AFFDL-TR-72-12

RECENT NOTES AND DATA ON INTERFERENCE HEATING

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FOREWORD

This report was prepared by R. D. Neumann of the High Speed Aero Performance Branch, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio. The work was performed as a part of the AFFDL in-house research under Task 136607 "High Speed Aerodynamic Heating to Military Flight Vehicles" Project 1366 "Aeromechanics Technology for Military Aerospace Vehicles", and covers work conducted between June 1970 and June 1971.

This report has been reviewed and is approved.

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ABSTRACT

This report presents recent observations and data on the shock interaction problem discussed by Neumann and Burke in AFFDL TR 68-152. Information on both two and three dimensional interactions are presented and the literature on the subject over the time period from July 1967 to August 1971 is reviewed in terms of the correlations presented by Neumann and Burke. While no new data are presented, some features of the interaction observed by various authors have been investigated in greater depth in order to clarify the features of the interaction process. Conclusions from these data relative to current hypersonic vehicle design studies of the space shuttle are drawn.

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FIGURE PAGE

LIST OF SYMBOLS

A	Constant (.322 for laminar flow, 0.0296 for turbulent flow)
C	Chapman Rubisen Constant
D	Tunnel Diameter
h	Heat Transfer Coefficient
K_3	Proportionality Parameter
L	Model Length
M	Mach Number
n	Exponent defined by boundary layer state
P	Pressure
$\dot{q}$	Heating Rate
Re	Reynolds Number
S_t	Stanton Number
T	Temperature
U	Velocity
X	Distance in the longitudinal direction
Y	Distance in the lateral direction
α	Angle of Attack
δ	Shock Generator Angle
Λ	Sweep Angle

Subscripts

e	Boundary layer edge
fp	Flate plate
int	Interaction Location
lam	Laminar
o	Condition ahead of the disturbance
Pk	Peak Condition
trans	Transition Point
turb	Turbulent
wc	Calculated Wall Value (Reference 13 Nomenclature)
wi	Without Interaction
wm	Measured Wall Value (Reference 13 Nomenclature)
∞	Free Stream

SECTION I

INTRODUCTION

A recent report by Murphy (Reference 1) compares the predictions of several analytic methods (References 2 to 6) with the two dimensional remote shock generator data of Needham (Reference 7) at Mach numbers 7.4 and 9.7. Murphy concludes that, although there is a uniform tendency to under-predict both skin friction and heat transfer at all Mach numbers, the inability of the methods to predict the experimental results is not wholly associated with short comings in the experimental data.

In 1967 Neumann and Burke presented a paper at the American Institute of Aeronautics and Astronautics Guidance, Control and Flight Dynamics Conference entitled "The Influence of Shock Wave-Boundary Layer Effects on the Design of Hypersonic Aircraft", which was later published as Reference 8. This report, which presents a body of data on two and three dimensional interactions and a prediction technique for evaluating interference heating, clearly indicates the tendency of the boundary layer to become turbulent in the two dimensional interaction region. It is therefore of interest to investigate how much of an analytic shortcoming is associated with boundary layer transition as compared with other analysis problems. This question forms the subject matter for the section on two dimensional interactions. The report also proposed that, in three dimensional interactions with a vertical fin mounted on a horizontal flat plate, an effectively new boundary layer originates at the reattachment point and this thinner boundary layer must be included in the analytical predictions. A correlation of the location of the peak heating with respect to the fin shock wave was made.

SECTION II

TWO DIMENSIONAL INTERACTIONS

Two dimensional interaction data in the present report were evaluated under both laminar and turbulent boundary layer assumptions. In both cases the heat transfer coefficient (or heating rate) ratios were plotted as a function of the incidence angle of the remote shock generator. The square root of the pressure ratio P_{PK}/P_{wi} was then plotted as open symbols; this is proportional to the laminar interaction heating ratio in which, from flat plate theory, $q_{PK}/q_{wi}\ \alpha\ (P_{PK}/P_{wi})\ 0.5$. The turbulent ratio was formed in a manner analogous to the laminar method except from flat plate theory the heating ratio is proportional to an 0.8 power on the pressure ratio. This relationship is valid as long as the undisturbed data ahead of the interaction is also turbulent. In the more general case however this is not true. Generally the data available ahead of the interaction or on a reference plate having no pressure gradient are laminar and it is the presence of the adverse pressure gradient that causes transition. For this case the undisturbed value is laminar and a new term relating turbulent to laminar flat plate flow is needed. This is supplied by employing the laminar and turbulent forms of the Eckert reference temperature method which in general is expressed as follows:

$$S_t(Re_{\infty,x})^n = A\left[\frac{\rho_e U_e}{\rho_\infty U_\infty}\right]^{1-n}\left[\frac{T_\infty}{T^*}\right]^{1-2n} C^*$$

Where n = 0.5 laminar
= 0.2 turbulent
A = 0.332 laminar
= 0.0296 turbulent

In ratio form, this expression reduces to the following (Reference 8, App I)

$$\left[\frac{\dot q_{turb}}{\dot q_{lam}}\right]_{fp} = 0.0892\left[Re_{\infty,x}\right]^{0.3}\left[\frac{T_\infty}{T^*}\right]^{0.6}$$

for the assumption of instantaneous transition at the leading edge.

This assumption can be made more physically realistic through observation that data do not undergo transition at the leading edge. The start of turbulent flow cannot always be distinguished from other flow details; however, it is a reasonable approximation to judge the departure of data from laminar flow characteristics as the start of the turbulent boundary layer. For this case the ratio is slightly changed as follows:

$$\rightharpoonup Re_{\infty,x}^{\;0.3} \longrightarrow \left[Re_{\infty}/in\right]^{0.3} \frac{X_{int}^{\;0.5}}{(X_{int}-X_{trans})^{0.2}} \quad (X \text{ in inches})$$

These two approximations are termed lines "A" (for zero transition Reynold's number) and "B" (for finite transition Reynolds number) on the graphs of data presentation.

Employing this format for graphical data an attempt has been made to characterize the boundary layer state in the interaction. Agreement with either the laminar correlation (the square root of the pressure ratio P_{PK}/P_{wi}) or the turbulent correlation (the 0.8 power of the pressure ratio $P_{PK}/P_{wi} \times \left[\frac{q_{turb}}{q_{lam}}\right]_{fp}$) is sought. Data from several sources were employed varying both Mach and Reynolds number. These data are outlined in Table I. The data set of primary importance is that of Needham (Reference 7) employed by Murphy in Reference 1.

TABLE I

	Reference	M_∞	$Re_{\infty x int}$
Kutschenreuter	9	10	16.8×10^6
Neumann and Burke	8	10	0.69 & 1.47×10^6
Needham and Holden	7, 10	9.7	1.17×10^6
Neumann and Burke	8	8.0	1.51×10^6
Needham and Holden	7, 10	7.4	2.77×10^6
Neumann and Burke	8	6.0	1.70×10^6

Kutschenreuter Data at Mach 10

Consider first the data of Kutschenreuter et al (Reference 9) whose model "A" is a two dimensional planar shock interaction model. The interaction occurs at a unit Reynolds number based upon free stream properties of 8.74×10^6/ft at Mach 10.8. Due to the ramp angle on the instrumented receiver plate a local "free stream" Reynolds number of 10.7×10^6/ft at a local Mach number of 9.997 was generated on the plate based upon measured pressure data ahead of the interaction. The pressure and heating data are shown in Figure 1 ratioed respectively to the undisturbed pressure and undisturbed heating levels at the point where peak heating occurs.

In spite of the high unit Reynolds number of this test the undisturbed data ahead of the interaction were laminar and agreed well with laminar flat plate theory. (See Figure 2). The interaction was obviously in turbulent flow and thus the correlation shown in Figure 1 contains not only the component due to impingement, which is proportional to the 0.8 power of the pressure rise, but also the increase due to boundary layer transition.

The heating rate ratio data are shown as solid data points and the turbulent correlation:

$$\left[\frac{\dot{q}_{PK}}{\dot{q}_{wi,lam}}\right] = \left[\frac{\dot{q}_{turb}}{\dot{q}_{lam}}\right]_{Fp} \left[\frac{P_{pk}}{P_{wi}}\right]^{0.8}$$

is shown as a dashed line.

There are no surprises in the data of Figure 1; it is clear that the interaction data should be and are turbulent. The purpose of the correlation was to demonstrate that the approach correctly predicts the heating trend and reasonably predicts its magnitude.

