



EXPERIMENTS ON ROUGHNESS EFFECTS ON BOUNDARY-LAYER TRANSITION UP TO MACH 16

Jack D. Whitfield and F. A. Iannuzzi

ARO, Inc.

January 1969

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FOREWORD

The work reported herein was conducted at the request of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65401F/06RB.

The results of tests presented herein were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The tests were conducted from September 1, to October 27, 1966, from December 5 to December 15, 1966, and from July 20 to July 27, 1967, under ARO Project Nos. VT2710 and VT2707. The manuscript was submitted for publication on October 23, 1968.

This research was presented at the AIAA Third Aerodynamic Testing Conference, San Francisco, California, April 8-10, 1968, and was published in preprint form as AIAA Paper 68-377.

This technical report has been reviewed and approved.

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ABSTRACT

Free-stream Mach number 14 to 16 experiments in a high Reynolds number hotshot-type wind tunnel with a sharp 9-deg cone model under relatively cold-wall conditions are presented that reveal the expected strong influence of Mach number and a unit Reynolds number effect similar to that obtained in conventional wind tunnels. Comparison of cone and hollow cylinder (i.e., equivalent to a flat plate) transition Reynolds numbers from several wind tunnels and ranges fails to reveal a conclusive picture concerning the relationship of cone and flat-plate transition Reynolds numbers. The effectiveness of spherical roughness in promoting premature boundary-layer transition is shown to decrease exponentially with increasing Mach number. The present results compare favorably with the hypersonic extension proposed by Potter and Whitfield for their original correlation. It is shown that care must be exercised in selecting the physical roughness size at hypersonic speeds because of possible flow field distortion.

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NOMENCLATURE

b	Leading-edge thickness
h	Enthalpy, Btu/lb _m
k	Height of roughness element above surface, in.
M	Mach number
N	Number of spheres
p	Pressure, psia
p'_O	Impact pressure measured by pitot probe
$\dot{q}$	Heat-transfer rate, Btu/ft ² -sec
Re_k	Reynolds number at height of roughness, k, $(U/\nu)_k \cdot k$
Re'_k	$Re_k (T_k/T_w)^{0.5+\omega}$
$Re_{t,\delta}$	$(U/\nu)_\delta \cdot x_t$
$Re_{x,\delta}$	$(U/\nu)_\delta \cdot x$
St	Stanton number, $\dot{q}/[\rho U(h_o - h_w)]$
T	Temperature, °K
U	Velocity, ft/sec
x	Distance from tip of cone, measured along the surface, in.
ϵ	Value of Re'_k where $x_t = x_k$

θ_c	Semivertex angle or half-angle cone
ν	Kinematic viscosity
ρ	Gas density
ω	Exponent in formula relating absolute viscosity, μ , to temperature, i. e., $\mu = T^\omega$ where $\omega = 0.87$

SUBSCRIPTS

aw	Adiabatic or insulated wall condition
k	At the station where roughness is applied to the surface
o	Wind-tunnel reservoir condition
t	At the station where the boundary layer undergoes transition
t_o	At the station where natural (untripped) boundary-layer transition occurs
w	Based on body wall conditions
x	Based on distance x
δ	Conditions at the outer edge of boundary layer
∞	Free-stream condition

SECTION I INTRODUCTION

The apparent strong influence of Mach number and unit Reynolds number on boundary-layer transition in hypersonic wind tunnels has been extensively discussed in the literature (Refs. 1-4) as has also the adverse effect of Mach number on successful tripping of laminar boundary layers (Refs. 1-3 and 5-8). Unfortunately, the experimental data on roughness effects on boundary-layer transition above local Mach numbers of five are not extensive. Potter and Whitfield (Ref. 1) proposed in 1965 an extension of their earlier roughness correlation (Refs. 2 and 3) up to a local Mach number of 8.5 for both sharp-nosed cones and flat plates, based on the then available data. The strong effect of wall cooling on roughness effectiveness is included in the correlation and its extension.

The present experimental work was undertaken under a hypersonic relatively cold-wall situation to amplify and extend the data upon which the hypersonic extension of Potter and Whitfield's correlation was based. Studies of both natural and roughness-induced boundary-layer transition are included.

SECTION II EXPERIMENTAL CONDITIONS

2.1 TEST FACILITY

The new experimental studies reported herein were conducted in the AEDC-VKF 108-in. hotshot wind tunnel (Gas Dynamic Wind Tunnel, Hypersonic (F), see Fig. 1) (Refs. 9 and 10) using nitrogen as the test gas at nominal free-stream Mach numbers of 14 to 16 and Reynolds numbers, based on local cone conditions and model length, up to 20×10^6 . This wind tunnel is equipped with an 8-deg included angle conical nozzle and offers the capability of testing either at the conventional 108-in. -diam test section or in a special upstream test section located at the 54-in. -diam section. During the course of this test, optical observations were available only at the 108-in. -diam location. The present tests were all conducted at the upstream 54-in. -diam test section in order to maximize the available unit Reynolds number at the desired test Mach number.

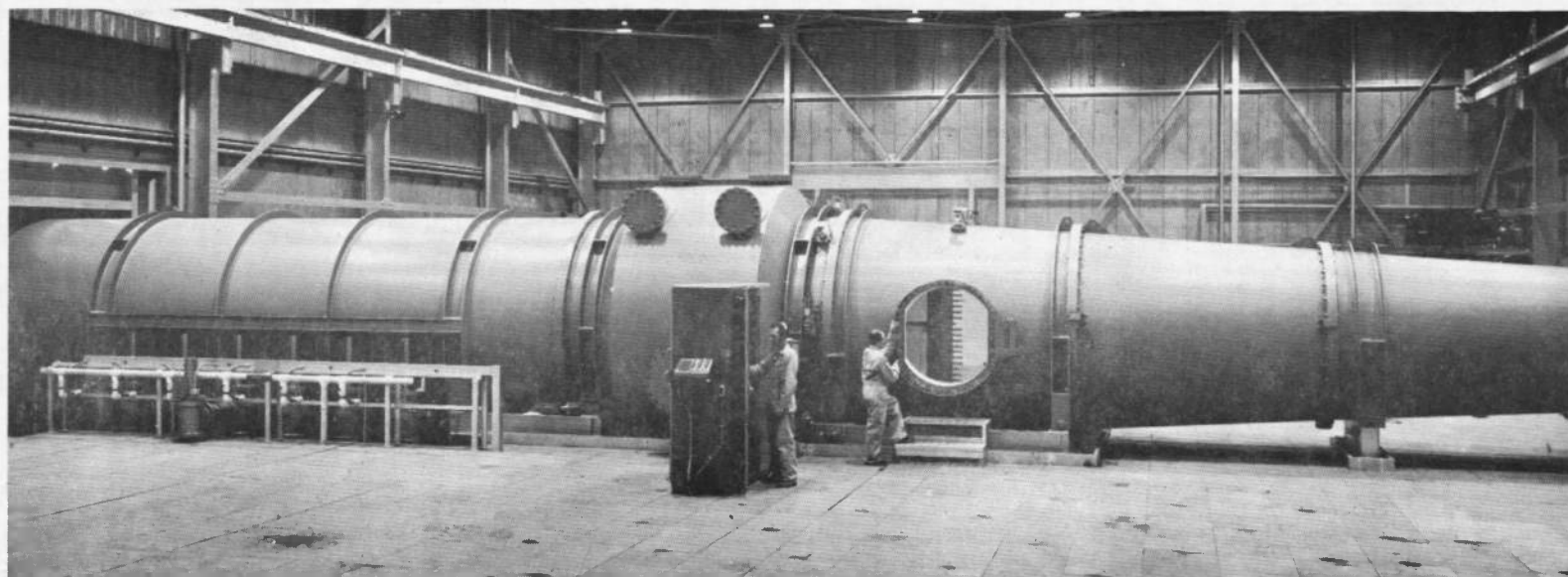
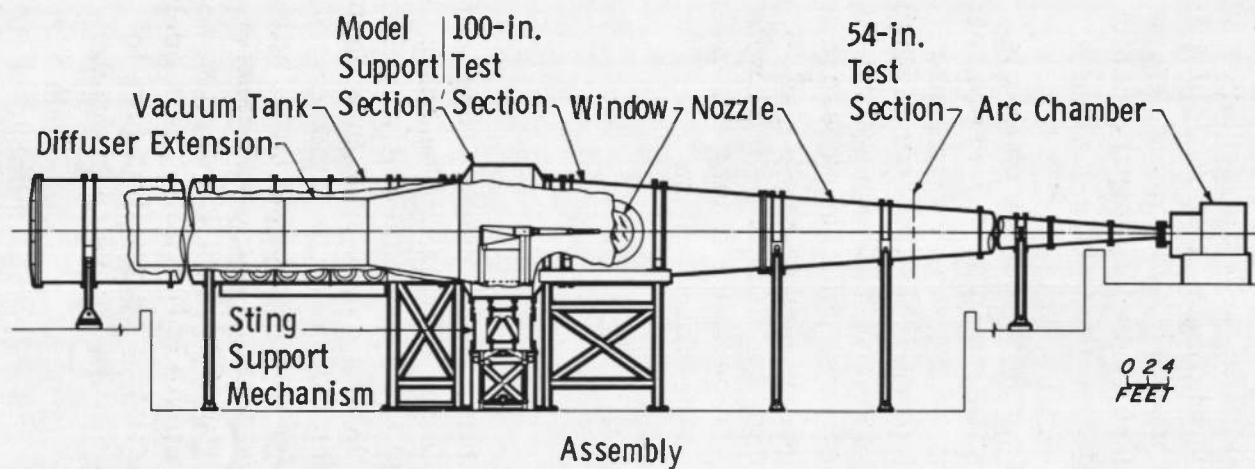


