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AERODYNAMIC FORCES ON A MODEL CONSTRUCTED FROM WIRE CLOTH IN LOW DENSITY HYPERSONIC FLOW

David E. Boylan

ARO, Inc.

April 1966

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FOREWORD

The work reported herein was done at the request of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) for the General Electric Company, Spacecraft Department, under Program Element 65402234.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The test was conducted from January 14 to 26, 1966 under ARO Project No. VL0642, and the manuscript was submitted for publication on February 9, 1966.

This technical report has been reviewed and is approved.

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ABSTRACT

Measured aerodynamic forces on a satellite-type vehicle constructed from tungsten wire cloth are presented. The test medium was nitrogen, with a Mach number of 10.15 and a Reynolds number of 388 in.^{-1}. The feasibility of using force models of this type is demonstrated. Because no other data on such a model are available to the author, no detailed comparison of aerodynamic features is offered. Drag coefficient at small angle of attack was found to be approximately the same as a roughly similar shape of nonporous construction, but corresponding lift coefficient slope was markedly reduced by the porosity.

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ILLUSTRATIONS

TABLE

NOMENCLATURE

A	Moment arm
C_D	Drag coefficient

C_L	Lift coefficient
C_M	Pitching-moment coefficient
D	Drag or model diameter
F	Restoring forces on balance
L	Lift
M_p	Static pitching moment
M_∞	Mach number
p_o	Total pressure
q_∞	Free-stream dynamic pressure
Re_∞	Free-stream Reynolds number
T_o	Total temperature
α	Angle of attack
λ_∞	Free-stream mean free path

SECTION I
INTRODUCTION

The experimental determination of the aerodynamic characteristics of vehicles of complex geometry in conditions simulating flight at extreme altitudes has become increasingly important. This is attributable, in part, to the complexity of the flow model required for an adequate theoretical analysis in the transitional flow regimes. Therefore, recourse to wind tunnels providing simulation of flight at high altitudes is necessary.

In the present test, the feasibility of using a model constructed of tungsten wire cloth was investigated. The problems of measuring and resolving very small aerodynamic loads, and of constructing a model which could withstand the high heat loads involved, were primary considerations.

SECTION II
APPARATUS

2.1 WIND TUNNEL

The investigation was conducted in the low density hypersonic tunnel (Gas Dynamic Wind Tunnel, Hypersonic (L)) of the von Kármán Gas Dynamics Facility (VKF), AEDC. This tunnel is a continuous-type, arc-heated, ejector-pumped facility, normally using nitrogen or argon as the test gas. A general description is contained in Appendix I.

2.2 AERODYNAMIC NOZZLE

The nozzle used for the investigation is an axisymmetric, contoured nozzle with no flow gradients in the test section. The useful test core is approximately 1.2 in. in diameter and 6.0 in. long. Flow conditions for this nozzle are listed in the following table.

Gas	Nitrogen
p_o, $lb_f/in.^2$	18.0
T_o, °K	3000
M_∞	10.15
Re_∞, $in.^{-1}$	388
λ_∞, in.	0.04*

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*For a static gas of billiard-ball molecules

Diagnostic techniques for flow calibration are discussed in Appendix I.

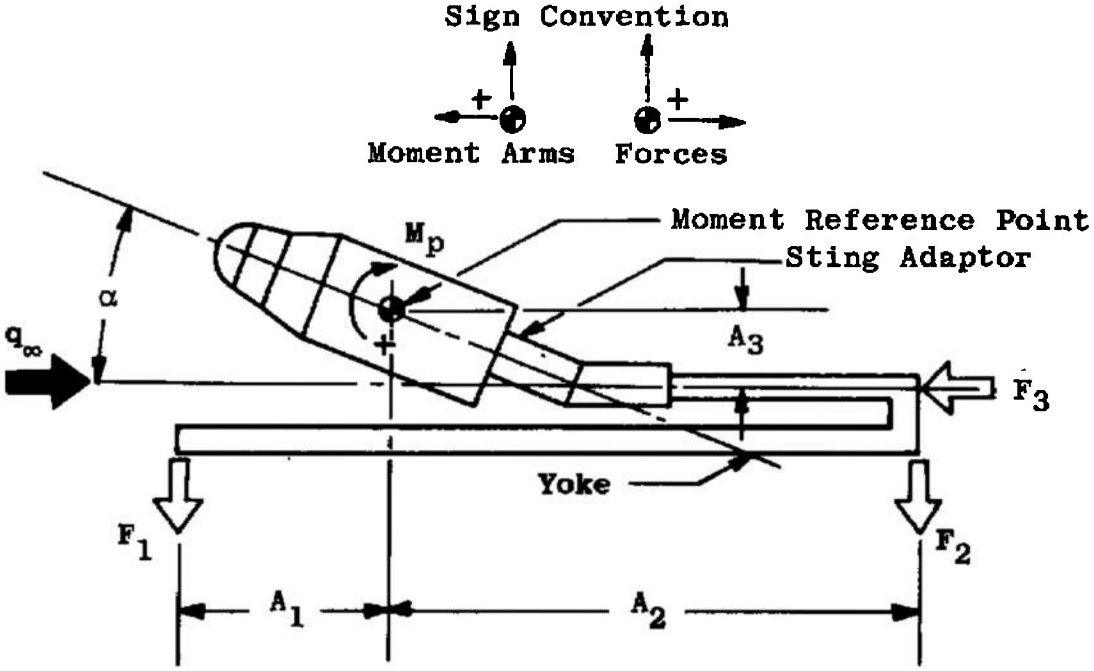
2.3 TEST MODEL

The model was constructed from 20 by 20 mesh tungsten wire cloth in the shape of a typical satellite. Figure 1 indicates model dimensions, and Fig. 2 is a photograph of the model mounted on the balance. High temperature silver solder was used where necessary, and the balance adaptor was connected to the model by piano wire of 0.010-in. diameter. Individual strands of the tungsten cloth had a diameter of 0.007 in. The model was exposed to the high temperature flow for repeated periods of approximately 30 sec during the test, and a large temperature gradient was noticed to exist over the surface of the model. However, no visible distortion or deterioration was found after any test run, so it was assumed that any influence of distortion of model or support system during a test run could be taken into account adequately by a correction to the angle of attack, which would meet the requirement for zero lift at zero effective angle of attack. This is discussed in Section III.

