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REST SEMIANNUAL PROGRESS REPORT
(1 January - 30 June 1968)
Volume III

A SHOCK TUNNEL INVESTIGATION OF HYPERSONIC LAMINAR BOUNDARY LAYER SEPARATION ON A 15-DEGREE CONE AT ANGLE OF ATTACK

(TASK 3.4, THREE-DIMENSIONAL BOUNDARY LAYER EXPERIMENTS)

Prepared by

AVCO GOVERNMENT PRODUCTS GROUP
MISSILE SYSTEMS DIVISION
201 Lowell Street
Wilmington, Massachusetts 01887

AVMSD-0217-68-RM, Vol. III
Contract F04(694)-67-C-0060
CDRL Item 5

July 1968

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SPACE AND MISSILE SYSTEMS ORGANIZATION
DEPUTY FOR REENTRY SYSTEMS
AIR FORCE SYSTEMS COMMAND
Norton Air Force Base, California 92409

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by

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J. A. Luceri, Manager REST Progr[redacted]

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FOREWORD

This report covers work performed during the period 1 January through 30 June 1968 under the Reentry Environment and Systems Technology (REST) Program contract. Avco's participation in this program, described in the REST program plan (AVMSD-0419-66-CR CR Rev. 1), includes theoretical, analytical and experimental study tasks in the general areas of aerophysics, observables and materials.

This semiannual progress report is comprised of the following Avco documents:

AVMSD-0217-68-RM Vol. I	Displacement and Flow Separation on Cones at Incidence to a Hypersonic Stream
AVMSD-0217-68-RM Vol. II	Kinetics and Thermochemistry of Sulfur Hexafluoride Decomposition.
AVMSD-0217-68-RM Vol. III	A Shock Tunnel Investigation of Hypersonic Laminar Boundary Layer Separation on a 15-Degree Cone at Angle of Attack

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This technical report has been reviewed and is approved.

Lt. T. Graham, REST Project Officer
SMYSE
Air Force Systems Command
Norton Air Force Base, California

ABSTRACT

A shock tunnel investigation of the pressure and heat transfer distributions on sharp and blunted 15-degree half angle cones at angle of attack was conducted. The test conditions were $M_\infty = 13.5$ and $Re_\infty /ft. = 1.5 \times 10^6$. Separation on a sharp cone with increasing angle of attack is a gradual process which is characterized by increasing heat transfer rates while the pressure is decreasing. The two base geometries tested (flat and spherical) indicated that separation was not influenced to a significant degree by base geometry. Limited experiments with X/R_N in the range of 13.5 to 27.5 indicated that bluntness did not significantly affect separation in this range of X/R_N. When X/R_N was in the range of 2.1 to 6.4 there was no indication of separation at angles of attack up to 18 degrees.

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J. F. Dempsey

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance obtained from his colleagues, and in particular the helpful discussions and suggestions of Dr. A. Burke (Manager, Fluid Physics Department), Dr. T. Fannelop (Chief, Gasdynamics Research Section) and A. Todisco. A special thanks is due S. Fuller for his efforts and skill in conducting the shock tunnel experiments.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

M_∞	=	freestream Mach number
P_∞	=	freestream pressure
P_b	=	base pressure
q	=	heat transfer rate
$q_{\alpha=0}$	=	heat transfer rate for the sharp cone at zero angle of attack
Re_∞	=	Reynolds number based on freestream conditions
$Re_{\infty L}$	=	Reynolds number based on freestream conditions and the model length
R_N	=	nose radius
X	=	distance along the cone surface, starting from tip or stagnation point
α	=	angle of attack
θ_c	=	cone half angle
ϕ	=	cone meridian angle. Based upon a head-on view and starting with the windward meridian

1.0 INTRODUCTION

The motivation for these experiments resulted from certain analytical studies of the three-dimensional boundary layer on blunted cones by Fannelop[1]. The approximate inviscid methods considered in Ref. 1 predict a favorable circumferential pressure gradient in the leeward region of the cone at angles of attack for which separation would be expected ($\alpha \geqq \theta_c$). Therefore, the mechanism to which separation could be attributed was not clear. It was thought possible that disturbances from the near wake could propagate upstream and influence the separation process. One way to explore possible base influence was to check the effect of varying base geometry. This would alter the character of the flow in the near wake and the manner in which the base pressure affects the boundary layer at the aft end of the cone.

An experimental program using a conical model was formulated, having the following primary objectives:

1) to determine if incipient separation is influenced to a significant degree by base geometry, and,

2) to obtain pressure and heat transfer rate distributions at various angles of attack.

2.0 MODEL, INSTRUMENTATION AND TEST FACILITY

2.1 MODEL

The model was a 15-degree half angle cone with several nose and base configurations. One nose attachment was sharp and the other two were spherically blunt with radii of 0.25 and 0.84 inch. The blunt cone configurations provided data with bluntness ratio's (X/R_n) in the range of 13.5 to 27.5 and 2.1 to 6.4, respectively. The base attachments were flat and spherical with a maximum diameter of 4.5 inches (see Figure 1). The model could be positioned at angles of attack between 0 and 22 degrees. The cone was supported by a strut on the windward meridian close to the base. The strut was of minimum size, consistent with the load and instrumentation lead wire requirements.

The cone meridian angle (ϕ) is measured in a clockwise direction based on a head-on view, with the windward meridian being designated $\phi = 0$.

2.2 INSTRUMENTATION

The model was instrumented with pressure and heat transfer gages. The pressure gages were peizoelectric transducers with a response time of a fraction of a millisecond and an operating range of about 0.005 to 100 psia. The transducers are described in detail in Ref. 2. The heat transfer gages are the conventional thin film platinum resistance thermometer type gages [3,4].

2.3 TEST FACILITY

The experiments were conducted in the Avco 20-inch shock tunnel at a Mach number of 13.5 and a free stream Reynolds number per foot of 1.5×10^6. The 20-inch shock tunnel is described in Ref. 5 and additional tunnel calibration data were presented in Ref. 6. The Mach number variations, both radially and axially, were less than $\pm$ 5 percent.

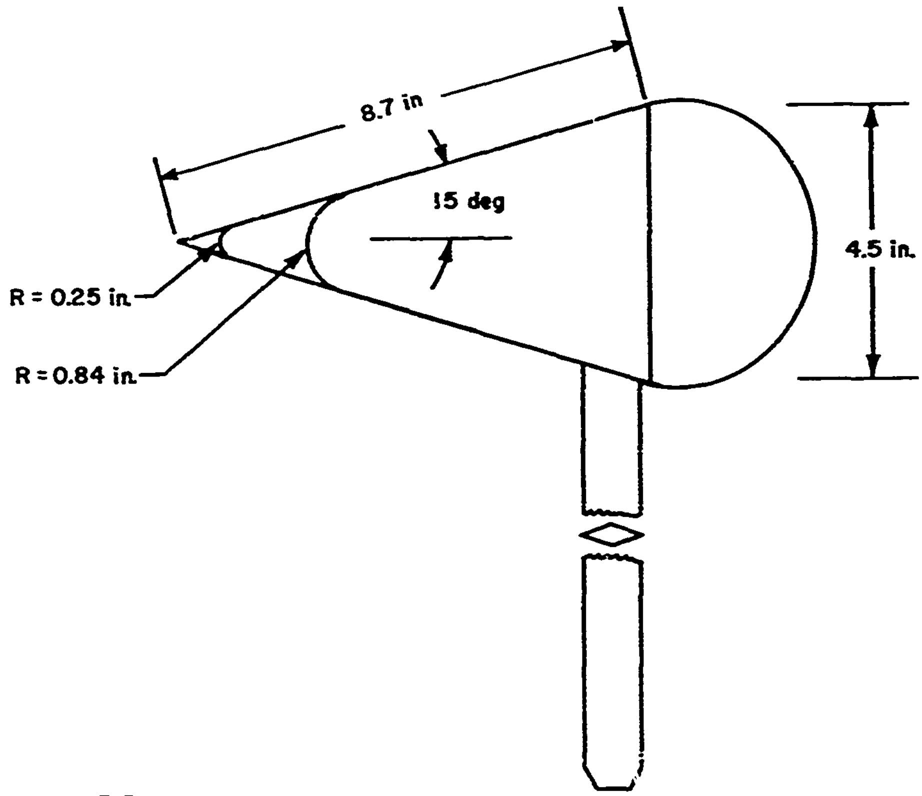

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Figure 1 SKETCH OF 15-DEGREE CONICAL MODEL

3.0 TEST RESULTS

3.1 STRUT INTERFERENCE EFFECTS AND BASE PRESSURE DATA

Strut interference on the near wake was of concern from the onset of the program and for this reason a determination was desired early in the program of whether or not the base pressures obtained were reasonable. To make such a determination, compatible with the scope of the program, the base pressure evaluation was accomplished by a comparison with other experimental data. The results of Softley and Graber[7] were useful in this regard. In Ref. 7 high Mach number base pressure data were obtained and the effect of support interference investigated. Shock tunnel base pressure data were obtained from "free-flying" models and models supported by fine threads (0.001-to 0.002-inch diameter) and small diameter wires (0.016-inch diameter). Figure 2 compares the base pressure data obtained in the present study (strut mounted model) with those of Softley and Graber. Also shown are base pressure results from other facilities obtained at lower Mach numbers. Keeping in mind the differences in cone angles (a higher base pressure would be expected with the larger cone angle[11]), it was concluded that the strut mounting did not strongly influence the base pressure.

Figure 3 presents the base pressure results, for the various configurations, as a function of angle of attack. The base pressure data shown for the flat base was obtained at a radial location 65 percent of the base radius in the plane of the leeward meridian. A limited amount of data was obtained at a location of 30 percent of the base radius, also in the plane of the leeward meridian. The pressure at this location was observed to follow similar trends, at a slightly higher magnitude. On the spherical base the pressure gage was located one-half inch above the model centerline in the plane of the leeward meridian. The base pressure would be expected to increase with angle of attack and with nose bluntness; however, the increases found could also include the effect of support interference.

