	0.0811	4.80	0.745
○		0.00538	031	7.45		0.351	768	479	0.1610	8.04	0.7822	0.374	5.39	0.7434	266	0.0594	5.27	0.730
○		0.00339	532	8.11		0.374	940	592	0.1064	7.00	0.7890	0.405	6.08	0.7277	539	0.0755	5.20	0.739
○		0.00342	553	0.59		0.393	1101	722	0.1597	7.09	0.7075	0.427	6.52	0.7231	390	0.0902	8.75	0.739
○		0.00344	531	8.90		0.415	1248	010	0.1542	6.20	0.7605	0.442	7.13	0.7305	405	0.0662	7.26	0.741
●		0.00408	533	8.21	0.039	0.399	740	492	0.1991	0.04	0.7065	0.410	4.45	0.7450	228	0.0904	4.44	0.747
●		0.00409	532	7.90		0.577	020	413	0.2040	4.78	0.7981	0.402	4.22	0.7475	213	0.0612	4.10	0.740
●		0.00410	532	8.72		0.411	097	599	0.1977	5.69	0.7936	0.439	4.96	0.7420	262	0.0625	4.99	0.740
●		0.00415	533	9.77		0.492	1053	097	0.1098	6.80	0.7886	0.499	6.09	0.7444	330	0.0524	0.09	0.747
ơ		0.00489	531	10.13	0.049	0.404	681	450	0.1920	5.30	0.7850	0.011	4.04	0.7525	254	0.0510	4.85	0.754
ơ		0.00494	032	10.93		0.522	796	631	0.1803	6.10	0.7920	0.549	6.52	0.7514	299	0.0500	5.49	0.751
ơ		0.00490	532	11.80		0.551	808	591	0.1698	8.84	0.7809	0.585	0.00	0.7427	335	0.0585	6.18	0.750
ơ		0.00489	530	9.12		0.440	535	350	0.2124	4.47	0.8000	0.462	4.00	0.7801	202	0.0470	3.99	0.754
●		0.00428	513	8.42	0.041	0.592	713	454	0.1979	0.06	0.7946	0.425	4.34	0.7535	214	0.0704	4.40	0.745
●		0.00420	013	9.09		0.436	921	536	0.1834	5.85	0.7920	0.459	0.37	0.7552	270	0.0493	5.29	0.747
●		0.00424	014	9.10		0.447	1045	737	0.1011	6.09	0.7821	0.462	5.86	0.7679	299	0.0329	5.41	0.740
●		0.00422	515	9.62		0.470	1130	776	0.1661	6.96	0.7692	0.493	0.53	0.7950	554	0.0304	0.21	0.740
●		0.00422	012	9.53		0.465	1142	760	0.1732	0.65	0.7903	0.400	9.17	0.7844	530	0.0300	5.92	0.746
■	1.75	0.00413	533	0.85	0.043	0.449	1068	711	0.1711	6.74	0.7900	0.464	5.83	0.7525	320	0.0712	6.01	0.746
■		0.00415	532	8.00		0.453	1056	666	0.1091	9.80	0.7895	0.491	5.67	0.7200	322	0.0783	6.18	0.748
■		0.00410	530	9.27		0.429	944	010	0.1703	0.55	0.7911	0.405	5.42	0.7286	292	0.0770	5.05	0.740
■		0.00406	030	6.78		0.414	925	541	0.1952	5.90	0.7931	0.442	5.11	0.7432	271	0.0620	5.12	0.745
■		0.00407	527	6.23		0.383	718	471	0.1985	0.08	0.7990	0.413	4.80	0.7527	240	0.0470	4.46	0.746
■		0.00412	554	8.59	0.045	0.437	1034	064	0.1720	6.03	0.7901	0.400	5.49	0.7167	288	0.0970	5.91	0.740
■		0.00410	551	8.05		0.400	880	570	0.1807	6.02	0.7920	0.454	4.92	0.7108	258	0.0990	5.55	0.746
■		0.00403	528	8.51		0.404	772	491	0.1907	5.48	0.7944	0.428	4.88	0.7478	255	0.0580	4.80	0.745
■		0.00400	529	6.00		0.500	958	425	0.2015	4.82	0.7971	0.404	4.01	0.7592	230	0.0440	4.31	0.748
■		0.00415	550	8.57		0.449	1099	729	0.1723	6.64	0.7901	0.401	0.70	0.7370	516	0.0670	6.91	0.745
■		0.00411	028	9.17		0.436	857	930	0.1791	0.23	0.7914	0.461	0.58	0.7479	302	0.0549	3.03	0.740
■		0.00410	528	6.62		0.406	016	535	0.1090	5.57	0.7940	0.454	4.94	0.7455	250	0.0508	4.69	0.745