2.4 THREE-COMPONENT FORCE BALANCE

The balance is of the external type and is composed of two lift and two drag components, with pitching moment being derived from these components. Although the two drag components could be used to determine yawing moment, only pitching moment is measured at this time. All components are operated on the nulling principle. Figure 3 indicates the mechanical arrangement of the balance, and Ref. 1 gives a complete description, with a discussion of the balance performance evaluation and accuracy.

The aerodynamic pitching moment of the model is resolved from the lift and drag forces and measured moment-arm lengths. The following sketch illustrates the method by which the pitching moment is determined. From the sketch it can be seen that the sum of all moments about the moment reference point is $M_p + F_1A_1 + F_2A_2 + F_3A_3 = 0$ where F_1, F_2, and F_3 are balance restoring or reaction forces of appropriate sign.



The distances A_1 and A_2 are determined from the known distance between components F_1 and F_2 and the measured position of the model moment reference point. Length A_3 is determined by the positions of the sting centerline and the moment reference point of the body.

The loads experienced during the tests were of a magnitude that would, except for the lift components near zero angle of attack, be well within the accuracy limit of the balance. For comparative purposes and error estimates, the following values may be used:

	Maximum Load, lb_f or in.-lbf	Accuracy, lb_f or in.-lb_f
Drag	$\pm 2 \times 10^{-2}$	$\pm 2 \times 10^{-4}$
Lift	$\pm 1 \times 10^{-3}$	$\pm 4 \times 10^{-5}$
Moment	$\pm 3 \times 10^{-3}$	$\pm 4 \times 10^{-5}$

SECTION III
EXPERIMENTAL PROCEDURE AND RESULTS

The relatively delicate nature of the model and the balance adaptor suggested the possibility of model distortion affecting angle of attack during a test run, thereby causing an error in the data. Also a slight distortion of the balance sting may result from very small errors in balance alignment or the influence of the model weight. This possibility was investigated, and the net effect was measured simply by plotting the data and noting the displacement of the angle-of-attack scale required to produce symmetry, i.e., $C_L = 0$ at $\alpha = 0$. This enabled a correction to the nominal angle of attack of each sting adaptor to be made. A total error of 1.20 deg was found to exist, and the data have been adjusted accordingly. Table I contains tabulated test data.

Figures 4 through 6 show the data reduced to coefficient form, viz, C_L, C_D, and C_M. The data are referenced to the model base area (neglecting the porosity) and diameter. Pitching moment is referenced about the model nose centerline. Also indicated are the absolute loads as measured by the balance. These force measurements suggest that models of this type can successfully be tested in the arc-heated, low density tunnel.

The existence of tare forces was considered to be a probable source of error in these measurements. For this reason the piano wire support was cut downstream of the model base, and tare measurements were made. These measurements were accomplished by supporting the model upstream of (but not touching) the balance adaptor. Tare forces were found to be very small and random in nature as the balance adaptor angle of attack was varied. Tare lift measurements were consistently less than 1 percent of maximum reading obtained with the model, and tare drag measurements were correspondingly less than one-half of 1 percent. It was concluded that the model support was essentially in a stagnant region of the wake, and the forces indicated in Figs. 4 through 6 represent the total aerodynamic loads on the model.

SECTION IV
CONCLUDING DISCUSSION

The results of the present investigation indicate the feasibility of using force models constructed from temperature-resistant wire cloth in the arc-heated, low density tunnel. The lower load levels were successfully resolved to provide adequate data trends.

No comparative data are available, but it may be noted that drag coefficient at small angles of attack is approximately the same as for the roughly similar shape of nonporous construction (Model A) discussed in Ref. 2. However, the corresponding lift coefficient slope is reduced well below that of the nonporous model.

Based on equality of Knudsen numbers and an assumed 5-ft-diam full-scale vehicle, this test simulated flight at 320,000 ft. On the other hand, considering equality of Reynolds numbers and a full-scale velocity of 26,000 fps, an altitude of 340,000 ft was simulated. In each case, the standard atmosphere of Ref. 3 was assumed in arriving at these simulation assessments.