The possibility of cone pressures being independent of base pressure even when the boundary layer has separated on the cone is significant and will be elaborated upon briefly before presenting further experimental results. As the angle of attack of a sharp cone approaches its half angle, one would expect the pressure on the leeward meridian to approach the free stream pressure (p_∞)*. At supersonic Mach numbers the cone base pressure is significantly below free stream pressure (see Figure 2). This means that at supersonic Mach numbers a cone can be at large angles of attack and maintain leeward pressures considerably larger than base pressure. The experiments of Tracy[10] are an example of such a condition. For his experiments at a Mach number of 8, the leeward meridian pressure was always larger than the base pressure, even when the angle of attack was over twice the cone half angle. This is analogous to the case of an infinitely long cone. For the hypersonic case a significant difference may occur. The base pressure can be larger than the free stream pressure and therefore, as the sharp cone approaches an angle of attack equal to its half angle the leeward pressure approaches the base pressure level. The difference between the supersonic and hypersonic case is shown schematically in Figure 4. It is possible then, that in the hypersonic case the base pressure may directly influence separation. It is therefore sug-

*For example, inviscid solutions of flow over a cone at angle of attack (e.g., Gonidou[12]) produce this result.

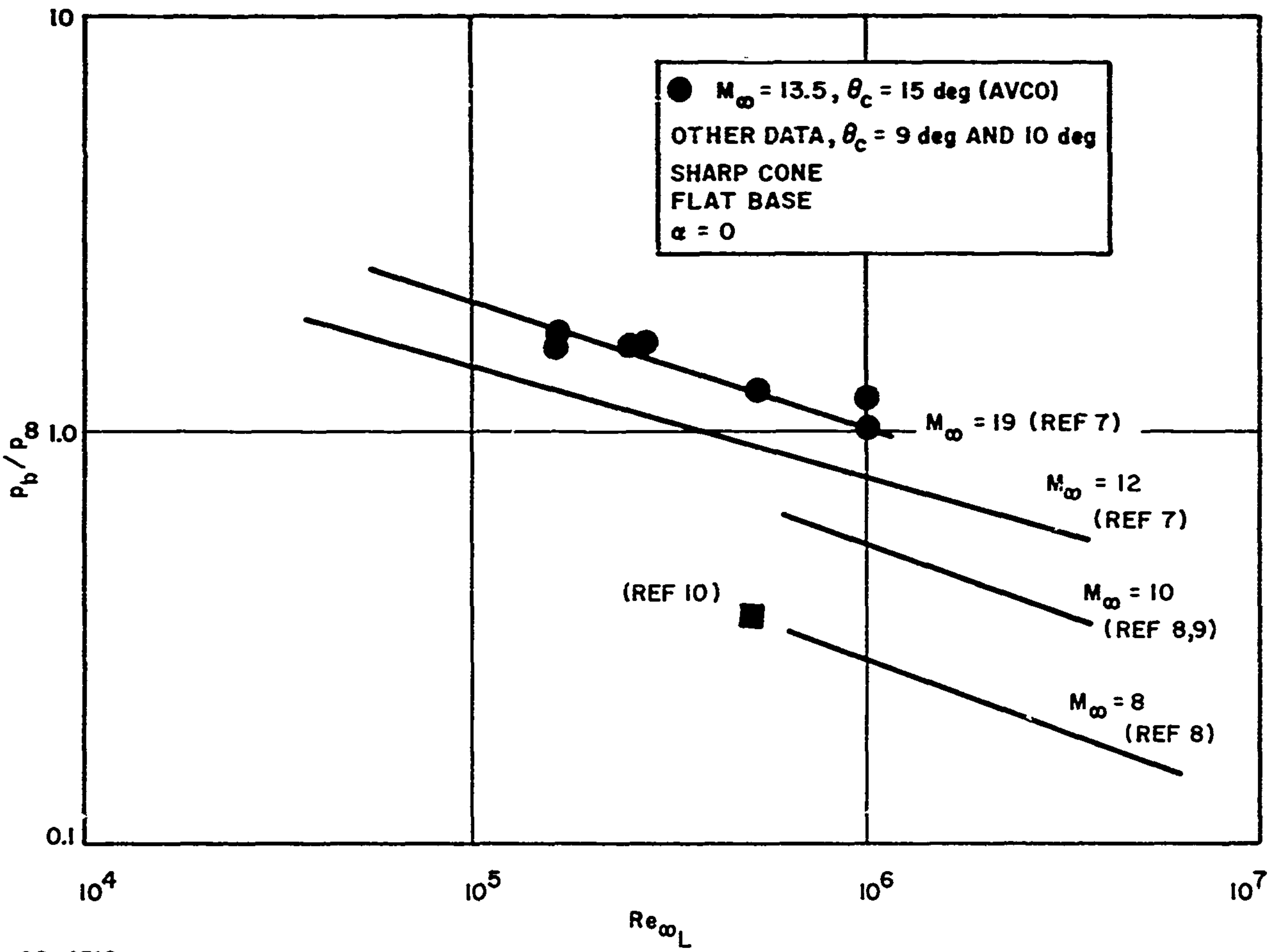

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Figure 2 SHARP CONE BASE PRESSURE COMPARISON

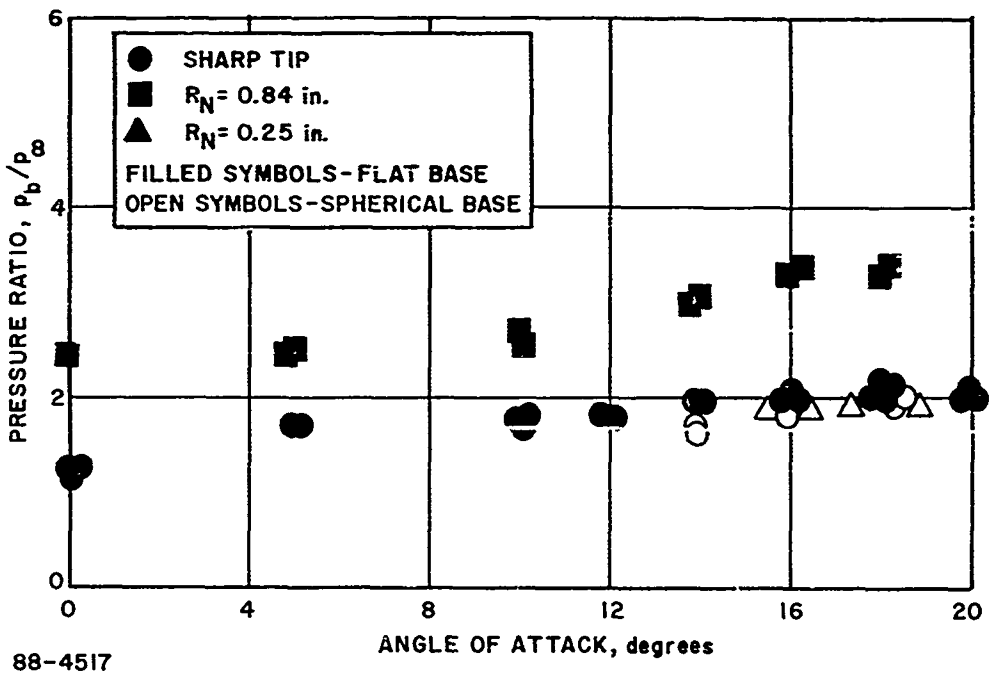

Figure 3 BASE PRESSURE VERSUS ANGLE OF ATTACK

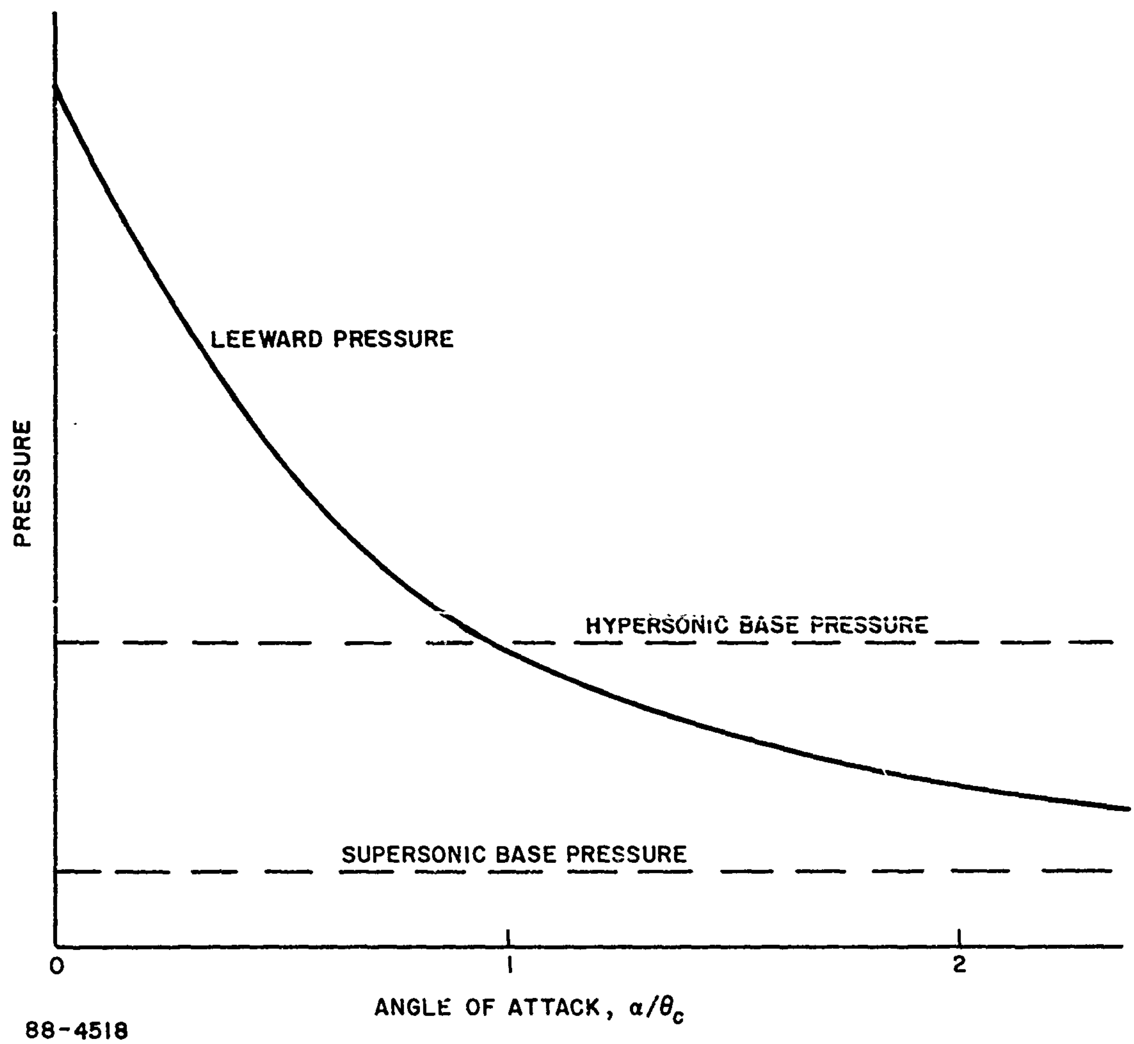

Figure 4 SCHEMATIC REPRESENTATION OF LEEWARD AND BASE PRESSURES

gested that the reader keep in mind the appropriate base pressure level when examining the cone pressure distributions of this investigation.