Fig. 1 108-in. Hypervelocity Tunnel F

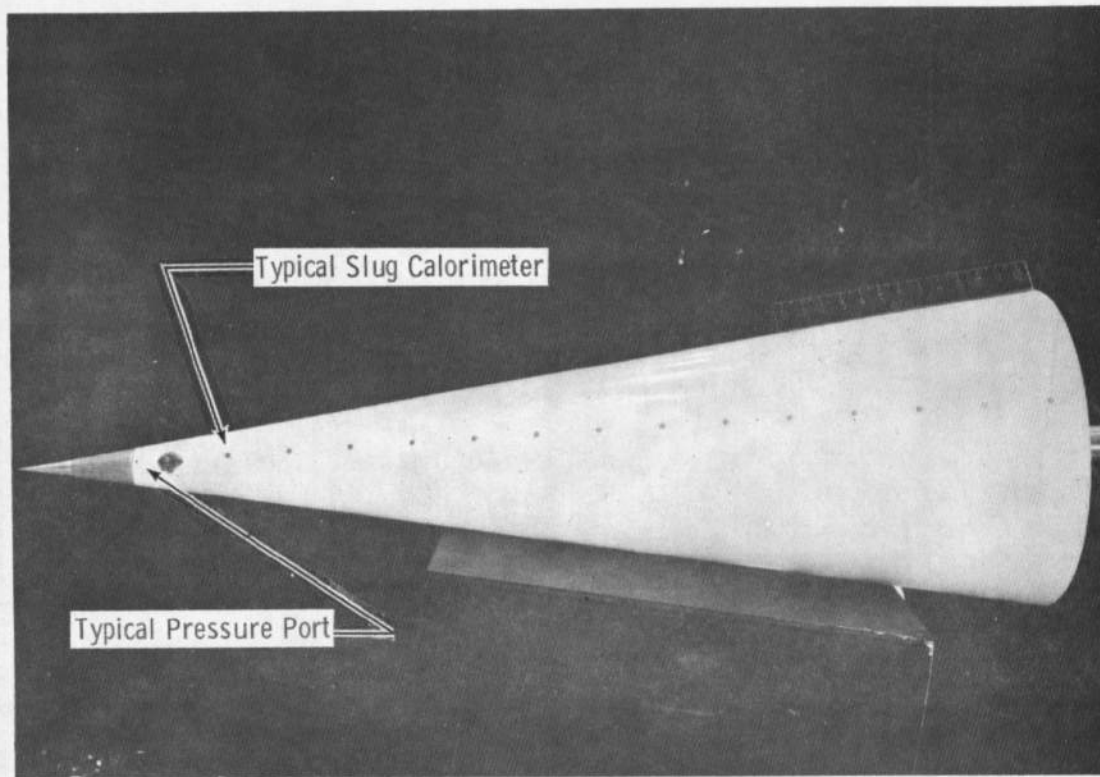
Hotshot-type wind tunnels offer only a quasi-steady test condition (i. e., some variation in flow conditions occurs during the approximately 100 msec of available test time); thus, data points at several unit Reynolds numbers can usually be obtained during the course of one run. The total unit Reynolds number variation during a given run ranges from about 35 to 50 percent. Unfortunately, other parameters, such as Mach number and total temperature, are also varying; however, the order of variation is not large. The variations in Mach number and total temperature did not usually exceed about 3 and 30 percent, respectively, during a given run. Reservoir pressures and temperatures, as measured during the useful run, were up to 15,000 psia and 2200°K during this study.

It should be noted that the definition of hotshot flow properties is based on the method outlined by Griffith and Lewis (Ref. 11) where test-section measurements of pitot pressure and stagnation heat-transfer rate are used to compute the total flow enthalpy. This is accomplished on a timewise basis during any given run as well as on a run-by-run basis. The total flow enthalpy, the measured arc-chamber pressure, and the assumption of isentropic nozzle flow are used as described by Grabau, et al. (Ref. 12) to obtain free-stream conditions. Model wall temperature remained essentially at room temperature during the brief test period (≈ 100 msec); thus a relatively cold-wall situation ($T_w/T_{aw} = 0.2$) existed for all of the hotshot data.

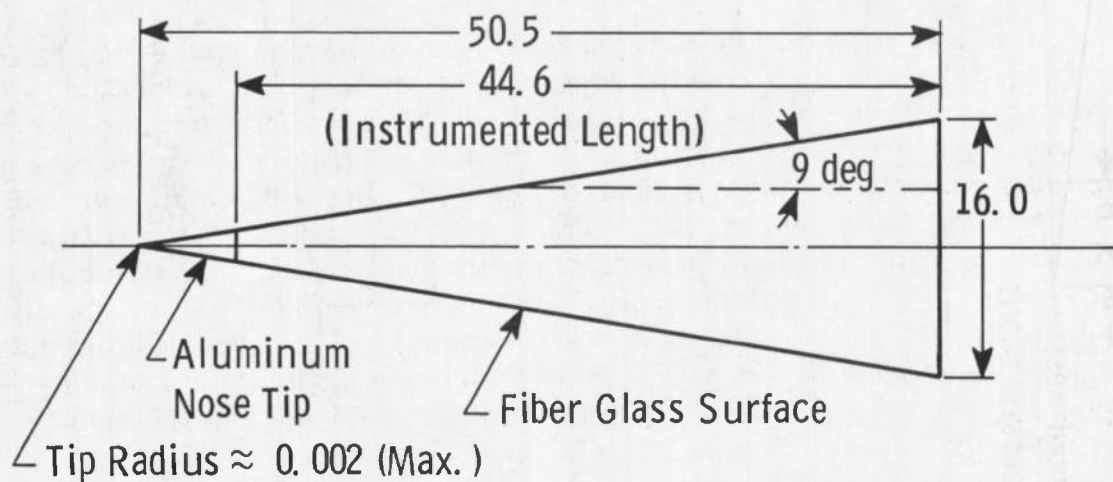
2.2 MODEL AND ROUGHNESS CONFIGURATION

The model used for the present tests was a sharp-nosed 9-deg half-vertex angle cone with a base diameter of 16 in. (Fig. 2). The basic model was constructed of fiber glass except for a 5.9-in.-long aluminum nose section. This nose section was removable, and several interchangeable nose pieces were used to insure a sharp tip (nose tip diameter ≈ 0.004 in. maximum) for each data run. The model was instrumented with two diametrically opposed rays of heat-transfer gages. The heat-transfer gages were located 3 in. apart, and one row was located 1.5 in. axially from the opposing row to provide more complete coverage. The model was instrumented with the slug-type heat-transfer gages discussed by Ledford (Ref. 13) and with surface pressure transducers of the wafer-type (Ref. 9).

Seven different roughness configurations were tested as illustrated in Fig. 3. In general, the spheres were aligned with the rays of heat-transfer gages; however, in the cases with an uneven number of equally spaced spheres only the top sphere was aligned with the heat-transfer gages.



a. Model Photograph



All Dimensions in Inches

b. Model Sketch

Fig. 2 Nine-deg Half-Vertex Angle Cone Model

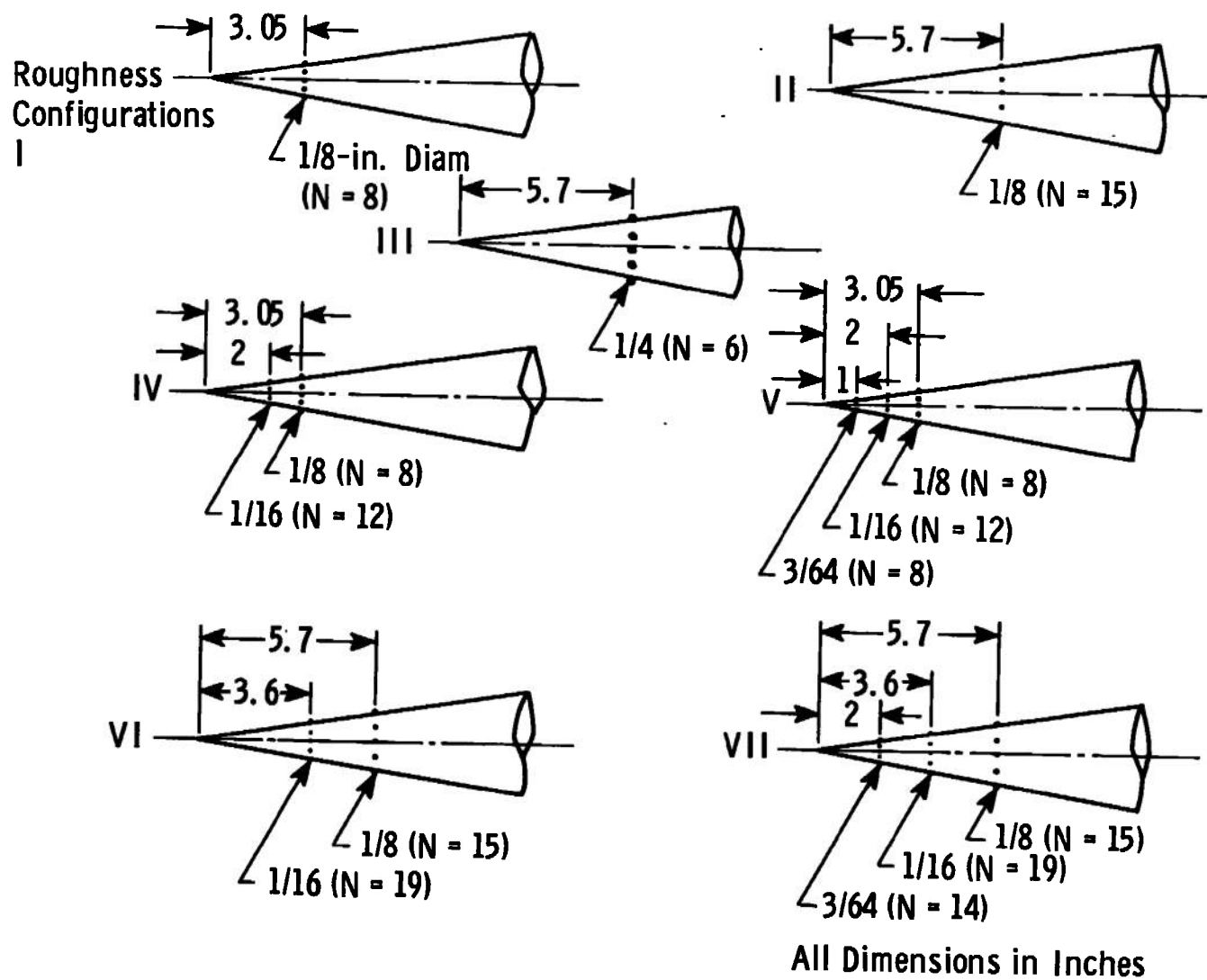


Fig. 3 Spherical Roughness Configuration Tested on a 9-deg Half-Vertex Angle Cone Model

SECTION III RESULTS AND DISCUSSION

3.1 NATURAL TRANSITION RESULTS

Since optical data could not be obtained during the present tests in the special upstream 54-in. -diam test section, it was necessary during the course of this research to rely exclusively on the distribution of surface heat-transfer rates. Typical smooth cone laminar heat-transfer and pressure distributions are presented in the upper and lower portions, respectively, of Fig. 4. Local cone conditions cited throughout this paper were obtained from the charts of Roberts, Lewis, and Reed (Ref. 14) corrected to the T_o of this experiment. The theoretical laminar heat-transfer estimates were made using Soloman's formula (Ref. 15) for the heat-transfer rate to a sharp-nosed cone. The quite large cone model (16-in. base diameter) used for the present research in the 54-in. -diam test section leads, of course, to measurable source-flow effects even with the shallow-angle conical nozzle (8-deg included angle). The effects of this source flow can be seen in both the heat-transfer and pressure distributions, particularly in the latter. A crude theoretical estimate of the influence of this source flow on the surface heat-transfer distribution was made by estimating local cone conditions from the measured surface pressure distribution by assuming an isentropic expansion or compression from the inviscid parallel flow cone pressure to the measured value. Theoretical laminar heat-transfer distributions based on both parallel flow and the above-described perturbed flow are shown in Fig. 4. A large effect on the surface heat-transfer distribution is not indicated by these estimates. It should be noted that the free-stream conditions quoted throughout this report are based on conditions at the same axial location as the cone base. The free-stream Mach number gradient was about 0.3 in Mach number per foot of axial length or $\Delta M = 1.3$ for the present model length and test conditions.