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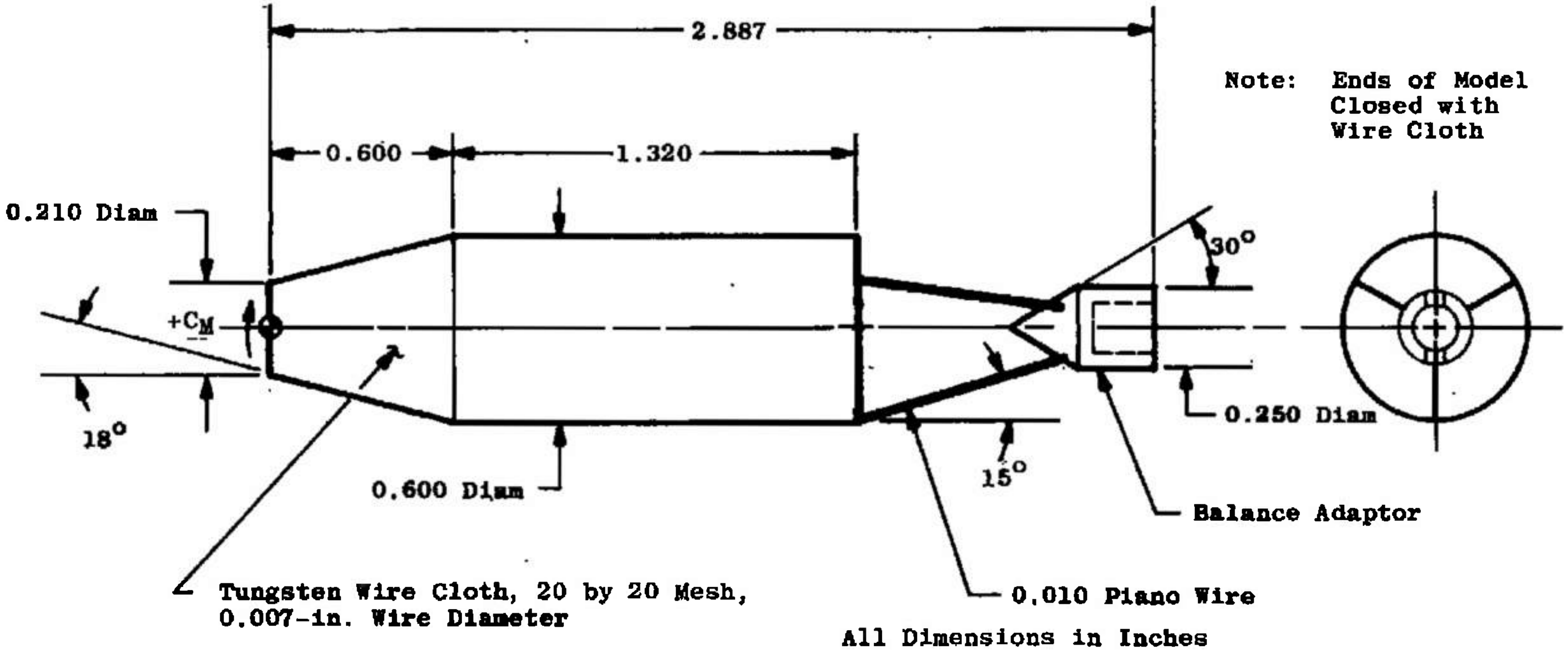