3.2 PRESSURE DATA

Figures 5 through 12 present the experimental measurements of cone pressure as a function of angle of attack for the various configurations tested. The pressures are nondimensionalized using the freestream pressure. The results on the windward side on the sharp cone are found to agree well with Newtonian theory throughout the angle of attack range tested. Pressures on the leeward side of the sharp cone agree with Newtonian theory at small angles of attack, but as the angle of attack approaches the cone half angle, the rate of change of the leeward pressure with angle diminishes, resulting in pressures of a larger magnitude than would be predicted by inviscid theory. Separation would intuitively be expected at an angle of attack in the neighborhood of the cone half angle. The pressure changes (for a given meridian location) through this angle of attack range are very gradual and in some cases the pressure was essentially constant. Such a pressure history would indicate that incipient separation on a sharp cone did not greatly change the inviscid flow from the unseparated case.

The blunt cone (R_N = 0.84 inch) pressure at zero angle of attack was less than the sharp cone value, which is characteristic of the overexpansion on a blunt cone (see, for example, Ref. 13). In the leeward region of the blunt cone the minimum pressure location would move downstream with an increase in angle of attack. If the effective cone half angle on the leeward meridian is considered to be $\theta_c - \alpha$ (for small α), then inviscid theory and experiment[13] would indicate the blunt and sharp cone pressures should be equal at approximately 5 degrees angle of attack. As the angle of attack increased over 5 degrees the blunt cone pressures would be larger than the sharp cone values. The experimental results of this investigation followed such a trend.

Data at 14, 16 and 18 degrees angle of attack were taken for a 0.25-inch nose radius. It was found that the pressure levels were equal to the sharp cone results, indicating no effect of small nose bluntness at large angles of attack. This result would suggest that for these angles of attack the leeward pressure is dominated by crossflow effects when X/R_N is large. Boundary layer transition results [14] on both the windward and leeward meridians of a blunt cone at angle of attack indicated a similar independence of nose radius as the cone approached an angle of attack equal to the cone half angle. Since boundary layer transition is dependent upon boundary layer history, these results would indicate the leeward boundary layers at large angles of attack are not significantly influenced by small nose bluntness, but are dominated by the crossflow.

Cone pressures with the spherical base were found to be the same as those with a flat base. It was therefore concluded that for these experiments base geometry did not have a significant effect upon separation. This conclusion is not meant to be interpreted, however, as an indication of no communication between base and leeward regions.

From the point of view of incipient separation the pressure data is more informative when viewed as a summary plot in terms of circumferential angle. Figure 13 presents the sharp cone data in such a manner. The pressure curves have been

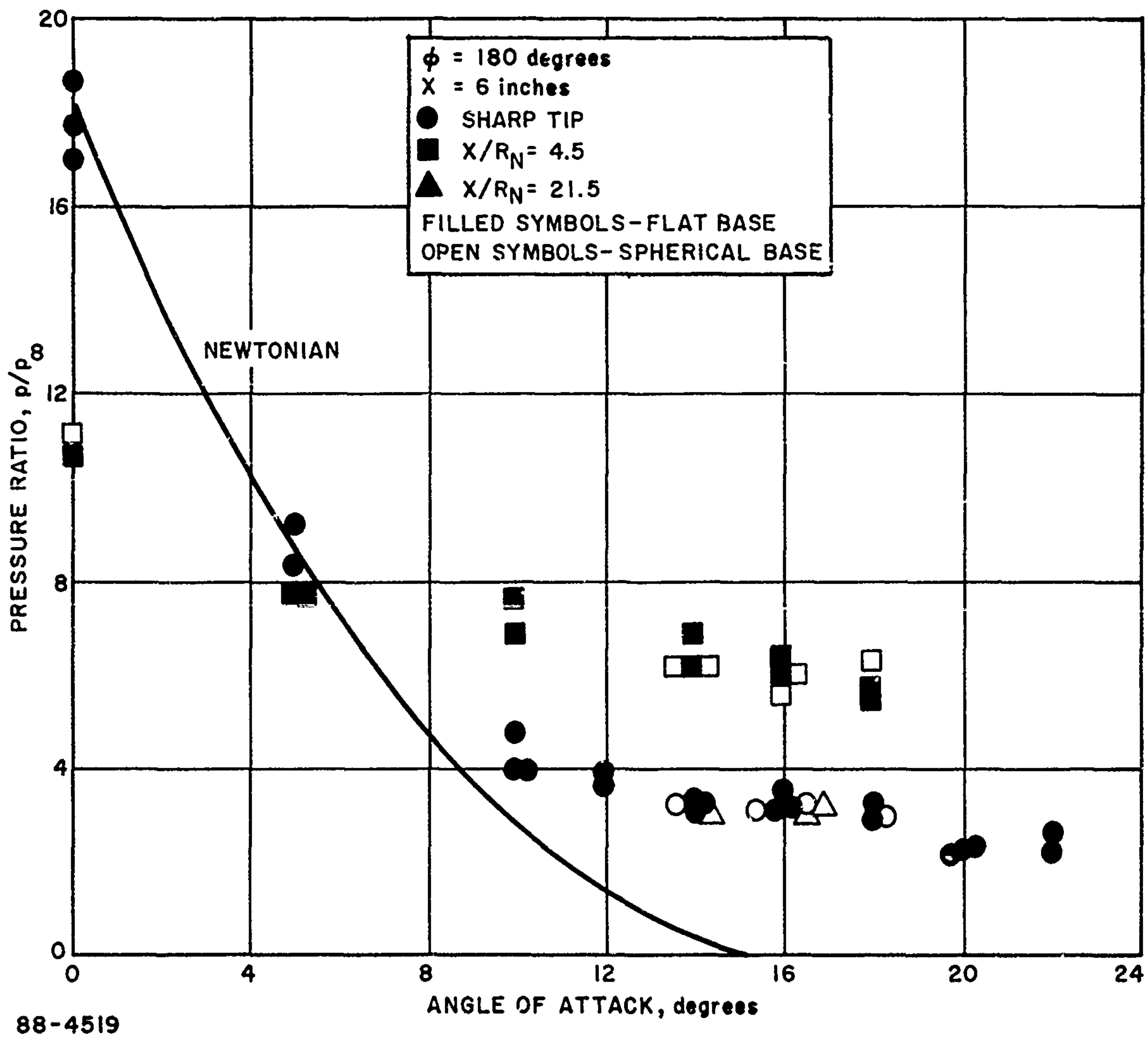

Figure 5 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 6 INCHES AND ϕ = 180 DEGREES

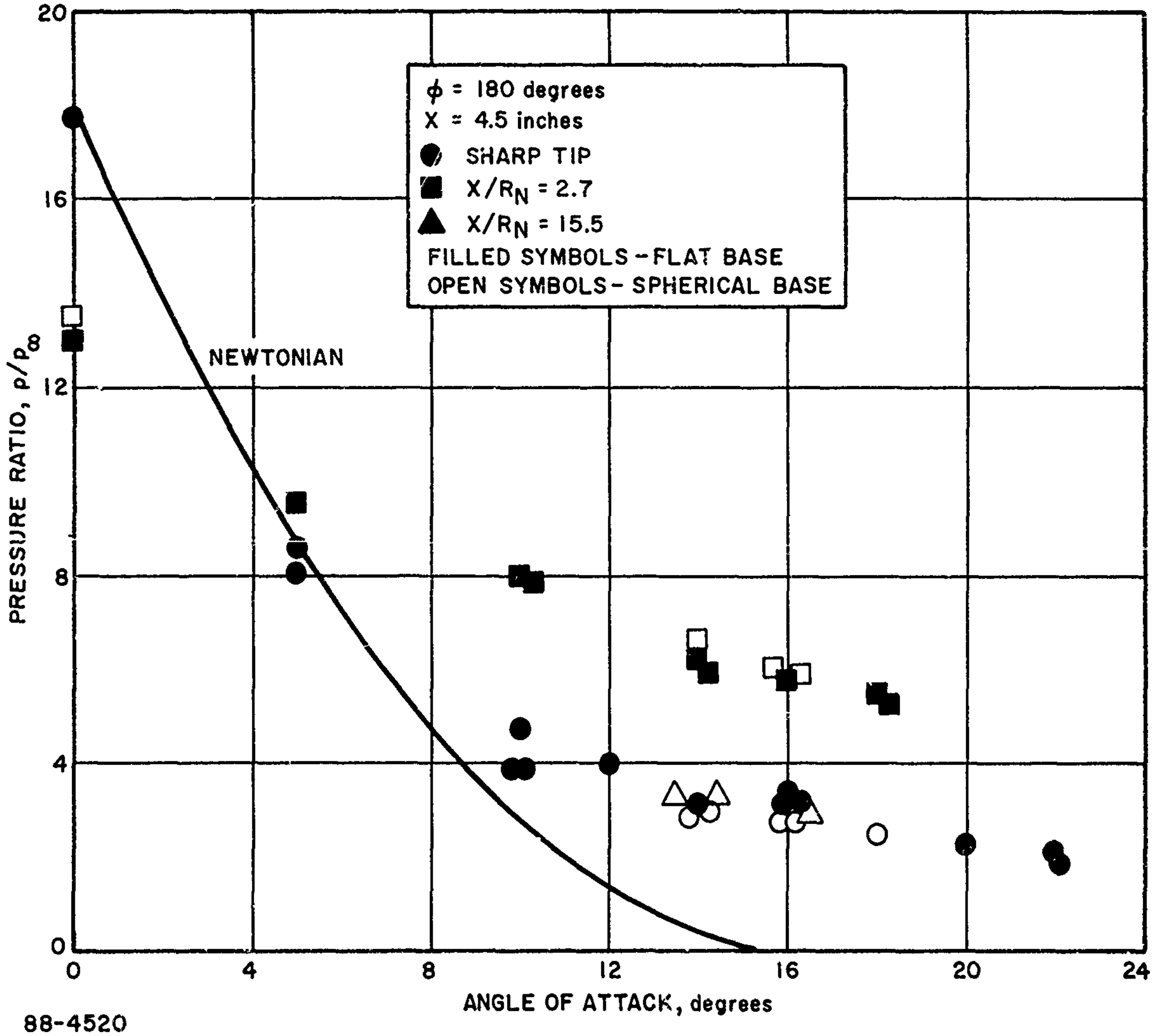

Figure 6 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 4.5 INCHES AND ϕ = 180 DEGREES