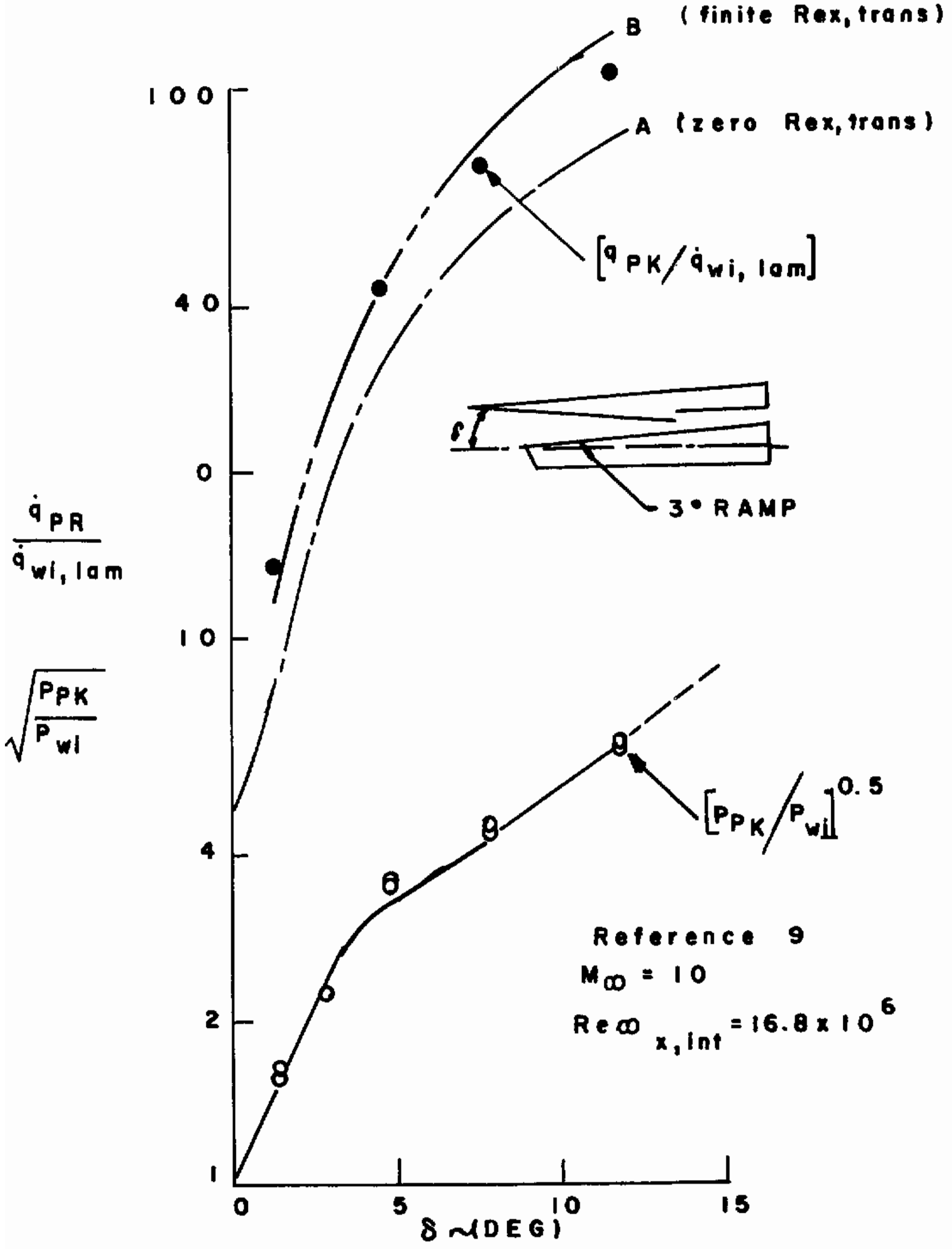


Figure 1. Two Dimensional Interaction Data of Kutschenreuter

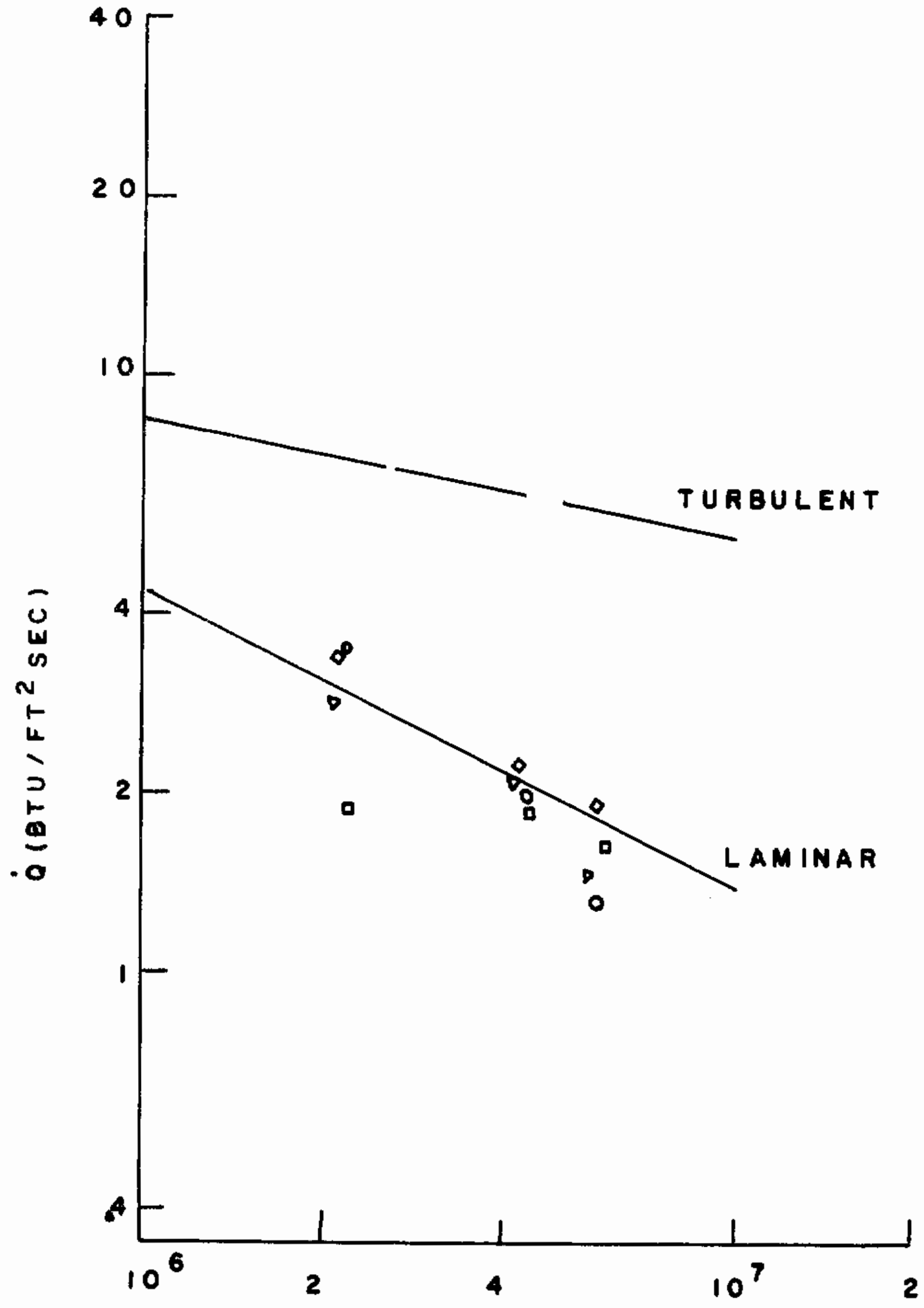


Figure 2. Undisturbed Planar Heating on Kutschenreuter's Model

Neumann and Burke Data at Mach 10

Data taken at Mach 10 in the AEDC Tunnel "C" and reported in Reference 8 are presented in Figure 3 in the same format as the previous data by Kutschenreuter. Pressure data, shown as open symbols, were taken at various Reynolds numbers bracketing the Reynolds number at which the heating data were taken. These data, shown as repeat symbols, were found to be insensitive to Reynolds number level except possibly at zero deflection angle, so these pressure data were employed in the heating correlation. Pressure data taken by Kutschenreuter are shown as a dotted line and agree quite well with the present Tunnel "C" data for deflection angles greater than five degrees. The lack of agreement at low angles of attack is due to the cylindrical nose bluntness of the shock generator employed in Tunnel "C".

Heating data at Reynolds numbers of 0.69×10^6 and 1.47×10^6 in the interaction are shown as solid symbols on Figure 3. The correlation "B" lines discussed previously are shown as dashed curves. It is noted that the correlation indicates fully developed turbulent flow occurs at a deflection angle on the order of ten degrees. As a result it must be concluded that the Reference 8 data at Mach 10 at very low Reynolds numbers were also transitional in nature and achieved fully developed turbulent data at the higher deflection angles. It is also somewhat questionable whether any fully laminar data were generated.