Fig. 1 Wire Cloth Force Model

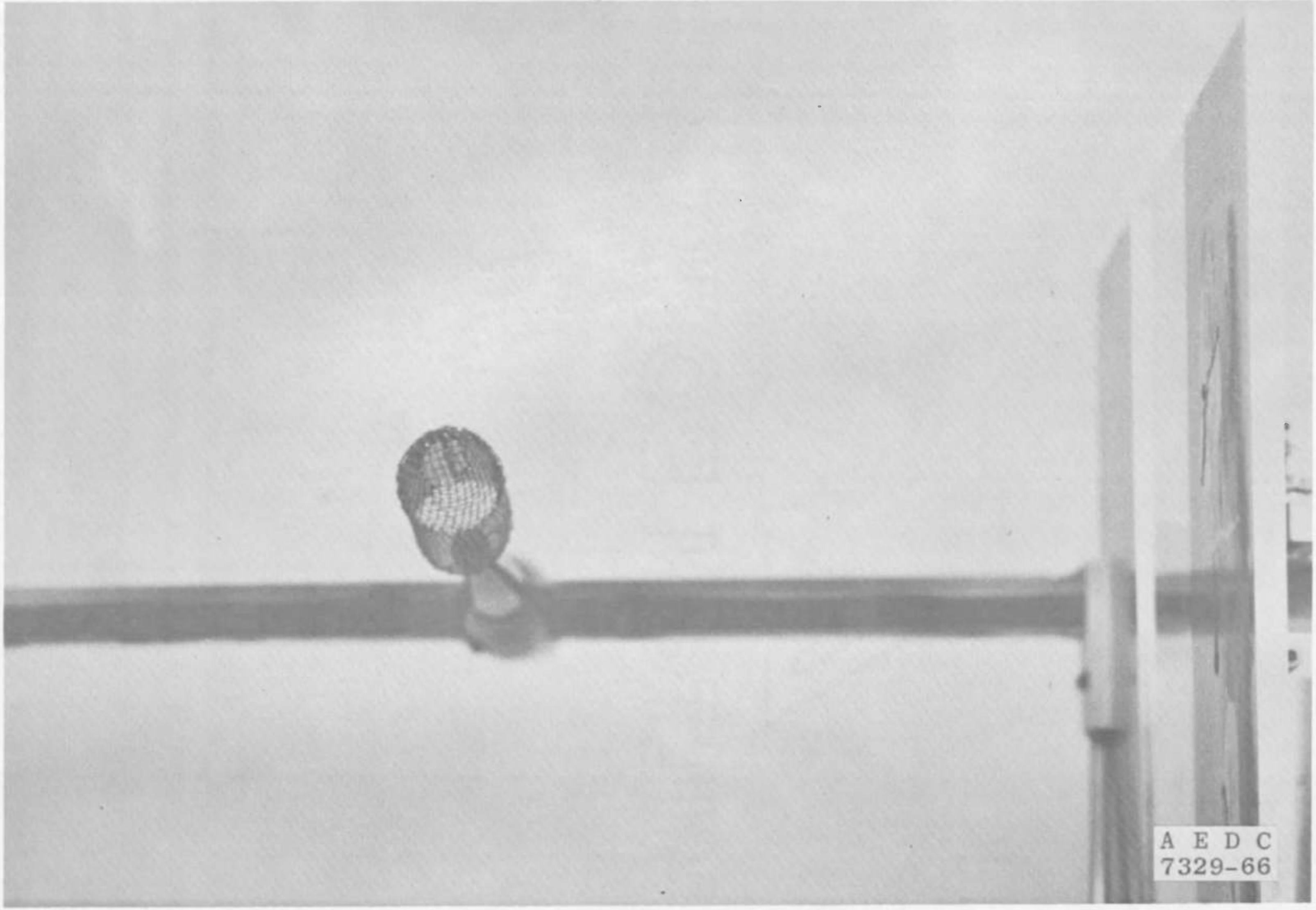


Fig. 2 Photograph of Model

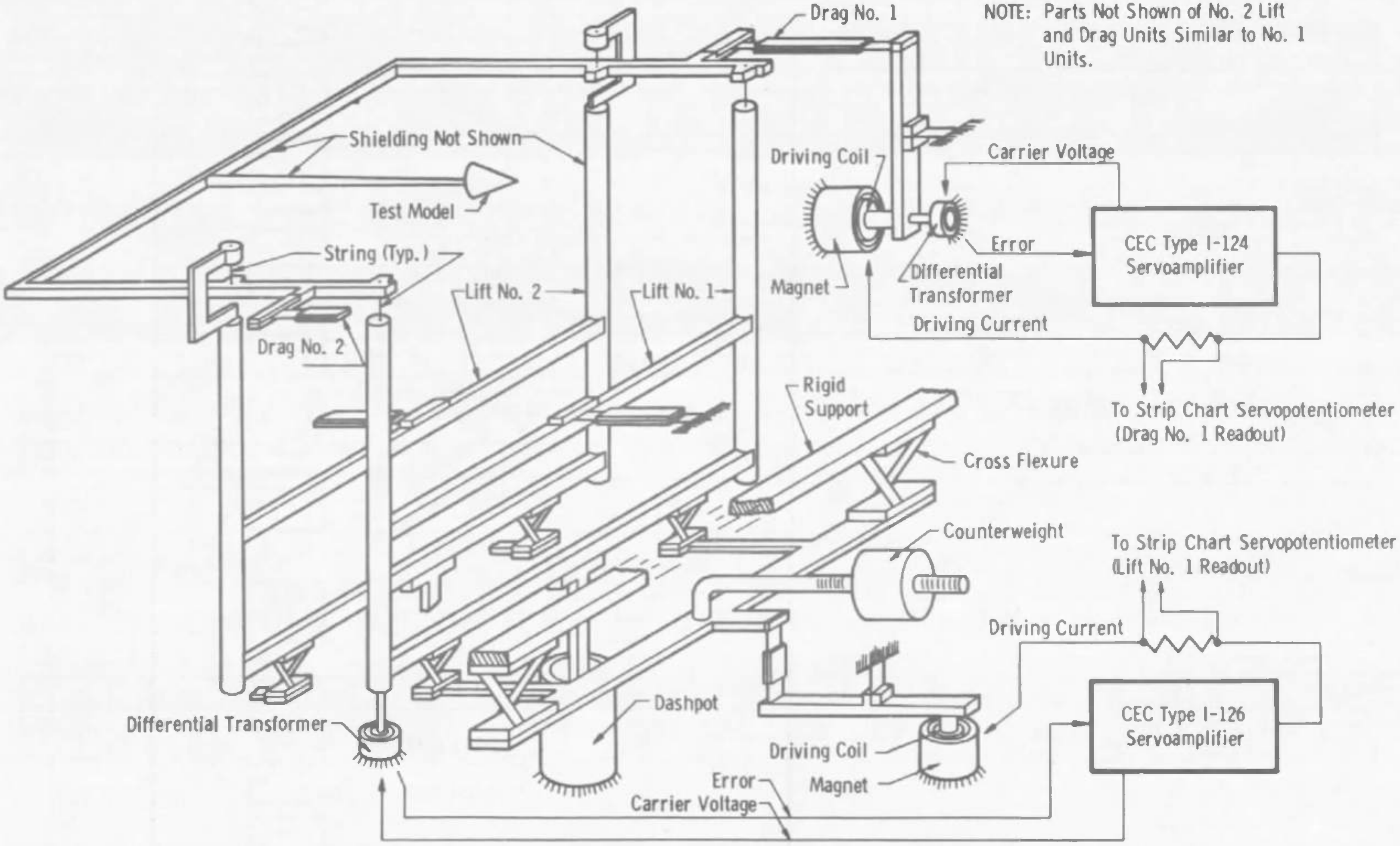