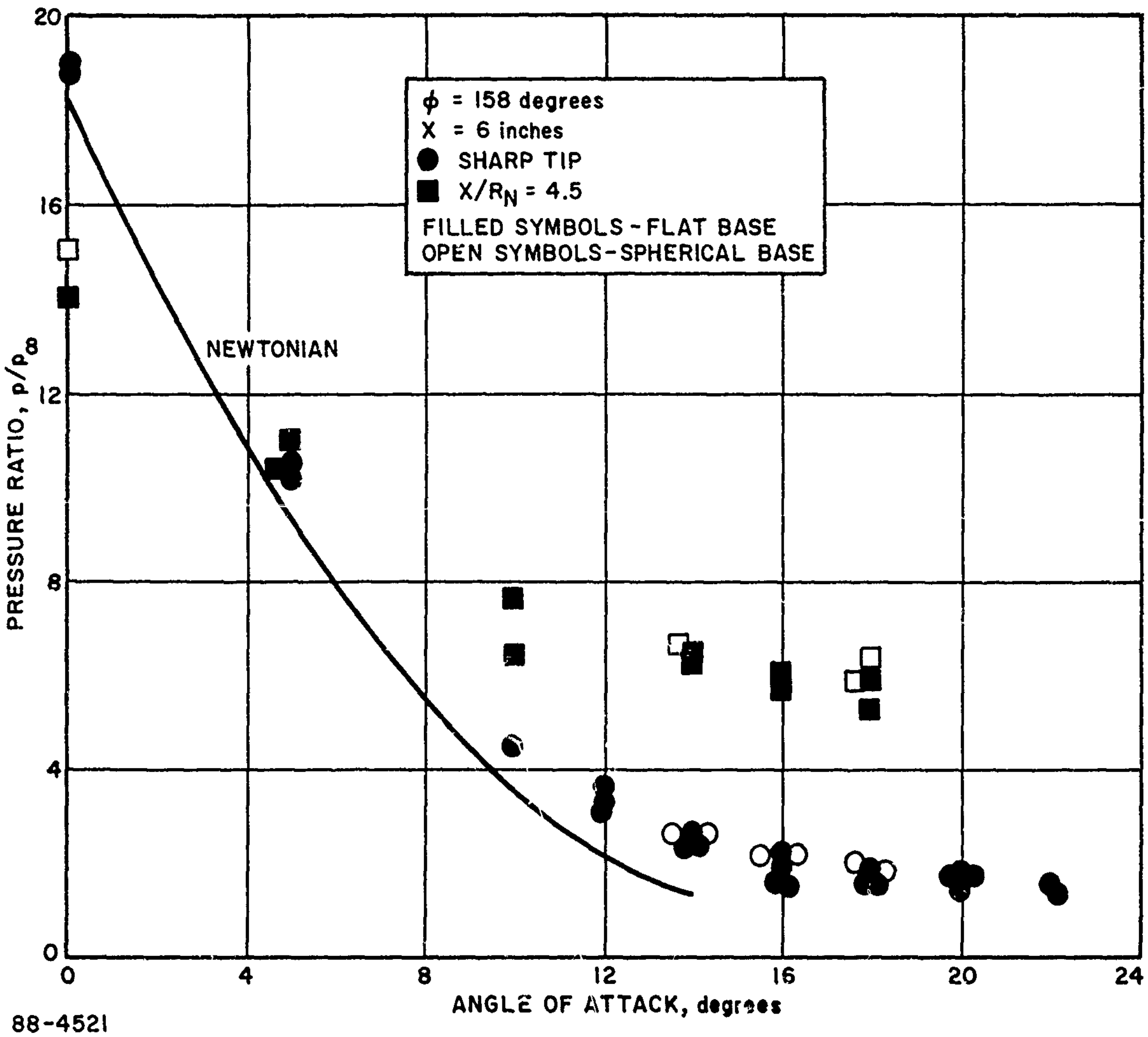

Figure 7 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 6 INCHES AND ϕ = 158 DEGREES

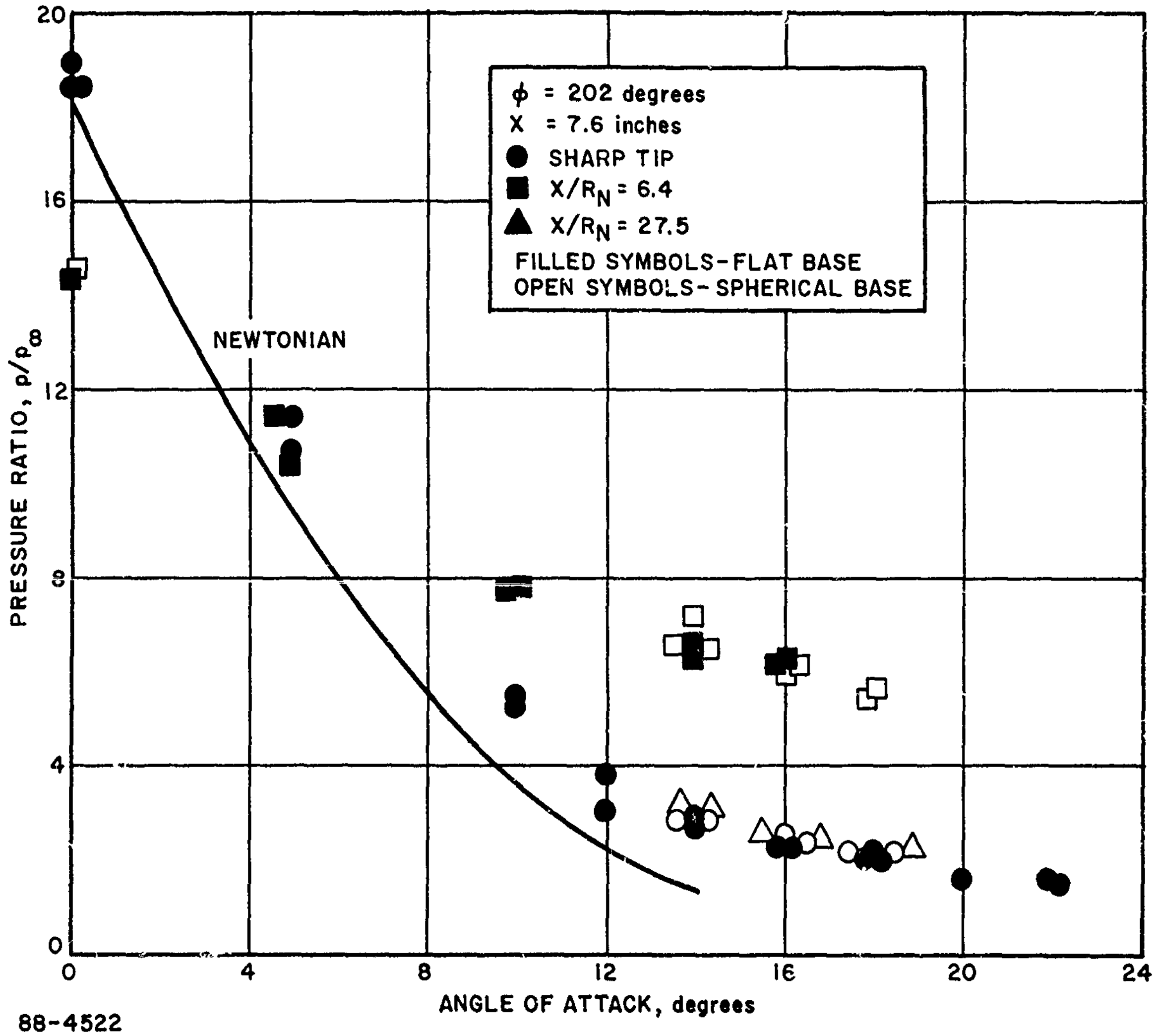

Figure 8 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 7.6 INCHES AND ϕ = 202 DEGREES

