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INVESTIGATION OF DRAG REDUCTION BY BOUNDARY-LAYER SUCTION ON A BODY OF REVOLUTION AT MACH NUMBERS 2.5, 3, AND 3.5

S. R. Pate

ARO, Inc.

February 1965

VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

INVESTIGATION OF DRAG REDUCTION BY BOUNDARY-LAYER SUCTION ON A BODY OF REVOLUTION AT MACH NUMBERS 2.5, 3, AND 3.5

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FOREWORD

The work reported herein was done at the request of the Air Force Flight Dynamics Laboratory (AFFDL), Air Force Systems Command (AFSC), for the Norair Division of Northrop Corporation under Program Element 62405334/1366, Task 136612.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1000. The test was conducted from October 26 to November 6, 1964 under ARO Project No. VA0446, and the report was submitted by the author on January 18, 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

Tests were conducted in the 40-in. supersonic tunnel of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for laminar flow control on a 9.2-in.-diam body of revolution. Test Mach numbers were 2.5, 3, and 3.5 with a Reynolds number range (based on boundary-layer rake location) from 9.9 to 51.7 million for angles of attack from 0 to ±2 deg. With suction and $\alpha = 0$, full-length (x = 77.8 in.) laminar flow was maintained at $M_\infty = 2.5$ and 3 up to the maximum available length Reynolds numbers of 41.8 and 51.7 million, respectively. At $M_\infty = 3.5$, for x = 67.8 in. laminar flow was maintained up to a length Reynolds number of approximately 14 million. The condition of the boundary layer was very sensitive to changes in angle of attack, and the maximum angles at which laminar flow could be maintained were $\alpha = \pm 1.3$ deg at $M_\infty = 2.5$, $\alpha = \pm 0.7$ deg at $M_\infty = 3$, and $\alpha = \pm 0.15$ deg at $M_\infty = 3.5$. Increasing the Reynolds number also decreased the maximum angle of attack. Wake, suction, and total drag coefficients and the corresponding suction coefficients are presented, along with some fully turbulent wake drag coefficients for the no suction case.

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NOMENCLATURE

A	Reference area based on wetted surface area determined by rake location (at $x = 77.8$ in., $A = 1752$ in.^{2})
C_{D_S}	Suction drag coefficient $\left(\frac{\text{suction drag}}{q_\infty A}\right)$
C_{D_T}	Total drag coefficient ($C_{D_W} + C_{D_S}$)
C_{D_W}	Wake drag coefficient (wake drag/$q_\infty A$)
C_{m_n}	Local suction coefficient ($m_n/\rho_\infty U_\infty A$)
C_{m_t}	Total suction coefficient $\left(\sum_{n=1}^{x} C_{m_n}\right)$
ℓ	Model nose length, 46.00 in.
M_L	Mach number outside the boundary layer
M_n	Suction chamber Mach number
M_∞	Free-stream Mach number
m_n	Local mass rate of suction, lb-sec/in.
p	Model surface pressure, psia
p_∞	Free-stream static pressure, psia
q_∞	Free-stream dynamic pressure, psia
R	Model base radius, in.
Re	Reynolds number
Re_x	Reynolds number based on rake location
r	Local body radius, in.
r_x	Body radius at the boundary-layer rake location, in.
T_n	Suction chamber temperature, °R
T_∞	Free-stream static temperature, °R
U_L	Velocity outside boundary layer, in./sec
U_∞	Free-stream velocity, in./sec
u	Local velocity in boundary layer, in./sec
x	Boundary-layer rake location measured from model nose, in.
y	Distance normal to model surface, in.

α Model angle of attack, deg

δ Boundary-layer total thickness, in.

θ_L Boundary-layer momentum thickness at rake location, in.

$$\int_0^{\delta} \frac{\rho u}{\rho_L U_L}\left(1 - \frac{u}{U_L}\right)\left(1 + \frac{y}{r_x}\right) dy$$

ρ Local density in boundary layer, $\frac{\text{lb-sec}^2}{\text{in.}^4}$

ρ_L Density outside boundary layer, $\frac{\text{lb-sec}^2}{\text{in.}^4}$

ρ_∞ Free-stream density, $\frac{\text{lb-sec}^2}{\text{in.}^4}$

ϕ Model circumferential angle, deg

SUBSCRIPTS

n nth suction chamber

SECTION I
INTRODUCTION

A number of test programs have been conducted in recent years in the VKF supersonic tunnels in support of Norair investigations of laminar flow control by the use of boundary-layer suction. These have included tests on swept and upswept wings in the 40-in. supersonic tunnel (Gas Dynamic Wind Tunnel, Supersonic (A)) and on a tangent ogive cylinder in the 12-in. supersonic tunnel (Gas Dynamic Wind Tunnel, Supersonic (D)).

The primary purpose of the current test program was to use boundary-layer suction to establish full-length ($x = 77.8$ in.) laminar flow on a body of revolution up to the highest length Reynolds number possible and to measure the suction requirements and wake drag. The tests were conducted in Tunnel A at Mach numbers 2.5, 3, and 3.5 over a Reynolds number range (based on rake location) from 9.9 to 51.7 million and angles of attack up to ±2 deg.

SECTION II
APPARATUS

2.1 WIND TUNNEL

Tunnel A is a continuous, closed-circuit, variable density wind tunnel with an automatically driven flexible plate-type nozzle and a 40- by 40-in. test section. The tunnel operates at Mach numbers from 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 300°F ($M_\infty = 6$). Minimum operating pressures are about one-tenth of the maximum at each Mach number. A description of the tunnel and airflow calibration information may be found in Ref. 1.

2.2 MODEL

The model, supplied by Norair, was supported by the tunnel sector as shown in Fig. 1. The nose section was a pointed body of revolution, 46 in. in length, having a maximum diameter of 9.2 in., and the aft portion was a 9.2-in.-diam circular cylinder (see Fig. 2). The model surface was vented with 150 suction slots through which a portion of the boundary layer was removed by applying suction. Slot spacing was constant, 0.50 in., and slot width varied from 0.0040 to 0.0080 in. as listed in Fig. 2.

Thirteen separate suction chambers were contained within the model and connected separately to individual flow metering boxes; thus variable suction was provided over the model surface (see Figs. 1c and 2). The model was instrumented to measure the surface pressure along four equally spaced rays, and ambient pressures were measured in each of the 13 suction chambers. Temperatures were measured at three body stations and in four of the 13 chambers.

2.3 BOUNDARY-LAYER RAKE

Two rakes, one each at ϕ = 180 and 270 deg (Figs. 1a, 3, and 5), were used to measure the boundary-layer pitot-pressure profiles. Each rake (Fig. 4) was composed of 10 probes ranging in height (distance from probe centerline to model surface) from 0.015 to 0.320 in. The rakes were mounted to a common collar which was automatically driven and provided each rake with a traverse distance of 10 in. upstream from station x = 77.8 in.

2.4 SUCTION SYSTEM

Suction (operating range from 0.04 to 0.14 psia) was provided by a 12-in.-diam vacuum line, which was connected separately by 2-in.-ID rubber pipe to each of the 13 metering boxes (Figs. 1c and 6). Flow regulation to each chamber was maintained by a throttling valve on each metering box. Calibrated nozzles facilitated measurement of the different levels of mass flow from each of the 13 suction chambers.

2.5 INSTRUMENTATION

Model data recorded during the test were boundary-layer pitot pressures, model surface static pressures, suction chamber ambient pressures and temperatures, metering chamber total pressures and temperatures, and metering nozzle static pressures. All model and rake pressures were measured with the standard Tunnel A pressure scanning system using 1- and 15-psid transducers referenced to a near vacuum. The 15-psid transducers were calibrated for ranges of 18, 6.8, and 2.6 psia, and the 1-psid transducers for 1, 0.4, and 0.16 psia. The precision of the system is estimated to be within one percent of the range being used. The metering chamber and nozzle pressures were measured with 1- and 5-psid transducers referenced to a near vacuum and considered accurate to within 0.2 percent of the transducer capacity. The data were processed on-line with the VKF instrumentation and computer system.

