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SHOCK WAVE-TURBULENT BOUNDARY LAYER INTERACTION IN HYPERSONIC FLOW

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ABSTRACT

A study is presented of attached and separated turbulent viscous interaction regions resulting from shock wave-boundary layer interaction in hypersonic flow. Both the interaction between a planar oblique externally generated shock with the turbulent boundary layer over a flat plate and the viscous interaction in a two-dimensional compression corner have been studied at free stream Mach numbers from 6.5 to 13.0, for Reynolds numbers from 10×10^6 to 100×10^6, at wall to free stream stagnation temperature ratios from 0.1 to 0.4. Measurements of the mean and fluctuating pressure, skin friction and heat transfer on the model surface, and schlieren photographs of the flow field were made for a series of incident shock strengths and turning angle of the compression surface so that attached, incipient separated and well separated turbulent interaction regions could be studied at each free stream condition. The direct measurements of surface shear indicated that turbulent boundary layer separation occurred well before an inflection point was observed in the pressure distribution through the interaction region. We found that the incipient separation conditions for both shock-and wedge-induced interaction regions from our measurements, together with those from earlier studies, could be correlated in the form $\frac{p_{INCIP} - p_0}{p_0} \propto M^3 C_{f_0}$. The length of the separated regions induced both by externally generated shocks and on compression surfaces was found to increase with increasing Reynolds number and wall-to-free stream stagnation temperature and decreasing Mach number of the free stream. Correlations for the plateau pressure and the heat transfer rate at reattachment and in the plateau region are presented.

The fluctuating pressure measurements indicated that turbulent viscous interaction regions in separated flow are highly unsteady and this unsteadiness is reflected in the observed motion of the separation and reattachment points which can undergo excursions of as much as one third of the local boundary layer thickness. The rms pressure fluctuation levels in the reattachment region were observed to be as large as one tenth the dynamic pressure of the free stream.

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2. INTRODUCTION

An important and challenging area in the fluid dynamics of hypersonic flight is the prediction of the properties of regions of mutual interaction between the boundary layer growth and an inviscid outer flow, at a surface discontinuity or from discontinuities in the inviscid flow such as shock or expansion waves. Such regions are important in the neighborhood of strong expansions such as those which occur in the base region on slender bodies; however, in general, interaction regions which occur in compressive flows arising on inlets, control surfaces or at wing-body junctions cause the most severe problems in hypersonic flight. In most cases of practical interest, the viscous interaction regions will be turbulent and have a highly complex three-dimensional structure; a general review of such regions can be found in Ref. 1; however, in order to understand the basic fluid mechanics viscous interaction regions so that rational analytical and semi-empirical prediction methods can be developed, the relatively simpler two-dimensional interaction problem must be understood first. The fundamental difficulty in analyzing regions of strong viscous-inviscid interaction is that it is no longer possible to describe independently the development of the viscous and inviscid flow field, and the problem is compounded if a separated region is formed in the interaction region with its intrinsically elliptic characteristics.

The viscous interaction region induced by the impingement of the planar oblique shock onto a boundary layer and the viscous-inviscid interaction in a two-dimensional flat plate-wedge compression corner are two classical examples of regions of shock wave-boundary layer interaction. However, although significant progress has been made within recent years in understanding regions of shock wave-laminar boundary layer interaction in both supersonic and hypersonic flow, the characteristics of turbulent interaction regions have not been well defined either experimentally or theoretically in high speed flows. This is partly because of the inherent complexity of turbulent interaction regions and partly for the lack of suitable experimental measurements and the facilities in which to make them.

A major problem in analyzing shock wave-turbulent boundary layer interaction is describing the mechanism of upstream influence and boundary layer separation in a turbulent flow. Here the central issue is whether a boundary layer subjected to a positive pressure disturbance responds upstream of the disturbance in such a way that a mutual and self-sustaining interaction between the viscous and inviscid flow takes place, independent of the nature of the downstream disturbance. It was thought at first that upstream influence could be described by upstream propagation through the subsonic region of the boundary layer. However, the theories of Howarth,[2] Tsien and Finston,[3] and Lighthill[4] postulated on this premise were found to predict upstream effects which were far smaller than those observed in experiment, and the significant differences between the upstream influence in laminar and turbulent interaction regions could not be explained using these models of the flow. A more successful model of the interaction region upstream of the disturbance, based on the mutual and self-sustaining interaction between the growth of the viscous layer and the resultant pressure changes in the outer inviscid flow, was first proposed by Oswatistsch and Wieghardt.[5] Subsequently, more sophisticated analyses[6-35] have used this "free interaction model" to describe shock interaction regions; and for laminar flows at supersonic and hypersonic speeds, many experimental studies have substantiated that indeed this is the major mechanism. However, for turbulent flows the situation is less well-defined; for, while the tunnel wall measurement in shock- and step-induced separated regions by Bogdanoff and Kepler[36] indicate that the initial pressure rise was independent of the agency promoting the interaction, the extensive studies of Chapman, Kuehn and Larson[21] yielded the opposite result.

Two of the first models to successfully employ the "free interaction" concept to describe upstream influence in laminar and turbulent boundary layers were developed by Crocco and Lees[6, 7] and Lighthill.[8] However, while Crocco-Lees assume that both inertial and viscous terms were of equal importance throughout the interaction region, Lighthill assumes that the viscous terms are important only in an incompressible sublayer, with flow above this sublayer being governed solely by pressure and inertial forces.

While both Crocco-Lees and Lighthill's analyses predict an increase in upstream influence with increasing Reynolds number for laminar flow, Lighthill's work predicts a decrease in upstream influence with increasing Reynolds number for turbulent boundary layer, while Crocco-Lees predict the opposite trend. Lighthill's model is accurate strictly at high Reynolds numbers of the order of 10^8 and, as noted in Section 3.4, it is in this high Reynolds number regime where experimental studies have indicated that a change in the Reynolds number trend for incipient separation might take place.

The Crocco-Lees analysis and the more recently developed integral methods which use the conventional boundary layer equations to describe the viscous layer all predict that hypersonic highly cooled-laminar flows, or turbulent flows above Mach 3 will exhibit a "supercritical response." The terms supercritical and subcritical were introduced by Crocco to describe the theoretical response of boundary layer to a pressure gradient acting uniformly across the viscous layer. For a supercritical flow (where $d\delta/dp$ is negative) the boundary layer will thin when opposed by an adverse pressure gradient and thus within the framework of the conventional momentum integral theory no mechanism exists for upstream influence. To overcome this limitation, Crocco suggested that the boundary layer undergo a rapid change or jump from a supercritical to a subcritical condition, and this artifice has been used to obtain solutions to separated flow problems. However, there is little experimental justification for this approach. Rather than "fix up" the analysis of turbulent interaction region using a super-subcritical jump, Honda[12] recognized the inadequacy of using the conventional boundary layer equations to describe turbulent interaction regions, devising a two-layer model in which both the longitudinal and normal pressure gradient terms were retained in the outer layer with the viscous terms considered important only in the sublayer. Although the analysis is strictly limited to low Mach number flows and adiabatic wall conditions, good agreement was demonstrated with experiment. Holden[27] also found that it was possible to remove the supercritical response problem upstream of shock wave-laminar boundary layer interaction in hypersonic highly-cooled flows by including the contribution of normal pressure gradient terms in the analytical model of the interaction region. Myring's[30] analysis of the development of turbulent boundary layers on compression surfaces, in which the pressure was assumed constant along Mach lines through the boundary layer, though inapplicable directly to the upstream influence problem, showed that adiabatic turbulent boundary layers can exhibit a subcritical response to hypersonic Mach numbers within this framework. It is clear that the mechanism of upstream influence and boundary layer separation in turbulent hypersonic flow cannot be described adequately within the framework of conventional boundary layer theory. The experimental studies described in Section 3 indicate that the basic interaction process leading to boundary layer separation takes place in the sublayer close to the wall. The flow above this sublayer in the original boundary layer appears to behave like an inviscid flow which is essentially deflected by the growth of the sublayer.

Although the incipient separation of a hypersonic laminar boundary layer can be predicted with good accuracy using momentum integral methods,[23] attempts to predict analytically the strength of the interaction to induce the incipient separation of a turbulent boundary have met with little success. The exact definition of the incipient separation condition in a turbulent interaction region is far from trivial; for although we can define incipient separation of a steady two-dimensional interaction as the condition where the skin friction is positive everywhere in the interaction region but at one point is vanishingly small, as is shown in Section 3.5, turbulent interaction regions are far from steady. The problem becomes one of defining incipient separation in an unsteady flow. We have found that defining this condition when the time average of the surface shear at one point on the surface is zero gave a consistent correlation of the measurements in shock- and wedge-induced interactions over a wide range of free stream conditions. In his experimental studies of incipient separation, Kuehn[37] equated the first appearance of an inflection point in the pressure distribution with the incipient separation condition. Although theoretical and experimental studies of laminar separated flow support this definition, there is a growing evidence which suggests this is inaccurate for high speed turbulent flows, as is discussed in Section 3.4. Hopefully, the identical incipient separation condition would be approached by either increasing the strength of the disturbance tending to promote the separation of an attached layer or reducing the strength of the interaction for separated flow. However, while experimental studies have indicated that this is the case for externally generated shock- and wedge-induced separated flows, the studies of turbulent interaction regions by Kuehn[37] indicated that significant hysteresis effect can take place on curved compression surfaces in a dynamic situation.

While the experimental evidence is unanimous in finding the pressure rise to induce incipient separation increases with increased Mach number, the variation with Reynolds number remains an open question. Although the effect of Reynolds number is weak, the studies of Kuehn[37] and Sterret and Emery[35] indicate increasing Reynolds number tends to push an attached interaction closer to separation, where the measurements of Roshko and Thomke[39] predict the reverse trend. A similar controversy exists on the influence of Reynolds number on the length of a separated region. The measurements of Hammitt and Hight,[40] Green,[41] and Roshko and Thomke,[39] made in tunnel wall boundary layer, show that increasing Reynolds number decreases the length of the separated region; those of Kuehn,[37] Chapman, Kuehn and Larson,[21] and Sterret and Emery,[38] on models placed in the center of the test core show the reverse trend. The Reynolds number based on boundary layer thickness was much larger for the measurements made on tunnel walls and, therefore, it appeared that there could be a change in the Reynolds number dependence. However, the present study was conducted over a range of Re_δ from 10^4 to 10^5 and this is the same regime where Hammitt and Hight, Gadd, and Green made their measurements, though at a lower Mach number. A discussion of possible reasons for the observed differences, together with correlations of incipient separation and the properties of well separated interaction regions, is given in Section 3.3 and 3.4.

Finally, in Section 3.5, we discuss the basic unsteadiness of separated interaction regions in hypersonic flow. Although, in the author's opinion, it has received very little attention, it is potentially one of the most important characteristics of these regions. This aspect of viscous interaction regions is of interest to aero-acoustical and fatigue engineers who wish to calculate the structural and dynamic loads on the aircraft's skin and the instrumentation attached to it, and to the control systems designer who wishes to draw up specifications for the servosystems. However, from our viewpoint, the most important question is whether the fluctuating component of the flow field makes a significant contribution to the basic fluid mechanics in terms of mean size and properties of the interaction regions. A correlation of measurements made on the flat plate under hypersonic highly cooled wall conditions is given, together with data obtained earlier on adiabatic walls. Very large fluctuating pressure levels were found in the reattachment region of both wedge- and externally-generated shock-induced separated flows, and the measured rms values are compared with earlier measurements made in supersonic flow under adiabatic wall conditions.

2. EXPERIMENTAL PROGRAM

The experimental program was conducted in Cornell Aeronautical Laboratory's 48" and 96" shock tunnels. When run under tailored interface conditions at low incident shock Mach numbers, running times greater than 25 milliseconds are obtained in the 48" tunnel, and unit Reynolds numbers of up to 80×10^6/ft are generated in the 96" tunnel, as shown in Fig. 1. Measurements were made at nominal Mach numbers of 6.5, 7.9, 8.6, 11.3, 13.0 and 14.7 by changing the nozzle geometry, at Reynolds numbers from 10×10^6 to 100×10^6 and at stagnation temperature ratios from 0.1 to 0.4 by varying the driver pressure and the incident shock Mach number, respectively. The free stream conditions at which the measurements were made are listed in Table I.