Needham and Holden Data at Mach 10 and 7.4

Finally the data of Needham (Reference 7) and Holden (Reference 10) were evaluated. (Apparently, separate analyses were conducted using the same set of data.) A composite of data was taken from both reports and plotted in Figure 4. These data were taken at Mach 9.7 at a Reynolds number in the interaction of 1.17×10^6.

The pressure data were very limited although the agreement of all previous pressure data for deflection angles of five degrees or greater allows the extrapolation of the pressure data to higher interaction

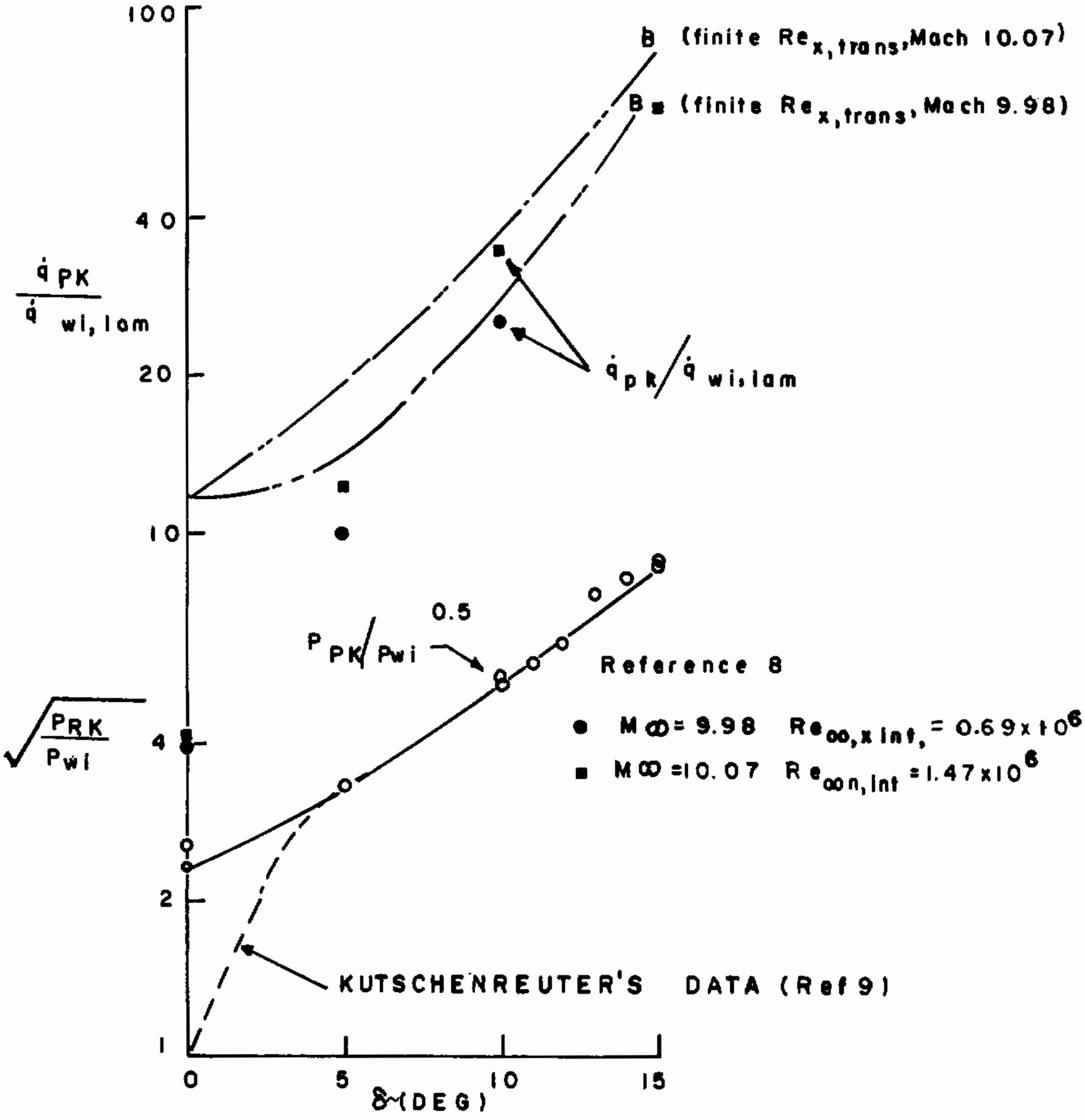


Figure 3. Two Dimensional Interaction Data of Neumann and Burke at Mach 10

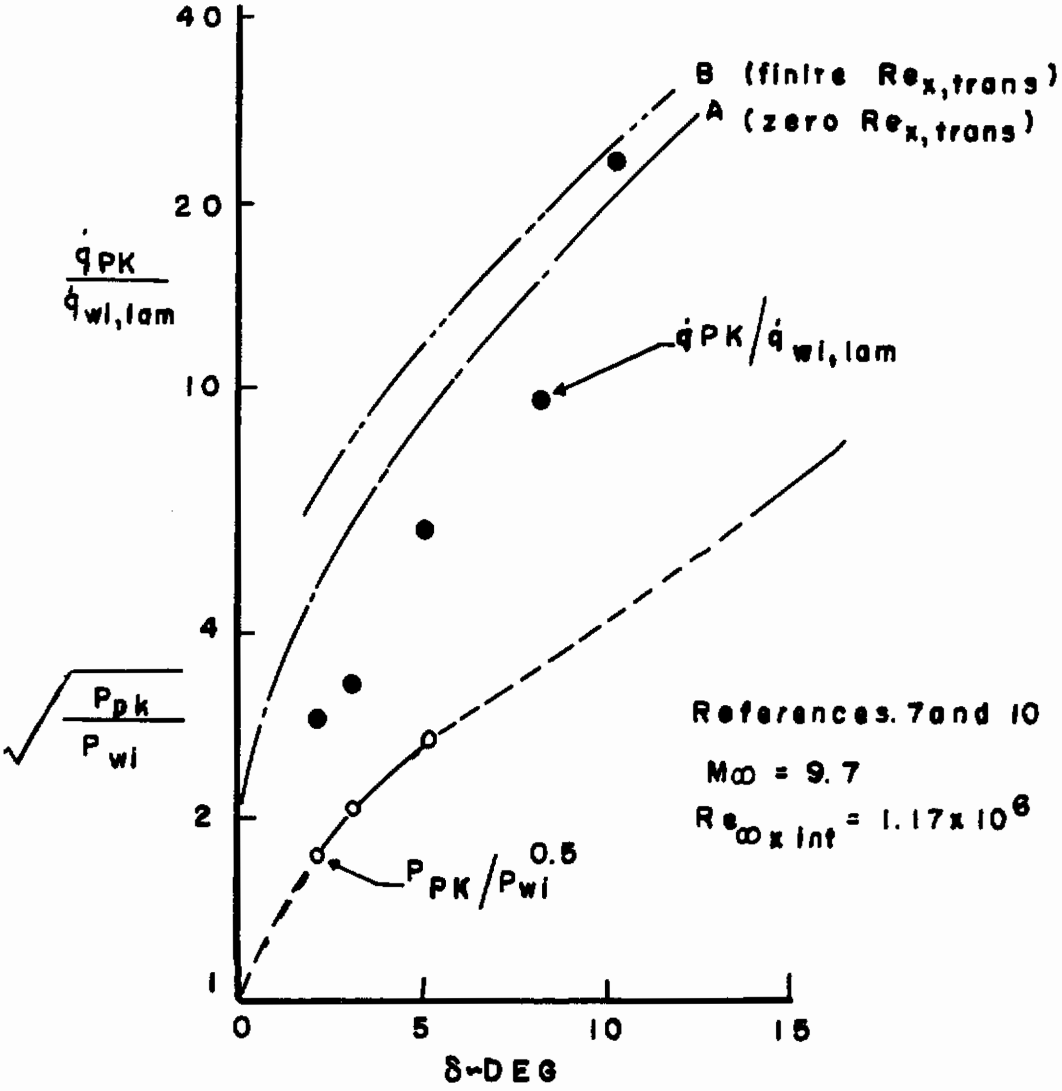


Figure 4. Two Dimensional Interaction Data of Needham and Holden at Mach 9.7

angles. The pressure data level was lower reflecting the lower Mach number (9.7 as opposed to 10).

The heating data and correlation curves are also shown in Figure 4. Fully developed turbulent flow was achieved at deflection angles greater than 10 degrees which is in agreement with the Neumann and Burke data.