The beginning of transition as denoted by the heat-transfer data for a smooth cone is illustrated in Fig. 5. Although an upswing in the heat-transfer data is noted at the higher Reynolds numbers, it is evident that the complete transition zone is not observed in this case. The turbulent estimates shown in Fig. 5 and subsequent figures are based on the charts of van Driest (Ref. 16).

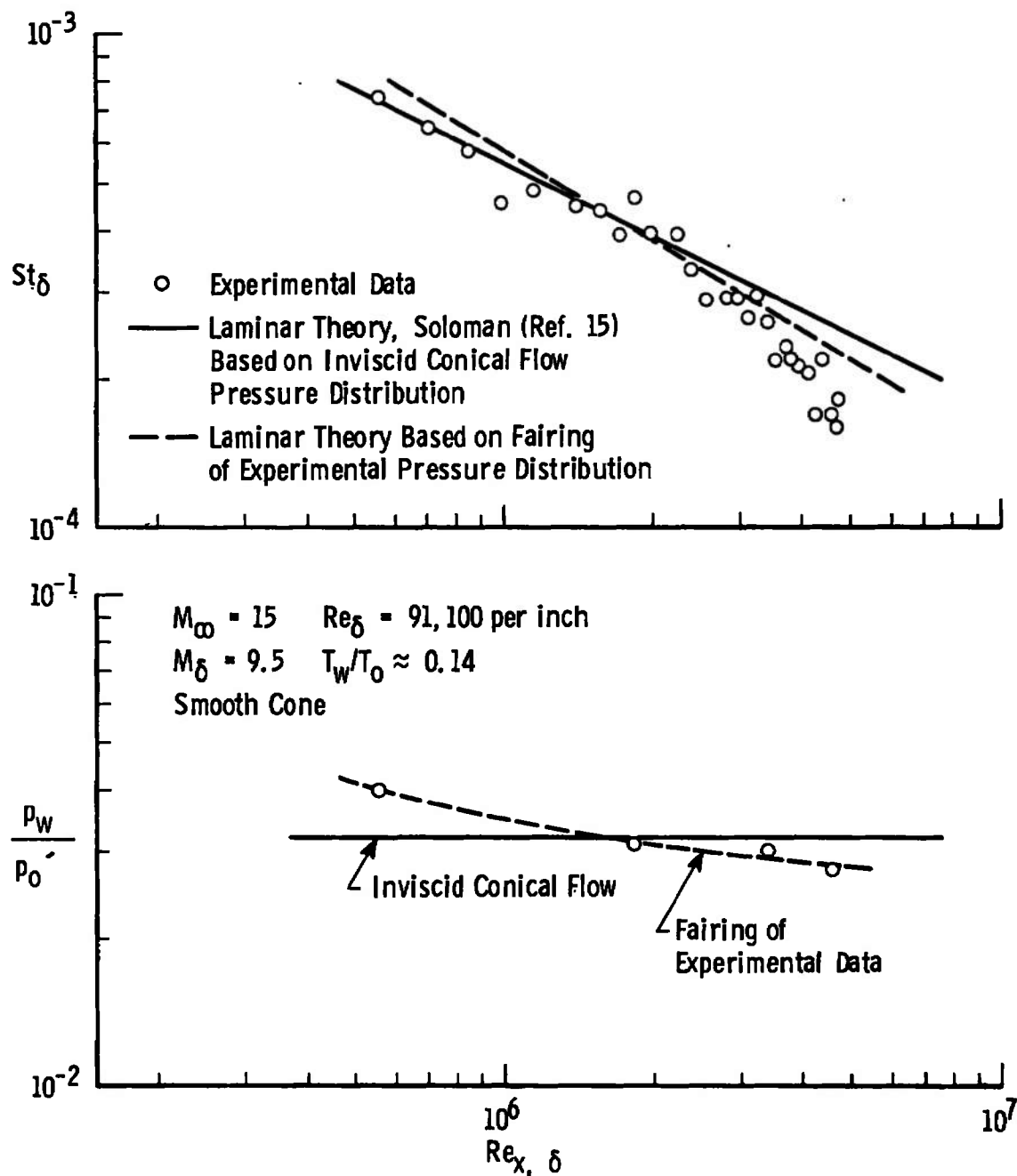


Fig. 4 Comparison of Theoretical and Experimental Pressure and Heat-Transfer Distribution on Sharp, Smooth Model at $M_{\infty} \approx 15$

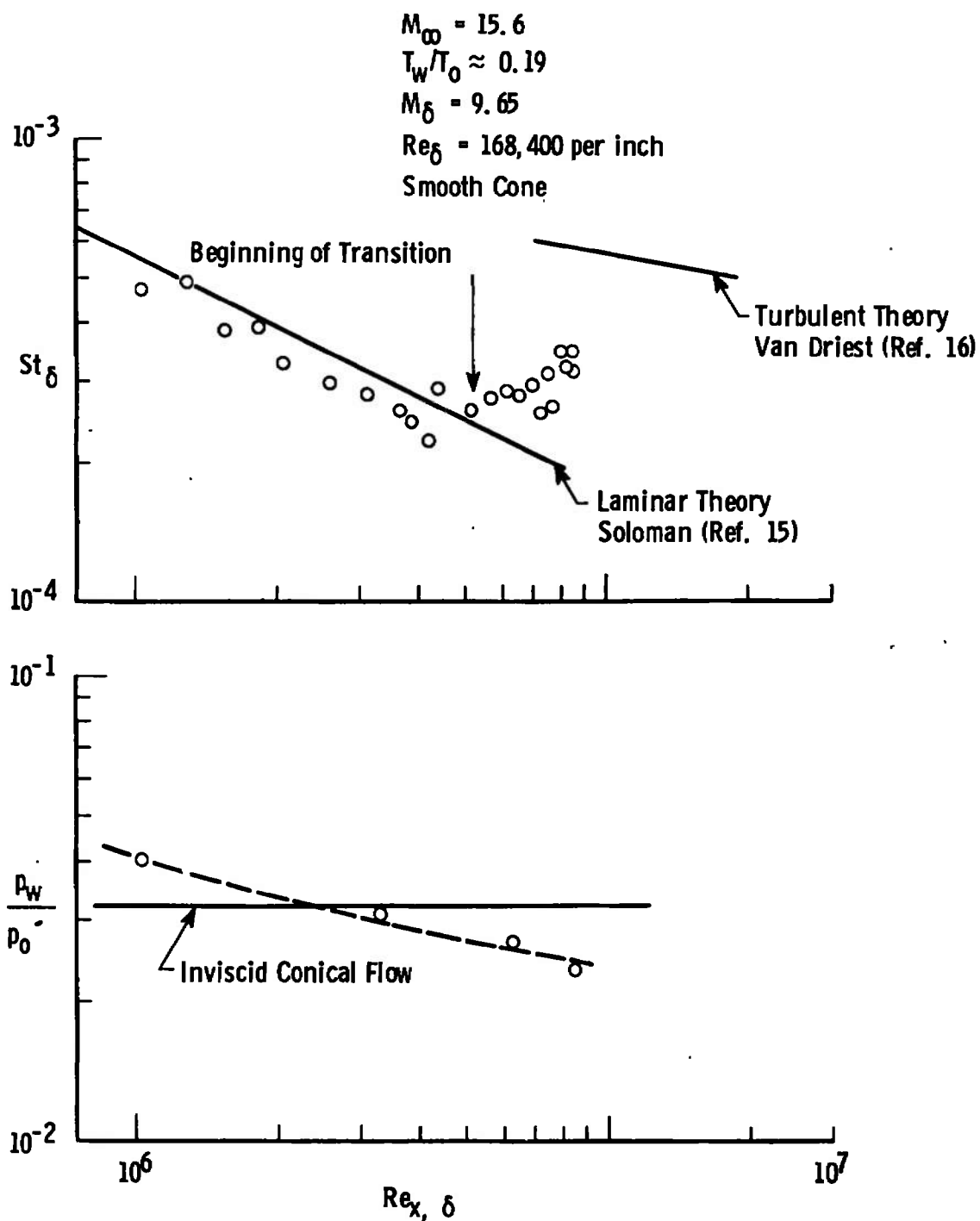


Fig. 5 Beginning of Transition as Denoted by Heat-Transfer Data

Natural transition (i. e., smooth cone) as denoted by the heat-transfer distribution is illustrated in Fig. 6. The laminar and turbulent heat-transfer estimates are again those due to Soloman (Ref. 15) and van Driest (Ref. 16), respectively. The rather large data scatter in the transition zone, as may be noted in Fig. 6, was exhibited during most of the present study. Figure 6 is considered reasonably typical in this regard since some distributions exhibited less scatter and a few exhibited more scatter. These latter sets of data were discarded since estimates of the beginning and end of transition were quite doubtful.