Fig. 3 Mechanical Arrangement of Balance

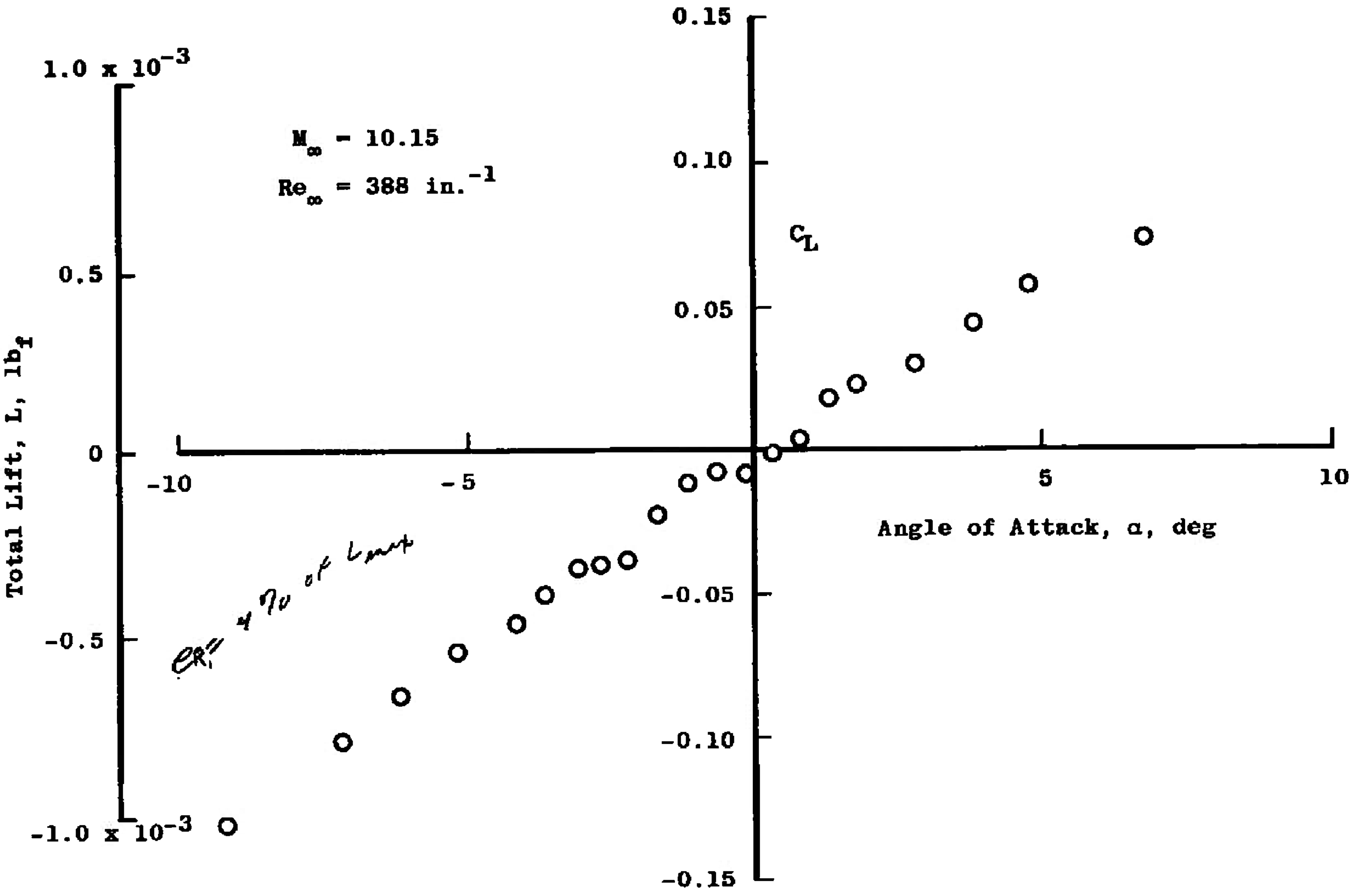


Fig. 4 Lift Force as a Function of Angle of Attack

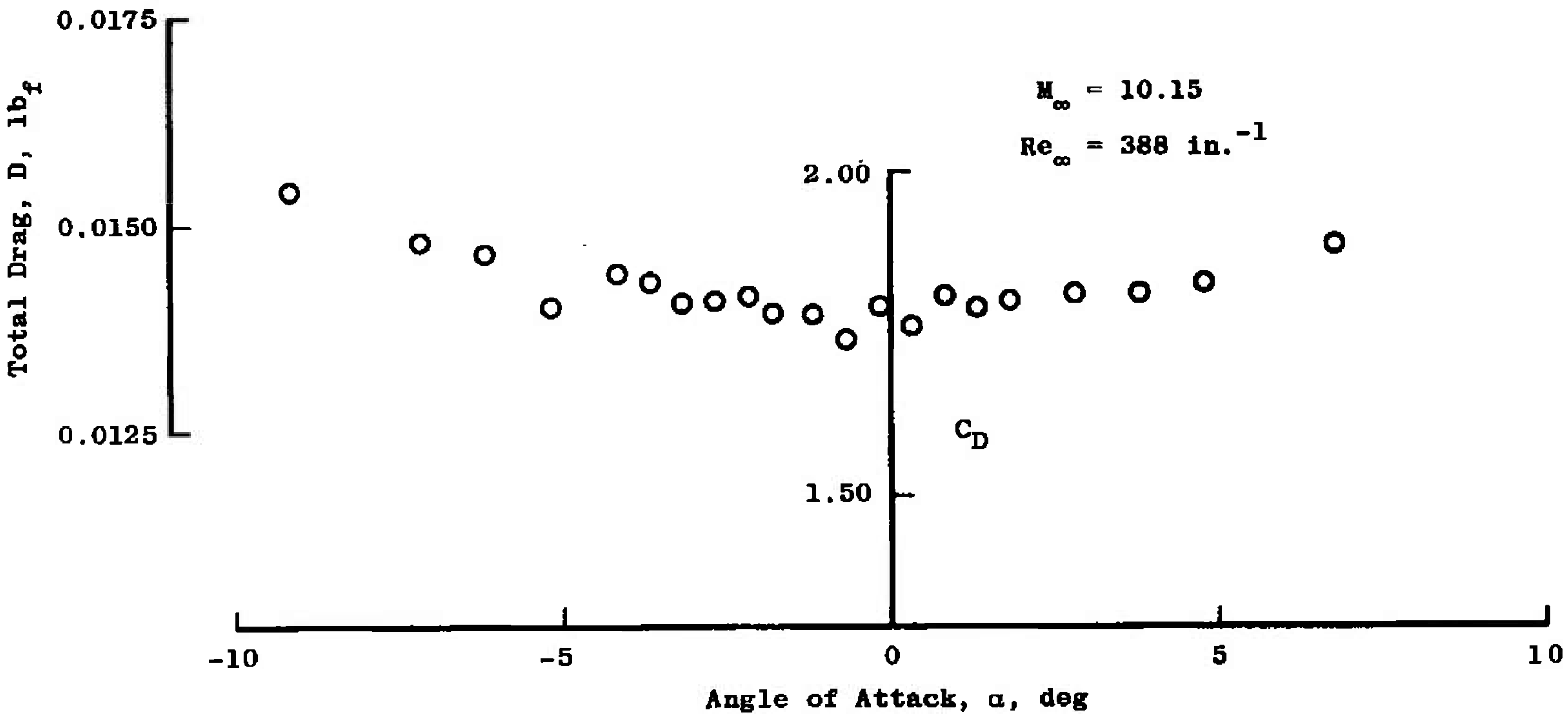