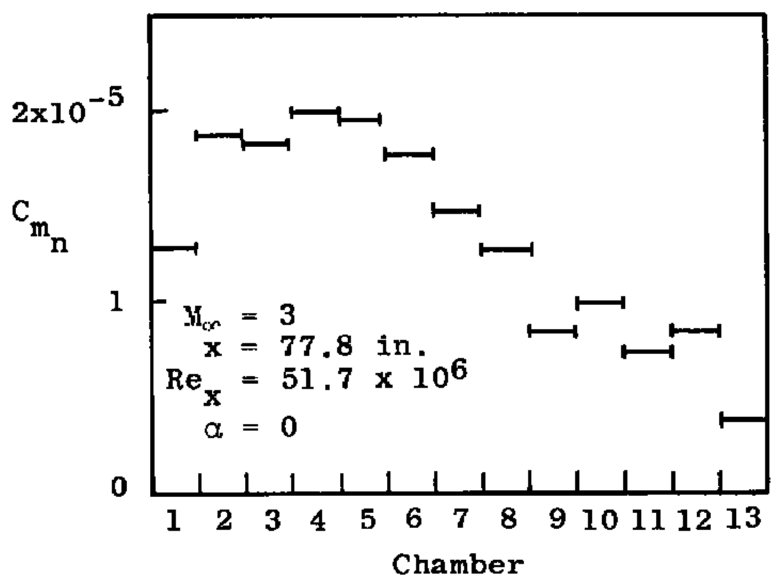
SECTION III
PROCEDURE

Testing was conducted with variable suction and no suction over the following range of test conditions:

Nominal Mach No.	Maximum Re/in. x 10^{-6}	Minimum Re/in. x 10^{-6}	Rake Location, in.	α, deg
2.5	0.55	0.17	67.8, 72.8, 77.8	0 to ±2
3.0	0.66	0.14	72.8, 77.8	0 to ±2
3.5	0.49	0.15	67.8, 77.8	0 to ±2

The condition of no suction was obtained by closing the metering chamber valves and leaving the slots unsealed. The effect of varying the suction quantities through the 13 chambers was observed by noting the changes in the boundary-layer pitot-pressure profile at a particular rake station.

The following chart shows a typical suction coefficient distribution for the case of optimum suction (lowest total drag) at one Reynolds number and zero angle of attack.



SECTION IV
DATA ANALYSIS

Reduction of the boundary-layer data consisted of determining the momentum thickness from a graphical integration of the momentum parameter. The momentum parameter was normalized with respect to the local free-stream conditions ($\rho_L U_L$), which were determined from the measured local static pressure on the model surface and the tunnel stilling chamber pressure. The loss in total pressure attributable to the model nose shock and the suction slot shocks was considered to be negligible.

When the conditions outside the boundary layer at the rake location differ from free stream ($U_L \neq U_\infty$) and the momentum equation of the wake is solved, then the wake drag coefficient (composed of skin friction and form drag) can be determined by using the method of Ref. 2.

$$C_{D_W} = \frac{4\pi r_x}{A}\,\theta_L \left(\frac{U_L}{U_\infty}\right)^{(3.145 - 0.28\,M_L^2 - 0.30\,M_\infty^2)}$$

where θ_L is the momentum thickness defined as

$$\theta_L = \int_0^\delta \frac{\rho u}{\rho_L U_L}\left(1 - \frac{u}{U_L}\right)\left(1 + \frac{y}{r_x}\right)dy = \int_0^\delta \frac{\rho u}{\rho_L U_L}\left(1 - \frac{u}{U_L}\right)d\left(y + \frac{1}{2}\frac{y^2}{r_x}\right)$$

The suction coefficient is defined as

$$C_{m_t} = \sum_{n=1}^{x} C_{m_n} = \sum_{n=1}^{x} \frac{m_n}{\rho_\infty U_\infty A}$$

Consideration of the reduction in skin friction drag by using suction must necessarily include an evaluation of the penalties in drag caused by suction. The total drag coefficient (C_{D_T}) then consists of a summation of the wake drag and suction drag coefficients ($C_{D_T} = C_{D_W} + C_{D_S}$).

The suction drag coefficient is determined by the power required to accelerate the air removed from the boundary layer to free-stream pressure and velocity and is based on the assumption that the flow is isentropic and the efficiency of the suction compressor is equal to the propulsive efficiency of the propulsion system. The suction drag coefficient can then be determined, as shown in Ref. 2, by

$$C_{D_S} = \sum_{n=1}^{x} \left(C_{D_S}\right)_n = \sum_{n=1}^{x} C_{m_n}\left(1 + \frac{M_n^2\,T_n}{M_\infty^2\,T_\infty}\right)$$

SECTION V
RESULTS AND DISCUSSION

Presented in Fig. 7 are the experimental and theoretical model surface pressure distributions for M_∞ = 2.5, 3, and 3.5 at α = 0. The theoretical pressure distribution was determined by the method of characteristics, and the agreement between theory and experimental data is good.

Typical boundary-layer profiles for Mach numbers 2.5 and 3.5 at α = 0 are shown in Fig. 8 for conditions of suction and no suction. The laminar profiles are for the optimum suction condition (lowest total drag) and the turbulent profiles for the conditions of no suction and the slots unsealed. The effect of suction on the boundary layer at M_∞ = 2.5 is illustrated by the schlieren photographs in Fig. 9.

As suction is increased, the wake drag will decrease and the suction drag increase; therefore a minimum value for the total drag will exist for a particular suction quantity which will be the optimum. Minimum total drag and optimum suction coefficients are presented in Fig. 10, along with the wake drag and suction drag coefficients, for M_∞ = 2.5, 3, and 3.5 for various length Reynolds numbers. For M_∞ = 2.5 and 3, Figs. 10a and b, respectively, full-length (x = 77.8 in.) laminar flow was maintained up to the maximum available Reynolds number of 41.8 and 51.7 million, respectively. At M_∞ = 3.5 (x = 67.8 in.) (Fig. 10c), laminar flow was maintained up to $Re_x \approx 14 \times 10^6$. Also presented in Fig. 10 are results from Ref. 3 obtained using suction on a 3.25-in.-diam ogive cylinder model in the VKF Tunnel D. The trend of the laminar flow results of Ref. 3 at the lower length Reynolds number values is in good agreement at all test Mach numbers with the laminar flow results obtained in the present investigation at the much higher Reynolds number values. The wake drag results from the two rakes at M_∞ = 2.5 and 3 (Figs. 10a and b) in general gave comparable results, thus indicating that laminar flow was established over the entire model length and circumference. At M_∞ = 3.5, (Fig. 10c) the side rake (ϕ = 180 deg) was laminar up to $Re_x \approx 14 \times 10^6$, but the top rake was turbulent, indicating the flow was laminar only over part of the model circumference.

Establishing laminar flow over the body of revolution model was quite sensitive to changes in angle of attack, or to be more exact, to the angle of flow inclination, as shown in Fig. 11. Figure 11c presents the maximum angle of attack at which laminar flow could be maintained at the established rake locations for Mach numbers 2.5, 3, and 3.5. The maximum angle of attack obtained was α = ±1.3 deg with Re/in. = 0.34×10^6

at $M_\infty = 2.5$, and it can be seen that the maximum angle decreased with increasing Mach number and increasing unit Reynolds number. The very small angle of attack ($\alpha = \pm 0.15$ deg) at which the flow became turbulent on the side rake at $M_\infty = 3.5$ is of the same order of magnitude as the tunnel flow angularity in the vertical plane, and this may account for the non-uniform results obtained at $\alpha = 0$ at this Mach number where the flow was turbulent at the top rake and laminar at the side rake.

It was observed during the test that maintaining laminar flow on the leeward side of the model was more sensitive to increases in angle of attack than on the windward side. Also, when the maximum angle for maintaining laminar flow was exceeded and the flow became turbulent, laminar flow could be re-established by lowering the angle of attack without any readjustment of the suction quantities.

In general, no attempt was made to obtain an optimum suction value at angle of attack, and this is illustrated in Figs. 11a and b by the lower values of C_{D_W} and higher values of C_{D_S} as compared to the $\alpha = 0$ results. However, suction was varied at $Re_x = 31 \times 10^6$ at $M_\infty = 3$ to show that the critical angle of attack could not be increased simply by increasing suction and that laminar flow at the critical angles could be maintained with suction quantities near the $\alpha = 0$ optimum suction values.

SECTION VI
CONCLUDING REMARKS

Tests were conducted at Mach numbers 2.5, 3, and 3.5 to determine the effectiveness of boundary-layer suction for laminar flow control on a body of revolution. On the basis of these tests the following conclusions are made:

1. Full-length ($x = 77.8$ in.) laminar flow was established at $M_\infty = 2.5$ and 3 up to the maximum available length Reynolds number (Re_x), based on rake location, of 41.8 and 51.7 million, respectively. At $M_\infty = 3.5$ ($x = 67.8$ in.) laminar flow was maintained up to $Re_x \approx 14 \times 10^6$.
2. The maximum angle of attack at which laminar flow could be maintained decreased with increasing Mach number and increasing unit Reynolds number with the maximum angles obtained being $\alpha = \pm 1.3$ deg at $M_\infty = 2.5$, $\alpha = \pm 0.7$ deg at $M_\infty = 3$, and $\alpha = \pm 0.15$ deg at $M_\infty = 3.5$.