■		0.00407	527	9.09		0.507	099	442	0.1999	5.00	0.7960	0.409	4.52	0.7542	231	0.0615	4.39	0.746
□̛		0.00495	029	0.09	0.050	0.449	590	384	0.2117	4.51	0.7996	0.461	4.22	0.7750	211	0.0558	4.01	0.754
ơ		0.00486	028	9.60	0.050	0.471	979	434	0.2010	4.95	0.7971	0.490	4.00	0.7727	241	0.0209	4.41	0.703
▲	1.50	0.00409	529	6.13	0.045	0.402	029	540	0.1896	5.03	0.7967	0.411	4.84	0.7767	252	0.0205	4.42	0.740
▲		0.00412	529	9.28		0.443	942	642	0.1798	0.52	0.7911	0.400	5.75	0.7517	512	0.0479	5.83	0.746
▲		0.00417	529	0.09		0.473	1090	720	0.1862	7.10	0.7890	0.500	6.38	0.7449	354	0.0550	0.38	0.747
▲		0.00413	527	8.90		0.425	917	562	0.1626	0.93	0.7930	0.451	5.29	0.7449	291	0.0578	0.27	0.740
▲		0.00409	525	8.00		0.396	602	450	0.2003	0.00	0.7970	0.400	4.73	0.7727	244	0.0288	4.36	0.748
◊	1.25	0.00384	512	7.28	0.043	0.338	880	099	0.2068	4.89	0.7866	0.507	4.03	0.7352	192	0.0704	4.09	0.743
◊		0.00390	612	6.72	0.043	0.305	701	452	0.2260	3.96	0.0040	0.542	3.13	0.7120	135	0.1125	3.40	0.745
◊̛		0.00079	510	8.33	0.059	0.440	499	309	0.2424	3.53	0.8085	0.479	2.99	0.7434	120	0.0800	3.14	0.702
◊̛		0.00578	510	10.18		0.402	050	405	0.2221	4.13	0.8026	0.018	3.58	0.7464	105	0.0990	3.70	0.700
◊̛		0.00570	011	10.72		0.520	002	676	0.2089	4.07	0.7992	0.542	4.31	0.7720	210	0.0501	4.11	0.757
◊̛		0.00077	510	10.95		0.004	745	507	0.2120	4.48	0.7999	0.538	5.84	0.7457	180	0.0049	4.02	0.750

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13 ABSTRACT

The thrust produced by a Gerdien-type d-c arc-jet using argon gas and exhausting into a low-pressure (approximately 2 mm Hg) test cell was measured and used to determine the momentum losses which occurred in the constant area anode nozzle. From these losses, a loss coefficient is defined which will yield good approximations for the gas total temperature and total pressure at the anode nozzle exit when applied to the standard constant area heat addition equations. The investigation was carried out for anode nozzles of different lengths and led to the fact that nozzle length was not a great contributor to these losses for relatively short nozzles (1.25 to 2.00 in.). Nozzle length was also found to play a very minor role in relation to the other contributing factors in determining the efficiency of the arc-heating process. The arc-jet was operated with gas flow rates of approximately 0.0034, 0.0042, and 0.005 lb/sec, electrical power input levels ranging from 2.7 to 5.8 kw, chamber pressures ranging from 6.7 to 11.7 psia, and gas inlet temperatures of approximately 530°R.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
arc-jets argon ~~arc heated~~ 3 anode nozzle effects momentum losses						

1. Arc heated argon

2 Argon -- Heating.

3 Argon -- Properties

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