Fig. 5 Drag Force as a Function of Angle of Attack

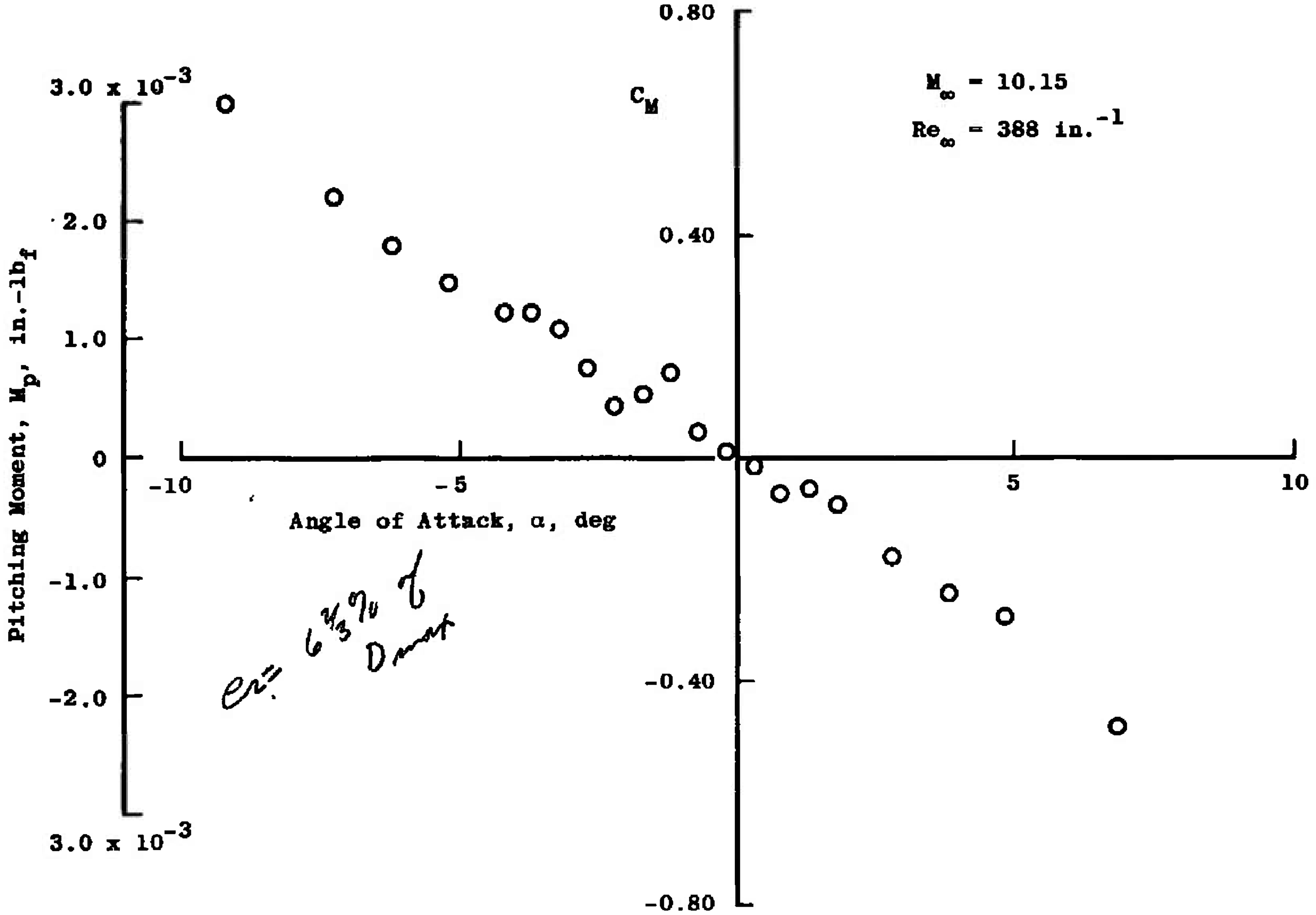
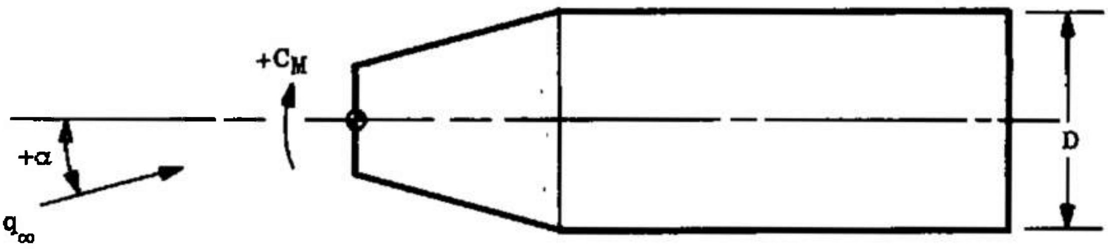