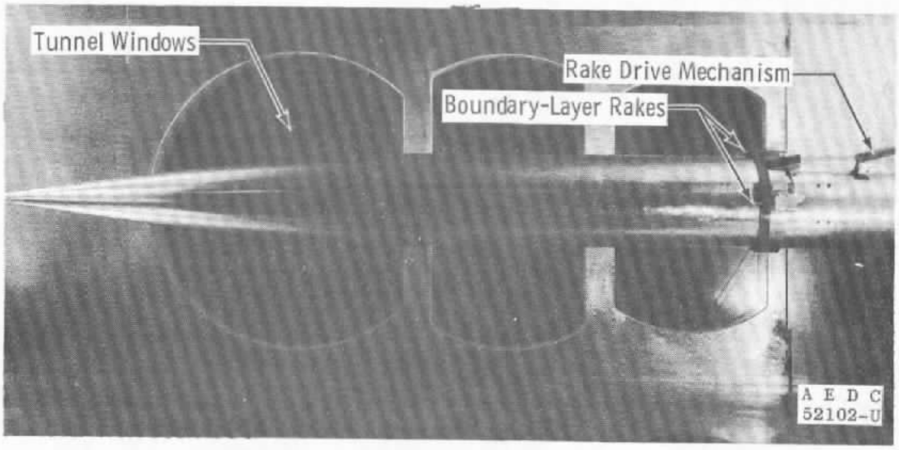
REFERENCES

1. Coats, Jack D. "Flow Characteristics of a 40-Inch Wind Tunnel at Mach Numbers 1.5 to 6." AEDC-TDR-62-130 (AD 277289), June 1962.

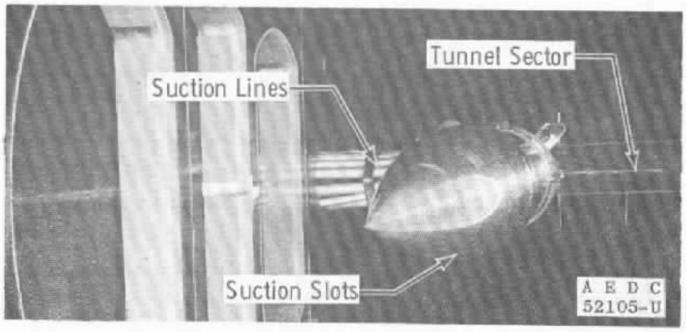
2. Groth, E. "Boundary Layer Suction Experiments at Supersonic Speeds." Boundary Layer and Flow Control edited by Lachmann, G. V., Vol. 2 Pergamon Press, New York, 1961.

3. Groth, E. "Low Drag Boundary Layer Suction Experiments at Supersonic Speeds on an Ogive Cylinder with 29 Closely Spaced Slots." Report No. NOR-61-162 (BLC-131), August 1961.

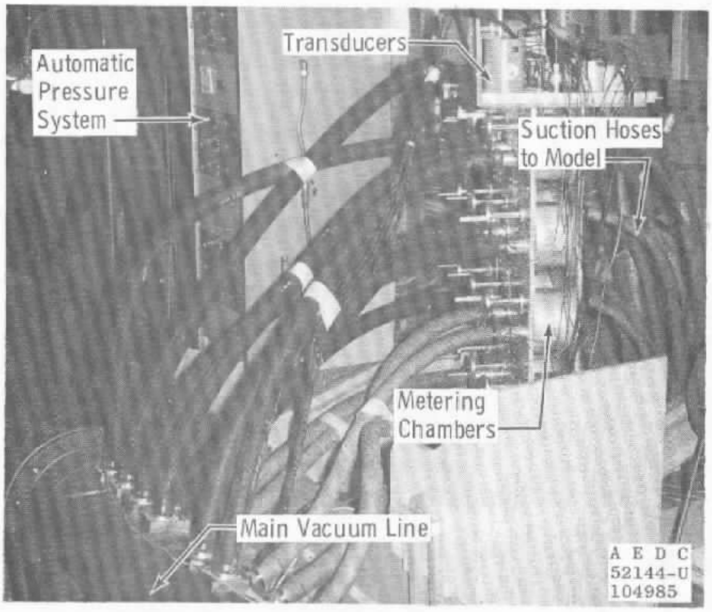
4. Van Driest, E. R. "Turbulent Boundary Layer in Compressible Fluids." Journal of Aeronautical Sciences, Vol. 18, No. 3, March 1951, pp. 145-160, 216.



a. Model Installation

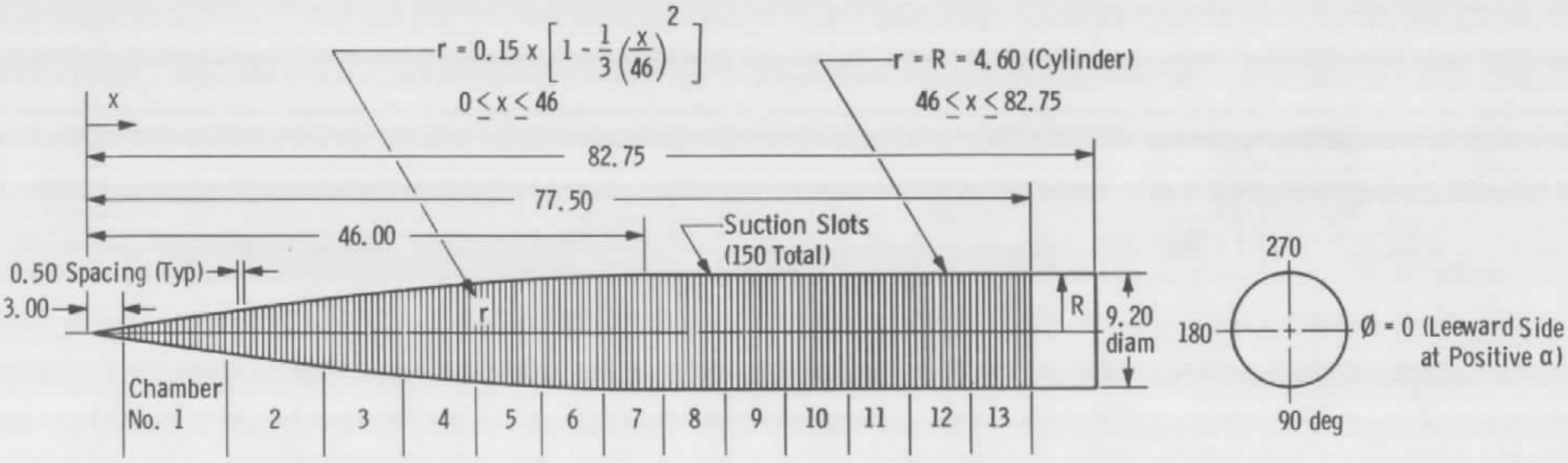


b. Model Installation



c. Suction Equipment

Fig. 1 Model Installation and Suction Equipment



All Dimensions in Inches

Suction Slot Locations and Dimensions		
Chamber No.	Slot No.	Slot Width (in.)
1	1-8	0.0040
1	9-18	0.0045
2	19-28	0.0045
2	29-34	0.0050
3	35-47	0.0050
4	48-59	0.0060
5	60-70	0.0060
6	71-80	0.0070
7-13	10 in each Chamber	0.0080
Total	150	

Pressure Orifice Locations			Thermocouple Locations		
No.	x, in.	Ø, deg	No.	x, in.	Ø, deg
1	14.25	180	1	23.25	180
2	14.25	270	2	45.25	180
3	14.25	0	3	70.25	180
4	14.25	90	4	Ch. No. 2	
5	29.25	180	5	No. 5	
6	34.75	270	6	No. 8	
7	40.25	180	7	No. 11	
8	50.25	270			
9	55.25	180			
10, 11	67.25	180, 270			
12, 13	72.25	180, 270			
14, 15	77.25	180, 270			
16-28	One in Each Chamber				