To focus more clearly on the transitional character of these Mach 10 data, both the Needham and Holden, and Neumann and Burke data were compared in the form of a ratio to their laminar and turbulent correlation lines and plotted in Figure 5 as a function of the remote generator deflection angle. In this presentation a value of unity corresponds to perfect agreement. Most of the data are transitional and four data points at high deflection angles are noted to be turbulent. Figure 6 presents an overall view of the Mach 7.4 data of Needham and Holden which demonstrate the same behavior as the Mach 10 data for deflection angles less than 5 degrees.

To complete the data presentation, data taken in Tunnel "B" at Mach numbers 6 and 8 and presented in Reference (8) are shown in Figures 7 and 8. These data conform to the presentation format previously discussed and were taken with a blunted remote generator - hence the rather large pressure at zero generator deflection angles. These data indicate the ease with which the adverse gradient caused by a remote two dimensional generator trips the boundary layer. All data except for that of Needham and Holden and Neumann and Burke at low pressure increments at Mach 10 were turbulent or nearly so. A comparison of data by Neumann and Burke at Mach 6 and 8 against that of Needham and Holden at Mach 7.4 indicates at least qualitatively that a blunt tipped generator is far more effective at promoting transition than the sharp wedge employed by Needham.

It is not clear in the data whether any laminar interaction data were generated. No data points agreed with the laminar correlation parameter although several at the low interaction pressures at Mach 10

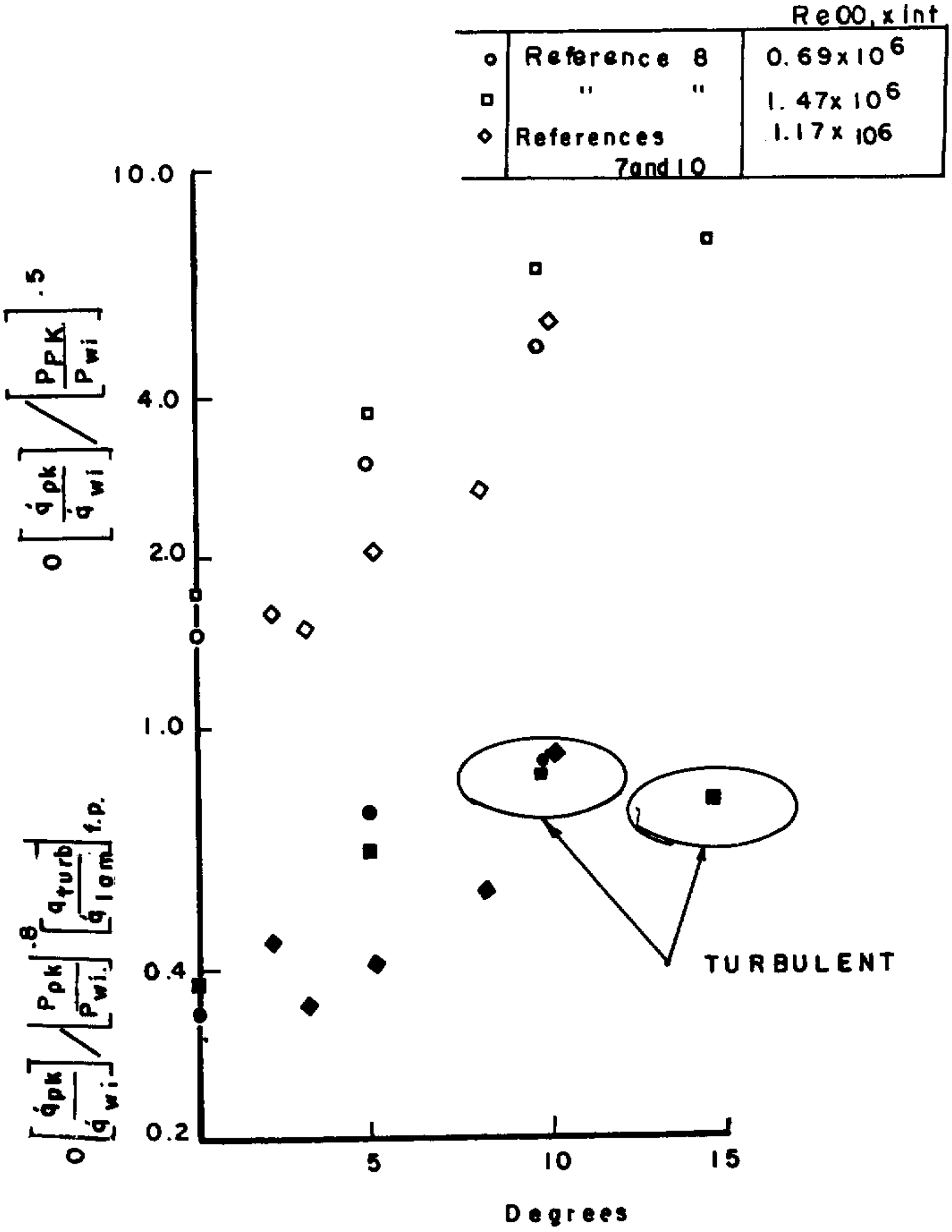
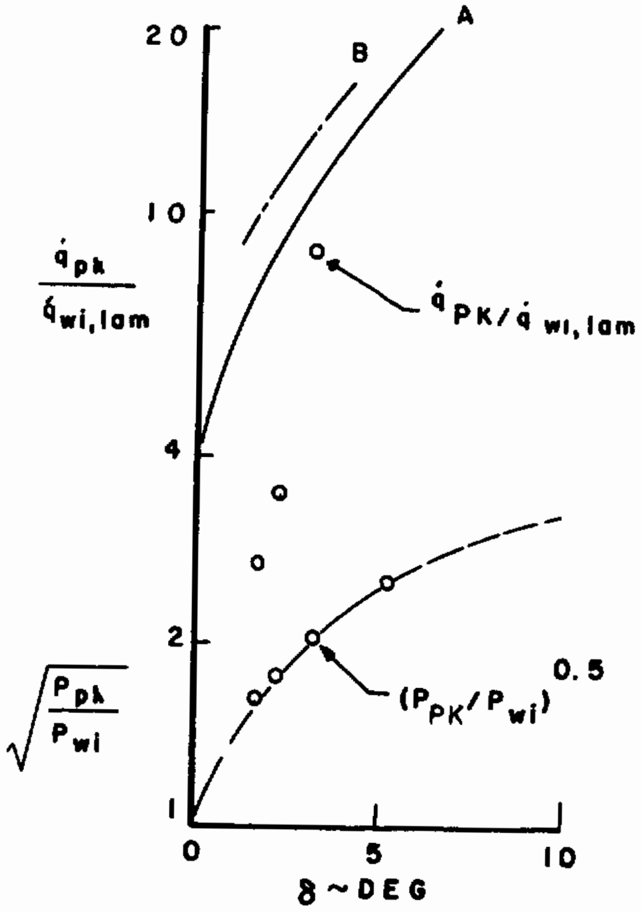