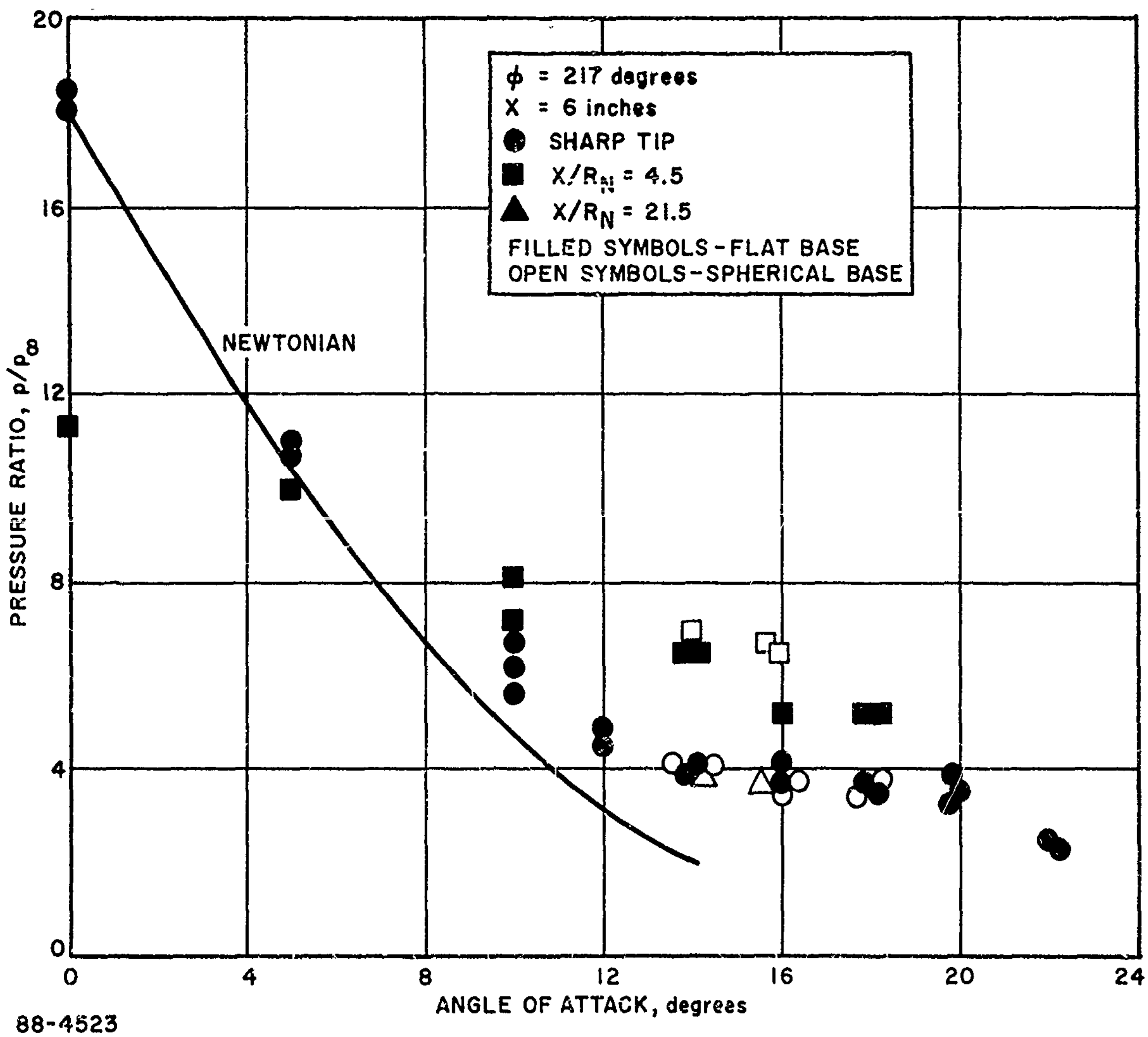

Figure 9 PRESSURE VERSUS ANGLE AT ATTACK FOR X = 6 INCHES AND ϕ = 217 DEGREES

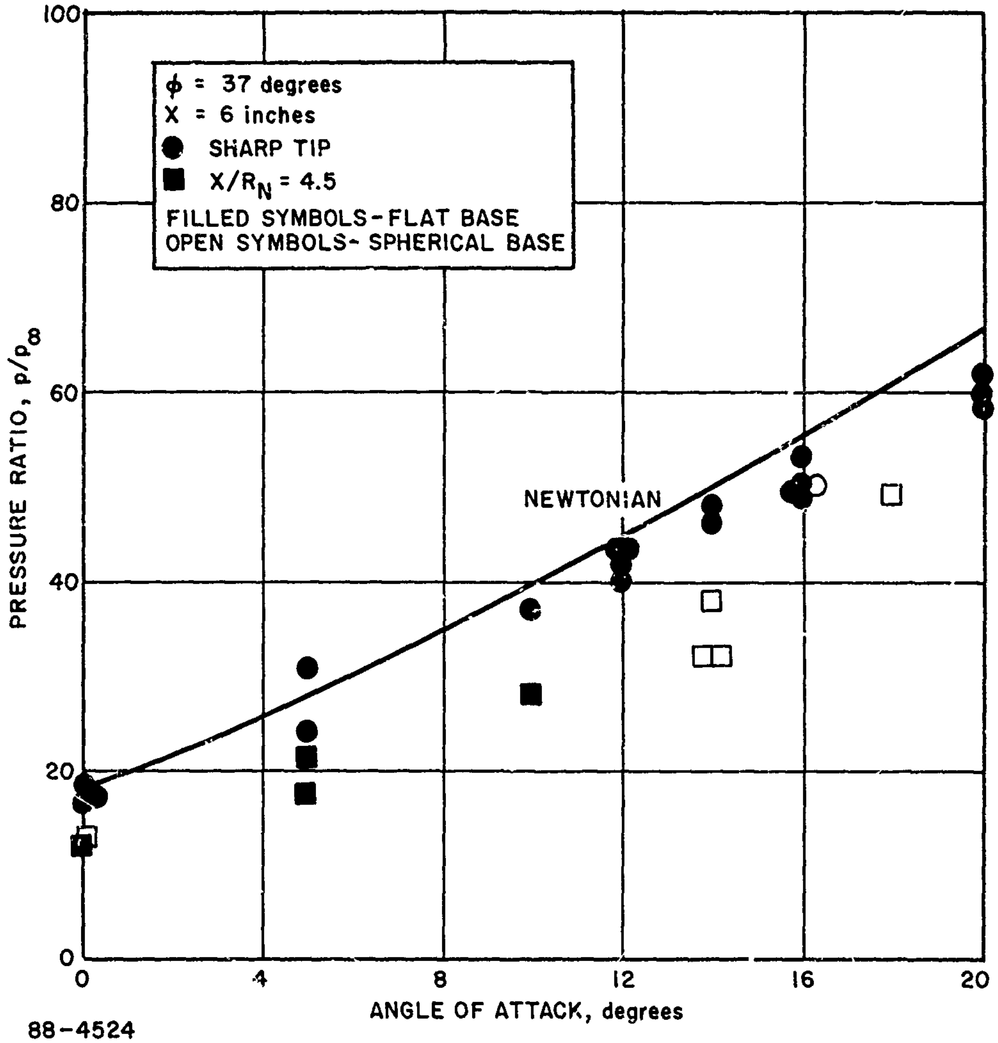

Figure 10 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 6 INCHES AND ϕ = 37 DEGREES

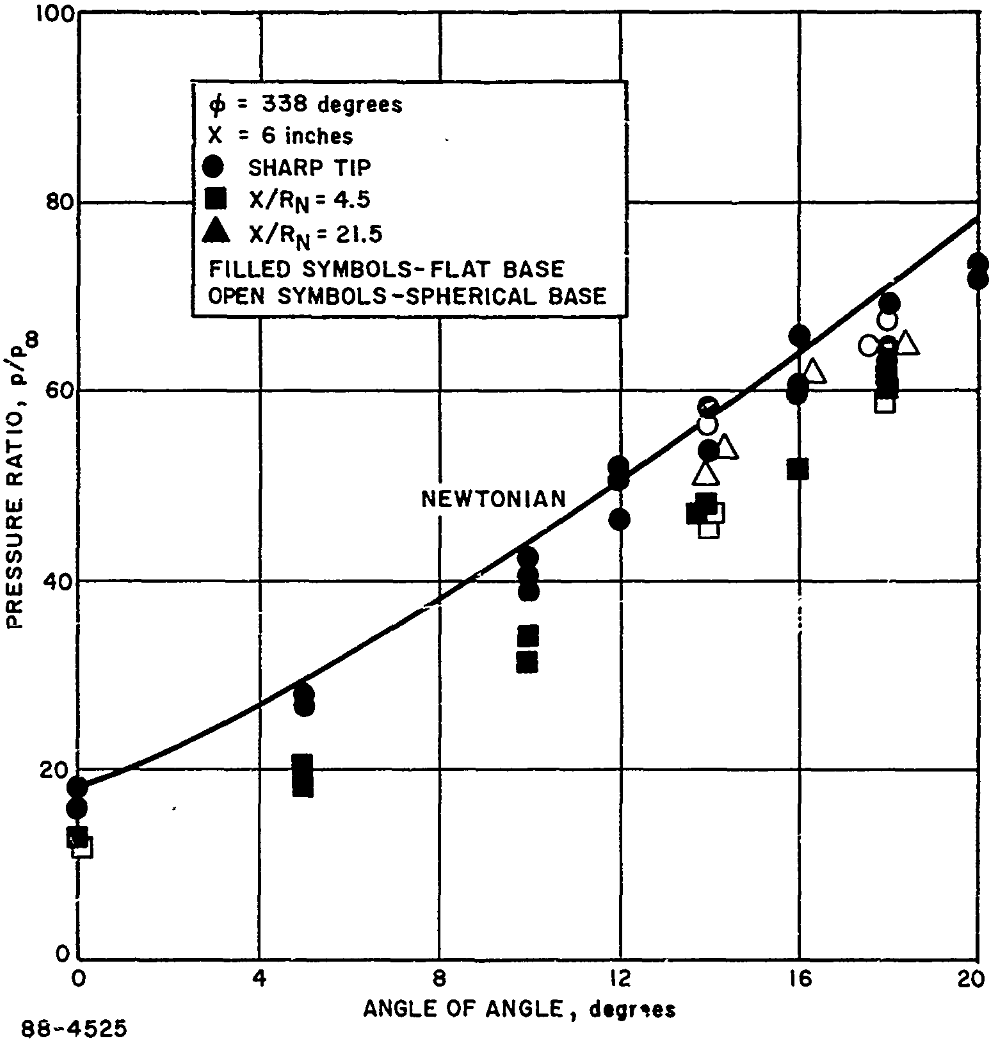

Figure 11 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 6 INCHES AND ϕ = 338 DEGREES