Regions of viscous interaction created both by the impingement of an externally generated shock onto a turbulent boundary layer over a flat plate and in a two dimensional flat plate-wedge compression corner were studied. The strength of the shock- or wedge-induced interaction was varied by changing the angle of the shock generator or wedge, respectively, so that measurements could be obtained in attached, incipient separated and well separated regions at each free stream condition chosen. Photographs of the two models used in these studies are shown in Figs. 2a and 2b. The basic flat plate, which is 18 inches in width, was instrumented with 40 pressure, 28 skin friction and 60 heat transfer closely-spaced gages. The outputs from these gages were recorded simultaneously. The shock generator, which could be placed at angles of up to 20° to the free stream, could also be translated both parallel and perpendicular to the flat plate so the point of shock impingement could be closely controlled. The wedge section of the flat plate-wedge model, which was 12 inches in length, could be adjusted up to 36° relative to the flat plate. Three interchangeable flat plate leading edges 15, 28, and 48 inches in length were used in the test program.

To make a meaningful study of regions of shock wave-turbulent boundary layer interaction, measurements of both the mean and the fluctuating flow field must be obtained. The present studies indicated that to obtain an accurate power spectrum for surface pressure a frequency response up to 100 kHz was required. The measurements of surface shear and heat transfer indicated that a frequency response of at least 10 kHz was required to follow the motion of the separation and reattachment points. We employed two types of pressure transducers in the present study. CAL-designed and constructed lead zirconium titanate piezoelectric transducers were used to obtain essentially the mean pressure, though the transducer-orifice combination could follow fluctuations up to 10 kHz. A second flush-mounted transducer, especially designed for high frequency measurements by PCB in Buffalo, N.Y. was used to obtain mean and fluctuating surface pressure measurements up to frequencies of 120 kHz. To prevent a resonance a special mounting system was used (see Fig. 3) to lock the gage firmly into the model. A thin insulating barrier of aluminized mylar was attached to the diaphragm of the transducer to prevent thermal heating effects.

To define accurately incipient separation and the positions of the separation and reattachment points in regions of shock wave-turbulent boundary layer interaction, we have used a CAL-developed gage which directly measures surface shear. This transducer, shown in Fig. 4, consists of a diaphragm which is supported flush with the model surface by two piezoceramic beams, which develop a charge when placed in bending by a surface shear on the diaphragm. A third beam is used to provide acceleration compensation. The beams are connected electrically to eliminate thermal, and normal and transverse pressure effects. An FET impedance transform circuit is mounted within the unit to eliminate cable noise at low levels of skin friction. The very large dynamic loads generated on the transducer during tunnel shutdown, when run at the high dynamic pressures (up to 15,000 $lb+/ft^2$) used in our studies, originally caused the diaphragms to be torn from the supporting beam. This problem was overcome by careful design of the flexure and by mounting the transducer in the seismic mass-rubber suspension system shown in Fig. 4.

The severe heating gradients which occur in the separation and reattachment regions make it important to minimize transverse heat conduction by making the surface of the model from a poor heat conductor. We have used platinum thin-film resistance thermometers which sense the transient surface temperature of a pyrex substrate. Because the platinum thin film has negligible thermal capacity, the temperature history of the surface can be related directly to the instantaneous heat transfer by classical semi-infinite slab theory. Analog networks were used to transform the outputs of the gages to a voltage which is directly proportional to the heat transfer rate. The basic thin-film gage has a frequency response of over 50 kHz.

The outputs from the transducers were recorded on a NAVCOR magnetic drum system and on a high frequency FM tape recorder, and also monitored on oscilloscopes. The NAVCOR system, which holds 48 channels in digital form, is essentially a low frequency system, whereas the 18 channel AMPEX FM recorder had a range of 0 to 1 MHz and was used to record the fluctuation data. The fluctuation measurements were recorded in analog form and subsequently processed by an analog-to-digital conversion/data storage system and digital computer program using a fast Fourier transform to yield the statistical properties of these measurements.

3. DISCUSSION AND CORRELATION OF EXPERIMENTAL MEASUREMENTS

3.1 Introduction

The objective of this experimental program was to obtain measurements of the mean and fluctuating properties of attached and separated turbulent interaction regions to determine how the strength and nature of the disturbance, the character of the undisturbed boundary layer, and the Mach number and Reynolds number upstream of the interaction influence the properties and development of these regions. Of course, turbulent interaction regions can be promoted in numerous physical situations; however, from the viewpoint of developing theoretical models and scaling parameters to describe these flows, measurements on regions of shock wave-boundary layer interaction resulting from an oblique shock incident on a flat plate turbulent boundary layer or in a compression corner, where neither separation nor reattachment is controlled by model geometry, are of most value. Pressure, heat transfer and skin friction measurements were made in shock- and wedge-induced interaction regions at Mach numbers from 6.5 to 13.0 for a series of shock generator and wedge angles so that attached, incipient separated and well separated flow could be examined at each condition. The Reynolds number and wall-to-free stream stagnation temperature ratio were varied at selected Mach number conditions to examine the effect of these parameters on the size and properties of the interaction regions. The test conditions at which the measurements were made are shown in Table I.

As in our earlier studies of laminar viscous interaction regions, we examined the time required to establish a steady separated turbulent interaction region and the effects of the finite model span. The fact that the interaction lengths obtained in the present study were an order of magnitude smaller than the laminar interactions examined earlier ensured that time establishment and span effects would be less important. In fact, the mean properties of separated turbulent interaction regions were established within 1 millisecond after the establishment of steady flow in the tunnel, a small fraction of the up-to-25 millisecond available test time. A model span of

18 inches was chosen for this program because increasing the model span to 24 inches or adding side fences did not cause a measurable change in the center line properties of the largest separated interaction region examined.

In addition to the studies of the shock- and wedge induced interaction regions skin friction and heat transfer measurements made on the basic flat plate provided an opportunity of evaluating some of the semi-empirical flat plate prediction methods in the hypersonic non-adiabatic wall regime where little experimental data is available.

3.2 Flat Plate Measurements

The methods for predicting the skin friction and heat transfer to the surface beneath a turbulent boundary layer depend to some extent upon experimental measurement to determine semi-empirical constants contained in the formulation. Thus the accuracy of these methods depends both on the precision of the experimental measurements and the range of the basic parameter covered in the experiments. Recently, the theories of Spalding and Chi,[42] Van Driest,[43,44] Coles,[45] and Sommers and Short[46] have been re-examined, with emphasis on their ability to predict skin friction and heat transfer to highly cooled surfaces in hypersonic flow. Whereas Bertram[47] and Cary[48] find best agreement between experimental measurements and the Spalding and Chi method, Hopkins and Inouye[48] claim the "Van Driest II" theory is superior in predicting the properties of flat-plate turbulent boundary layers under highly cooled hypersonic conditions. In part, the agreement, or lack of it, between theory and experiment results from the framework in which the experimental results have been evaluated and the assumptions made on the magnitude of the Reynolds analogy factor.

A comparison between the measurements made in the present study on the flat and the semi-empirical theory of Spalding is shown in Fig. 5. It can be seen that the Spalding-Chi method, though in reasonable agreement with the measurements at low hypersonic Mach numbers, underestimates the heat transfer and skin friction by significant amounts at Mach 13. In this correlation we calculated the effective length of the turbulent boundary layer x_E by equating the momentum thickness of the laminar boundary layer at transition to the momentum thickness of a turbulent boundary layer which was assumed to grow from a vertical origin a distance ℓ_v upstream of transition, and thus $x_E = L + \ell_v - \ell_t$ where L and ℓ_t are the distance from the leading edge to the measurement station and transition point, respectively. Here we defined the end of transition as the point in the transition region where the heat ransfer rate reaches a maximum. For measurements at Mach 6, 5, 7.9 and 8.6 the boundary layers were fully turbulent within several inches from the leading edge; at Mach 11.3 and 13 the transition points were 12" and 24" from the leading edge giving effective length of the turbulent boundary layer at the measurement stations of 32 and 26.5, respectively. Thus, although errors can be introduced in calculating Re_x because of uncertainties in the relationship between Re_θ and Re_x at high Mach numbers, this moves the measurements along the abscissa and thus would not change the conclusions significantly.

The simultaneous measurements of skin friction and heat transfer made during the test program provided us with the opportunity to evaluate the Reynold analogy factor for turbulent boundary layers under high Mach number, non adiabatic wall conditions where little experimental evidence is available in air. Fig. 6 shows the measurements made in the present study together with those of Neal[50] and Wallace. Bertram and Neal's[51] modification to Karman's incompressible theory is in closer agreement with the measurements than the frequently used relationship suggested by Coburn[52] which gives a value for our conditions 20% larger than measured in experiment.

3.3 Development and Properties of Separated Interaction Regions

The object of the studies described herein was to determine the effect of Mach number and Reynolds number of the free stream, wall-to-free stream stagnation temperature ratio and initial properties of the boundary layer as well as the strength and nature of the interaction on the development and properties of both shock- and wedge-induced interaction regions. With few exceptions the measurements which have been made in studies to determine the characterization and scaling laws of turbulent viscous interaction regions were obtained with instrumentation having very limited frequency response. However, the present studies indicated that the fluctuating component of a turbulent separated flow field is of considerable importance at hypersonic speeds. The separation and reattachment regions are areas in which the surface properties show the greatest degree of fluctuation. The output traces from skin friction gages just upstream and downstream of separation, examples of which are shown in Fig. 7, indicate that the separation point can move as much as two thirds of a boundary layer thickness about a mean position. Because of the large pressure gradients in these regions, this movement is reflected in large pressure fluctuations. However, we will defer a discussion of the aspect of the subject until Section 3.5 and concentrate on observations of the mean properties of the interaction regions.

Separation is first observed in the laminar sublayer and a well-defined separation bubble is clearly visible as shown in Fig. 8a. The initial development of the separation region takes place by an elongation into the laminar sublayer, with the separation and reattachment shocks combining within the boundary layer to form a single shock. Only when the separation point has fed well forward of the junction is a well-defined plateau region formed. Then, in contrast to laminar interaction regions, the separation shock originates at the bottom of the boundary layer and is contained within the boundary layer until it coalesces with the reattachment compression process. The corresponding pressure, heat transfer and skin friction distributions are shown in Fig. 9 and, in contrast to our measurements in laminar separated regions, exhibit an increase in heat transfer through separation to reach a well defined plateau just upstream of the reattachment compression process.

In separated regions induced by externally generated shocks, separation first takes place in the region where the incident shock strikes the laminar sublayer (see Figs. 11 and 12). The separation point moves forward with increasing strength of the incident shock until the separation shock becomes visible in the inviscid flow downstream of the incident shock (see Fig. 11b); as yet separation is still downstream of the point where the incident shock passes through the edge of the boundary layer. For large incident shock strengths, the separation point feeds well forward of the incident shock and boundary thickening occurs ahead of the incident shock in an analogous fashion to laminar flow separation. However, as in wedge-induced separated regions, viscous-inviscid interaction takes place almost entirely within the original boundary layer. The structure wedge- and shock-induced turbulent interaction regions at Mach 13 (shown in Fig. 13) are similar to those at Mach 8; however, as we might anticipate, the viscous interaction region and the associated shocks are even more firmly embedded within the original boundary layer. The measurements made for the shock- and wedge-induced interaction regions discussed above are shown in Figs. 14 and 15.

The mean distribution of skin friction, heat transfer and pressure for shock- and wedge-induced interaction regions were similar for well separated flows with identical total pressure rises. Both the pressure and heat transfer distributions are characterized by well-defined plateaus in the recirculation region and large gradients in the separation and reattachment regions. The maximum heat transfer rates generated in the reattachment regions of these flows are, of course, of considerable importance. We found that for separated interaction regions the maximum pressure and heat transfer measurements over the Mach number range from 6.5 to 13 could be correlated in the form

$$\frac{q_{MAX}}{q_o} = \left(\frac{p_{MAX}}{p_o}\right)^{0.85},$$

as shown in Fig. 16, with data from other sources. The plateau pressure and heat transfer in the separated region are also of interest and correlations of these measurements together with other studies at lower Mach numbers are shown in Figs. 17, 18, 19. The variation of plateau pressure with Mach number follows the trends predicted by the simple theory proposed by Tucker and Roshotko and differs markedly from those predicted by the Todisco and

Reeves theory. Plotted in terms of the Chapman scaling parameter and Mach number, as shown in Fig. 18, we find that although the lower Mach number measurements follow the correlation proposed by Enrich and Popinski, the measurements above Mach 9 tend toward the correlation proposed by Erods and Pallone.[77] The correlation of heat transfer in the plateau pressure regions suggests that this quantity can be computed from the plateau pressure ratio.