Figure 5. Laminar and Turbulent Correlations of Mach 10 Data



References 7and 10

$M_o = 7.4$

$Re_{\infty,x,int} = 2.77 \times 10^6$

Figure 6. Two Dimensional Interaction Data of Needham and Holden at Mach 7.4

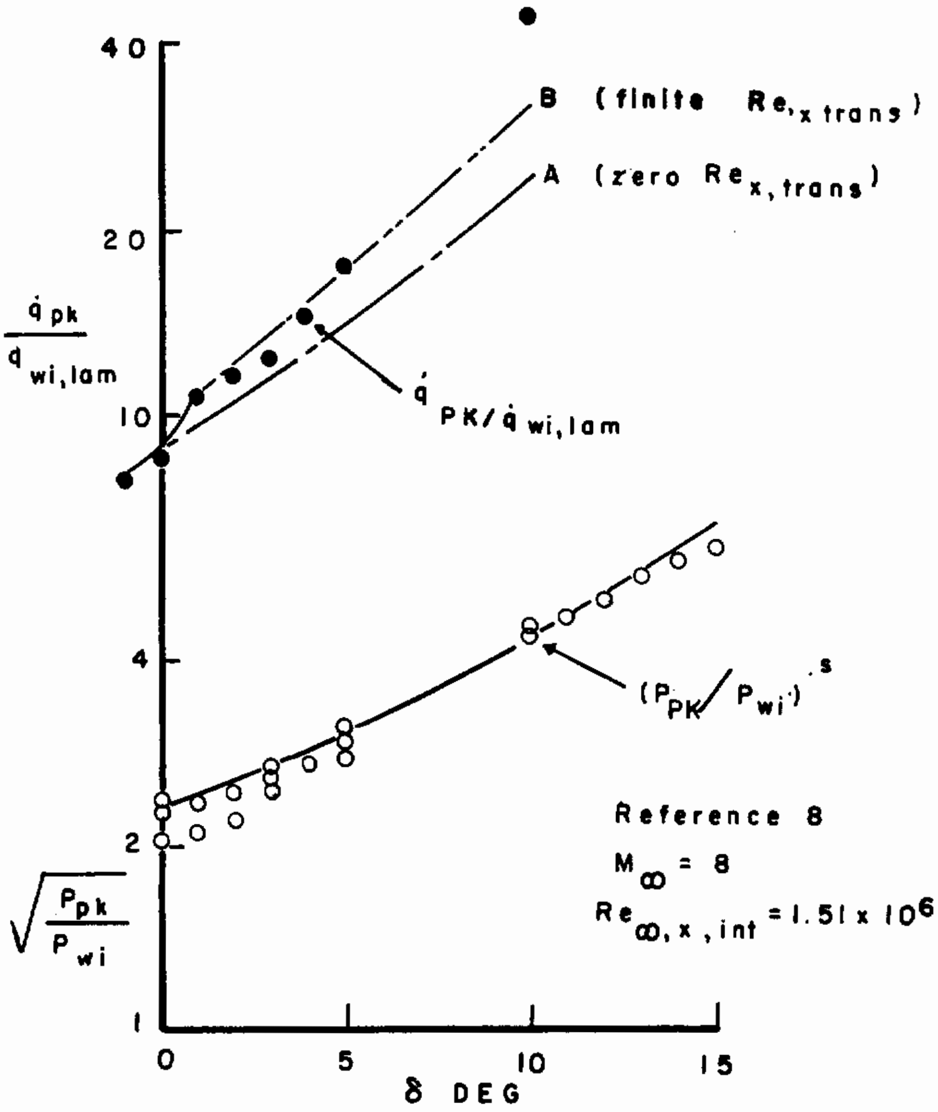


Figure 7. Two Dimensional Interaction Data of Neumann and Burke at Mach 8

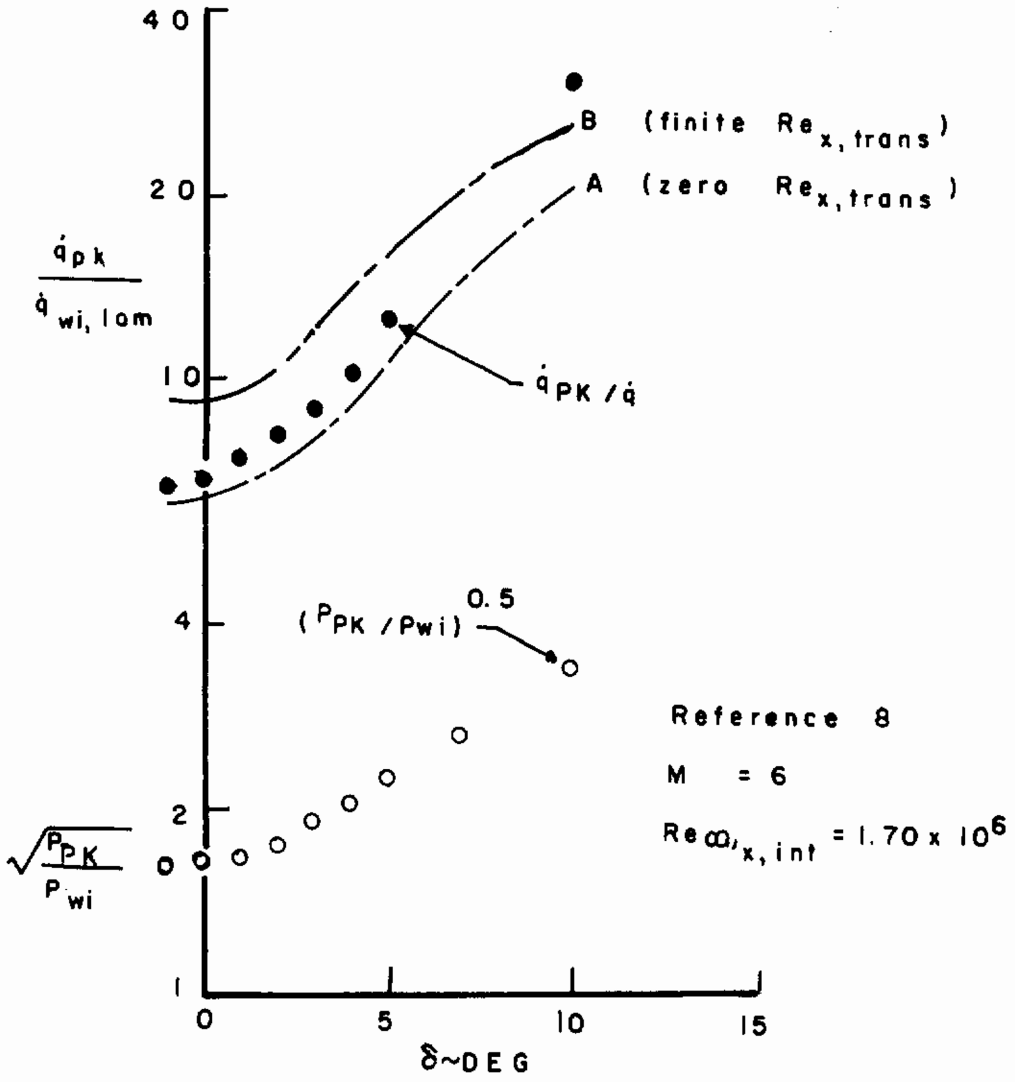


Figure 8. Two Dimensional Interaction Data of Neumann and Burke at Mach 6

present a laminar trend with deflection angle. It is not easily understood whether any data point or even data set is interacting in a laminar, transitional or turbulent boundary layer and it is only through observation of both data levels and data trends that we can establish the true nature of the interaction. It is regrettable but understandable that no one has systematically varied the interaction Reynolds number to map out the regions of laminar, transitional and turbulent interaction at a test point.

SECTION III

THREE DIMENSIONAL INTERACTIONS

The three dimensional interaction prediction technique as presented in Reference 8 differs from the two dimensional problem through the inclusion of two additional factors. One of these is that a new boundary layer is effectively generated at the reattachment point of the interaction with the original boundary layer having been bled off through the separated region. The origin of this new boundary layer must be considered when calculating the heating rate. A correlation of the location of the peak heating with respect to the fin shock wave shows that the reference length to use in boundary layer calculations is 0.215 of the distance downstream from the fin leading edge. This relationship was derived for laminar and turbulent interactions at Mach numbers 6 and 8. The other difference is the use of an adverse pressure gradient term (K_3) as presented in Reference 11. This factor is on the order of 1.75 for the Mach numbers 6 and 8 runs in Reference 8.

Including these two effects results in very good agreement, not only with the data used to empirically determine the correlations, but also with other data as seen in Reference 8 and in the remainder of this section.

Bertram and Henderson

Bertram and Henderson, in Reference 12, present data on a 90-degree interior corner model at Mach 20. They conclude for such a corner [corners composed of planar surfaces at arbitrary incidence] that (a) when transition to turbulent flow occurs, the peak in heating virtually disappears and that (b) sweeping the blunt leading edge largely eliminates the high, induced heating except for a region in close proximity to the corner. While these conclusions are borne out for the conditions of their reports, the general applicability to other conditions is questioned. Figure 9 presents data on a sharp, unswept fin at 7.5 degrees local incidence angle in a turbulent boundary layer. Contrary to Bertram's