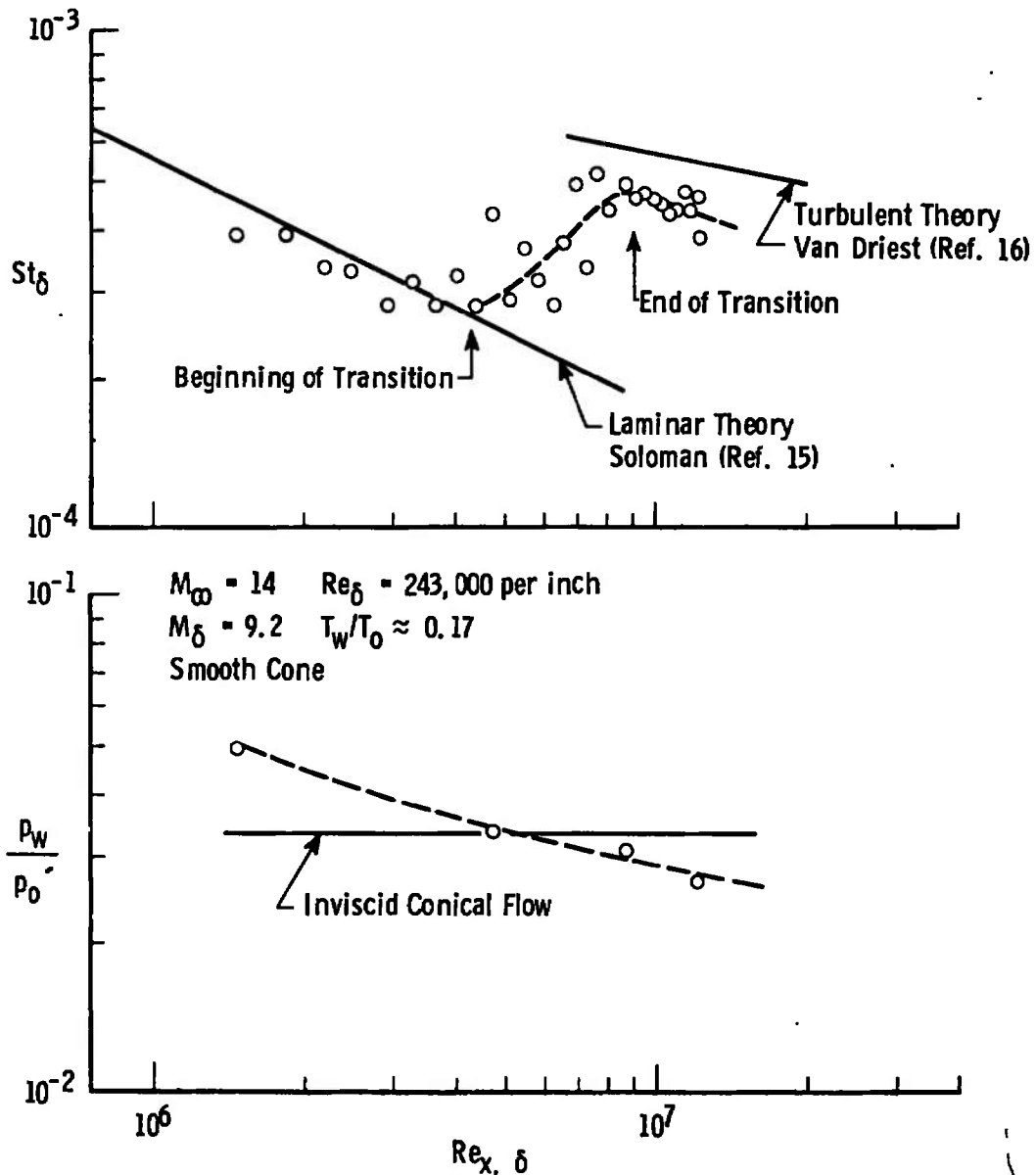


Fig. 6 Natural Transition as Denoted by Heat-Transfer Distribution

Smooth cone transition Reynolds numbers ($Re_{t,\delta}$), based on inviscid local flow properties and the estimated beginning and end of transition locations as determined from the surface heat-transfer distributions, are summarized in Fig. 7. The data presented in Fig. 7 were obtained from several runs at varying unit Reynolds number conditions and thus with some variation in free-stream Mach number as well. Since the variation in free-stream Mach number was relatively small (± 0.3) for the data in Fig. 7, no attempt has been made to define a Mach number trend from only these data. The variation in $Re_{t,\delta}$ for the end of transition data in Fig. 7 is attributed herein to a variation in unit Reynolds number, U_δ/ν_δ . The unit Reynolds number effect noted here is qualitatively similar to the effect which is nearly always observed in conventional wind tunnels (Refs. 1-4) and to the effect Potter (Ref. 17) has recently observed in an aeroballistic range. Unfortunately, the scatter of the beginning of transition data prohibits an assessment of whether or not a unit Reynolds number effect exists in this case. Based on the present end of transition data and previous lower Mach number studies (Refs. 1-4) of both the beginning and end of transition, it is suspected that a unit Reynolds number effect on the beginning of transition does exist, but a firm conclusion will have to await more definitive data at this Mach number.

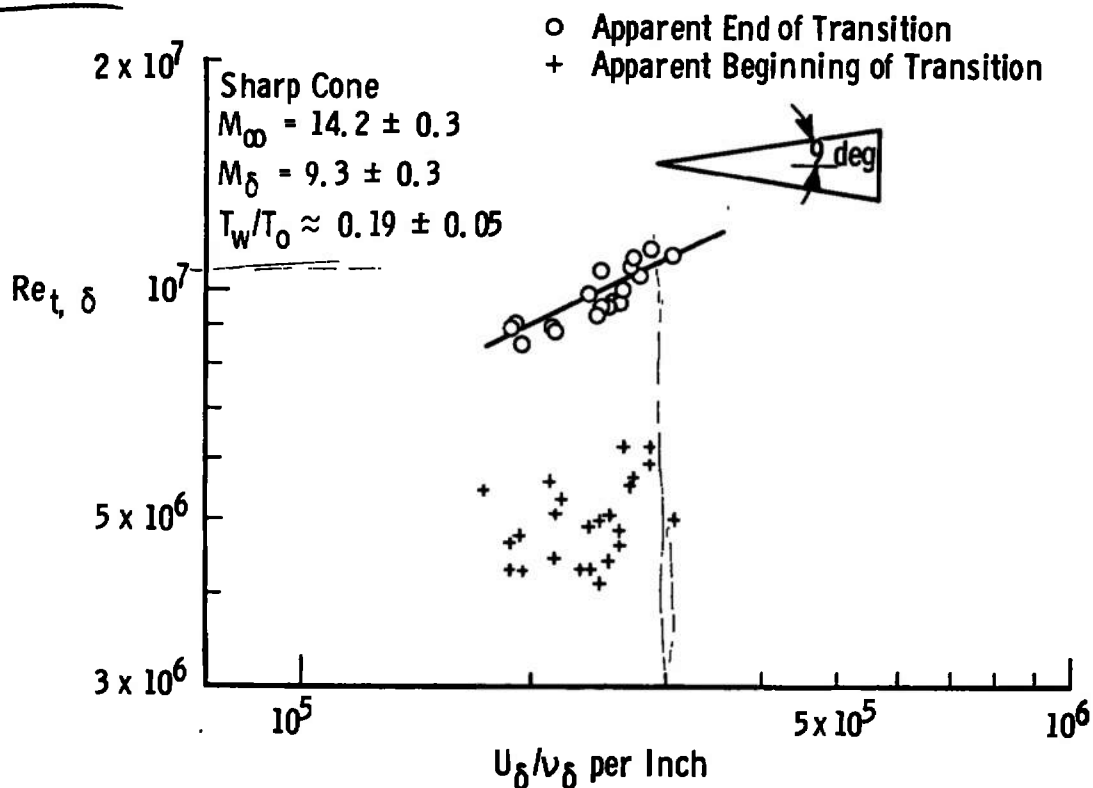


Fig. 7 Apparent Beginning and End of Boundary-Layer Transition as a Function of Local Unit Reynolds Number

The faired curve of the end of transition data in Fig. 7 was used to estimate $Re_{t,\delta}$ for $U_\delta/\nu_\delta = 300,000$ per inch for comparison with the cone transition data previously summarized by Potter and Whitfield (Ref. 1). Such a comparison is shown in Fig. 8, which includes other data from the National Aeronautics and Space Administration (NASA) (Refs. 18 and 20) and the Jet Propulsion Laboratory (JPL) (Ref. 19). Considering the fact that data from many different facilities are involved, the wind-tunnel data in Fig. 8 are surprisingly consistent. In view of the recent studies by Pate and Schueler (Ref. 21) concerning the influence of aerodynamic noise in supersonic wind tunnels, such consistency cannot be expected. The exception to the present consistency lies with the aeroballistic range data. The recent data from Potter (Ref. 17), extrapolated to $U_\delta/\nu_\delta = 300,000$ per inch, lie well below the wind-tunnel cone data; in fact, the aeroballistic range and wind-tunnel data differ in this case by a factor of two. The aeroballistic range G data previously published by Potter and Whitfield (Ref. 1) are also included in Fig. 8. Unfortunately, these data did not include a systematic study of the unit Reynolds number effect; thus an accurate estimate for $U_\delta/\nu_\delta = 300,000$ per inch is not available; however, since the wind-tunnel data and the recent range data from Potter (Ref. 17) indicate similar unit Reynolds number effects, a reasonable estimate seems possible. Such an estimate, based on $Re_{t,\delta} \propto (U_\delta/\nu_\delta)^{0.4}$, is shown in Fig. 8. Again the aeroballistic range data appear low relative to the wind-tunnel data by approximately a factor of two. It should be noted that the AEDC-VKF Range K data from Potter (Ref. 17) were obtained with a wall to total temperature ratio of about 0.2, whereas the AEDC-VKF Range G data from Potter and Whitfield (Ref. 1) were obtained with a wall to total temperature ratio of about 0.1.

Consideration of the recent hollow-cylinder transition data of Pate and Schueler (Ref. 21) obtained in various size wind tunnels adds further confusion to the comparison of cone and flat-plate transition data presented in Fig. 8. Pate and Schueler established an apparent strong influence of tunnel size on their hollow-cylinder transition data. The hollow-cylinder data from Ref. 1 shown in Fig. 8 were obtained in 12-in. and 50-in. wind tunnels. Pate and Schueler's data (Ref. 21), obtained in the AEDC Propulsion Wind Tunnel Facility's 16-ft supersonic wind tunnel, have been extrapolated to a unit Reynolds number of 300,000 per inch and compared to the present data in Fig. 8. This hollow-cylinder transition point agrees well with the cone transition data; however, this agreement is believed to be fortuitous. It is further noted that this hollow-cylinder data point is even in excess of the range cone transition data which were obtained at even higher Mach numbers. The question again arises, are cone transition Reynolds number fundamentally higher than flat-plate values? With the apparent interplay of

effects attributable to Mach number, unit Reynolds number, wall to total temperature ratios, wind-tunnel generated noise, and possible unknown effects in the range tests, it does not now appear possible to answer this question from the presently available data.