The effects of Reynolds number, Mach number, and wall-to-free stream stagnation temperature ratio on the scale of the interaction region have been a source of controversy since the experimental studies of these regions were begun. Dealing first with the less controversial aspects, our studies at Mach numbers from 6 to 13 showed that the length of the separated region decreased with increasing Mach number and decreasing wall-to-free stream temperature ratio, though the latter trend was weak. The Mach number dependence is shown graphically in the schlieren photographs shown in Figs. 20, 21 and 22 and this trend is consistent with the results of earlier experimental studies in supersonic flow. The weak effect of wall-to-free stream temperature ratio is in marked contrast to behavior of laminar interaction regions, but is again consistent with the results of studies in supersonic flow and those of Gulbran et al[53] and Elfstrom at hypersonic speeds.

The influence of Reynolds number on the length of the separated regions remains unresolved. Most of the early studies of shock wave-turbulent boundary layer interaction were made in the turbulent boundary layer over a tunnel wall. Major discrepancies were found between experiments conducted under the same nominal conditions in different experimental facilities and, for example, the measurements of Bogdonoff and Kepler differed considerably from those of Gadd (see Ref. 13) for identical free stream Mach numbers and interaction strength when both experimenters had indicated that there was little effect of free stream Reynolds number on the length of the separated region. Hammitt and Hight[40] found that the separated length was influenced by Reynolds number; however, their results were not in quantitative agreement with earlier measurements with identical free stream conditions and interaction strengths but in different facilities. It was concluded at that time that both the model and tunnel geometry were important factors in the absolute scale size of the interaction and there appeared to be little object in obtaining correlation of scale size in terms of the initial boundary layer thickness and properties of the free stream. However, the measurements of Hammitt and Hight[40] and more recently by Green,[41] Roshko and Thomke,[54] all on tunnel walls, indicated that increasing Reynolds number decreases the length of the interaction region. In contrast, the studies of Chapman, Kuehn, Larson and Kuehn, and more recently our studies and those of Elfstrom et al[55] at hypersonic speeds, all conducted on models mounted in the test section, have indicated that an increase in the Reynolds number increases the length of the separated region. This Reynolds number effect in our studies is shown graphically in the schlieren photographs of the separated regions in Figs. 21 and 22 for Mach 7.9 and 13 airflows. Both wedge- and shock-induced interactions exhibit the same qualitative and quantitative variation with Reynolds number over the entire Mach number range (6.5 to 13) investigated in our studies.

The reason for the differences in Reynolds number dependence observed in these experiments is far from clear. Tripping was employed to achieve turbulent boundary layers in Chapman et al and Kuehn studies, introducing the possibility that the boundary layer was not fully turbulent in the interaction regions. This argument has been advanced to discount the results from these studies. However, in our experimental studies, we tested at very large unit Reynolds numbers with large models (see Section 2) so that natural transition took place up to 27 inches upstream of the interaction (or several hundred boundary layer thicknesses) and the heat transfer and skin friction measurements upstream of the interaction indicated the boundary was fully turbulent.

There is a real possibility that there is a change on Reynolds number dependence; however, our studies were conducted over a range of Re_{δ} from 10^4 to 10^5 and this is in the same regime where Hammitt and Hight, and Green, made their measurements, though at lower Mach numbers. Because of the suspicion that both model and tunnel geometry may influence measurements on tunnel walls, as described in the following section, and the fact that significant nonequilibrium effects can exist in turbulent wall boundary layers well downstream of a nozzle exit, we believe that measurements made under these conditions must also be carefully examined.

3.4 Incipient Separation

A major objective of the program was to determine whether the incipient separation phenomenon at hypersonic speeds was independent of method of inducing interaction. If incipient separation can be induced on a flat plate-wedge compression surface for the same total pressure rise that it takes to separate an identical boundary layer with an externally generated oblique shock, then this has far reaching implications for the correlation and modeling of these flows. We also wished to determine how incipient separation varied with Mach number and Reynolds number of the free stream and wall-to-free stream stagnation temperature ratio, to develop correlations and compare with existing measurements.

The first appearance of a region of reverse flow adjacent to the wall, or a condition where there is a vanishingly small separated region, is referred to as incipient separation. Although in steady laminar flow we can define incipient separation as the condition where skin friction is positive everywhere in the interaction region, but at one point is vanishingly small, the definition for unsteady flow, like a turbulent interaction region, is not as simple. In the present study, where dynamic measurements of surface shear were made, we defined incipient separation as that condition where the time average of surface shear at one point only in the interaction region was zero. In the present studies the widely used separation criterion proposed by Kuehn,[37] which equates the first appearance of an inflection point in the pressure distribution to incipient separation, was examined in detail for both wedge-induced and externally generated shock-induced interaction regions. Our measurements indicated that this criterion seriously over predicted the pressure rise to achieve incipient separation in hypersonic flow regime, particularly for externally shock-induced interactions where separation was found to take place first well downstream of the point where the shock enters the boundary layer. A schlieren photograph of the incipient separation condition at Mach 6.5 is shown in Figure 10. Zero surface shear was first observed close to the point where the incident shock intersects the sublayer and, as shown in the figure, a separation shock is generated which is distinct from the reflected shock. Not until the separation shock has fed well forward of this initial point is there evidence from the pressure and heat transfer distribution that separation has occurred. On flat plate-wedge compression surfaces a separation bubble is first observed in the laminar sublayer and can be seen clearly in the schlieren photographs in Fig. 8a. As the strength of the interaction was increased beyond this condition, the presence of separation was indicated by heat transfer and pressure distribution. The insensitivity of pressure to detect small regions of separated flow has been found also in supersonic flow for externally generated shock-induced regions by Green,[41] and for wedge-induced interaction regions by Spaid and Frishett.[56] Oil flow measurements were used in these two studies to detect incipient separation which was found to occur in significantly smaller pressure rises (by a factor of over 2 in Spaid and Frishett studies) than if changes in the pressure distribution were used to detect incipient separation. In the present studies the pressure rise for incipient separation using separation criteria based on skin friction measurements and schlieren photographs was from 10 to 30 percent smaller than if the separation criteria were based on changes in the pressure distribution.

The wedge angles and flow deflection angles (twice the angle of the shock generator) to induce incipient separation in wedge- and shock-induced interaction regions at Mach numbers from 6.5 to 13 determined in the present study are shown in Fig. 23. It would first appear that there is a significant difference in the strength of the interaction required to promote separation in the two types of flow studied. However, because of the large turning angles, the two-stage compression process through the incident and reflected shocks is more efficient than the wedge compression process and the pressure rise to incipient separation is almost identical for wedge- and shock-induced interaction regions. Thus, for these two superficially very different types of flow we find the important and somewhat surprising results that the pressure rise to induce incipient separation is independent of the mechanism by which it is promoted. A correlation of the two sets of measurements is shown in Fig. 24 in terms of the pressure, total pressure rise $\frac{p_{INCIP} - p_0}{p_0}$ and the parameter $M^3 C_{f_0}$ derived from a balance between the inertial and viscous forces at the wall $\frac{\partial \tau}{\partial y} = \frac{\partial p}{\partial x}$, which in the spirit of Chapman's analysis can be approximated by $\frac{p_{INCIP} - p_0}{L} \sim \frac{\tau_w}{\delta}$ where the scale of the interaction L is approximately $M_0 \delta_0$ and thus $\frac{p_{INCIP} - p_0}{p_0} \sim M^3 C_{f_0}$. In addition to showing the correlation between the measurements from the two types of interaction we have included data from other sources at lower Mach numbers. The measurements appear to follow the "Chapman like" scaling law up to Mach 11.3, with the measurements at Mach 13 falling below this line. It is clear from the present and previous studies that the pressure rise to induce incipient separation increases with increased Mach number, though at hypersonic speeds the flow deflection angle to induce separation is not a strong function of Mach number. The effect of Reynolds number is weak; however, our studies as well as those of Kuehn,[37] Sterrett and Emery[38] and Elfstrom et al[55] indicate increasing Reynolds number tend to push an attached region close to separation. The tunnel wall measurements of Roshko and Thomke,[54] which show consistently higher pressure ratios to induce incipient separation than the other studies, exhibit the reverse trend in Reynolds number. This is shown more clearly in Fig. 25 where we have plotted wedge angle to induce incipient separation versus the Reynolds number based on boundary layer thickness. Also plotted are the measurements of Spaid and Frishett made at Mach 2.9 also on a tunnel wall. In these latter studies incipient separation was determined from observations of the surface pressure and oil flow measurements. Apart from the large discrepancies in the incipient separation condition determined from pressure and oil flow measurements, the results imply that the detection method itself may introduce a Reynolds number dependence. The difference between incipient separation as indicated by oil measurements and that deduced from pressure measurements is so large that one questions whether the fluctuating nature of the turbulent boundary layer close to incipient separation, together with the low response characteristic of the oil film technique, might have combined to yield the very low wedge angles for incipient separation measured by Spaid and Frishett.

In attempting to explain the Reynolds number trends found by Kuehn, Roshko and Thomke observed that Kuehn's measurements may have been influenced by near-transitional and tripped boundary layer phenomena which result in a nonequilibrium boundary layer in the interaction region. However, they fail to discuss the fact that the characteristics of a boundary layer on a tunnel wall in which their measurements were made may also differ from the equilibrium turbulent boundary layer over a flat plate. Recent experimental studies by Wallace,[57] Bushnell et al[58] and Fiore[59] and theoretical studies by Bushnell[51] have indicated that the structure of a turbulent layer on a tunnel wall may differ significantly from the boundary layer over a flat plate because of the nonequilibrium, nonsimilar effects introduced by the favorable pressure gradient history. The difference between these flows is demonstrated most graphically under cooled walled conditions where theoretical studies indicate this effect causes the total temperature-velocity relationship to depart from the Crocco relationship. The correlations of total temperature and velocity obtained by the above authors indicate that, although measurements through flat plate boundary layers are in agreement with the Crocco relationship, the total temperature is related to the velocity through the boundary layer on the tunnel wall by a quadratic relationship. Bushnell's studies have indicated that distances on the order of 60 to 100 boundary layer thicknesses in a constant pressure region downstream of the nozzle may be necessary before an equilibrium boundary layer similar to that over a flat plate is established. We feel that it might be pertinent, therefore, to also reserve judgment on the incipient separation trends with Reynolds number from measurements obtained on tunnel walls.

3.5 Unsteady Characteristics of Turbulent Interaction Regions

A feature of both shock- and wedge-induced separated turbulent interaction regions studied in our experimental program was the inherent unsteady characteristics of these flows. Apart from interest in the rms fluctuation levels and power spectra from the designer's viewpoint, an important question is whether the fluctuating component of the flow field makes a significant contribution to the basic fluid mechanics in terms of the mean size and properties of the interaction regions. This leads us to question whether a mean flow model can describe adequately a turbulent separated region in hypersonic flow.

The pressure fluctuation level in an attached turbulent boundary layer at hypersonic speeds under cooled wall conditions was determined from the wall pressure measurements at Mach 6.5, 7.9 and 8.6. The instrumentation used in the study is described in Section 2. The measurements, together with data obtained earlier under adiabatic wall conditions, are shown in Fig. 27. The theory shown in this figure was derived from the semi-empirical approach suggested by Lowson,[60] where Wallace's[61] electron beam measurements of the density across a hypersonic cooled turbulent boundary layer were used to find the "effective source" of the pressure fluctuations and leads to the formula

$$p' = 0.006 \frac{\rho_{es}}{\rho_e} q_\infty$$

where q_∞ is the dynamic pressure in the free stream and ρ_{es} and ρ_e are the local densities at the edge and at point of maximum density fluctuation in the boundary layer. Some "feel" for the disturbances in a turbulent boundary layer which give rise to the pressure fluctuations observed at the surface can be gained from the schlieren photograph of a Mach 11.3 constant pressure boundary layer shown in Fig. 26. The weak shock originating in the transition region can be seen in this photograph together with disturbances on the inviscid flow beneath this shock which have their origins at the inviscid flow-boundary layer interface. Measurements in the transition region of a hypersonic turbulent boundary layer indicated that the pressure fluctuations recorded there were of an order of a magnitude larger than in a constant pressure equilibrium turbulent boundary layer, as shown in Fig. 28.