104986

Fig. 2 Model Geometry

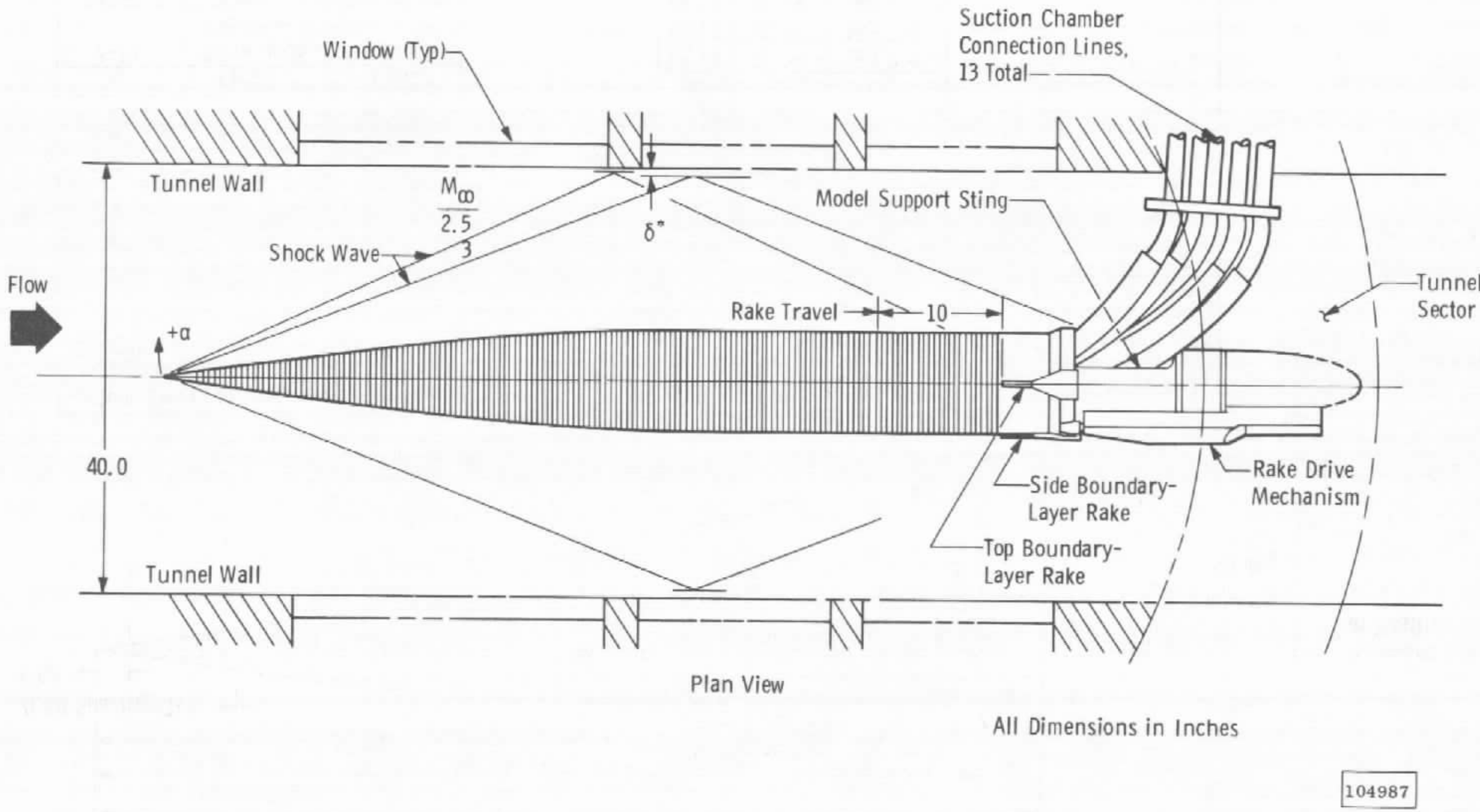
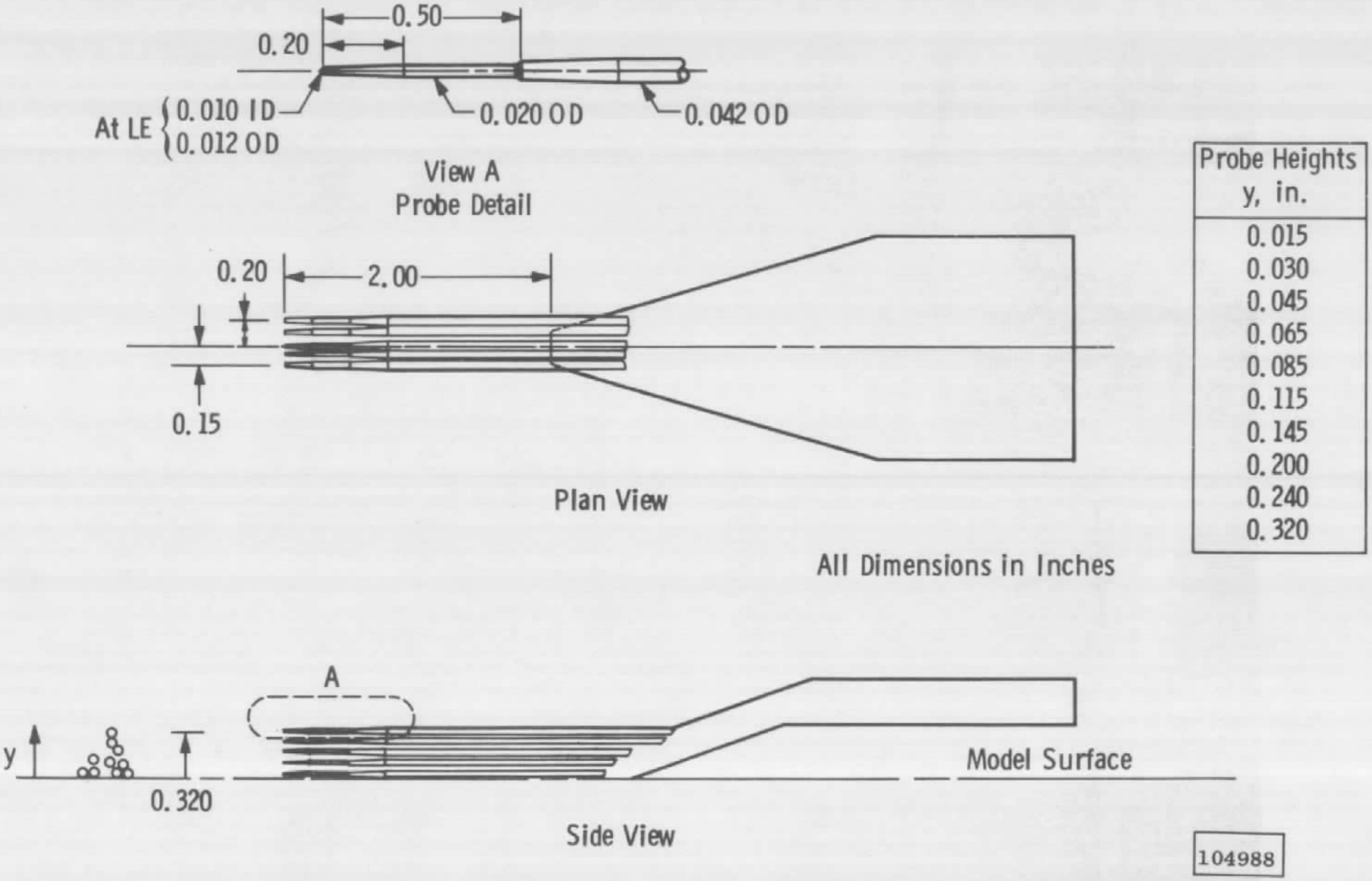