	Symbol	θ_c , deg	Tunnel	$U_\delta/\nu_\delta \times 10^{-6} \text{ in.}^{-1}$	Ref.
Cones	○	9	VKF (F)	0.3	Present Data
	●	10	VKF (Range K)	1.76	17
	◐	10	VKF (Range K)	0.3*	17
	○	10	VKF (E)	0.3	1
	△	6	VKF (C)	0.3	1
	□	7.1	VKF (C)	0.3	1
	◇	9	VKF (B)	0.3	1
	▽	10	VKF (C)	0.3	1
	▽	10	NASA (Lewis)	0.3	18
	△	10	JPL	0.3	5
	◇	10	JPL	0.3	19
	○	10	NASA (Lewis)	0.3	20
	◆	5	VKF (Range G)	1.76 - 2.26	1
	◆	5	VKF (Range G)	0.3*	1
Hollow Cylinders ($b \approx 0$)	—	-	VKF (D, E, B)	0.3	1
	x	-	PWT (16S)	0.3*	21

*Extrapolated

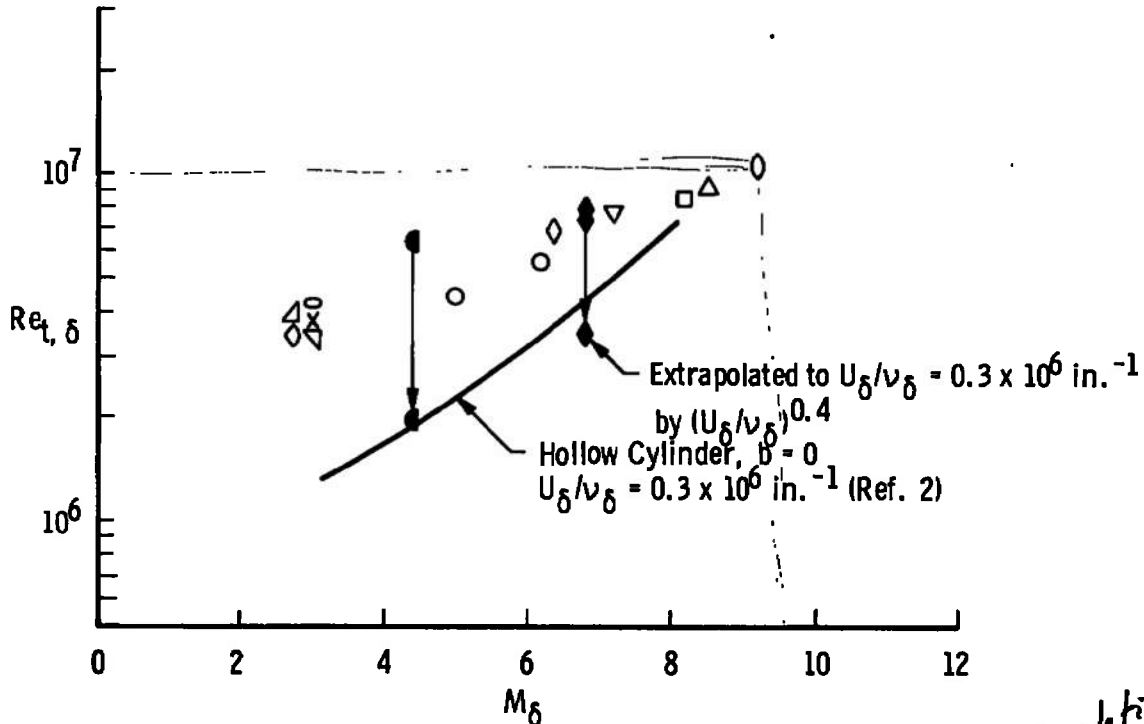


Fig. 8 Qualitative Influence of Mach Number on Reynolds Number of Transition on Planar and Axisymmetric Bodies with Negligible Pressure Distribution

Completion

3.2 ROUGHNESS-INDUCED TRANSITION

The desirability of producing, in many cases, turbulent flow on wind-tunnel models is well known. The increasing difficulty of accomplishing this at hypersonic speeds without an unacceptable distortion of the basic model flow field has been discussed in the literature (Ref. 1). One objective of the present research is to extend our knowledge of roughness effects to higher hypersonic Mach numbers. The correlation of Potter and Whitfield (Refs. 1-3) was used as the basic guide, and the experiments were designed to test the applicability of this correlation at higher hypersonic Mach numbers. Following Refs. 1-3, the parameters of interest are

$$Re_k = (U/\nu)_k \cdot k \quad (1)$$

where U_k/ν_k is the unit Reynolds number in the undisturbed boundary layer corresponding to condition at height k and location x_k , and k is the height of the roughness.

And

$$Re'_k = Re_k (T_k/T_w)^{0.5+\omega} \quad (2)$$

while

$$\epsilon = \text{the value of } Re'_k \text{ where } x_t \approx x_k. \quad (3)$$

Single, double, and triple rows of spheres were tested during the present investigation (Fig. 3). The effect of a single row of 0.125-in.-diam spheres located 3.05 in. downstream of the nose tip (Configuration I) is shown in Fig. 9 where it may be seen that the transition Reynolds number was reduced to about 43 percent of the natural or untripped level. This particular case represents the lowest transition Reynolds number achieved with the single row of spheres. An attempt to trip the boundary layer with a single row of spheres at lower unit Reynolds number was made utilizing 0.250-in.-diam spheres (Configuration III). The results of this test are shown in Fig. 10. Although increased heat-transfer rates are observed, it is evident from comparisons with the turbulent theory and the natural transition results that successful tripping did not occur. It should also be noted that the surface pressure distribution (i. e., see lower portion of Fig. 10) was markedly distorted by these large spheres; thus it can only be concluded that these spheres distorted the model flow field beyond acceptable levels.

Multiple rows of spheres were, as previously noted, tested during the present investigation. An example of heat-transfer distributions obtained with a multiple row of spheres (Configuration V) is shown in Fig. 11.

This particular example was selected since it illustrates one of the data interpretation problems encountered. Data from the upper and lower rays of heat gages are identified separately in Fig. 11, and it may be noted that considerable scatter exists in the region that may be termed the end-of-transition zone. An attempt was made to select a mean location, considering both the upper and lower rays of heat gages, as noted in Fig. 11.

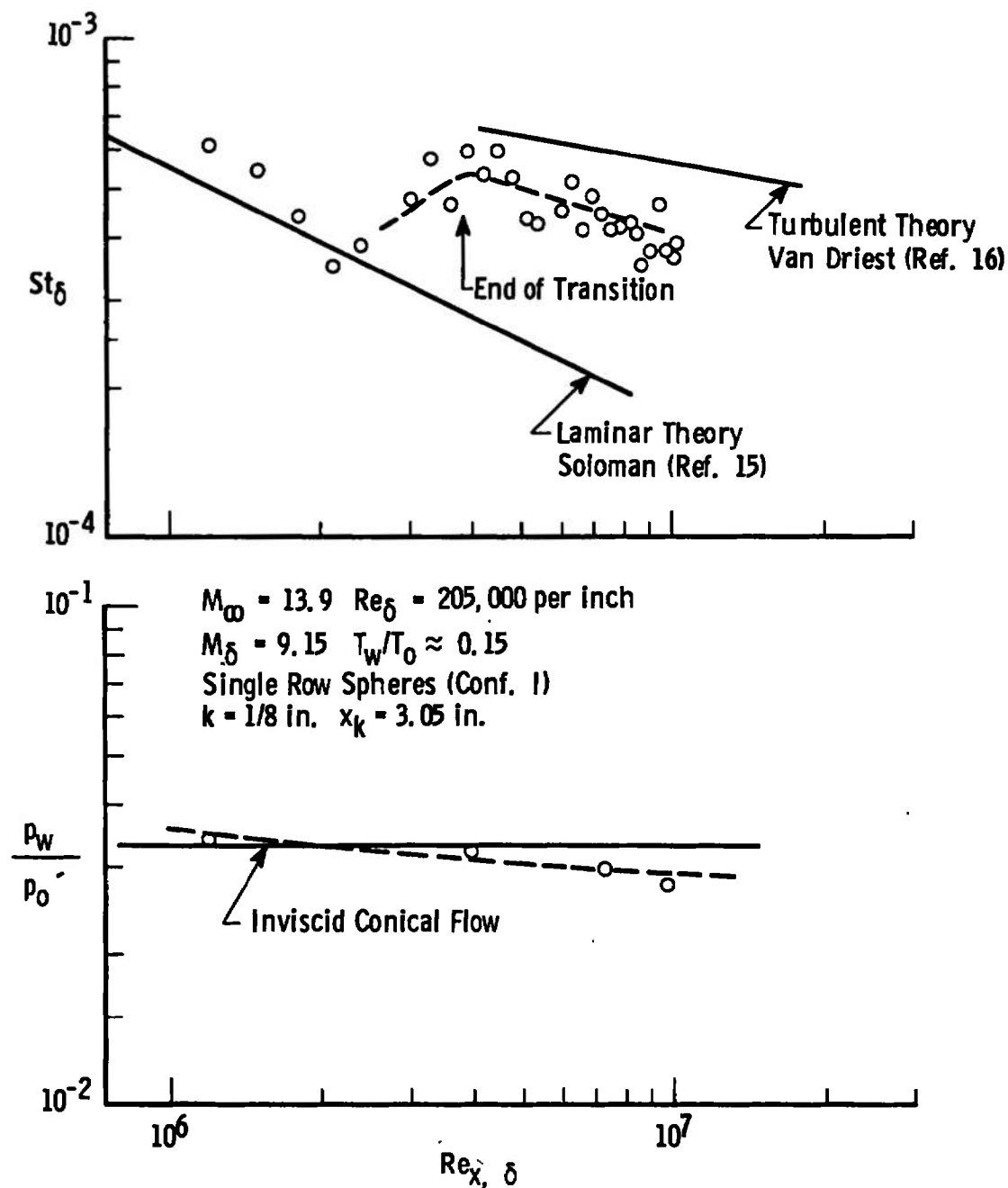


Fig. 9 Effect of 0.125-in.-diam Spheres on Surface Heat-Transfer and Pressure Distribution