Very large fluctuating pressure levels were found in the separated interaction regions of both wedge- and externally generated shock-induced separated flow. The schlieren photographs of wedge-induced interaction regions shown in Fig. 29 illustrate graphically both the unsteadiness in a turbulent interaction region at Mach 6.5 and an even greater degree of unsteadiness in a transitional interaction at Mach 15. The largest values of rms pressure fluctuations were found in the reattachment regions of these flows, as shown in Fig. 28, and could reach as large as two tenths of the dynamic pressure of the free stream. The pressure fluctuation levels found in the separation and plateau regions were smaller than those at reattachment primarily because the mean pressure levels were much smaller. The calculated value for $\acute{p}$ was found to be as large as 0.7 of the mean pressure close to the separation and reattachment points. This is slightly larger than found by Kistler in a step induced separated region at Mach 4. Our skin friction measurements suggest the gross movement of the separation and reattachment points in a major mechanism in the generation of such high fluctuation levels, with this movement resulting from shock-turbulence interaction. The extremely large pressure gradients in the separation and reattachment of hypersonic interaction regions ensure that small pressure perturbation resulting from shock-turbulence interaction will be amplified, inducing large pressure changes at a given point on the wall in the separation and reattachment regions. The power spectrum obtained from pressure measurements in the reattachment region shown in Fig. 30 supports this model and indicates that the greatest power is contained in the low frequency and of the spectrum. Our dynamic measurements of skin friction indicate that the motion separation and reattachment points were compatible with Strouhal numbers of 5×10^{-4} where the greatest power is contained. It is of interest to note that our measurements support those of Coe and Rechstein[62] who find that the power increases below a Strouhal number of 10^{-3}, whereas Speaker and Ailman[63] indicate that the power decays below this nondimensional frequency.

CONCLUSIONS

Measurements of the mean and fluctuating pressure, skin friction and heat transfer have been obtained in turbulent viscous interaction regions on flat plate-wedge compression corners and in incident shock-boundary layer interaction regions from Mach 6.5 to 13.0 at Reynolds numbers from 10 to 100 million.

Measurements of incipient separation, using surface shear measurements as the separation criteria, indicated that for the two interactions studied this condition was independent of the mechanism of inducing separation and could be expressed in the form $\frac{p_{INCIP} - p_0}{p_0} \propto M^3 C_{f_0}$. Incipient separation could not be determined accurately using surface pressure measurements. Wedge- and shock-induced separated regions having the same strength (total pressure rise) exhibited similar surface pressure, heat transfer and skin friction distributions. Correlations are presented of the pressure and heat transfer characteristics of these regions. The lengths of both shock- and wedge-induced separated regions were found to decrease with increasing Mach number, and decreasing Reynolds number and wall-to-free stream stagnation temperature ratio, though the latter trends were weak. Large rms pressure fluctuations of the order of a tenth of the free stream dynamic pressure were observed in the reattachment region of separated flows which are believed to result from the unsteady motion of the separation and reattachment points induced by shock-turbulence interaction.

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Table I

MAJOR TEST CONDITIONS

FREE-STREAM MACH NUMBER M_∞	RESERVOIR PRESSURE P_o (psia)	RESERVOIR TEMP. T_o(°R)	FREE-STREAM VELOCITY V_∞	FREE-STREAM TEMP. T_e(R)	FREE-STREAM DENSITY ρ_∞ – SLUGS/FT^3	REYNOLDS NUMBER (PER FOOT)	T_W/T_o	L_E INCHES
6.25	3750	5400	6360	430	3.02×10^{-4}	5.9×10^6	.16	21.4
6.50	1860	1400	4010	160	4.00×10^{-4}	12.0×10^6	.38	22.7
6.60	3060	1350	3960	150	6.75×10^{-4}	21.0×10^6	.39	24.1
6.60	4550	1420	4000	150	9.98×10^{-4}	31.0×10^6	.38	24.8
7.90	2670	1560	4280	120	9.0×10^{-4}	9.0×10^6	.35	20.4
7.90	4630	1590	4310	120	3.62×10^{-4}	16.0×10^6	.34	22.5
8.6	4570	1820	4640	120	2.12×10^{-4}	9.8×10^6	.30	20.4
11.4	19300	2850	5920	110	1.68×10^{-4}	11.0×10^6	.19	32.7
13.0	19900	3400	6600	110	6.42×10^{-5}	4.7×10^6	.16	26.4/46
14.9	19900	4200	7540	110	2.05×10^{-5}	17.0×10^6	.13	32.4

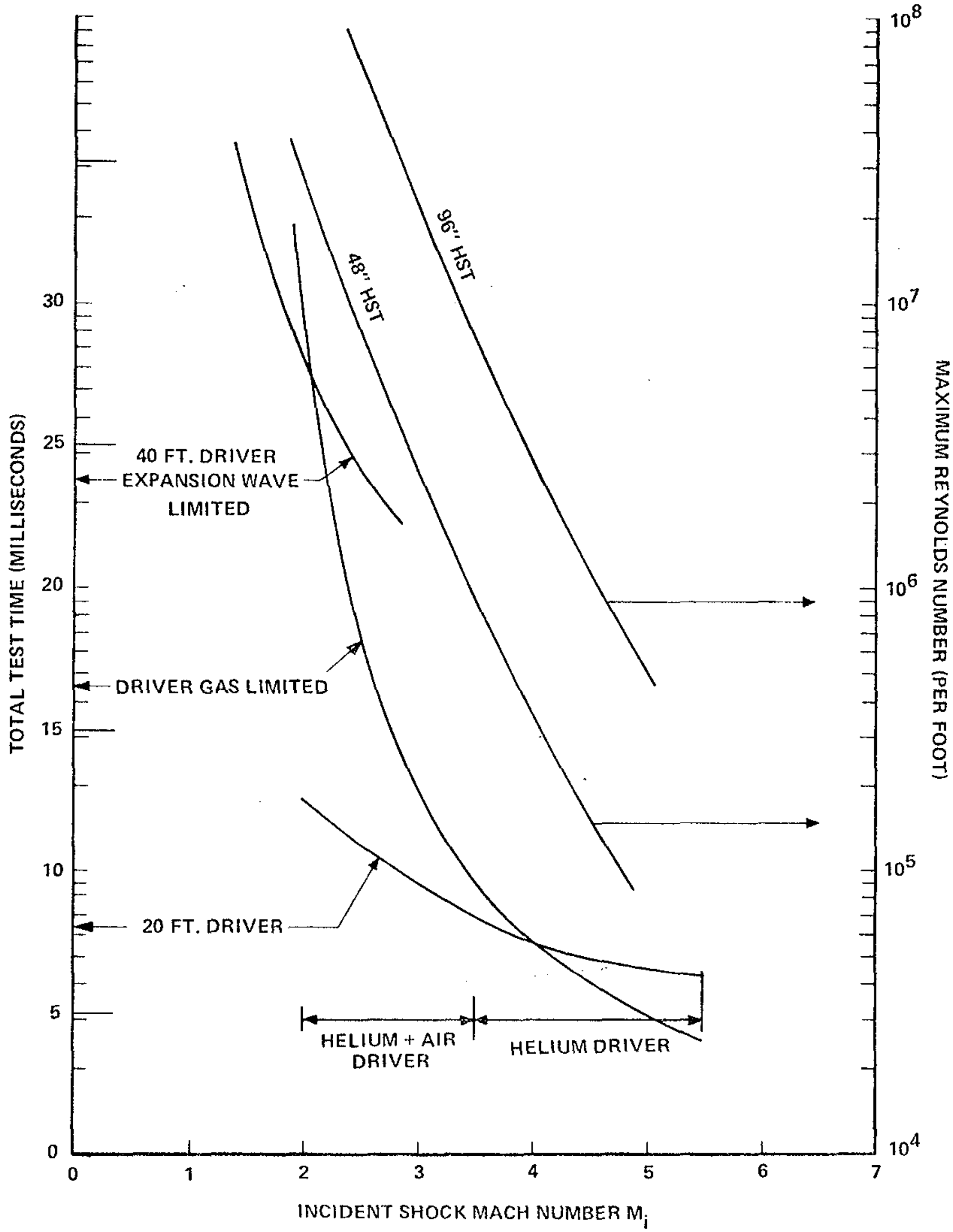
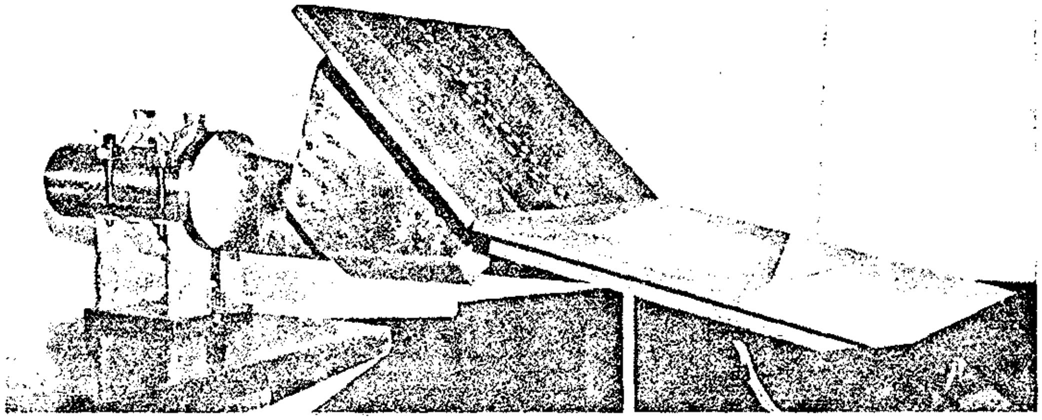
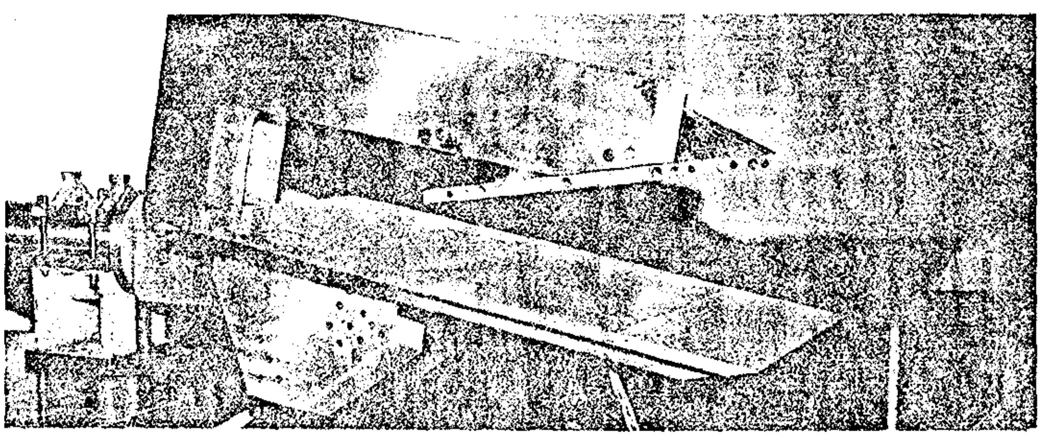