Fig. 6 Pitching Moment as a Function of Angle of Attack

er = 6⅓% of Dmax

TABLE I
TABULATED TEST DATA



Reference Area = Base Area
Reference Length = Base Diameter
$M_\infty = 10.15$
$Re_\infty = 388 \text{ in.}^{-1}$
$q_\infty = 3.98 \text{ lb}_f/\text{ft}^2$

Angle of Attack Corrected for Model Distortion

α, deg	C_D	C_L	C_M
0.3	1.76	-0.0019	-0.0183
0.8	1.81	0.0044	-0.0635
1.3	1.79	0.0176	-0.0531
1.8	1.80	0.0232	-0.0827
2.8	1.81	0.0295	-0.1788
3.8	1.81	0.0436	-0.2457
4.8	1.83	0.0574	-0.2877
6.8	1.89	0.0730	-0.4833
-0.2	1.79	-0.0079	0.00921
-0.7	1.74	-0.0081	0.0455
-1.2	1.78	-0.0122	0.1526
-1.7	1.78	-0.0227	0.1140
-2.2	1.81	-0.0384	0.0918
-2.7	1.80	-0.0402	0.1595
-3.2	1.80	-0.0412	0.2318
-3.7	1.83	-0.0499	0.2594
-4.2	1.84	-0.0597	0.2608
-5.2	1.79	-0.0699	0.3125
-6.2	1.87	-0.0851	0.3843
-7.2	1.89	-0.1012	0.4692
-9.2	1.97	-0.1303	0.6393

APPENDIX I
TUNNEL L

TUNNEL DESCRIPTION

Tunnel L, shown in Fig. I-1, is a low density, hypersonic, continuous-type, arc-heated, ejector-pumped facility, normally using nitrogen or argon as the test gas and consisting of the following major components, in streamwise order:

1. Continuous, water-cooled, d-c arc heater, Thermal Dynamic F-40 or U-50, both modified slightly, with a 40-kw selenium rectifier power supply. Gas is injected without swirl in the F-40 arc heater and with or without swirl in the U-50 unit. Unless otherwise noted, all testing is done without use of swirling gas injection.
2. Cylindrical, water-cooled settling section of variable size, but normally of 3-in. diameter and 6- to 10-in. length
3. Axisymmetric, aerodynamic nozzle, variable sizes with 0.10- to 1.20-in.-diam throats and 2.0- to 8.2-in.-diam exits. Three contoured nozzles having no flow gradients in the test section are currently available, in addition to older conical nozzles. Table I-1 gives the major characteristics of the contoured nozzles.
4. Cylindrical test section tank of 48-in. diameter surrounding the test section and containing instrumentation, cooling water connections, and probe carrier
5. Axisymmetric diffuser with interchangeable designs for varying test conditions, convergent entrance, constant-area throat, divergent exit sections, and water-cooled entrance
6. Water-cooled heat exchanger
7. Isolation valve
8. Air ejector of two stages
9. Connection to the VKF evacuated, 200,000-cu-ft, spherical vacuum reservoir and its pumping system.

All critical components of the tunnel and related systems are protected by back-side water cooling. The two-stage ejector system is driven by air instead of steam because of the ready availability of high pressure air at the tunnel site. Although the working gas is normally nitrogen or argon, other gases may be used. Typical ranges of operation with heated flow are given in Table I-2, and unheated-flow operational ranges are given in Table I-3. The first published description of this tunnel appeared in Ref. I-1.

TUNNEL INSTRUMENTATION AND CALIBRATION

Gas flow rate to the arc heater is measured through use of calibrated sonic-flow orifices, and reservoir pressure is measured with a Consolidated Electrodynamics Corporation Electromanometer®. Inaccuracy of these systems, on the basis of comparison with other means of measurement, and repeatability are estimated to be less than ±0.5 percent for both flow rate and reservoir pressure.

Total enthalpy at the nozzle throat is determined by use of a calorimeter which, on the basis of comparison of results and repeatability, appears accurate to within ±4 percent limits of error. This measurement is supplemented by a probe system which measures local total enthalpy and mass flux in the test section with an estimated error limit of ±2 percent for mass flux and ±5 percent for enthalpy.

Impact pressures are measured with variable reluctance, differential pressure transducers and water-cooled probes. Calibration of the transducers is accomplished by means of an oil-filled micromanometer and a McLeod gage. Inaccuracy in impact pressure measurement is believed not to exceed ±2 percent limits. Static pressures are measured by the same method but are not used for primary calibration purposes because of the very large corrections for viscous- and rarefied-flow phenomena.

The establishment of reservoir conditions, determination of impact pressures, and proof of inviscid, adiabatic core flow through the nozzles form part of the flow calibration. This information is used in a calculation which accounts for nonequilibrium expansion of the gas throughout the nozzle to yield the needed flow properties. References I-2 through I-7 contain information on various aspects of these measurements.

A three-component balance is used for measuring lift, drag, and pitching moment on aerodynamic bodies in Tunnel L. This is described in Ref. I-8.