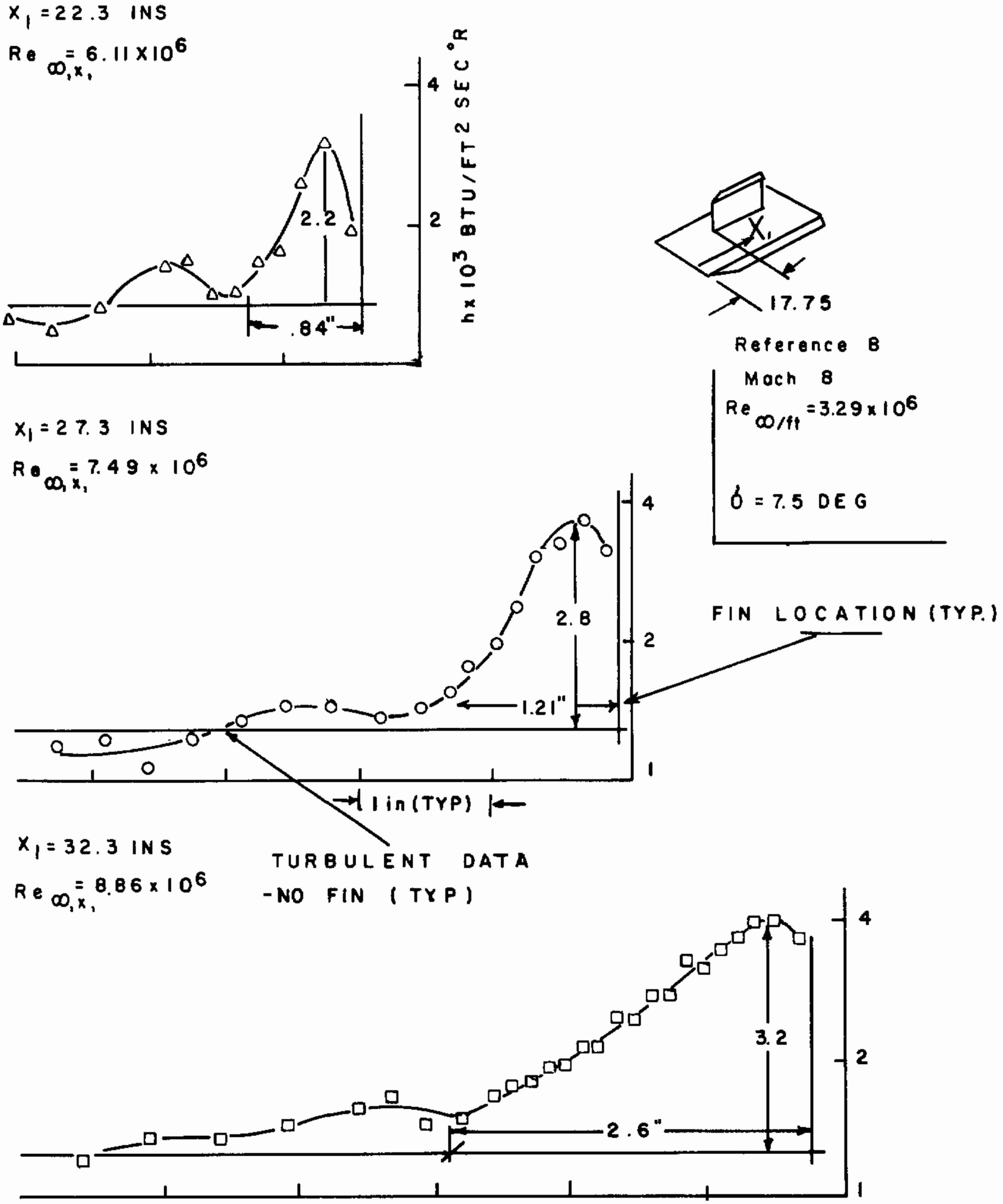


Figure 9. Turbulent Fin Interaction Data at Mach 8

findings, the peak heating in a turbulent boundary layer due to interaction increases with increasing Reynolds number (from 2.2 to 3.2 times the undisturbed value) and, as well, the width of the interaction region increases.

Admittedly, the two experiments have differences in model design, fin orientation and total length Reynolds number; it is important to understand that merely tripping the boundary layer does not automatically cause the peak heating to virtually disappear.

Figure 10 presents data on the effect of sweeping the fin in a laminar boundary layer. It is seen that sweeping the fin essentially has a negligible effect on the maximum laminar heating for either the sharp or blunted fin, though the blunt fin data at zero sweep has more than one peak.

Figure 11 presents similar data for the turbulent boundary layer case. These data were taken at a model station 32.3 inches from the plate leading edge and 14.55 inches from the fin leading edge. The Reynolds number based on plate running length and free stream conditions is 8.9 x 10^6 and, in addition, the plate boundary layer is tripped turbulent by series of roughness elements 3.7 inches from the nose. These data are in gross disagreement with Bertram's conclusion that sweeping the blunt fin leading edge eliminates the heating increase. The heating peaks relative to undisturbed flat plate flow are far greater in Figure 11.

In a sense we must concur that sweeping the blunt fin in a turbulent boundary layer largely eliminates the high, induced heating except for a region in closer proximity to the corner. Figure 11 indicates that sweeping the blunt fin from 0 to 60 degrees moves the interaction closer to the fin and, at 60 degrees, blunt and sharp fins have the same characteristics (bluntness phenomena are not apparent) however, it is not correct to characterize the peak as occurring in a region in close proximity to the fin.

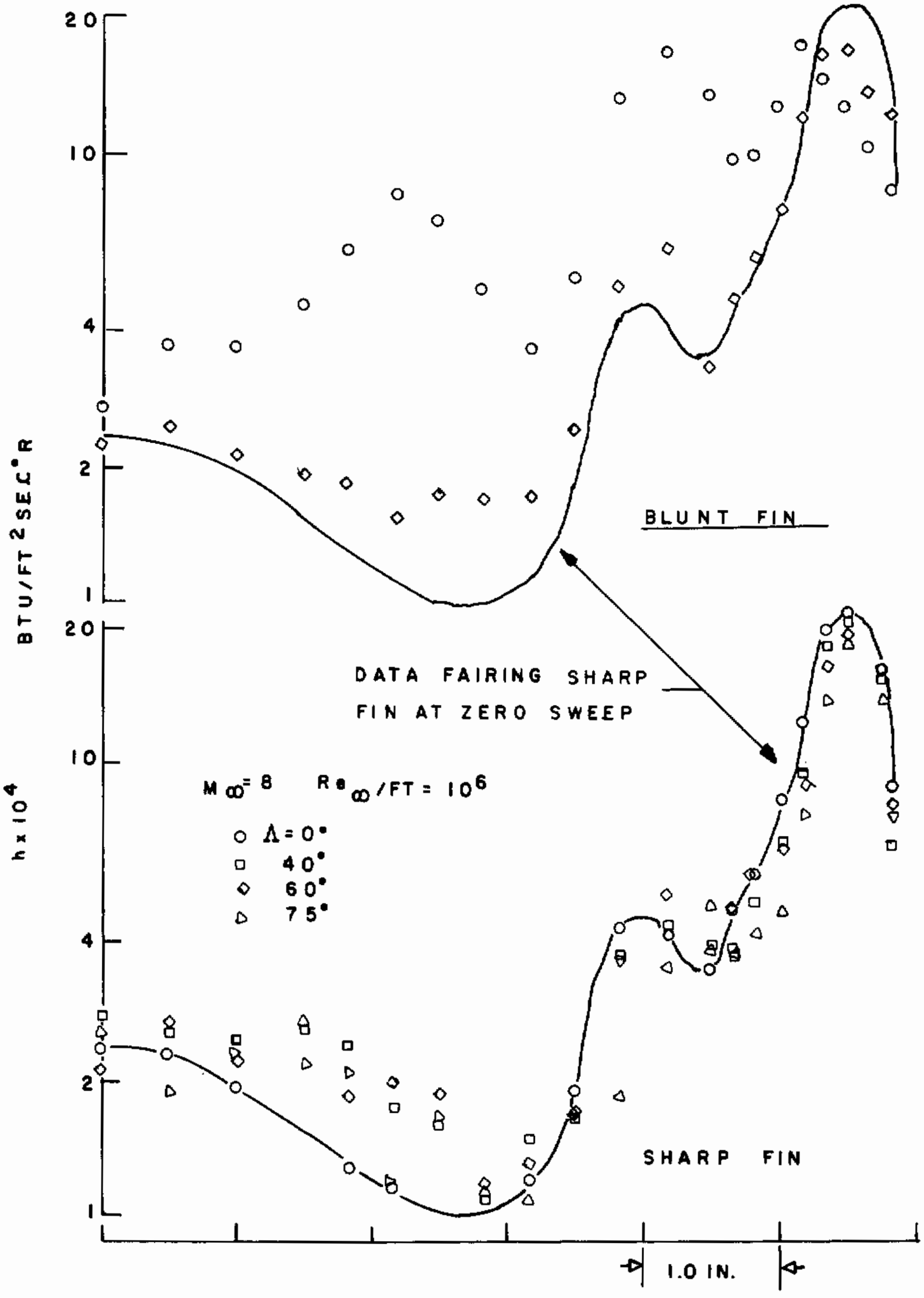
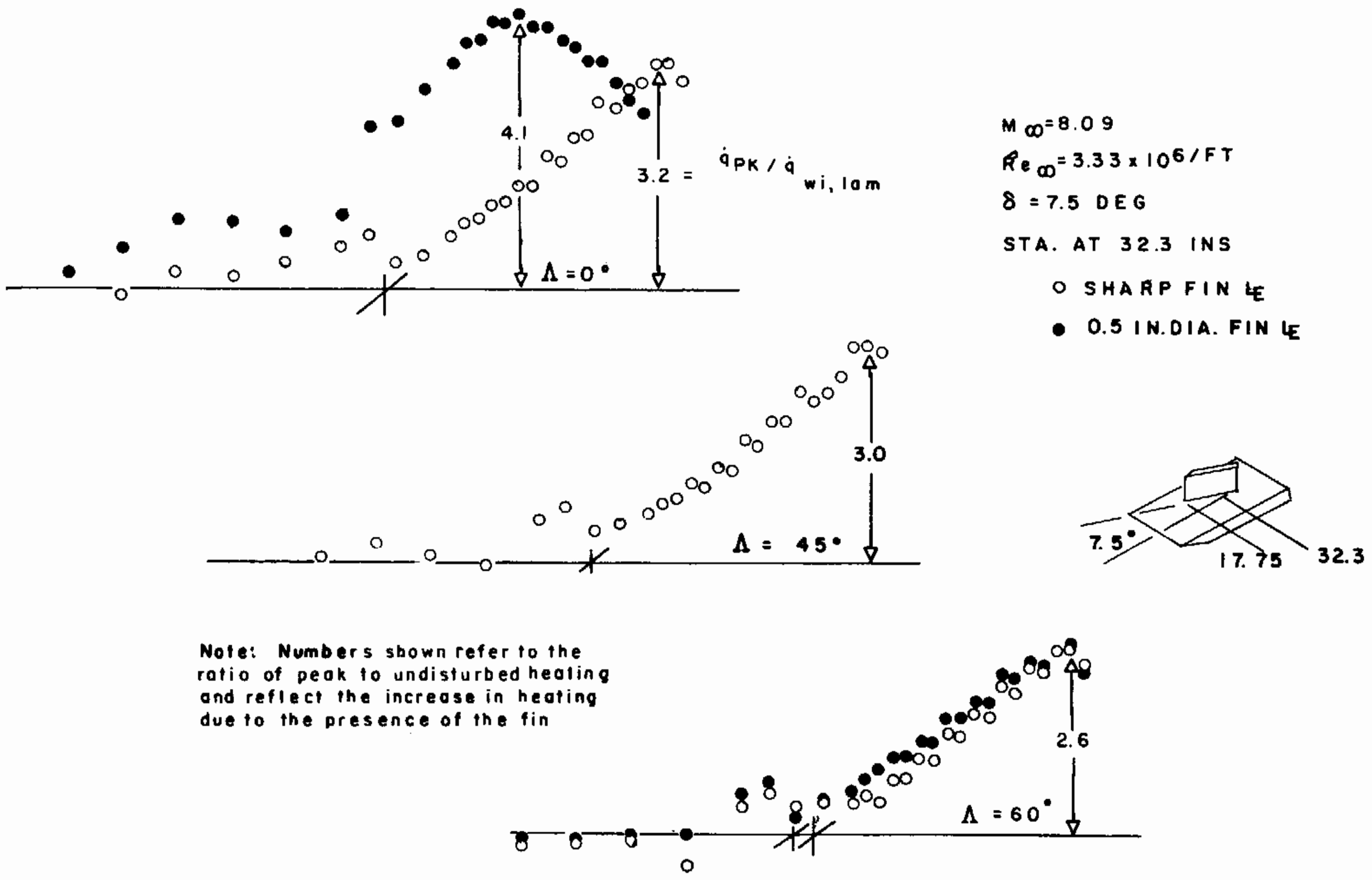