Figure 1 TEST TIME AND MAXIMUM REYNOLDS NUMBER CONDITIONS FOR THE CAL HYPERSONIC SHOCK TUNNELS

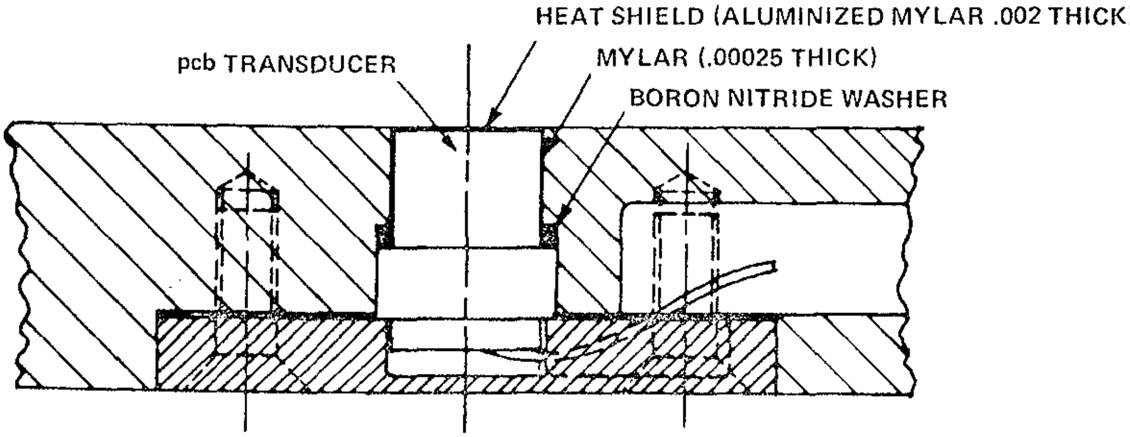


(a) FLAT PLATE–WEDGE COMPRESSION SURFACE



(b) SHOCK GENERATOR AND FLAT PLATE

Figure 2 SHOCK INTERACTION MODELS



(a) TYPICAL MOUNTING TECHNIQUE USED IN MODEL

Figure 3 HIGH FREQUENCY PRESSURE MOUNTING

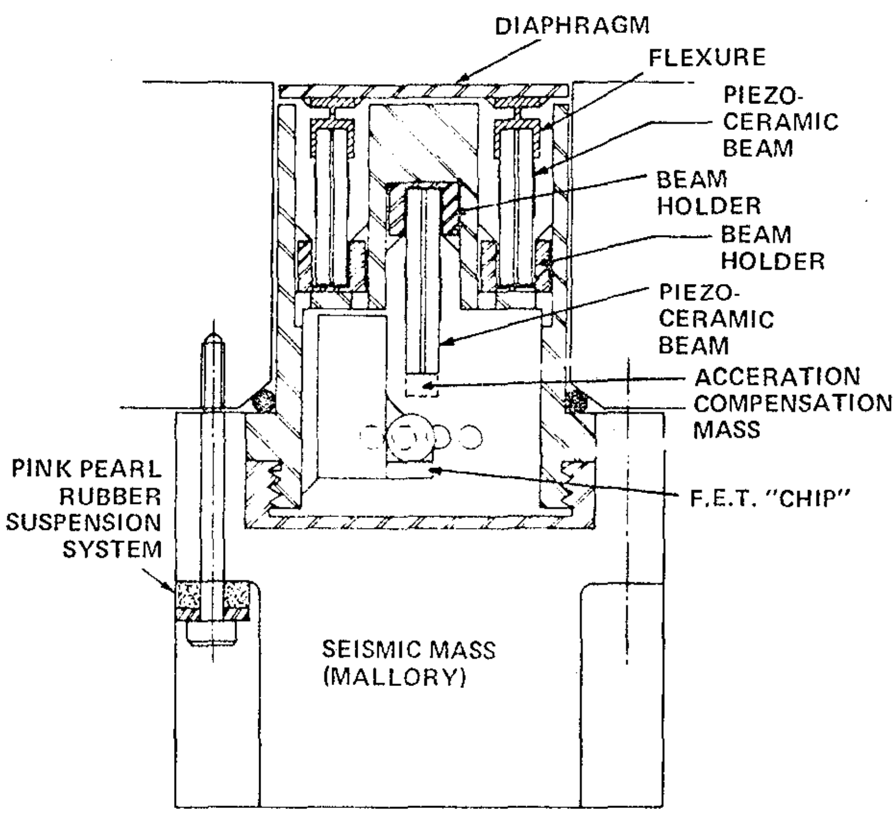


Figure 4 DRAWING OF SECTION THROUGH SKIN FRICTION TRANSDUCER

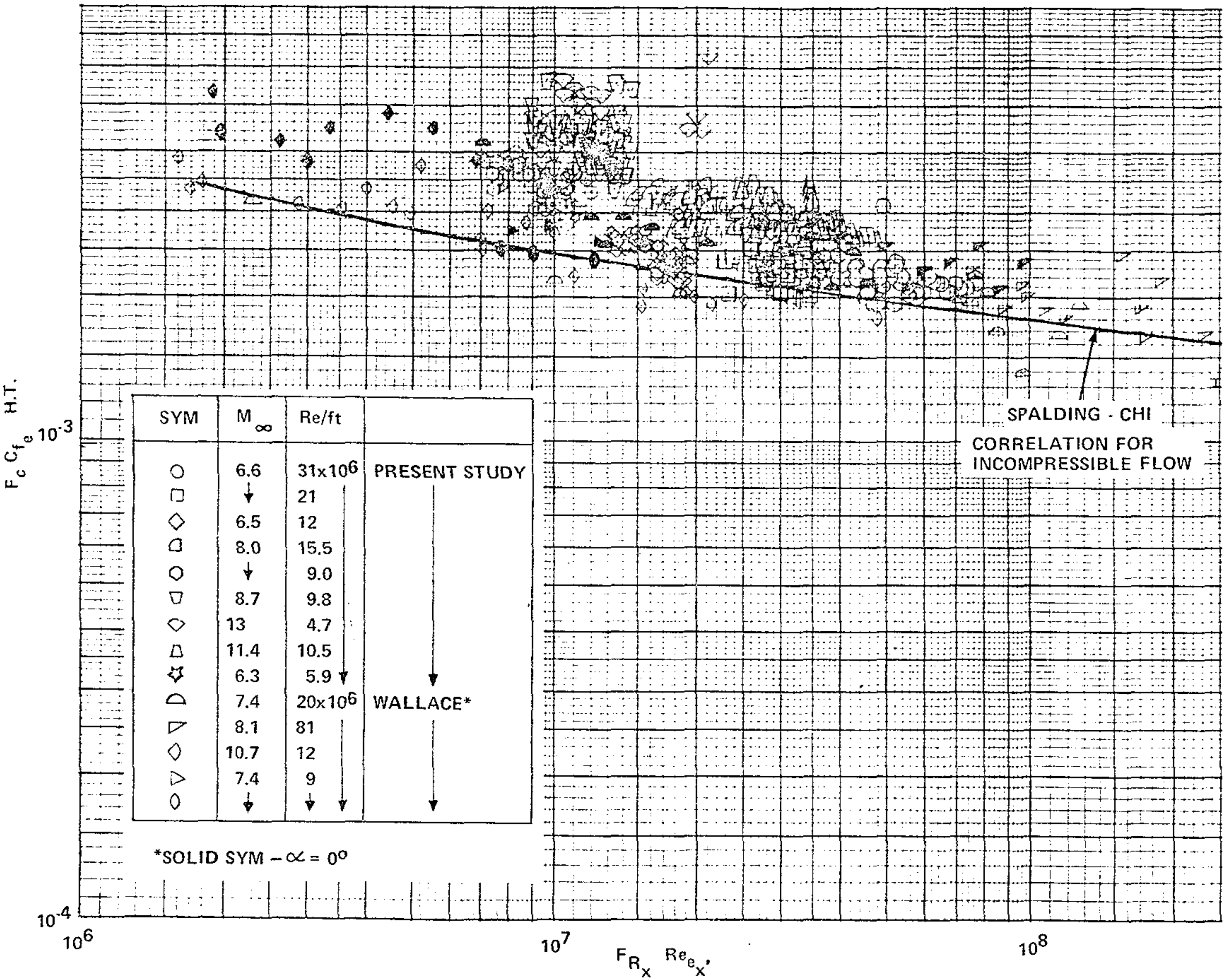
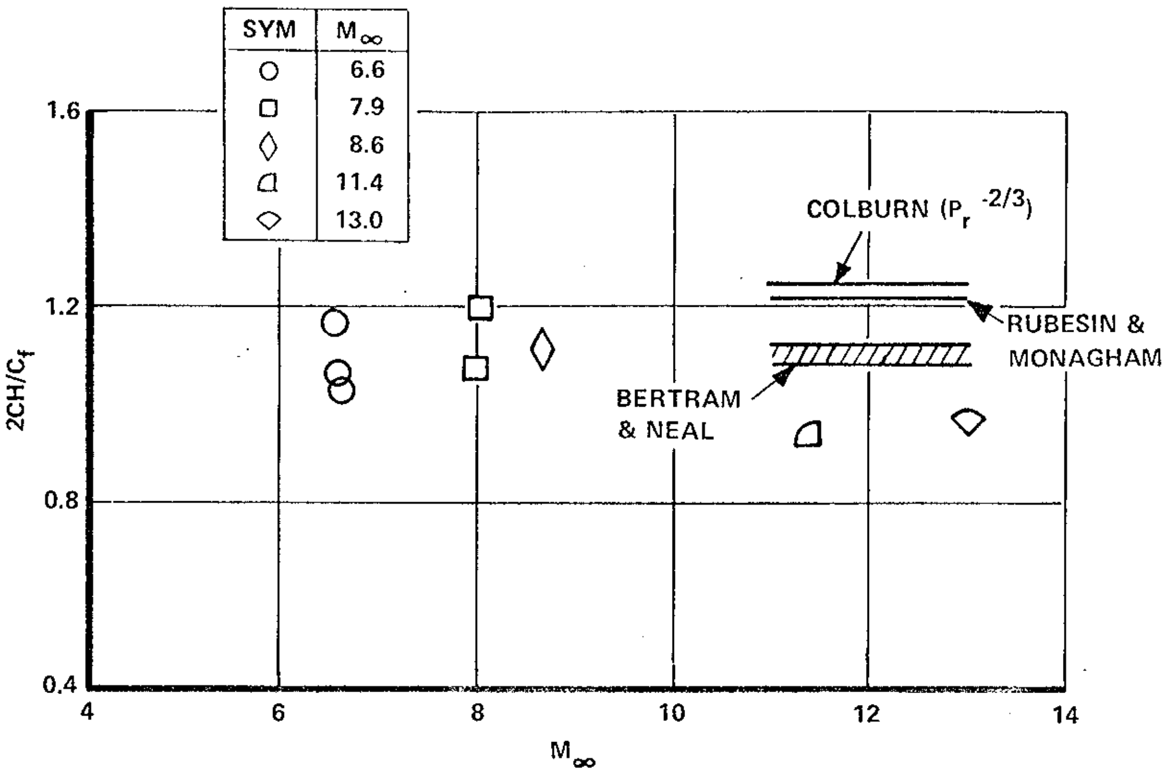


Figure 5 COMPARISON BETWEEN THE SPALDING-CHI-THEORY AND HEAT TRANSFER MEASUREMENTS IN HYPERSONIC TURBULENT BOUNDARY LAYERS OVER SHARP FLAT PLATES ($2\, C_H/C_f = 1$)