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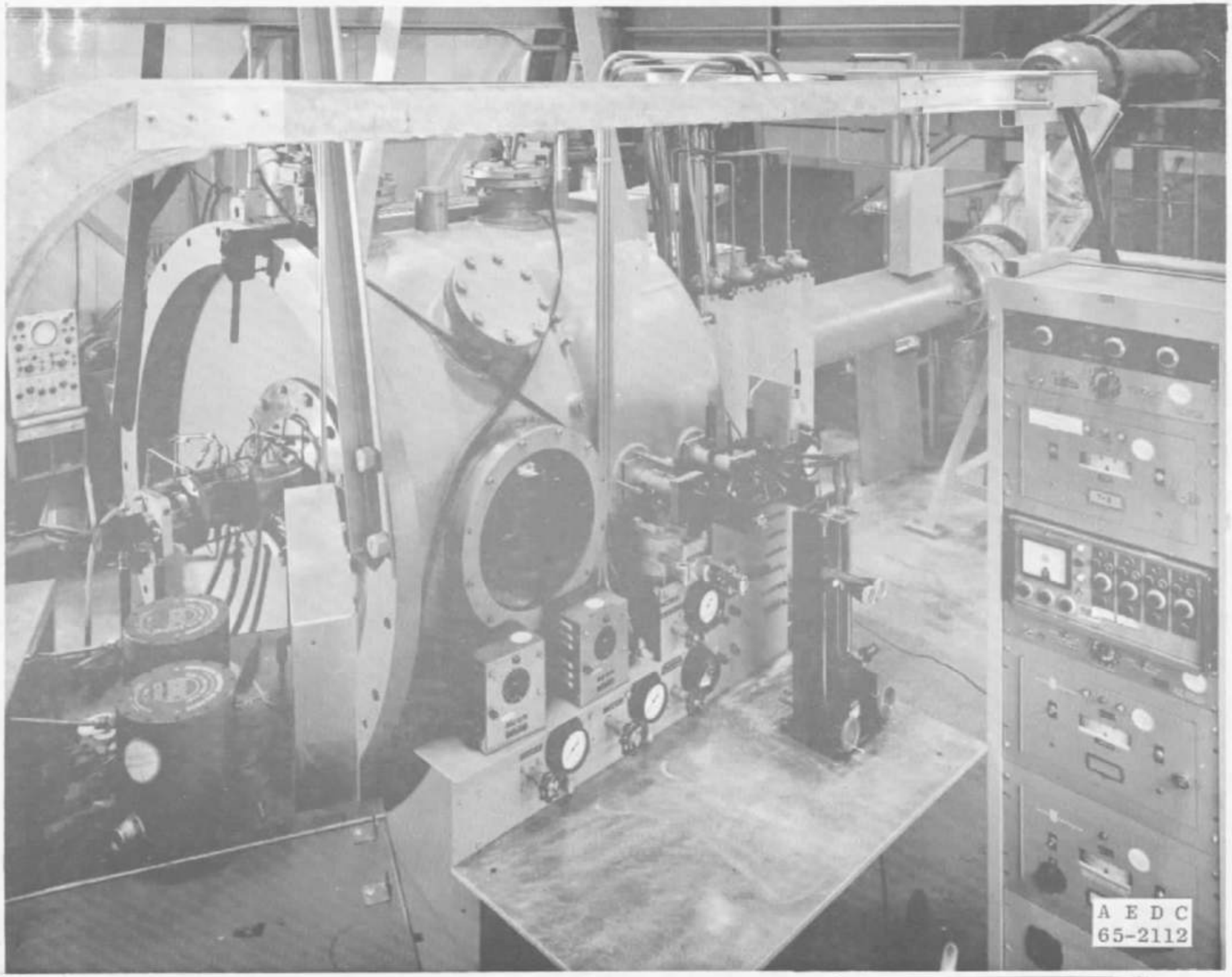

Fig. 1-1 Tunnel L

TABLE I-1
MAJOR CHARACTERISTICS OF TUNNEL L CONTOURED NOZZLES

	Lower Reynolds No.	Higher Reynolds No.	Cold Flow
Total Pressure, psia	18.0	30.0	0.235
Total Temperature, °R	5400	4500	530
Mass Flow Rate, lb_m/hr	7.76	14.2	22
Throat Diameter, in.	0.1481	0.1469	1.2226
Exit Diameter, in.	8.160	4.814	5.494
Test Section Core Diameter, in.	1.5	2.0	3.2
Test Section M_∞	10.15	9.3	4.05
Test Section Unit Reynolds No., $in.^{-1}$	388	1200	1760

TABLE I-2
TUNNEL L OPERATING CONDITIONS WITH ARC HEATER

	Nitrogen	Argon
Total Pressure, psia	7.0 to 30.0	0.5 to 6.4
Total Enthalpy, Btu/lb_m	740 to 2130	280 to 960
Total Temperature, °R	2300 to 7200	2300 to 7700
Mach Number	4.8 to 10.8	3.7 to 16.1
Unit Reynolds Number, Free Stream, in.$^{-1}$	300 to 3500	270 to 4700
Unit Reynolds Number behind Normal Shock, in.$^{-1}$	35 to 1140	14 to 1080
Mean Free-Path, Free-Stream, Static Billiard-Ball Gas Model, in.	0.002 to 0.058	0.002 to 0.057
Uniform Flow Core Diameter at Test Section, in.	0.2 to 2.0	0.5 to 1.5

TABLE I-3
TUNNEL L OPERATING CONDITIONS WITHOUT ARC HEATER

	Nitrogen	Argon
Total Pressure, psia	0.06 to 2.7	0.08 to 3.0
Total Enthalpy, Btu/lb_m	140	70
Total Temperature, °R	530	530
Mach Number	3.8 to 5.8	4.0 to 8.0
Unit Reynolds Number Free Stream, $in.^{-1}$	620 to 15,000	1600 to 50,000
Unit Reynolds Number behind Normal Shock, $in.^{-1}$	190 to 3500	264 to 3800
Mean Free-Path, Free-Stream, Static Billiard-Ball Gas Model, in.	0.0005 to 0.012	0.0001 to 0.006
Uniform Flow Core Diameter at Test Section, in.	0.8 to 3.2	0.5 to 1.0

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13 ABSTRACT

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