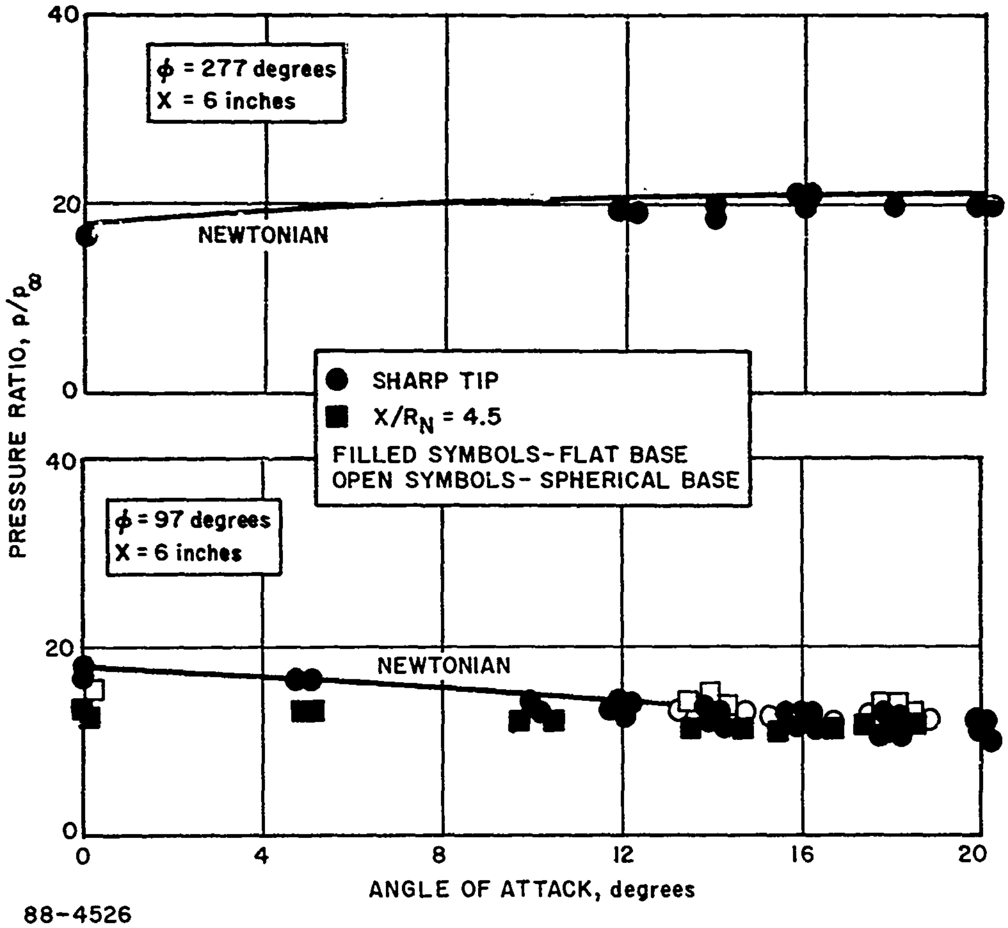

Figure 12 PRESSURE VERSUS ANGLE OF ATTACK FOR X = 6 INCHES AND ϕ = 277 DEGREES AND 97 DEGREES

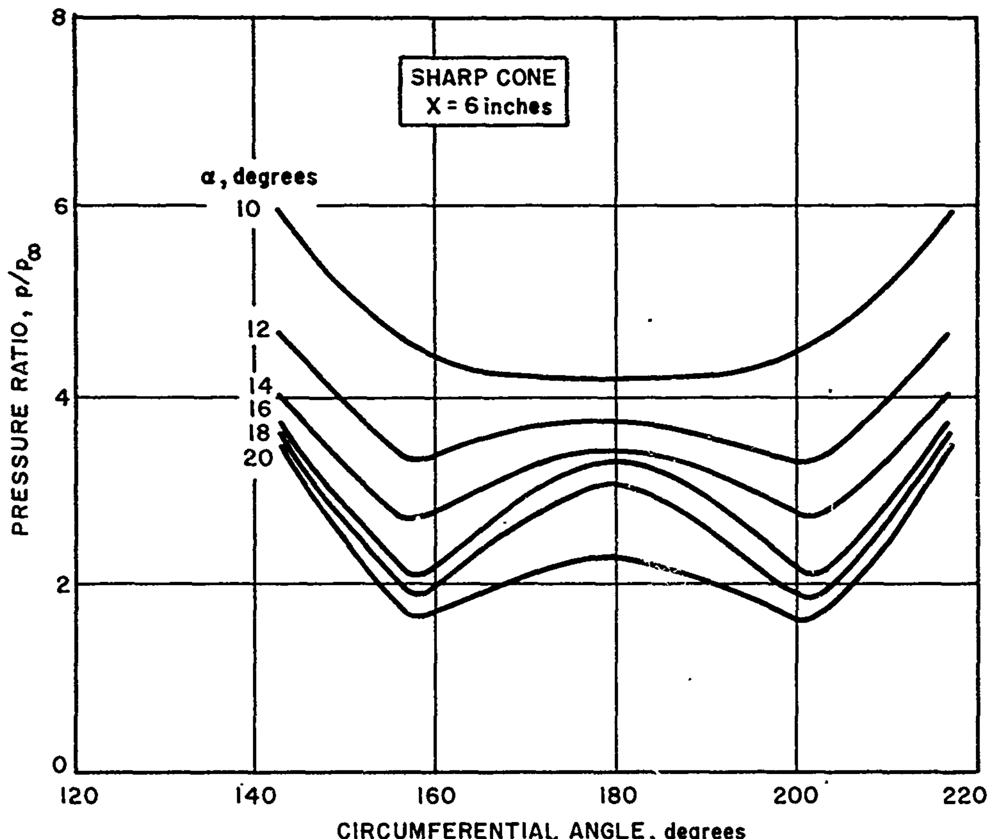

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Figure 13 SHARP CONE PRESSURE VERSUS CIRCUMFERENTIAL ANGLE drawn from data on three meridians, and therefore are an approximate representation of the pressure variations. The trends are clearly evident; however, the circumferential angle at which minimum pressure occurred can only be approximated. A small adverse pressure gradient was observed at an angle of attack of 12 degrees, with symmetric minimum pressure locations off the leeward meridian. As the angle of attack was increased, the adverse gradient increased. At angles of attack less than the cone half angle of 15 degrees, the entire leeward region of the cone maintained pressures larger than the base pressure. At α = 16 degrees the minimum pressure dropped to base pressure level, while the leeward meridian pressure remained significantly larger than base pressure. At α = 20 degrees the minimum cone pressure was below base pressure level and the leeward meridian pressure was approximately equal to base pressure.

Tracy[10] and Rainbird[15,16] have obtained cone pressure data at large angles of attack at lower Mach numbers. Their data have the same general features as those in Figure 13. Also, a comparison of cone leeward pressure at large angles of attack with cylinder base pressure results[17] suggests a similarity between the two flow situations.

From the data obtained in this investigation it was not possible to determine accurately the angle of attack at which incipient separation occurred or the nature of the separation phenomenon. However, the fact that incipient separation is a gradual process, occurring without any significant pressure perturbation means that knowledge of the precise angle of attack at which three-dimensional incipient separation occurs is more of an academic problem than an engineering problem.

A summary of the pressures on the leeward region of the blunt cone (X/R_N = 4.5) is presented in Figure 14. The leeward pressures were found to vary only slightly with angle of attack and with circumferential angle. As the angle of attack exceeded the cone half angle, the data indicated the presence of a small adverse pressure gradient. Since the pressure differences involved were within the experimental scatter the existence of the adverse gradient remains questionable. This point is inconsequential, however, since an adverse gradient of this magnitude would probably be insignificant in regard to separation.

These present results are consistent with one of the three-dimensional separation models identified by Maskell[18] and observed experimentally by Ceresuela, Kretzschmar, and Rehback[19]. In this case the separation line originates from a saddle point on the leeward generator and the separated layer encloses a "bubble". A pictorial representation of this separation pattern is shown in Figure 15. Upstream of the separation bubble the flow is nose-dominated whereas at large X/R_N (within the separation bubble) the flow is crossflow dominated, as it is on the sharp cone. With this type of separation occurring it would then appear unlikely that separation would be observed in the present investigations at X/R_N = 4.5 and angles of attack up to 18 degrees.

3.3 HEAT TRANSFER DATA

Figures 16 and 17 present heat transfer rates in the leeward region of the sharp cone as a function of angle of attack. The leeward meridian heat transfer rates reached a minimum at angles of attack of 12 to 14 degrees, and then increased with further increases in angle of attack. It is interesting to note that between