Figure 10. Effect of Sweep and Bluntness on Laminar Fin Interaction Heating



Note: Numbers shown refer to the ratio of peak to undisturbed heating and reflect the increase in heating due to the presence of the fin

Figure 11. Effect of Sweep on Turbulent Fin Interaction Heating

Watson and Weinstein

Watson and Weinstein, in Reference 13, present measurements on three sharp leading edge 90-degree internal corner models with wedge angles (both wedges) of 0, 5 and 10 degrees in Mach 20 helium flow. They conclude that peak heating levels cannot be accounted for by consideration of the peak pressure only (the technique used herein for two dimensional interactions) and that a large portion of the increased heat transfer is evidently due to the influence of a localized vortical flow. No attempts were made to correlate vorticity effects.

Figure 12 shows the Watson and Weinstein data compared with the three dimensional method of Neumann and Burke (Reference 8) with a K3 value of 2.0. (The square data point is from Reference 12 at Mach 20.3). It is seen that the correlation is very good and, while no consideration was given to the effects of local vortical flow as reportedly demonstrated in oil flow photographs in Reference 13, it is significant that these Mach 20 data correlate with a method developed from Mach 6-10 data on a different configuration.

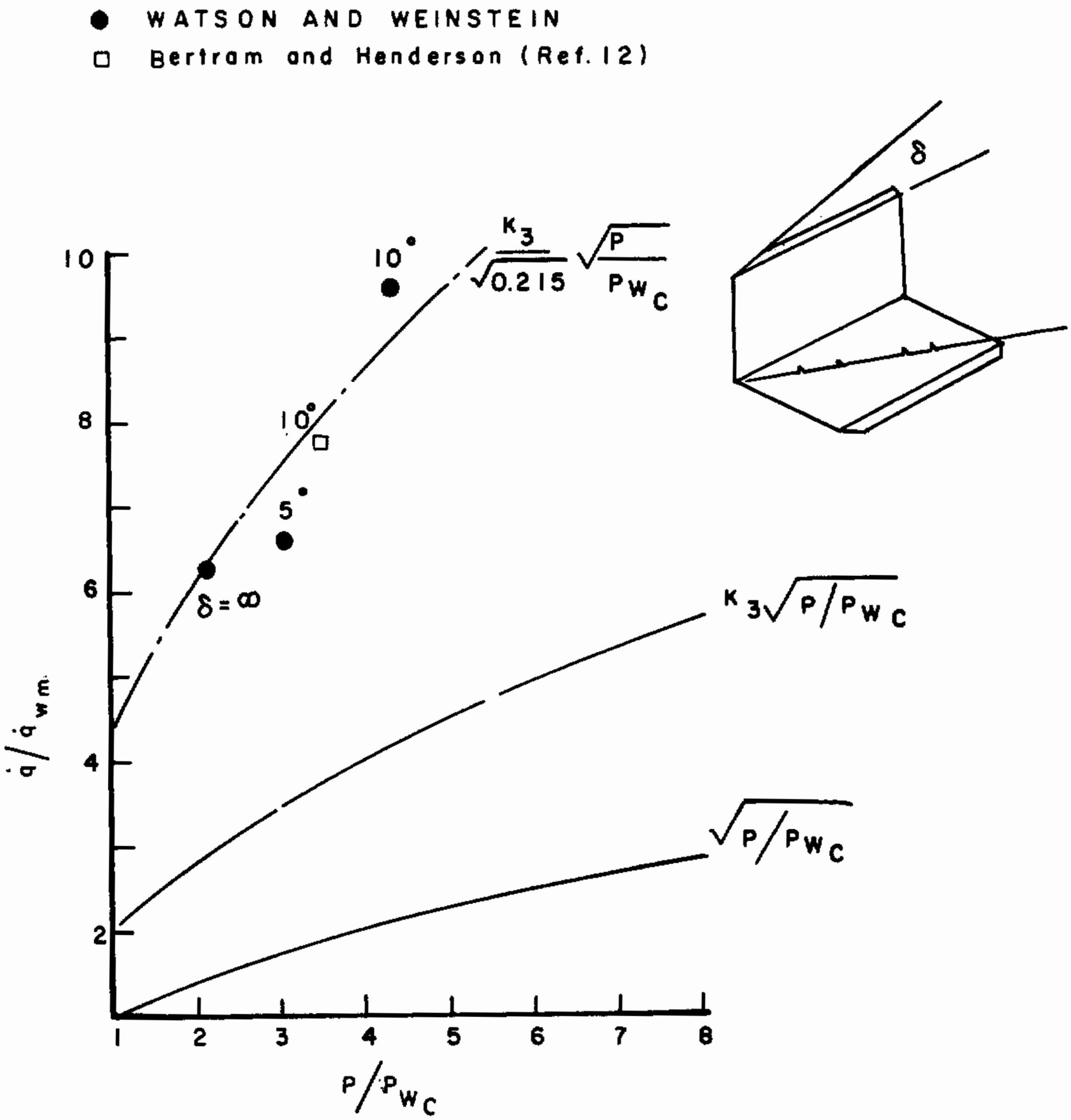


Figure 12. Correlation of Watson and Weinstein's Data

SECTION IV

PRACTICAL CONSIDERATIONS

In applying the methods and data of Reference 8 (summarized herein) to more practical configurations, two features of the interaction are important to consider. These are (1) the fact that model scale is important since the interaction process requires a finite length to fully develop and (2) the interaction is inherently a high gradient process taking place in a relatively small area about the fin. (See Figures 9 through 11 of this report). Let us apply these features of the interaction toward the evaluation of heating about a canard of a space shuttle configuration.