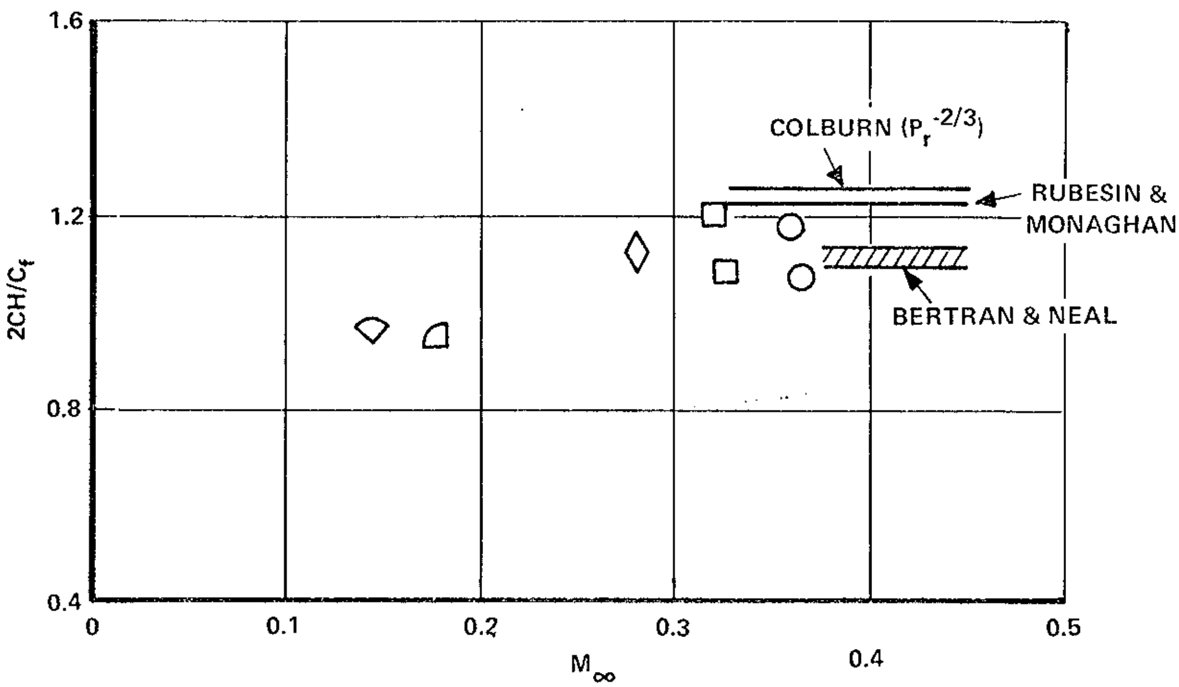


Figure 6 REYNOLD ANALOGY FACTORS FOR HYPERSONIC TURBULENT FLAT PLATE BOUNDARY LAYERS

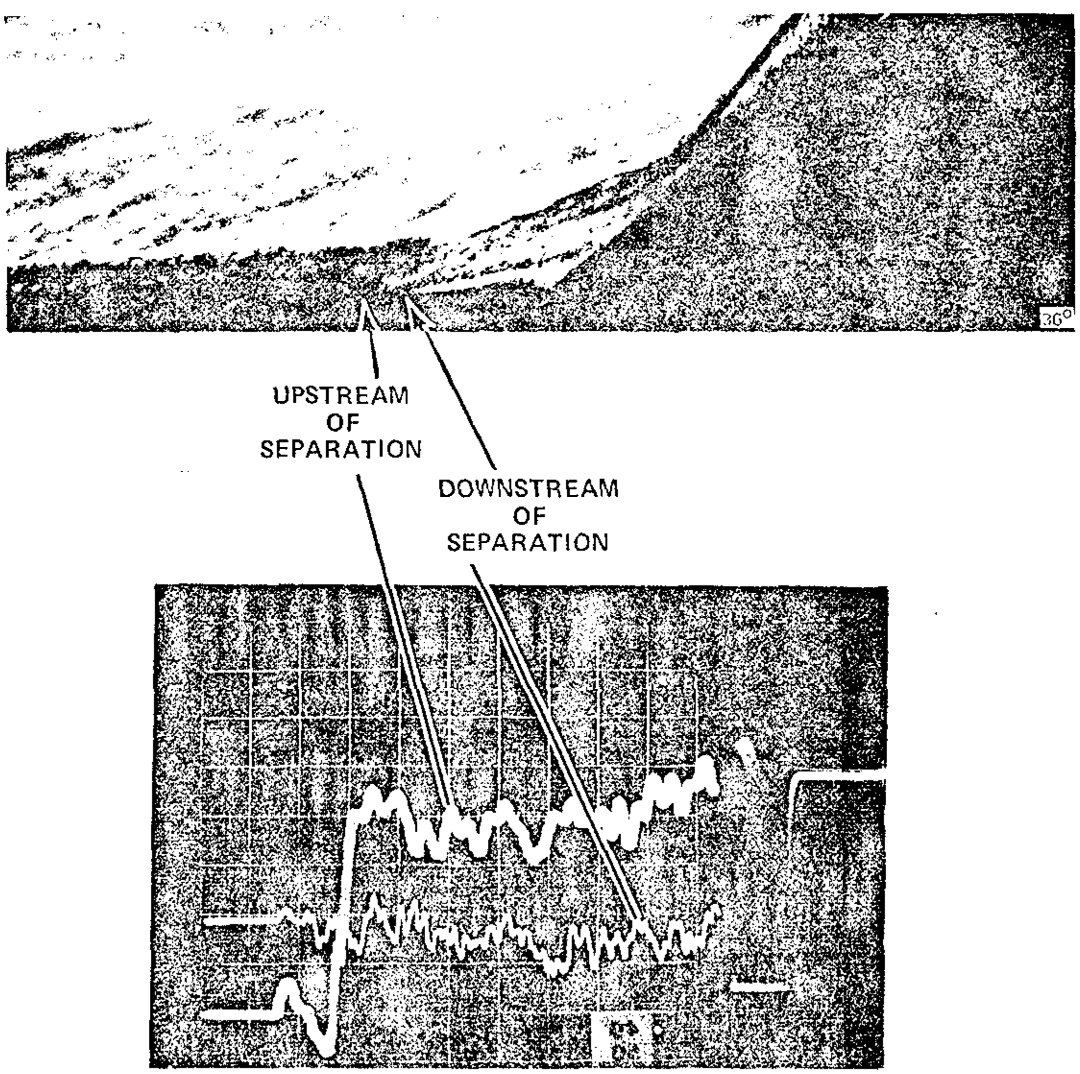


Figure 7 OUTPUT FROM SKIN FRICTION GAGES IN THE SEPARATION REGION

(a) WEDGE ANGLE = 27°

(b) WEDGE ANGLE = 30°

(c) WEDGE ANGLE = 33°

(d) WEDGE ANGLE = 36°

Figure 8 **THE DEVELOPMENT OF A WEDGE-INDUCED SEPARATED FLOW (M_∞ = 8.6 Re_L = 22.5 x 10^6)**

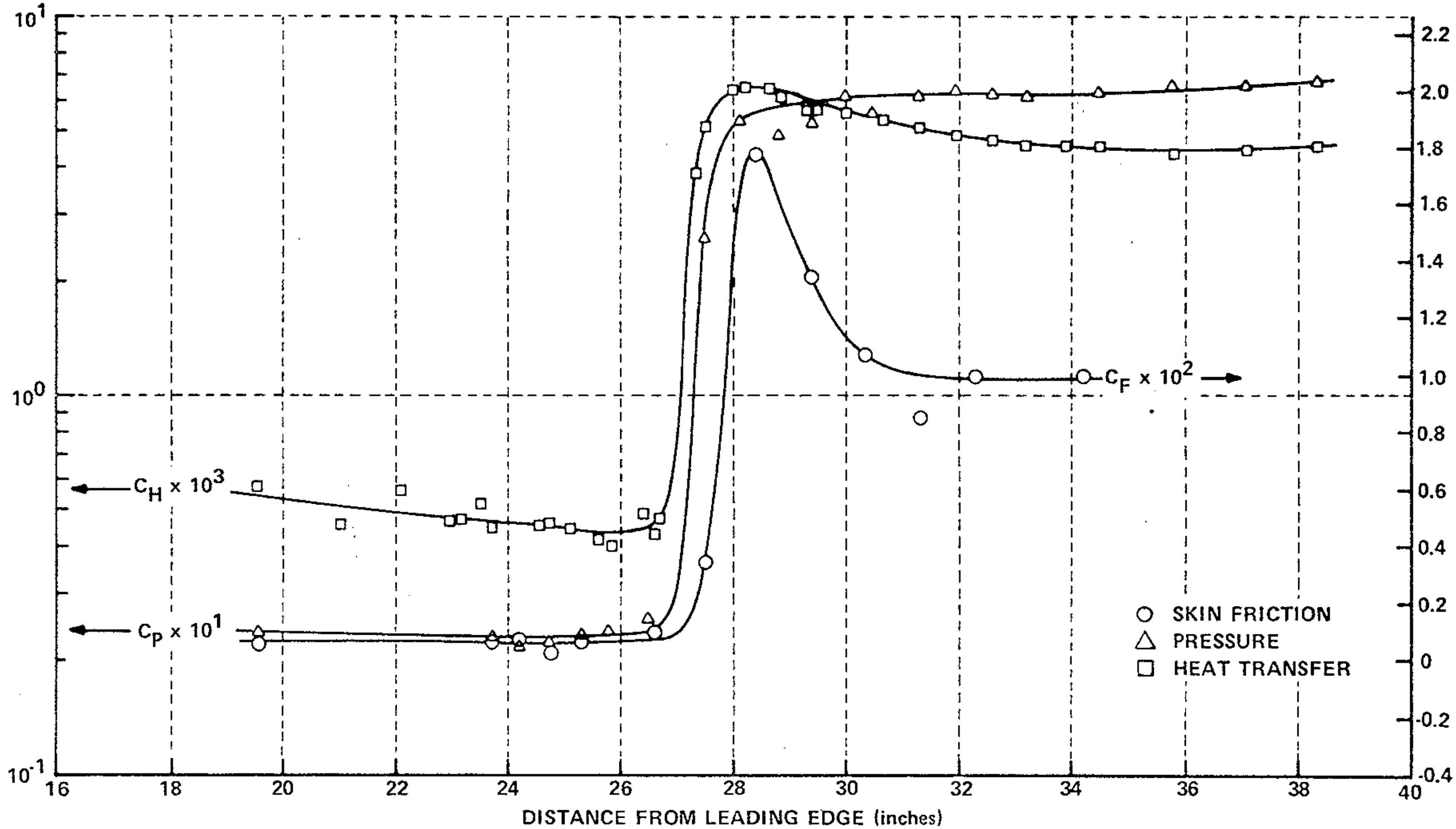


Figure 9a PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN WEDGE-INDUCED INTERACTIONS ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{WEDGE} = 30^o$)

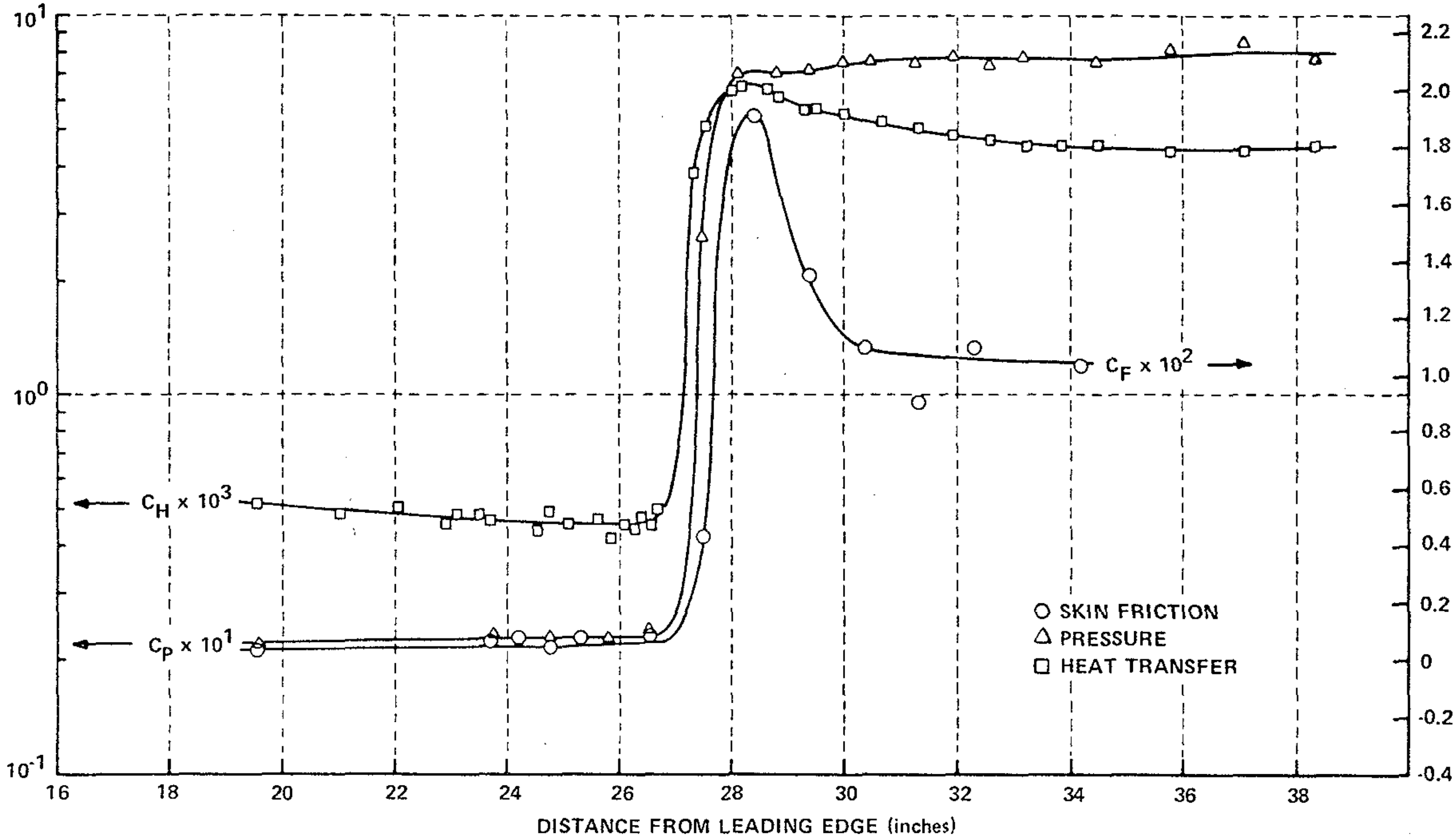


Figure 9b PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN WEDGE-INDUCED SEPARATED FLOW ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{WEDGE} = 27^o$)