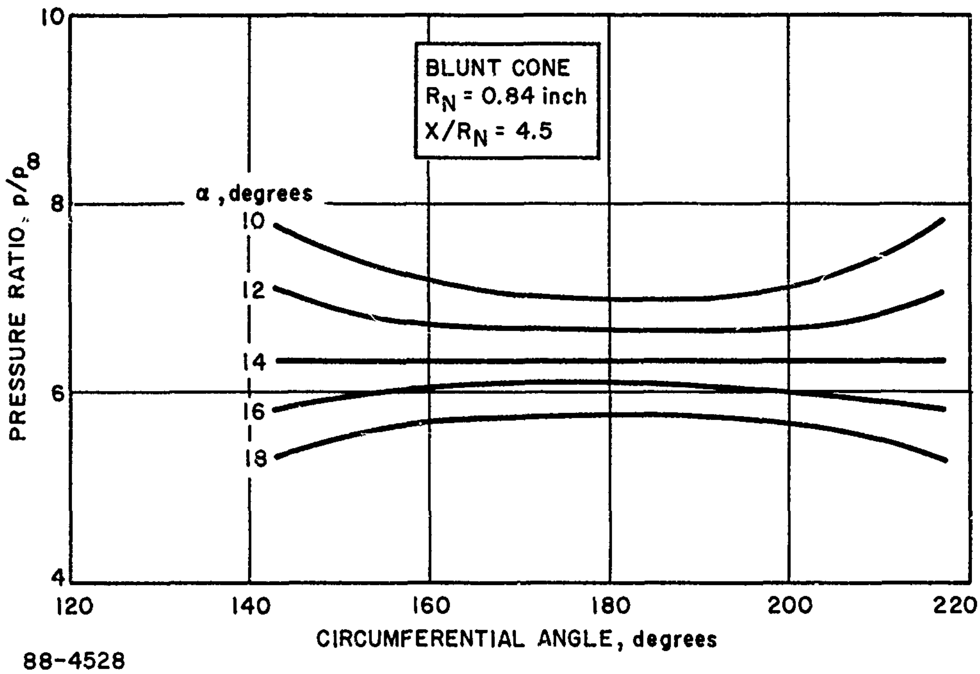

Figure 14 BLUNT CONE PRESSURE VERSUS CIRCUMFERENTIAL ANGLE

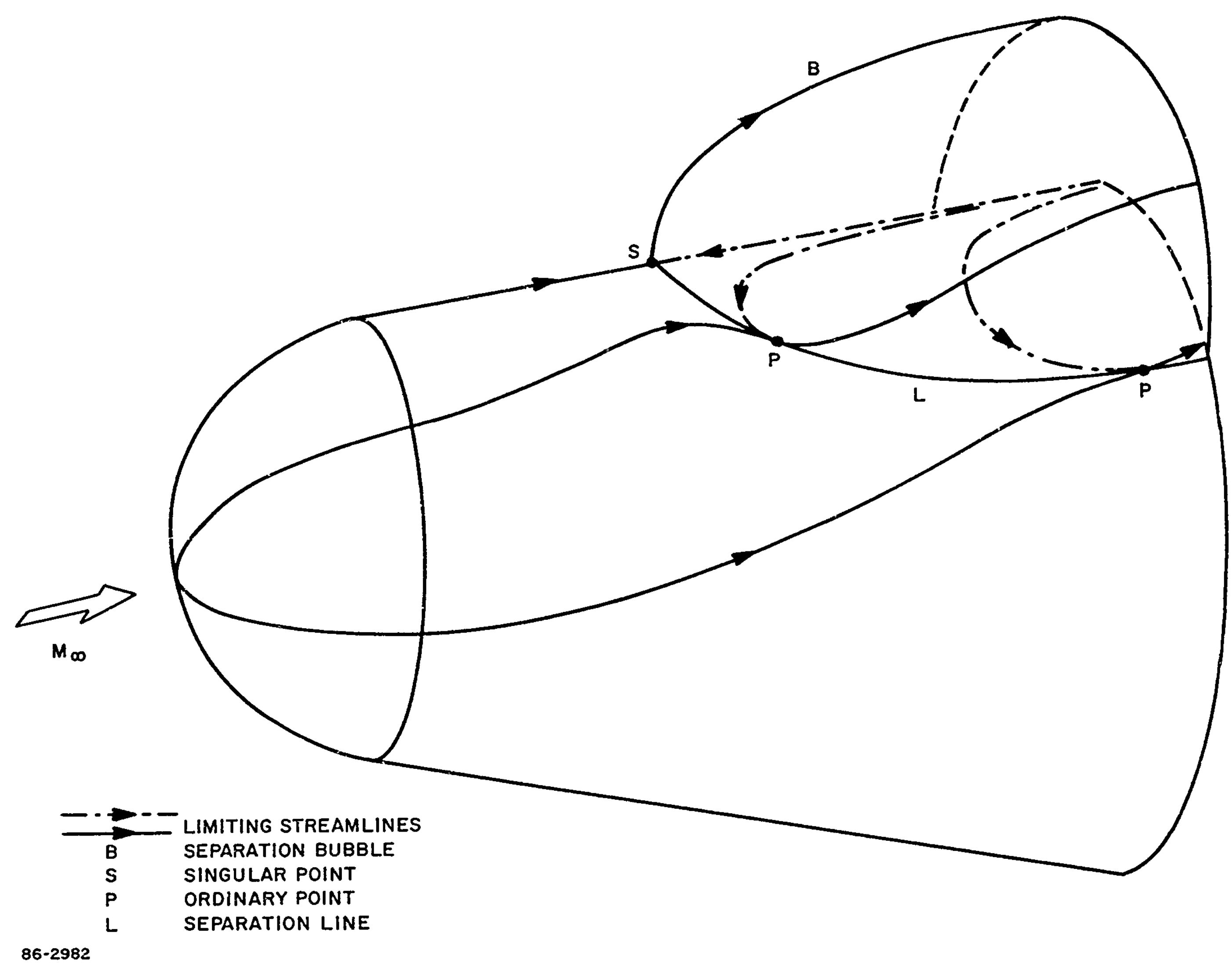

Figure 15 HYPOTHETICAL LIMITING STREAMLINES AND SEPARATION BUBBLE FOR FLOW AT LARGE INCIDENCE TO A BLUNTED CONE (FROM REF. 1)

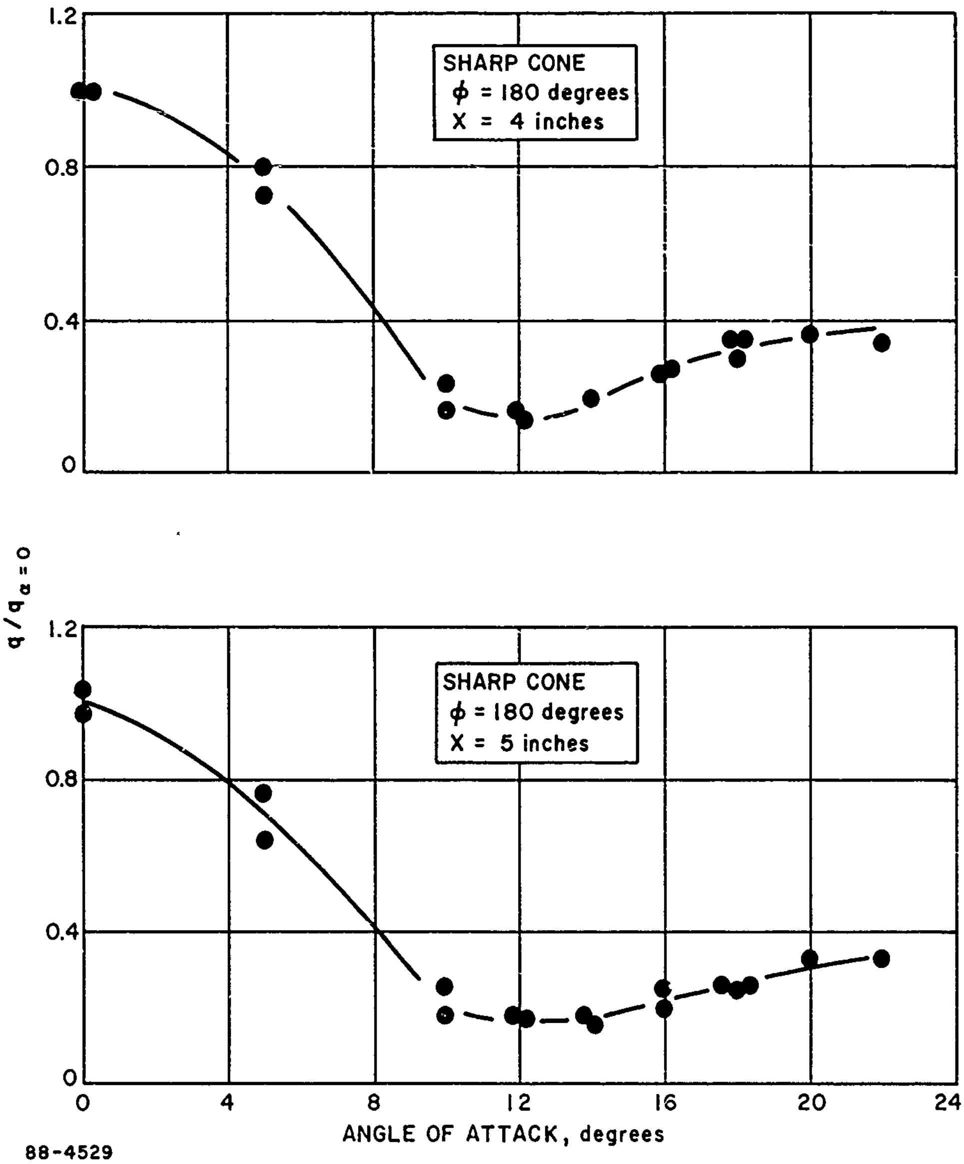

Figure 16 HEAT TRANSFER VERSUS ANGLE OF ATTACK FOR ϕ = 180 DEGREES

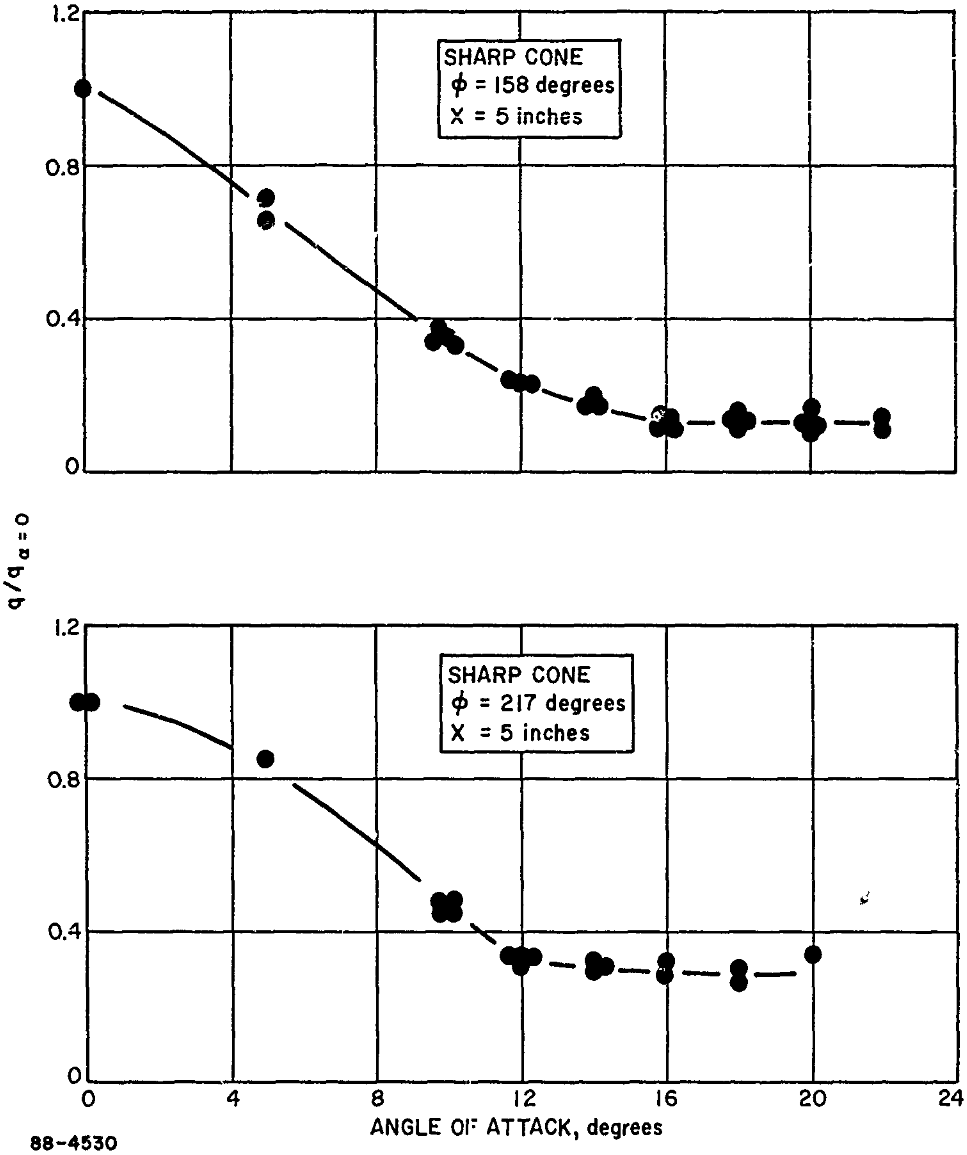

Figure 17 HEAT TRANSFER VERSUS ANGLE OF ATTACK FOR ϕ = 158 DEGREES AND 217 DEGREES

the angles of attack of 14 and 20 degrees, the heat transfer rate is increasing while the pressure is decreasing. This is apparently a characteristic of separated flow over a sharp cone. This same feature has been observed by Tracy[10]. The heat transfer rates on the 158-degree and 217-degree meridians maintained essentially constant value at the high angles of attack. Figure 18 contains data obtained for the blunt nose configuration at $X/R_N = 3.3$. The heat transfer rates are referenced to the zero angle of attack sharp cone angle. At angles of attack in the vicinity of the cone half angle, the heat transfer rates were insensitive to angle of attack changes.