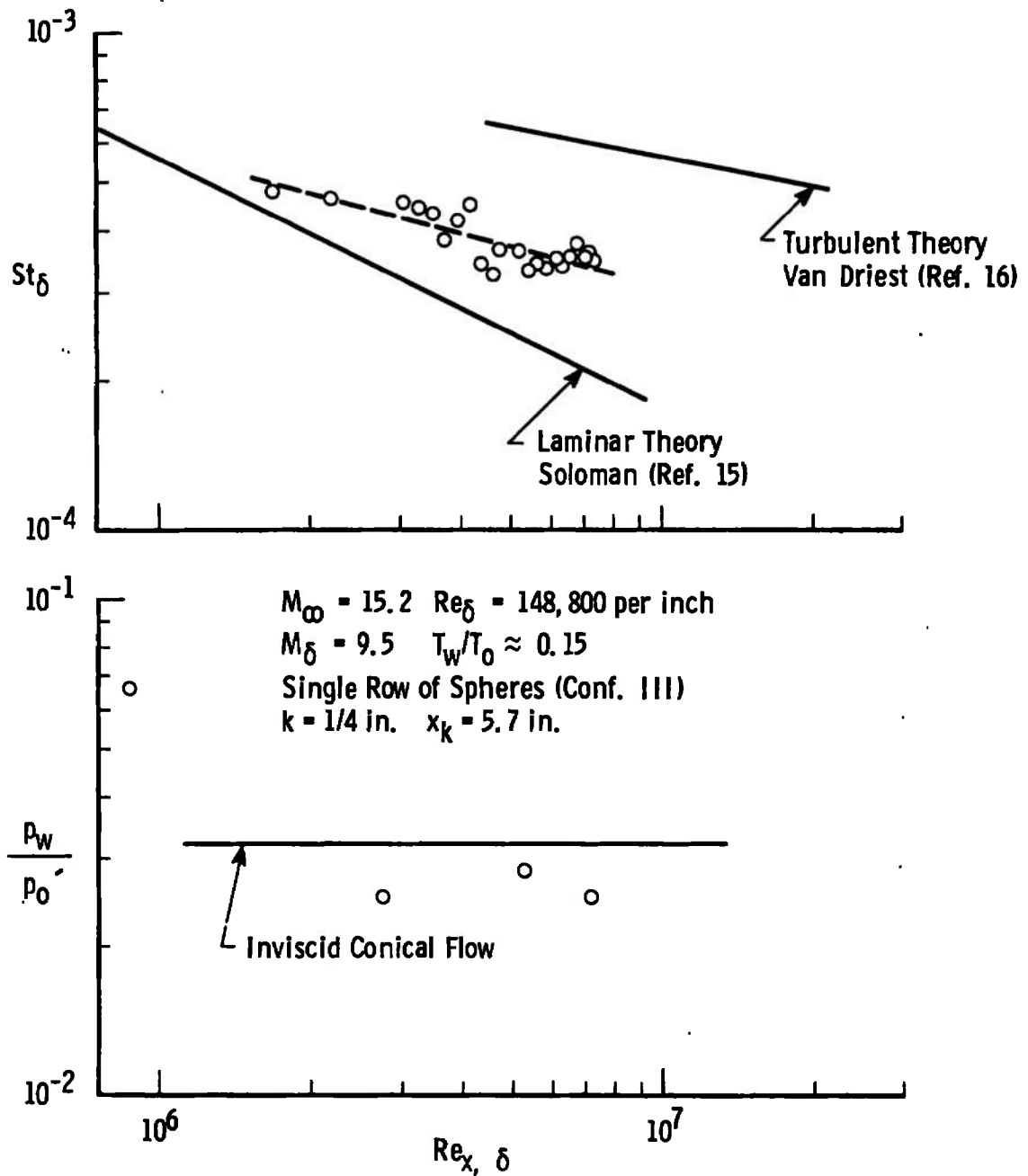


Fig. 10 Effect of 0.25-in.-diam Spheres on the Heat-Transfer and Pressure Distribution

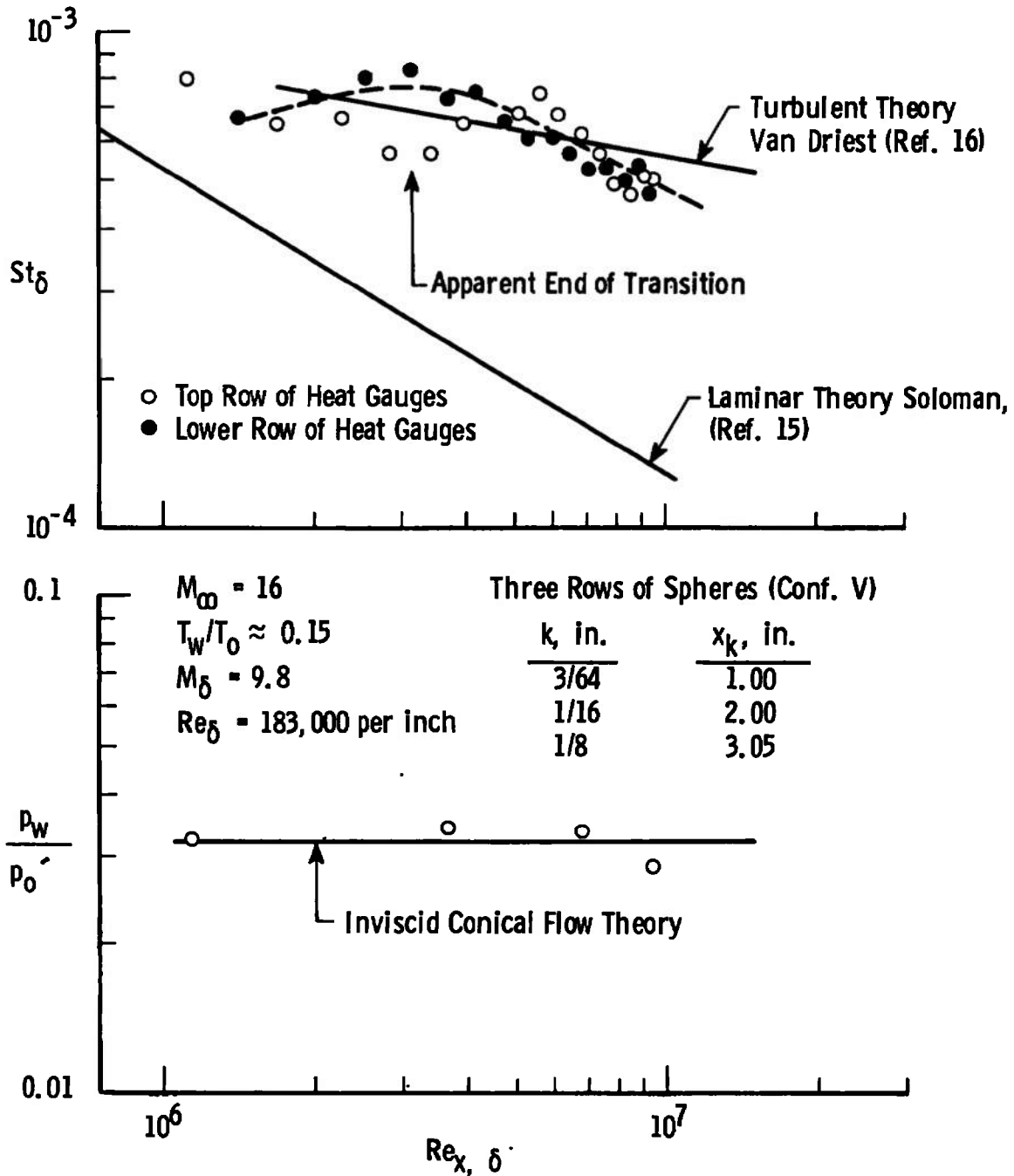
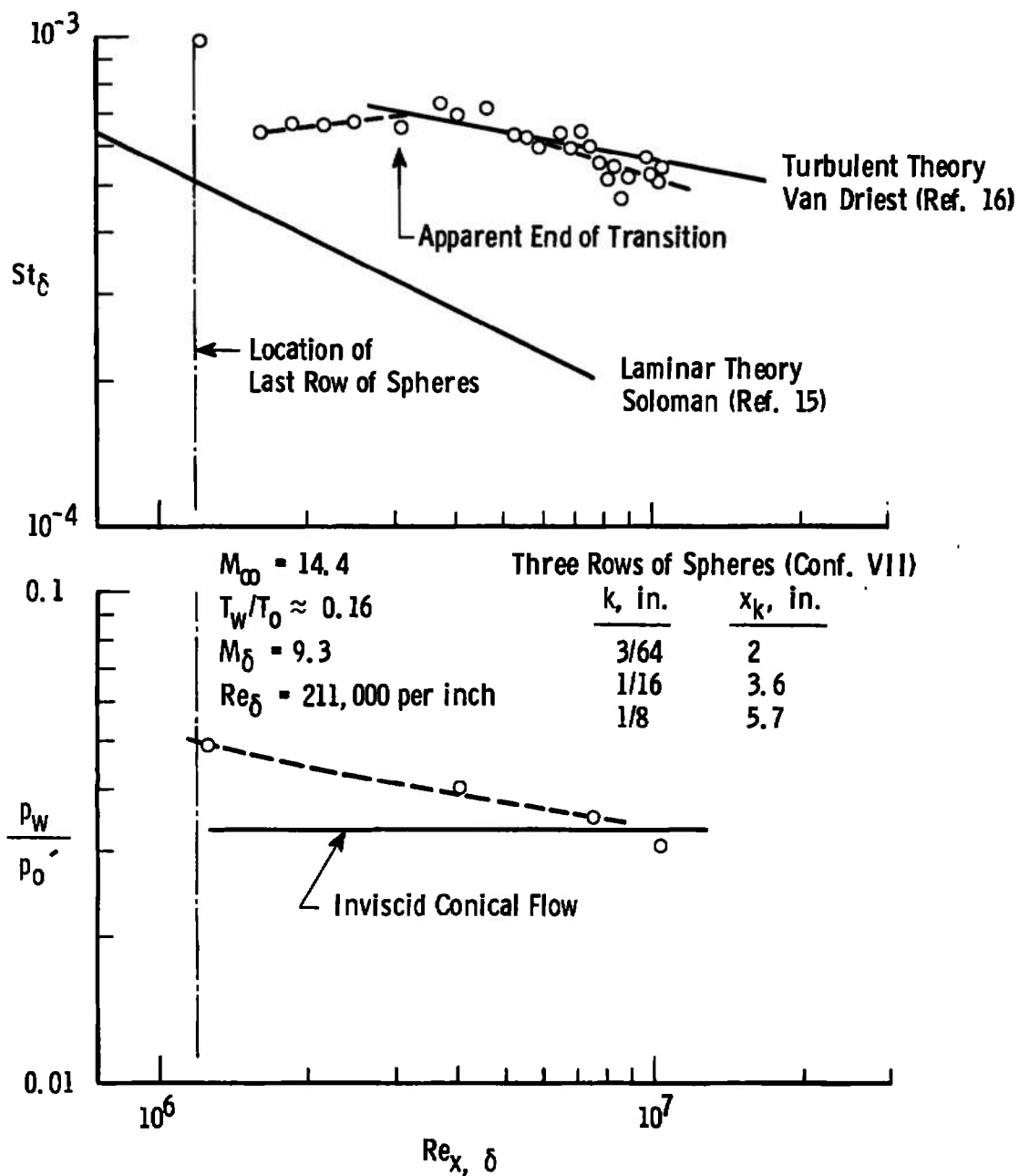


Fig. 11 Effect of Multiple Rows of Spheres on Heat-Transfer and Pressure Distribution at $M_\infty \approx 16$

The multiple rows of spheres were also studied with the spheres at two different axial locations. Comparisons of the forward and aft locations of the triple row configurations, V and VII, are shown in Figs. 12b and a, respectively. Differences due to the axial location of the spheres were, in general, insignificant with respect to the location of apparently fully turbulent flow. Some differences in the transition zone may be observed, and these apparently arise from the close proximity of the spheres to the first heat gages; note, for example, the first heat-transfer rate immediately downstream of the last row of spheres in Fig. 12a as compared with Fig. 12b.