Fig. 3 Sketch of Model Installation and Tunnel Test Section



Probe Heights y, in.
0.015
0.030
0.045
0.065
0.085
0.115
0.145
0.200
0.240
0.320

Fig. 4 Sketch of Boundary-Layer Rake

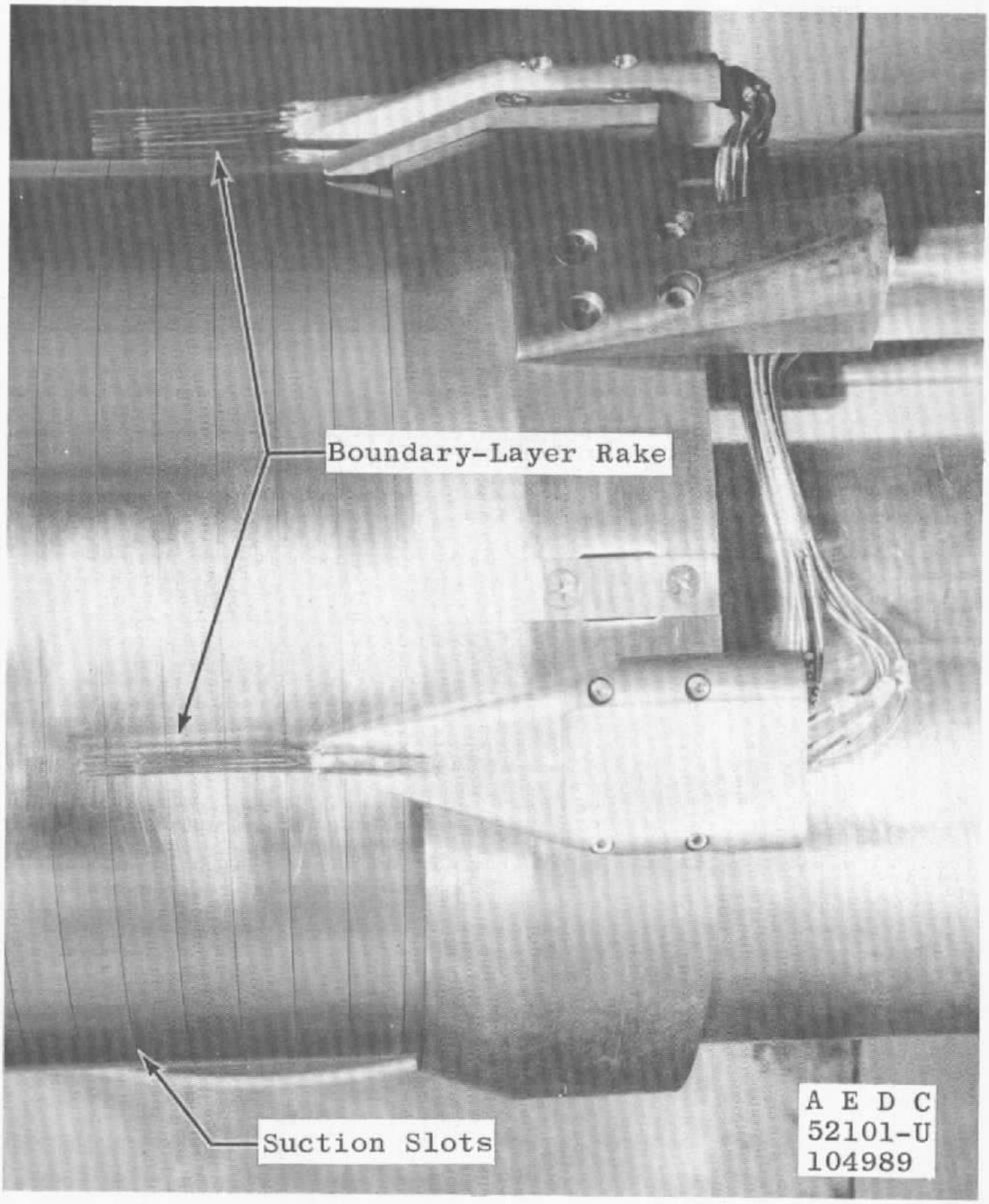


Fig. 5 Rake Assembly

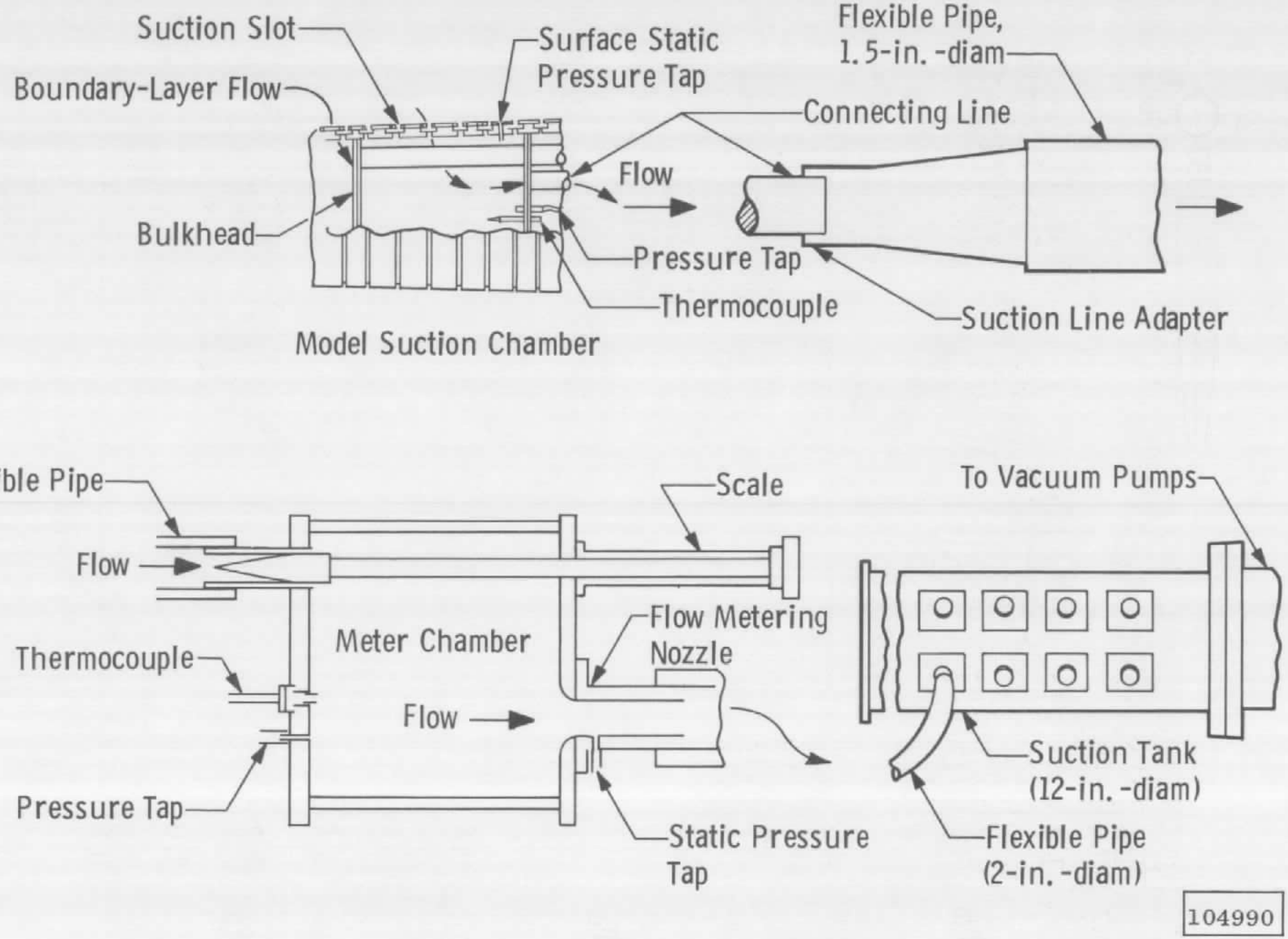


Fig. 6 Schematic Drawing of Suction System