40

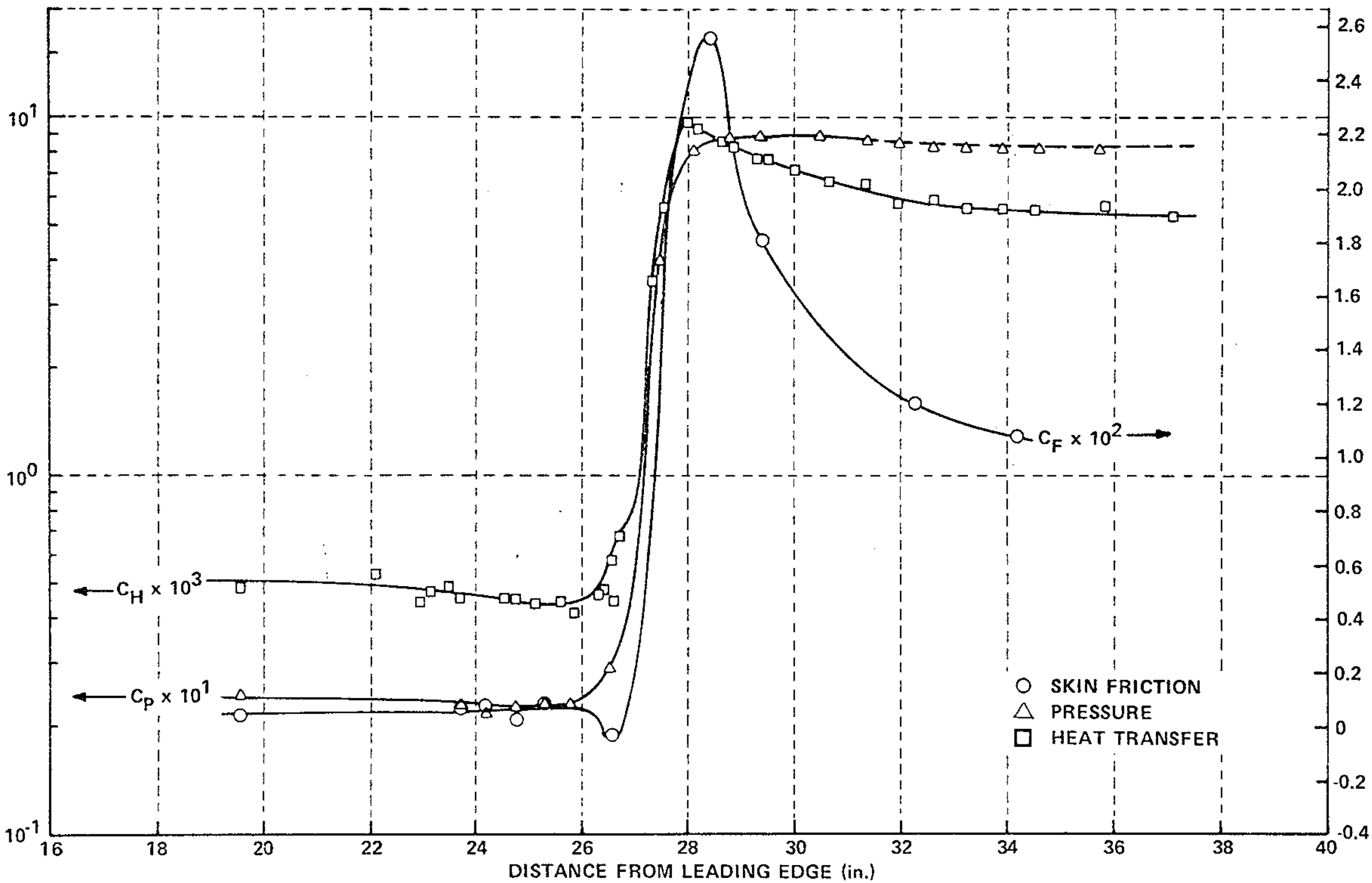


Figure 9c PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN WEDGE-INDUCED INTERACTIONS ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{WEDGE} = 33^\circ$)

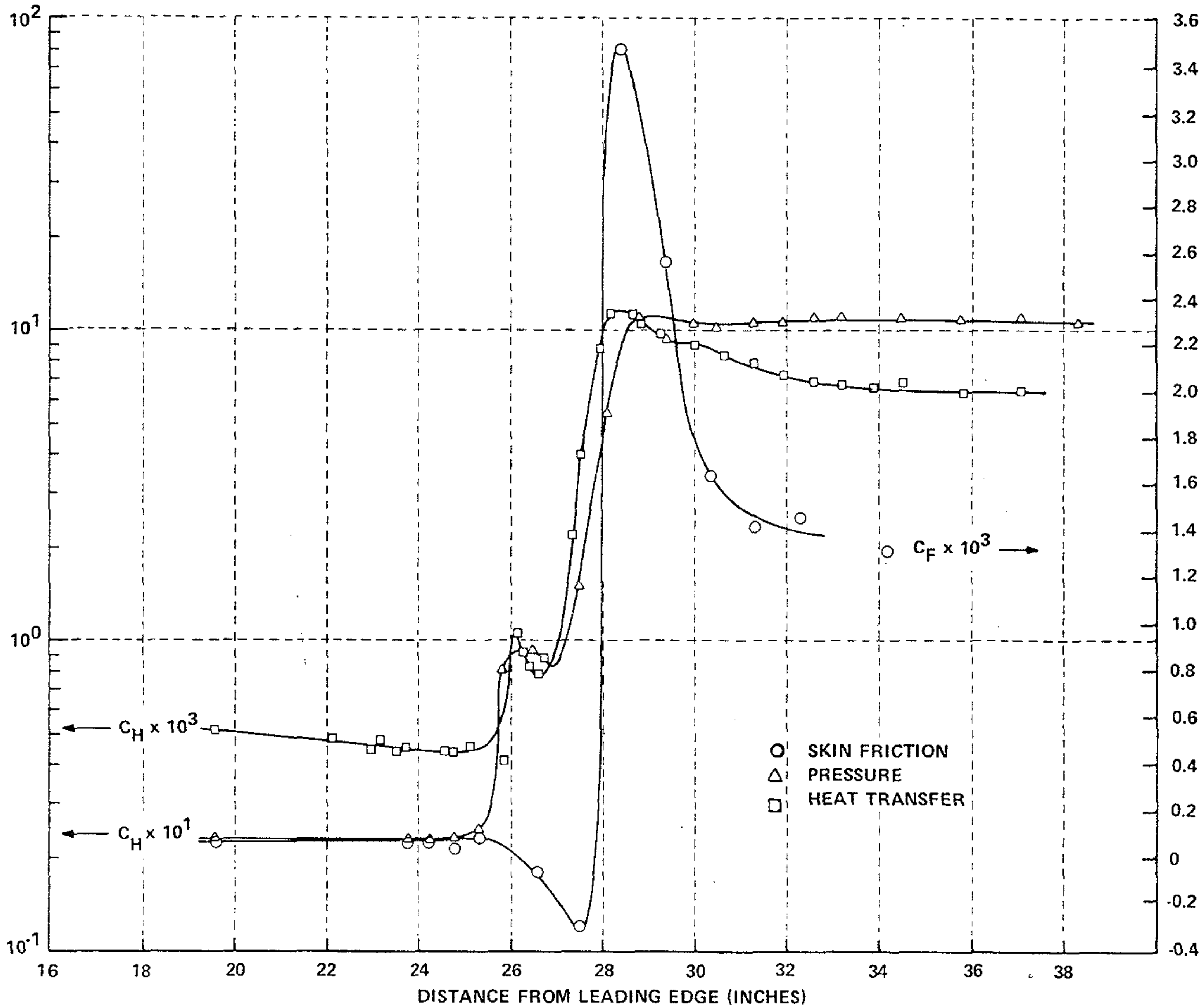


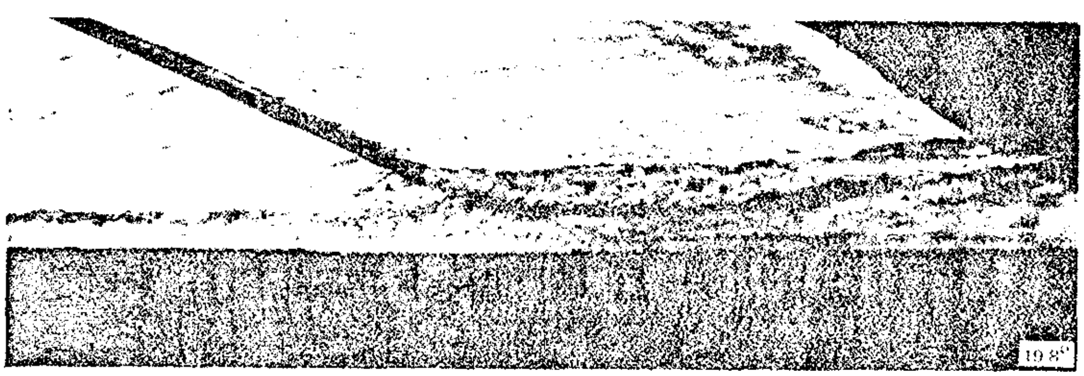
Figure 9d PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN WEDGE-INDUCED INTERACTION REGIONS ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{WEDGE} = 36^o$)

Figure 10 INCIPIENT SEPARATION AT MACH 6.5 AND $R_{e_L} = 27 \times 10^6$

(a) SHOCK GENERATOR ANGLE = 12.5°

(b) SHOCK GENERATOR ANGLE = 15°

(c) SHOCK GENERATOR ANGLE = 17.5°



(d) SHOCK GENERATOR ANGLE = 19.8°

Figure 11 THE DEVELOPMENT OF A SHOCK-INDUCED SEPARATED FLOW (M_∞ = 8.6 Re_L = 22.5 x 10^6)

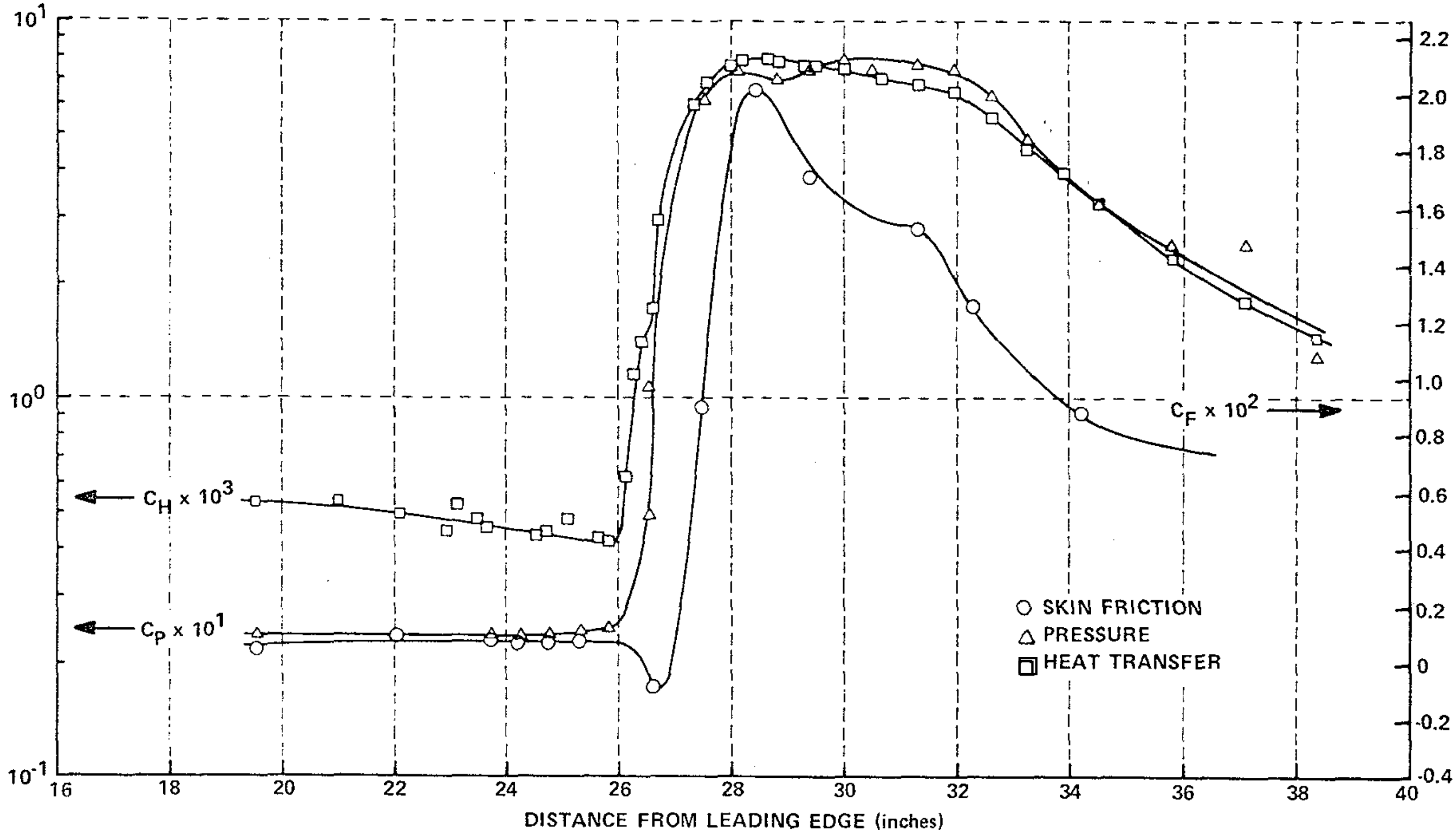


Figure 12a PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN SHOCK-INDUCED INTERACTION REGIONS ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{SHOCK} = 12.5^\circ$)