The demonstrated model length characteristics of such a configuration to allow testing over a wide angle at attack range ($0 \leq \alpha \geq 60°$) are shown in Figure 13. This figure illustrates that a model length roughly half the tunnel diameter can be accommodated. Combining this with the previously outlined interaction features it is apparent in Figure 14 that, for available tunnel sizes, measured interference data levels will not be representative of full scale trends, being underpredicted by roughly a factor of 2, and that the width of the interference heating spike will be marginal for the generation of high quality thermocouple data. The situation is far worse if a turbulent boundary layer interaction is to be evaluated as the length to achieve a stable turbulent interaction as the unit Reynolds numbers tested is at least twice that for the laminar case.

To these apparent physical limitations we must add the problem of determining boundary layer state. This problem is difficult enough for "classically" simple two and three dimensional interactions discussed in this report. For actual flight configurations the problem is compounded since trend data (data with varying total pressure increments) due to an interaction cannot be achieved without corresponding changes to the basic configuration.

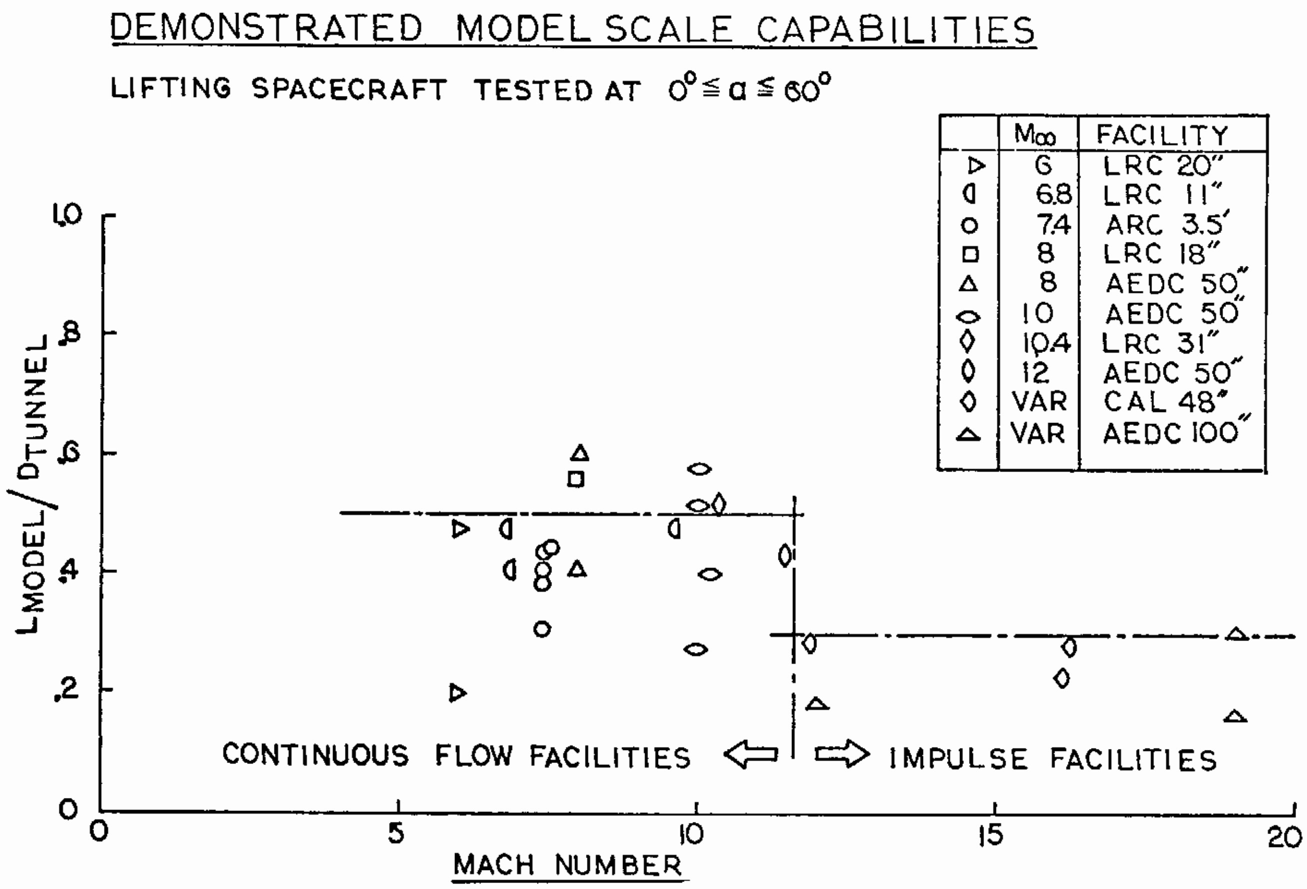


Figure 13. Demonstrated Model Scale Capabilities for Booster Testing

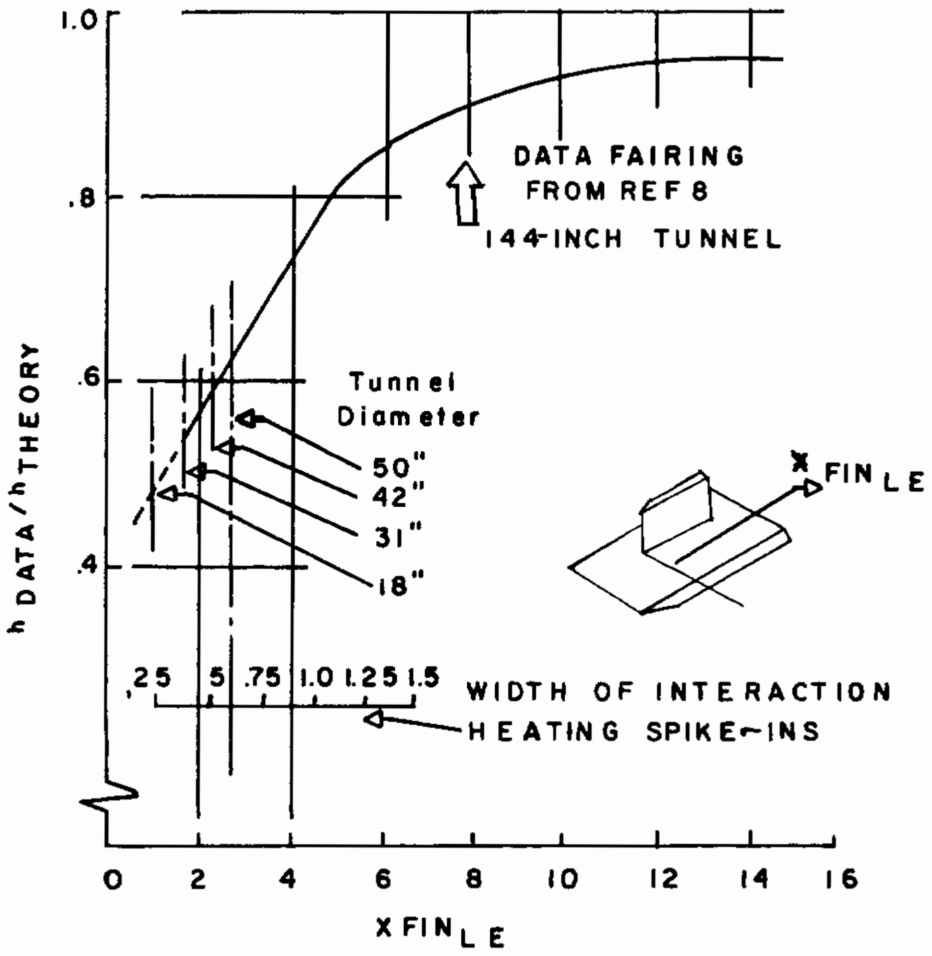


Figure 14. Scale Effects on Fin Heating Data

SECTION V

CONCLUSIONS

This report has presented a review of data and concepts in the area of interference heating to two and three dimensional configurations. The methods developed in Reference 8 have been restated, elaborated on and applied to data more recently available. Specific conclusions from the work are as follows:

1. Questions regarding boundary layer state due to the interaction continue to occur. These questions are not easily resolved and result in "apple and orange" comparisons such as in Reference 1. As the interfering configurations become more complex, more exacting criteria will have to be developed to categorize the interaction without generating expensive trend data at each point.

2. Three dimensional interaction methods proposed by Neumann and Burke have been found to agree with Mach 20 data of Watson and Weinstein.

3. Data features seen on these classically simple interactions, when applied to the space shuttle test program, indicate that test data from available facilities may be underpredicting the flight case by a factor of 2.

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13. ABSTRACT

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