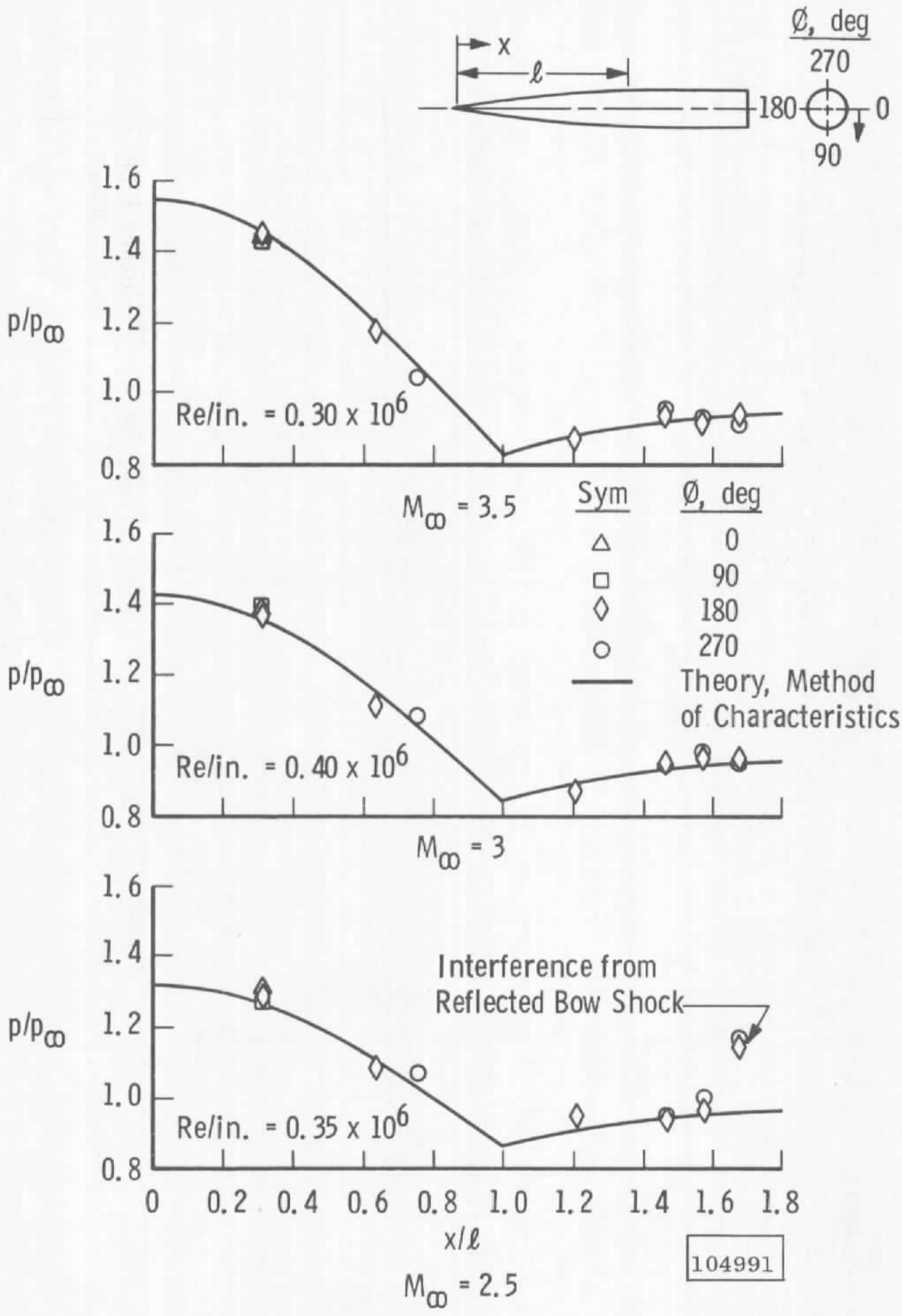
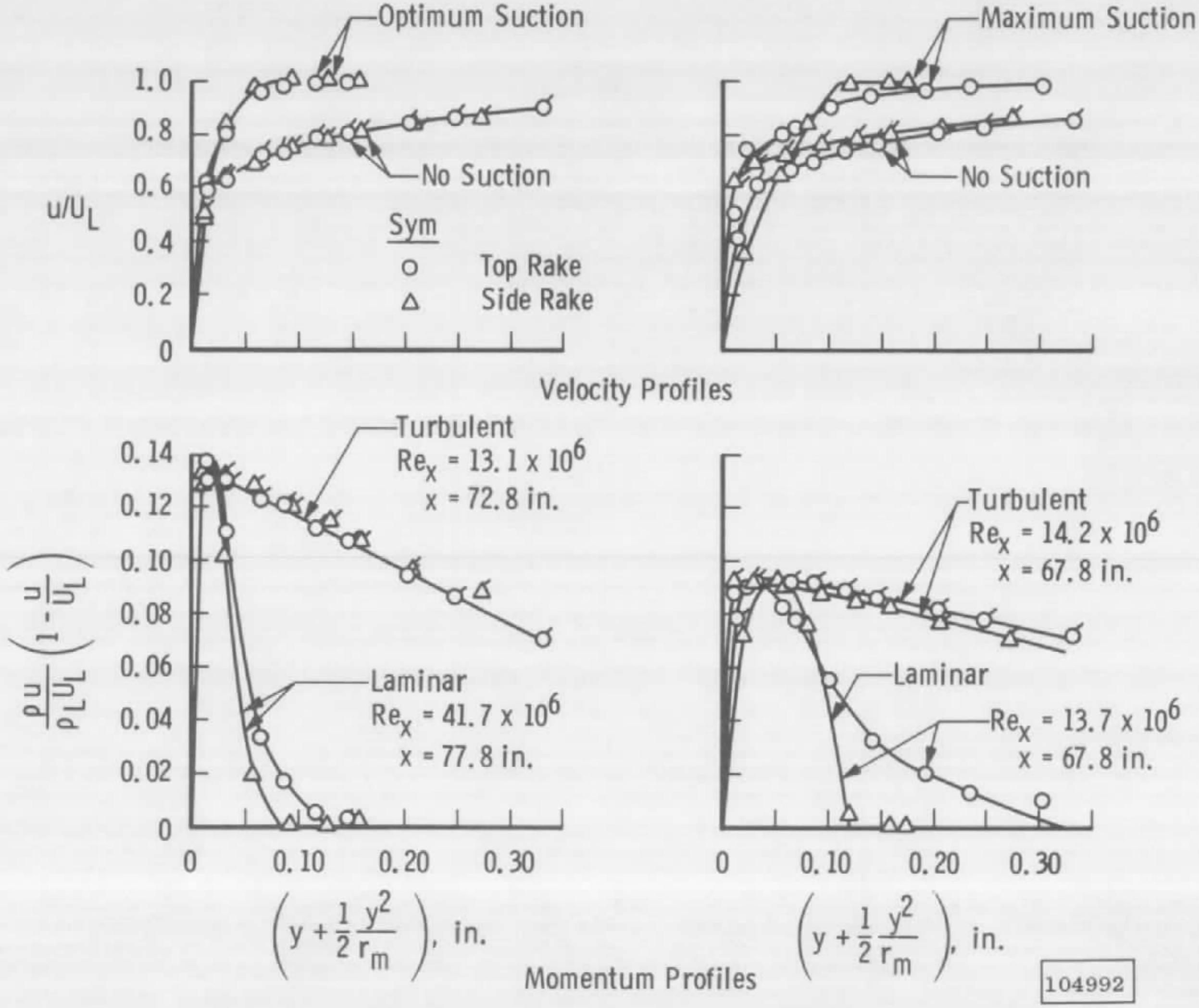


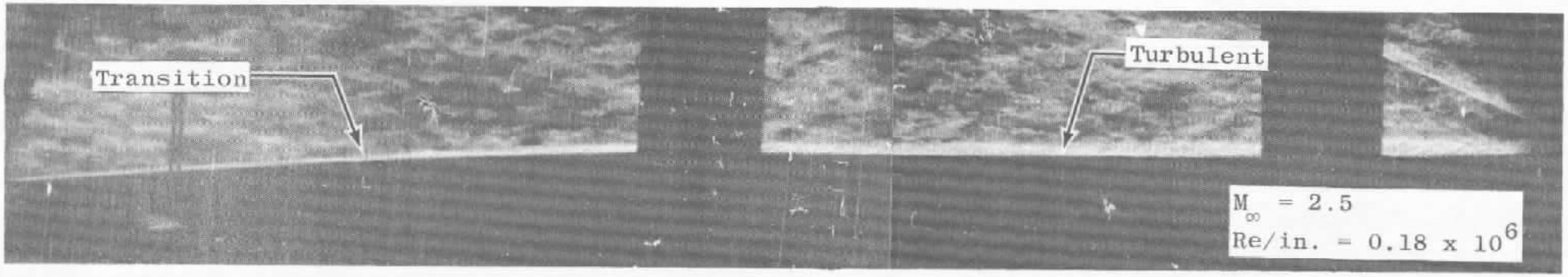
Fig. 7 Surface Pressure Distribution at $\alpha = 0$



a. $M_\infty = 2.5$

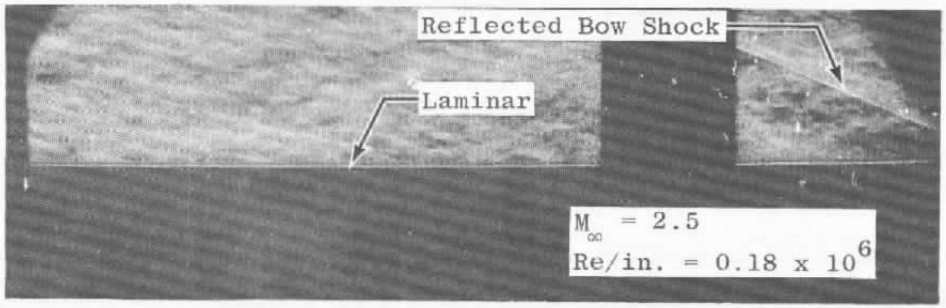
b. $M_\infty = 3.5$

Fig. 8 Boundary-Layer Profiles for $M_\infty = 2.5$ and 3.5, $\alpha = 0$ with and without Suction