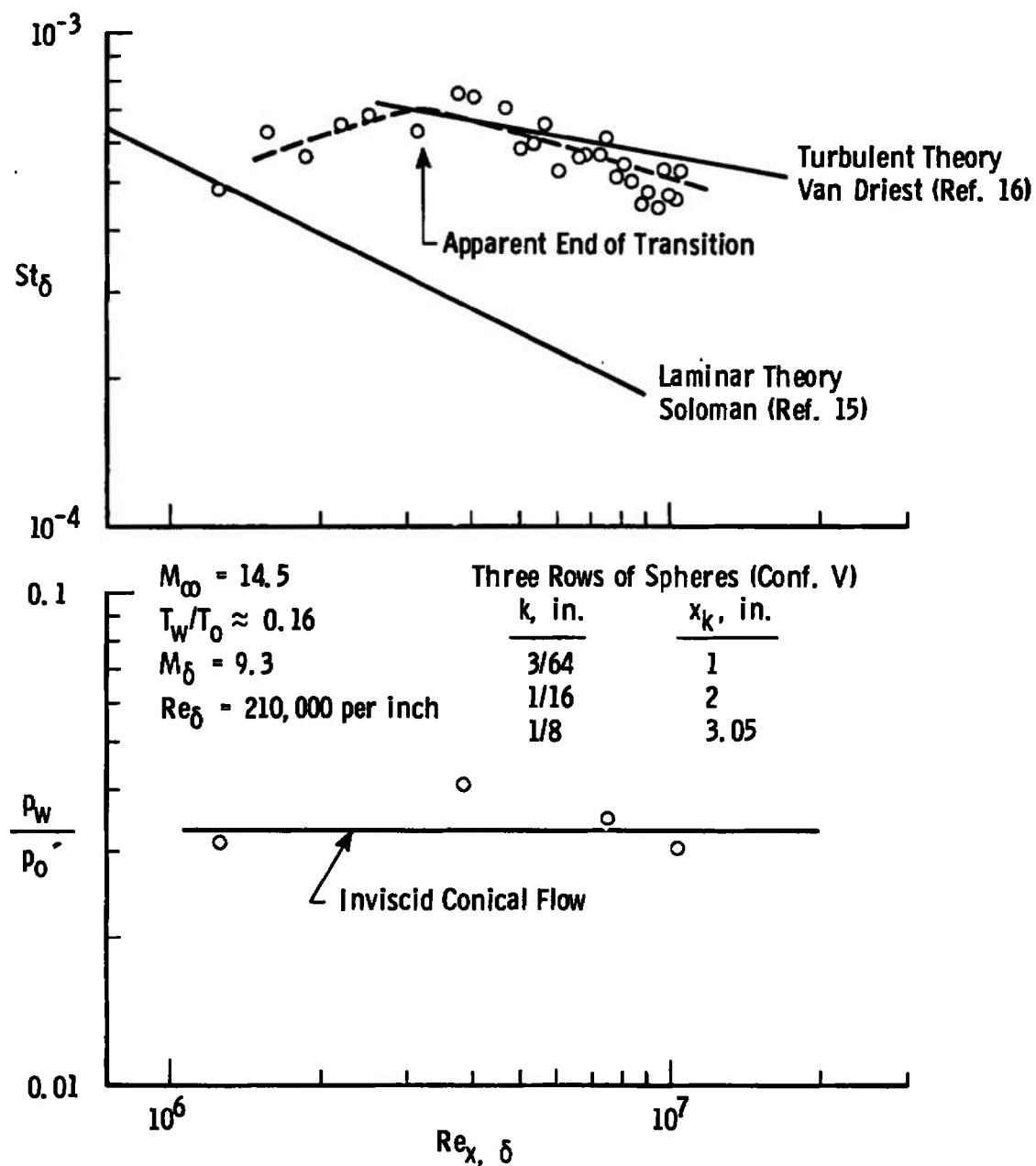
The data from all successful, tripped cases are summarized and compared with smooth cone data in Figs. 13a and b for $M_\delta \approx 9.75$ and 9.25, respectively. Considering the more complete $M_\delta \approx 9.25$ case (Fig. 13b), a clear advantage of the double row of spheres over the single row of spheres is not evident. Conversely, a clear advantage of the triple row of spheres appears evident in both the $M_\delta \approx 9.25$ and 9.75 cases. This is somewhat surprising since in each case the difference between the two- and three-row roughness configurations is represented by the smallest (3/64-in. -diam) spheres. It was expected that the influence of each additional row would become progressively less since decreasing sphere sizes (hence decreasing Re'_k values) were used for each successive row. It should be noted here that the precision of the present transition Reynolds number may not be sufficient to resolve the single versus double row roughness influences. The precision is, however, quite sufficient to define the overall roughness influence.

The roughness experiments described herein and summarized in Fig. 13 furnish data with which the high Mach number extension proposed by Potter and Whitfield (Ref. 1) for their original roughness correlation (Ref. 3) may again be re-examined at even higher local Mach numbers. The original correlation curve, i. e., Fig. 28 of Ref. 3: $(x_t/x_{t,o})^{1/2} - (Re'_k/\epsilon) (x_k/x_{t,o})^{1/2}$ versus Re'_k/ϵ , was used in conjunction with the present data to deduce effective ϵ values. The ϵ values which place the present data on the original correlation curve were found by trial and error. The values of ϵ deduced from the present data are compared to the original correlation (Ref. 3) and the proposed high Mach number extension (Ref. 1) of Fig. 14. Data from other sources are also included in Fig. 14. The present data again indicate the strong influence of local Mach number on roughness effectiveness, i. e., high values of ϵ denote low roughness effectiveness. It should be noted that sufficient data do not exist to clearly establish the uniqueness of the roughness parameter ϵ variation with Mach number and configuration. Based on previous studies, first-order effects should be adequately represented; however, second-order effects of, say, absolute Reynolds number may be present and not properly accounted for.



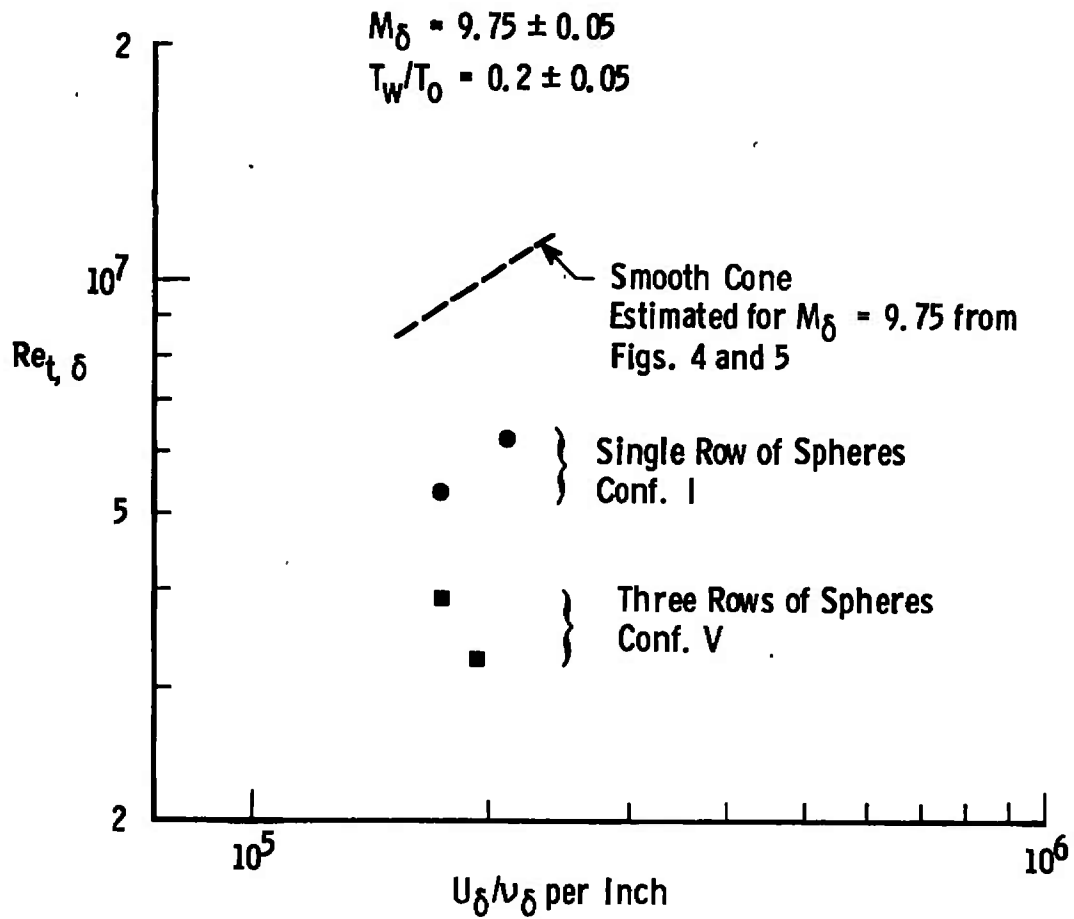
a. Three Rows of Spheres, AFT Location

Fig. 12 Effect of Multiple Rows of Spheres on Heat-Transfer and Pressure Distribution at $M_\infty \approx 14$



b. Three Rows of Spheres—Forward Location

Fig. 12 Concluded



a. $M_\infty \approx 16.00$

Fig. 13 Apparent End of Boundary-Layer Transition for Various Roughness at $M_\infty = 14$ and 16