Figure 19 contains a summary of the heat transfer rate results. These curves were constructed from data obtained on meridians of 158, 180 and 217 degrees, as was the pressure data, therefore some arbitrariness was necessary in the shape of the curves. Characteristic changes in the sharp cone heat transfer rate data, which are apparently associated with separation, are evident, as was the case with the pressure data. However, those features of the heat transfer data lag the corresponding pressure data features by 2 or 3 degrees angle of attack. For example, at a 12-degree angle of attack the minimum heat transfer rate was at the leeward meridian, whereas the pressure data already indicated an adverse pressure gradient for this angle of attack. A significant difference in the heat transfer and pressure results can be seen at angles of attack greater than the half angle. The heat transfer rate proceeded to increase as the pressure decreased, until at $\alpha = 20$ degrees the heat transfer rate on the leeward meridian was over 30 percent of the zero-angle-of-attack value.

Figure 19b contains a summary of the blunt cone heat transfer rate results. It can be seen that the heat transfer rates in the leeward region of the blunt cone were insensitive to angle of attack between $\alpha = 10$ and 18 degrees. At $\alpha = 18$ degrees there was still no indication of separation.

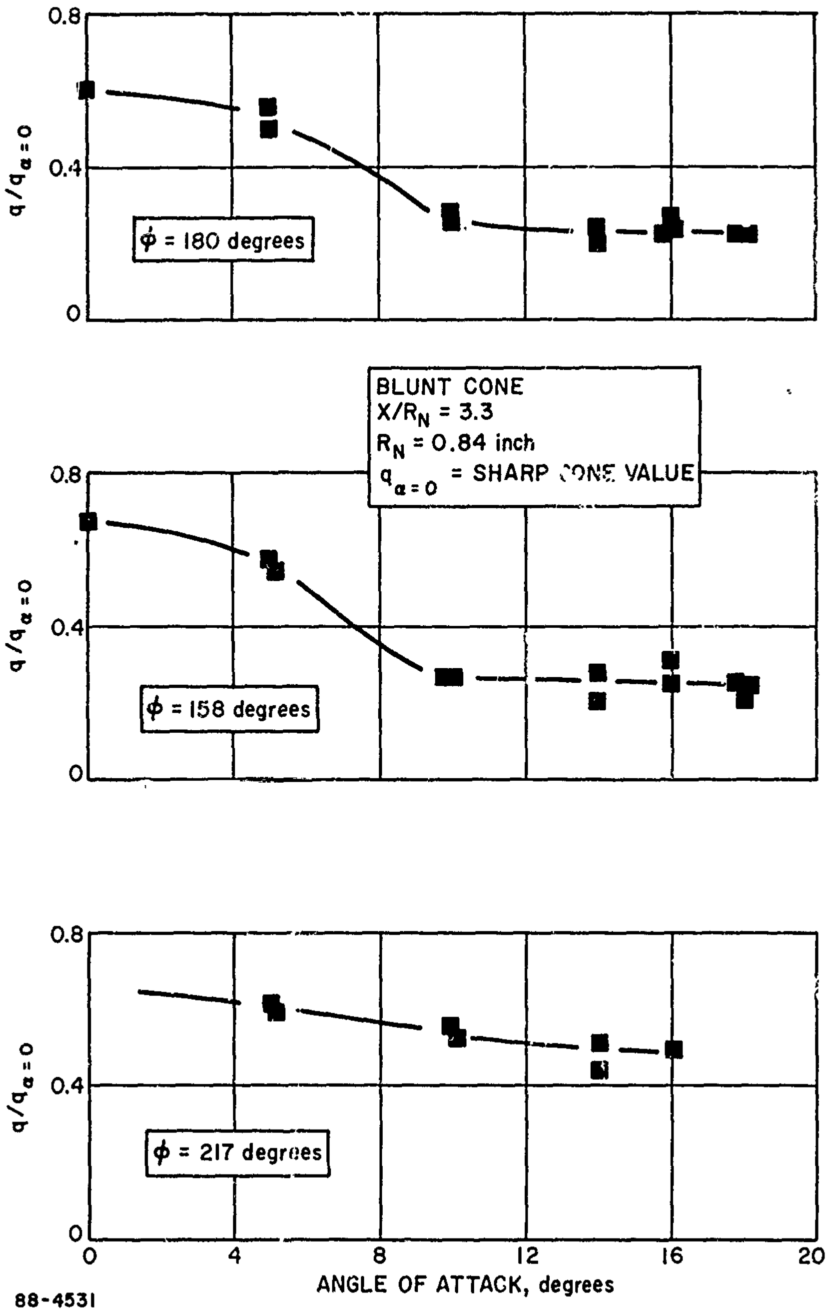

Figure 18 BLUNT CONE HEAT TRANSFER VERSUS ANGLE OF ATTACK

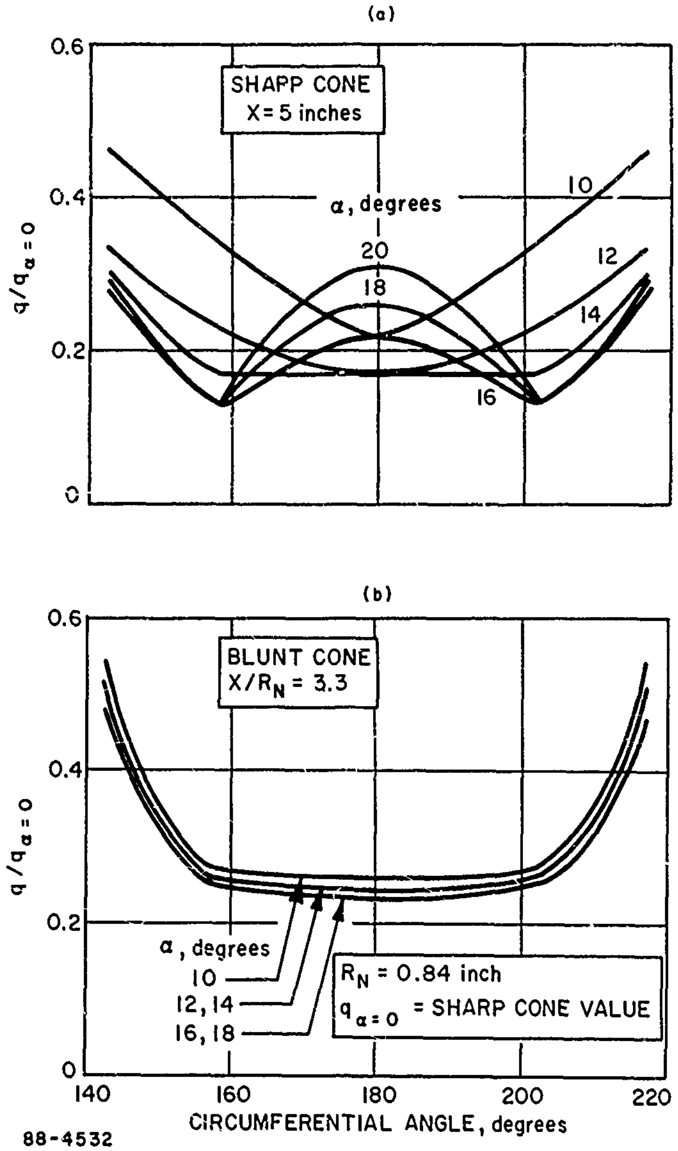

Figure 19 HEAT TRANSFER VERSUS CIRCUMFERENTIAL ANGLE

4.0 CONCLUSIONS

The following conclusions resulted from this investigation:

1) Separation on a sharp cone at angle of attack is a gradual process. This means that precise knowledge of the angle of attack at which cone incipient separation occurs is more of an academic problem than an engineering problem.

2) From the data obtained with the two base geometries (flat and spherical) it can be inferred that separation was not influenced to a significant degree by base geometry.

3) Increasing angle of attack in the range of flow separation on a sharp cone is characterized by increasing heat transfer rates while the pressure is decreasing.

4) Limited experiments with X/R_N in the range of 13.5 to 27.5 indicated that bluntness did not significantly affect separation in this range of X/R_N.

5) When X/R_N was in the range of 2.1 to 6.4 there was no indication of separation at angles of attack up to 18 degrees.

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13. ABSTRACT

A shock tunnel investigation of the pressure and heat transfer distributions on sharp and blunted 15-degree half angle cones at angle of attack was conducted. The test conditions were $M_\infty = 13.5$ and Re_∞/ft. = 1.5 x 10^6. Separation on a sharp cone with increasing angle of attack is a gradual process which is characterized by increasing heat transfer rates while the pressure is decreasing. The two base geometries tested (flat and spherical) indicated that separation was not influenced to a significant degree by base geometry. Limited experiments with X/R_N in the range of 13.5 to 27.5 indicated that bluntness did not significantly affect separation in this range of X/R_N. When X/R_N was in the range of 2.1 to 6.4 there was no indication of separation at angles of attack up to 18 degrees.

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