No Suction

Flow



With Suction

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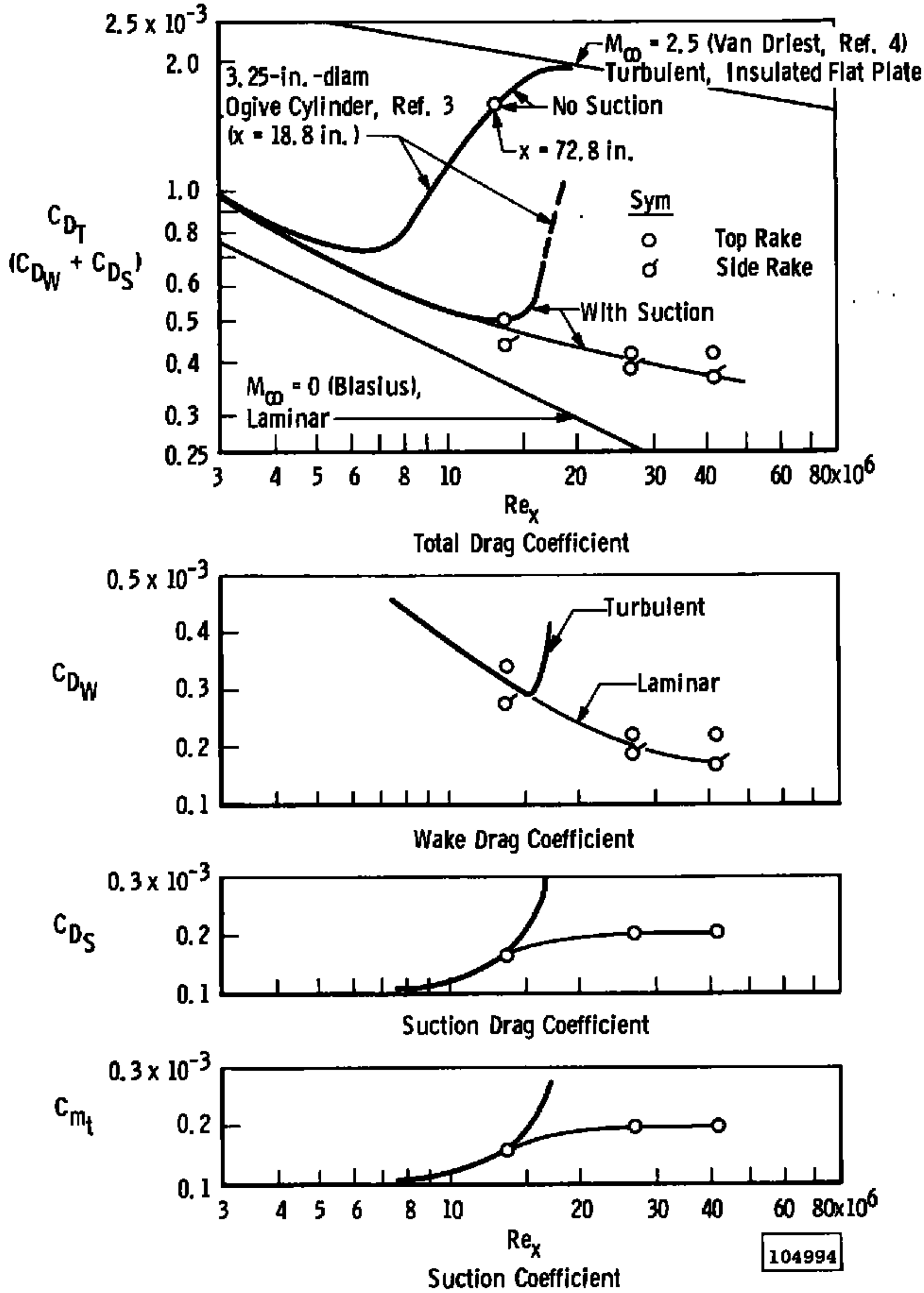
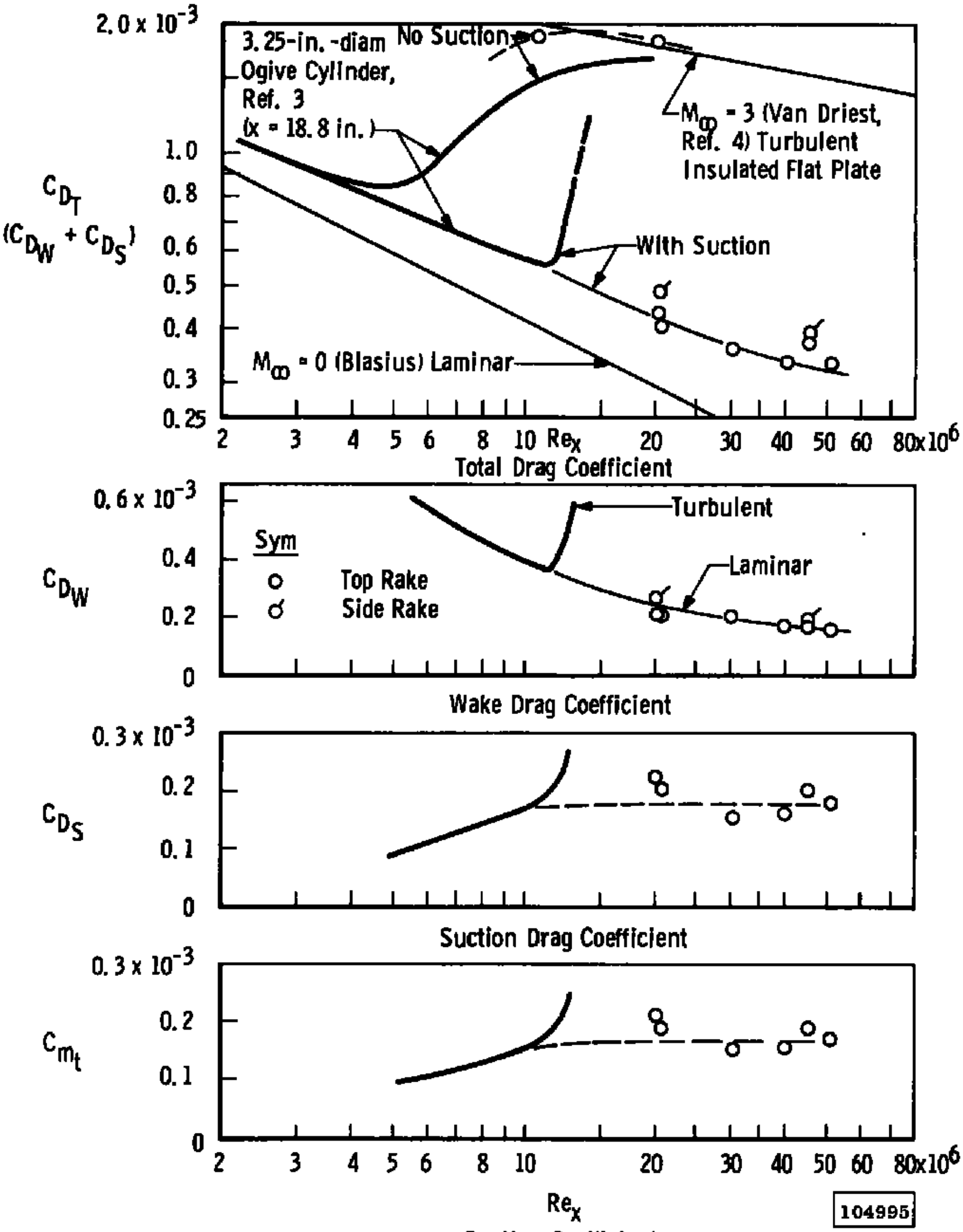
Fig. 9 Schlieren Photographs Illustrating the Effect of Suction on the Boundary Layer



a. $M_\infty = 2.5$, $x = 77.8$ in.