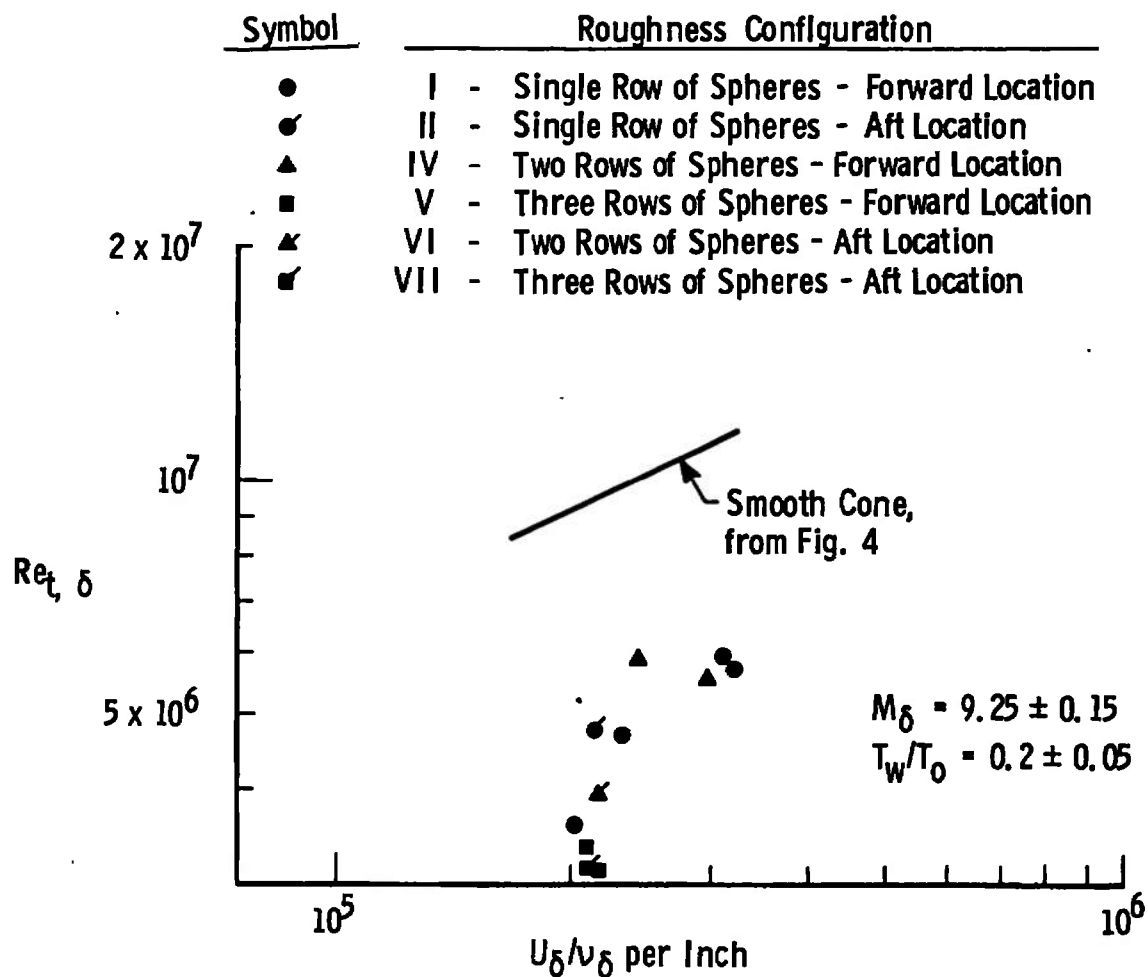
b. $M_{\infty} \approx 14.00$

Fig. 13 Concluded

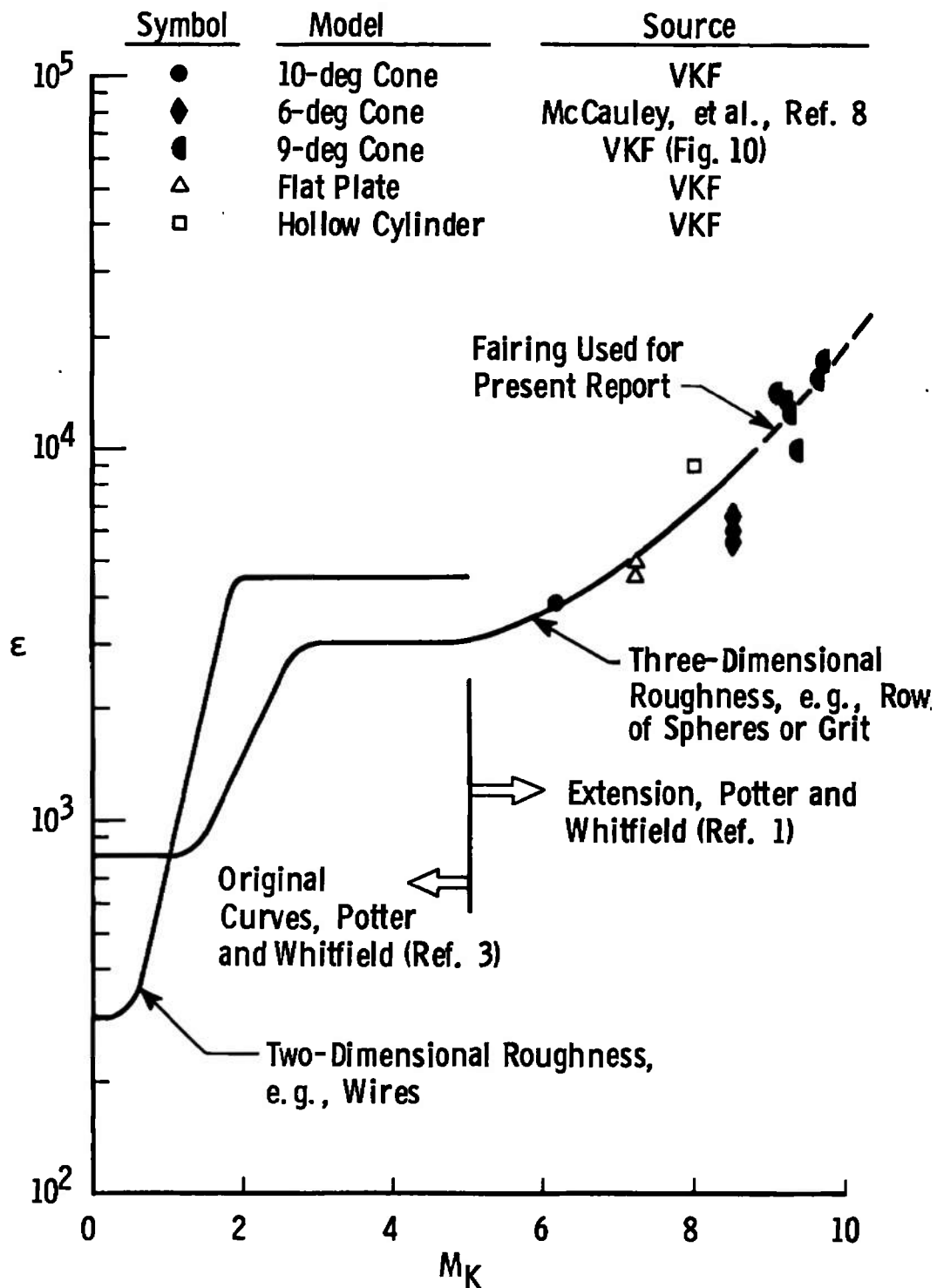


Fig. 14 Comparison of the Present Data with the Extended ϵ Curve for Planar and Axisymmetric Bodies with Negligible Pressure Gradient

The ϵ curve, when used with the correlation curve, $(x_t/x_{t,o})^{1/2} - (Re'_k/\epsilon) (x_k/x_{t,o})^{1/2}$ versus (Re'_k/ϵ) , permits estimates of x_t for planar or axisymmetric flows with zero pressure gradient influenced by roughness. The influence of wall temperature on roughness effectiveness is contained in the Re'_k parameter. It should be noted that the roughness size corresponding to $Re'_k = \epsilon$ or $x_t = x_k$ may be quite large for hypersonic flow; thus the advisability of seeking this limit should be carefully considered. In general, it does not appear practical in locally hypersonic flow fields to seek the limit of $x_t = x_k$. It is further evident that the actual physical dimensions of the roughness elements relative to the boundary-layer and flow-field dimensions must be carefully considered to avoid excessive flow-field distortion (e.g., see Fig. 10). The correlation of roughness effects on transition reveals, of course, nothing in regard to the allowable maximum roughness size relative to the boundary-layer and flow-field dimensions.

Several other criteria for estimating roughness sizes have been published in the literature, e.g., van Driest and Blumer (Ref. 6) and McCauley, Saydah, and Bueche (Ref. 8). These methods offer only an estimate of the "effective" roughness size but do not provide a direct estimate of the transition location to be expected. Subcritical roughness sizes cannot, in general, be treated by these criteria which offer only an estimate of the "effective" roughness size. The correlation of Potter and Whitfield (Refs. 1-3) provides the only method available, to the authors' knowledge, which offers a quantitative estimate of the transition location for a given roughness size.

SECTION IV CONCLUDING REMARKS

Mach number 14 to 16 transition experiments in a high Reynolds number hotshot-type wind tunnel with a sharp 9-deg cone under relatively cold-wall conditions reveal the expected strong influence of Mach number and a unit Reynolds number effect similar to that observed in conventional wind tunnels and recently even in aeroballistic ranges. Comparison of the present data to other wind-tunnel data and aeroballistic range data reveals a confusing picture concerning the relationship of cone and flat-plate transition Reynolds numbers. It is no longer clearly evident that experimental cone transition Reynolds numbers are greater than flat-plate values, even at moderate supersonic Mach numbers. The role of wind-tunnel generated noise (see Pate and Schueler, Ref. 21), and perhaps unknown extraneous effects in aeroballistic range tests is not understood at this time.

The effectiveness of roughness at hypersonic speeds has again been shown to decrease exponentially with increasing Mach number. The present results compare favorably with the hypersonic extension that Potter and Whitfield (Ref. 1) proposed for their original correlation (Ref. 3) and offer an extension to even higher Mach numbers. It is also shown that excessively large roughness elements may serve only to distort the model flow field, even though the correlation would predict boundary-layer tripping should have occurred; thus considerable care must be exercised in utilizing roughness at hypersonic speeds. It is suggested that limit cases, i. e., $x_t = x_k$, will become increasingly less practical as Mach numbers are increased.

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