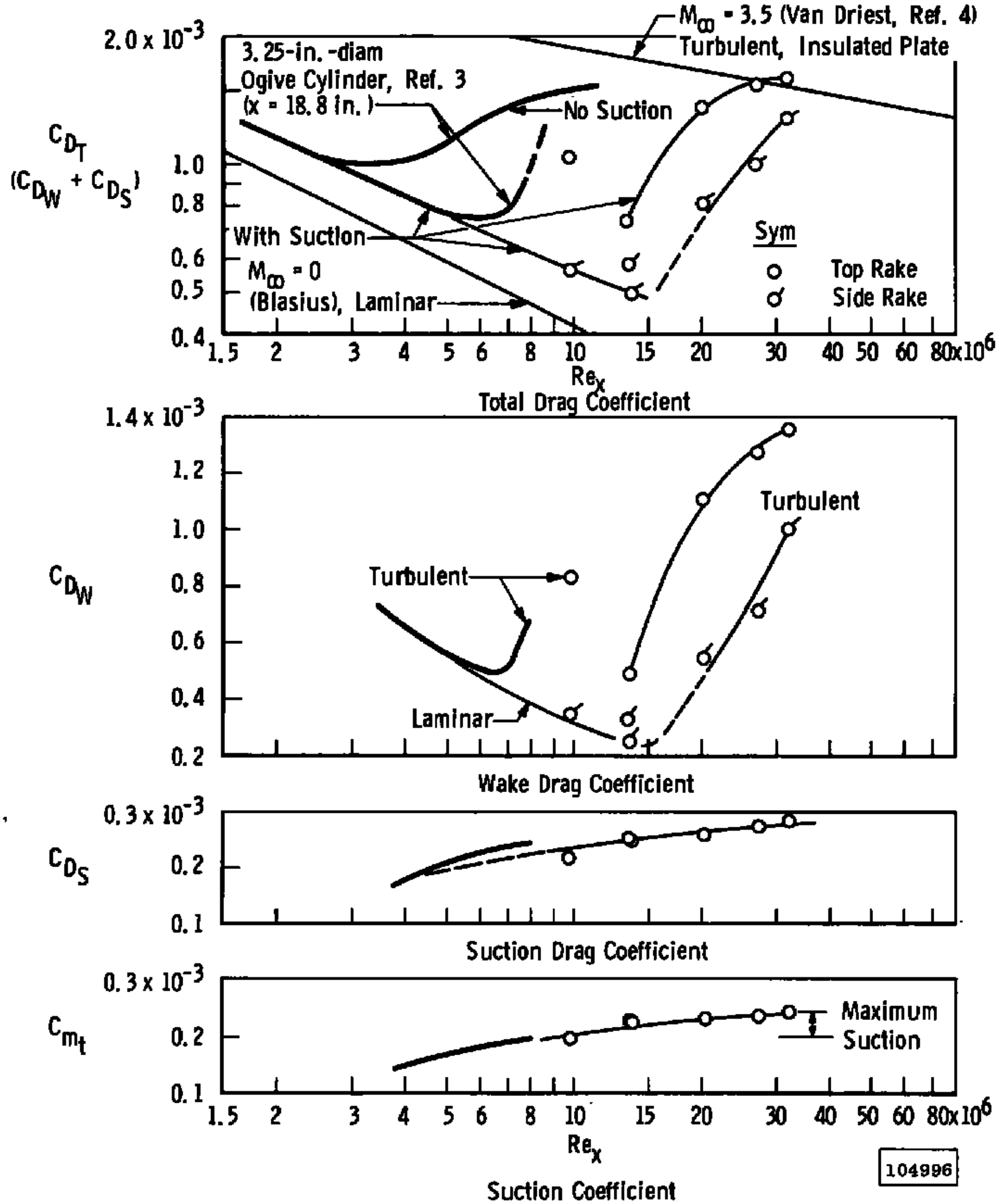
Fig. 10 Drag and Suction Coefficients versus Reynolds Number for $\alpha = 0$ and $M_\infty = 2.5$, 3, and 3.5



Suction Coefficient

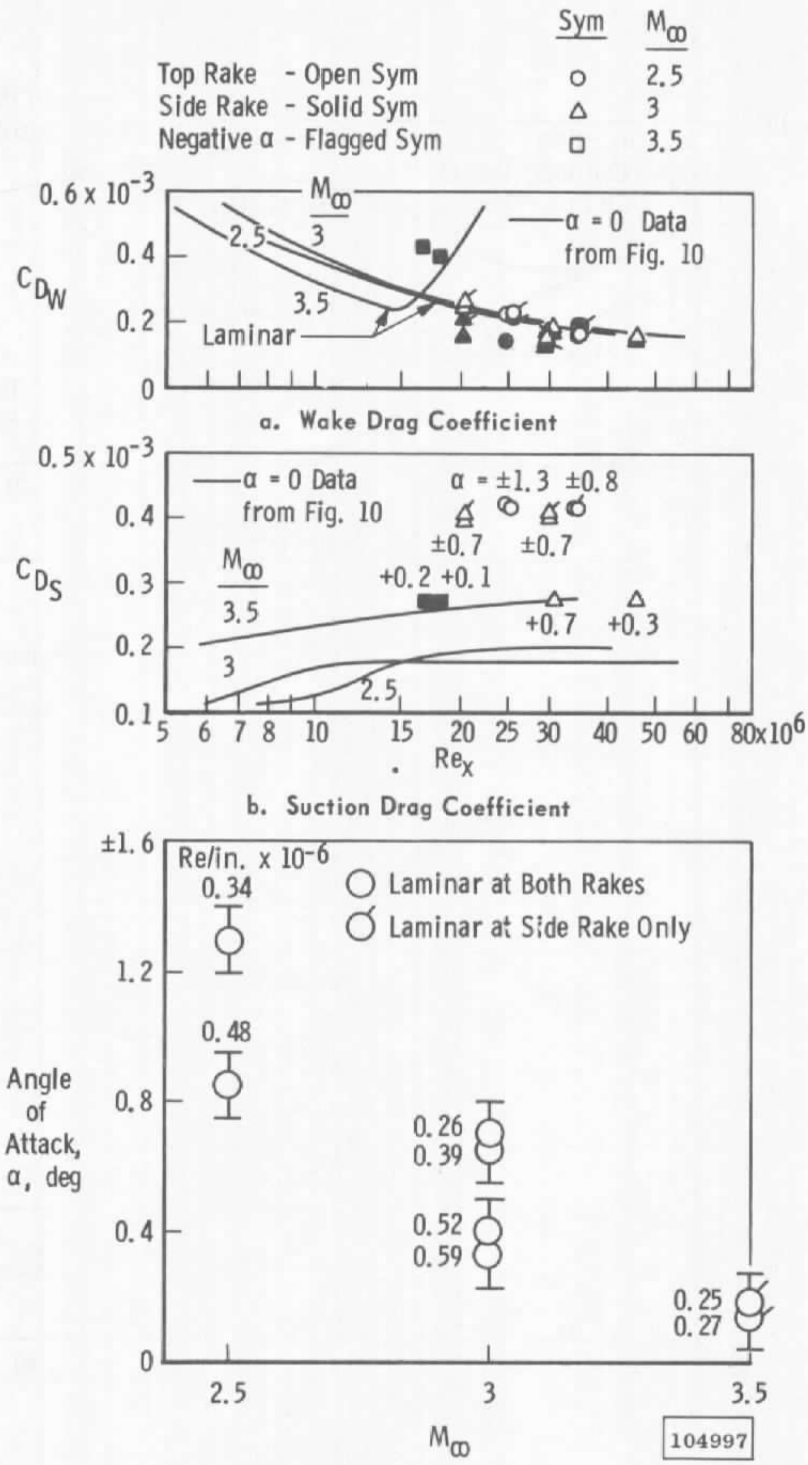
b. $M_\infty = 3$, $x = 77.8$ in.

Fig. 10 Continued



c. M_∞ = 3.5, x = 67.8 in.

Fig. 10 Concluded



a. Wake Drag Coefficient

b. Suction Drag Coefficient

c. Maximum Angle of Attack for Maintaining Laminar Flow at M_∞ = 2.5, 3, and 3.5

Fig. 11 Laminar Flow Results at Angle of Attack

FDMG

Model Construction - Air Force Contract 33(615)-2372

The Boeing Company
Aero-Space Division
Attn: Mr. R. Henks

1. The Gasdynamics Branch is concerned about the cost of model construction for the Cornell Shock Tunnel under the subject contract. While you ~~have,~~ no doubt have allowed sufficient money for model construction within the Boeing Company, a recent evaluation of model building procurements indicates that the Boeing model shop charges from 3 to 5 times that of the smaller model building contractors. In addition to this, Cornell Aeronautical Laboratory has found it both cheaper and more expedient to contract out model construction projects. A recent flat plate model to be used in an Air Force contract with Cornell was subcontracted to Micro Craft, Inc who bid about half of the construction price estimated by ~~of~~ the Cornell shops.

2. While it is not our intent to recommend to you any particular subcontractor under this program, we do strongly recommend that several bids from experienced model building firms be obtained prior to model fabrication so that the most economical course of action may be ascertained.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D	
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)	
1 ORIGINATING ACTIVITY (Corporate author) Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A
3 REPORT TITLE INVESTIGATION OF DRAG REDUCTION BY BOUNDARY-LAYER SUCTION ON A BODY OF REVOLUTION AT MACH NUMBERS 2.5, 3, AND 3.5	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) N/A	
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13. ABSTRACT

Tests were conducted in the 40-in. supersonic tunnel of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for laminar flow control on a 9.2-in.-diam body of revolution at Mach 2.5, 3, and 3.5 with a Reynolds number range (based on boundary-layer rake location) from 9.9 to 51.7 million for angles of attack from 0 to ±2 deg. The condition of the boundary layer was very sensitive to changes in angle of attack. Increasing the Reynolds number also decreased the maximum angle of attack. Wake, suction, and total drag coefficients and the corresponding suction coefficients are presented, along with some fully turbulent wake drag coefficients for the no suction case.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
boundary-layer suction						
drag reduction						
laminar flow						
supersonic flow						

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