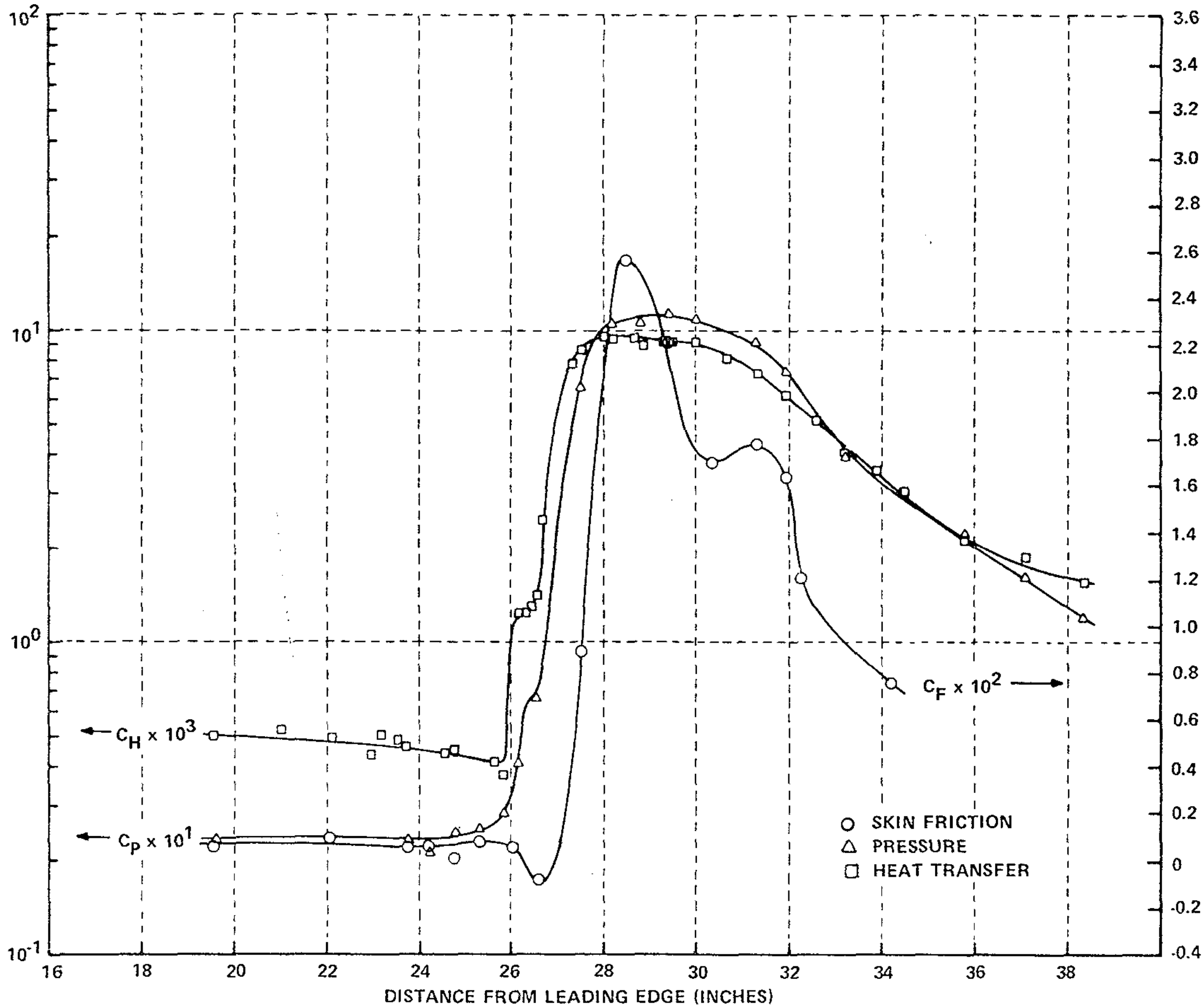


Figure 12b PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN SHOCK-INDUCED INTERACTION REGIONS ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{SHOCK} = 15^o$)

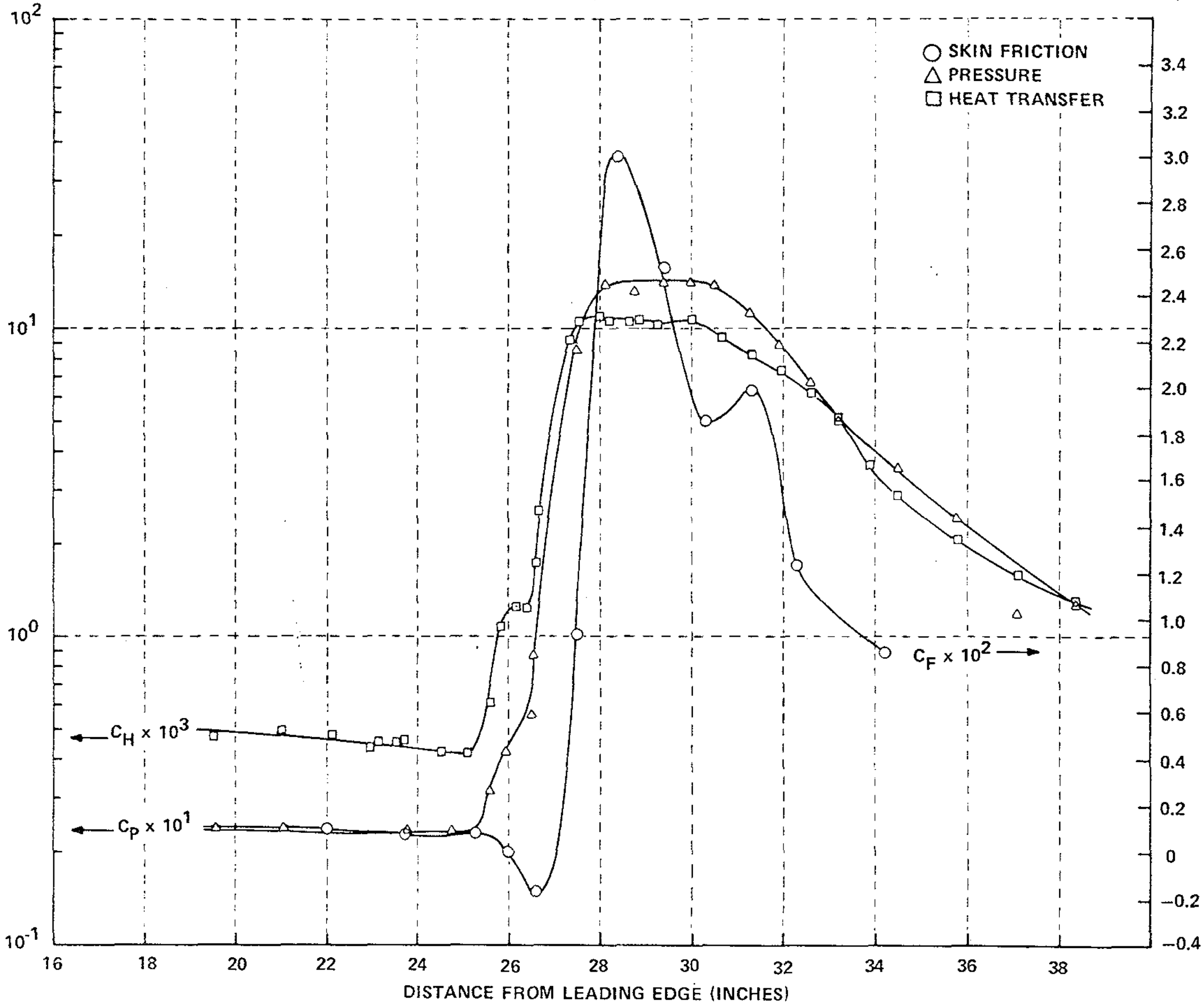


Figure 12c PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN SHOCK-INDUCED INTERACTION REGIONS ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{SHOCK} = 17.5^o$)

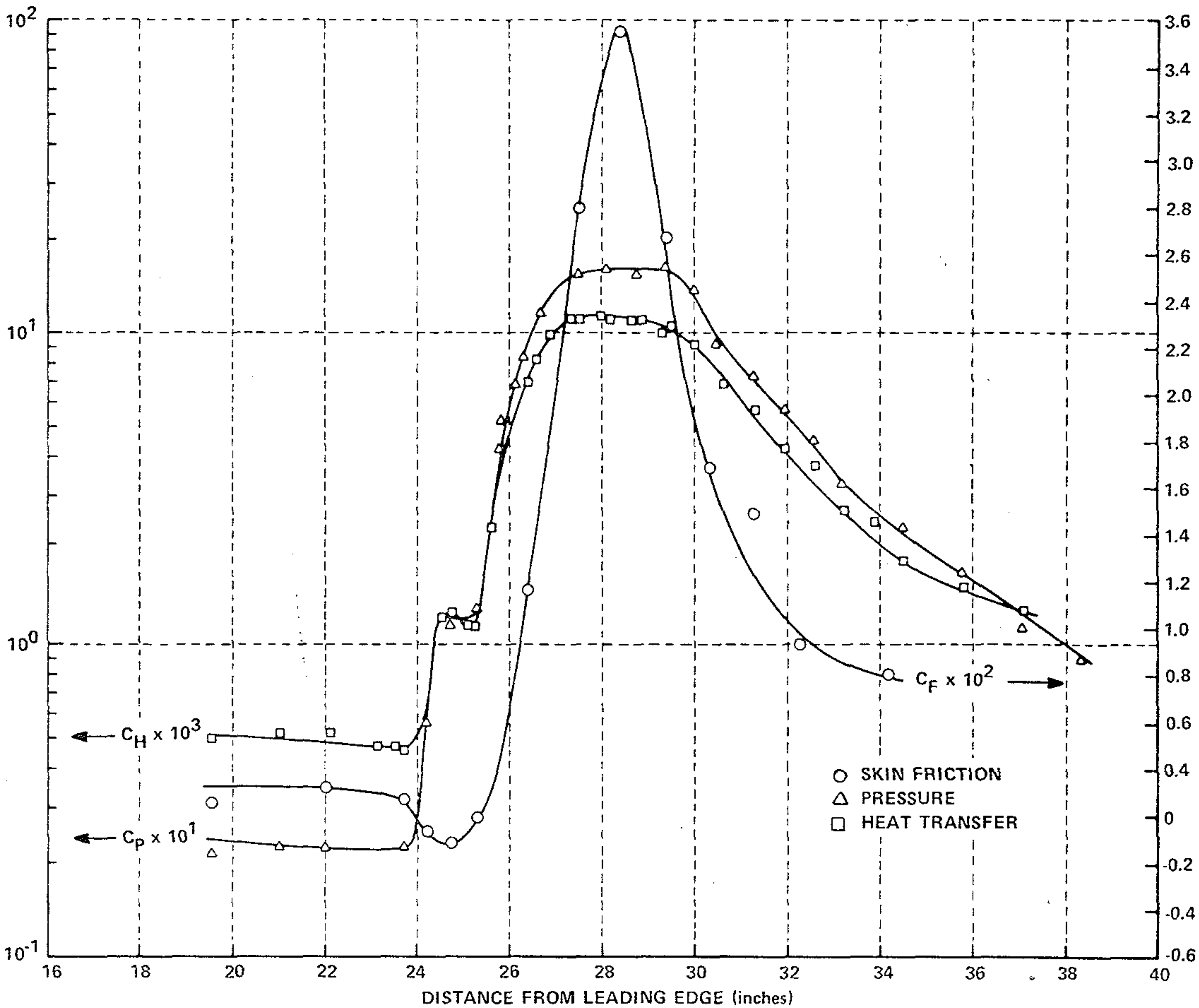


Figure 12d PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN SHOCK-INDUCED SEPARATED FLOW ($M = 8.6$ $Re_L = 22.5 \times 10^6$ $\theta_{SHOCK} = 19.8^o$)

WEDGE-INDUCED SEPARATED FLOW ($M = 13$, $R_{e_L} = 17 \times 10^6$)

SHOCK-INDUCED SEPARATED FLOW ($M = 13$, $R_{e_L} = 17 \times 10^6$)

Figure 13 SHOCK AND WEDGE-INDUCED INTERACTION REGION ($M = 13$ $R_{e_L} = 17 \times 10^6$)

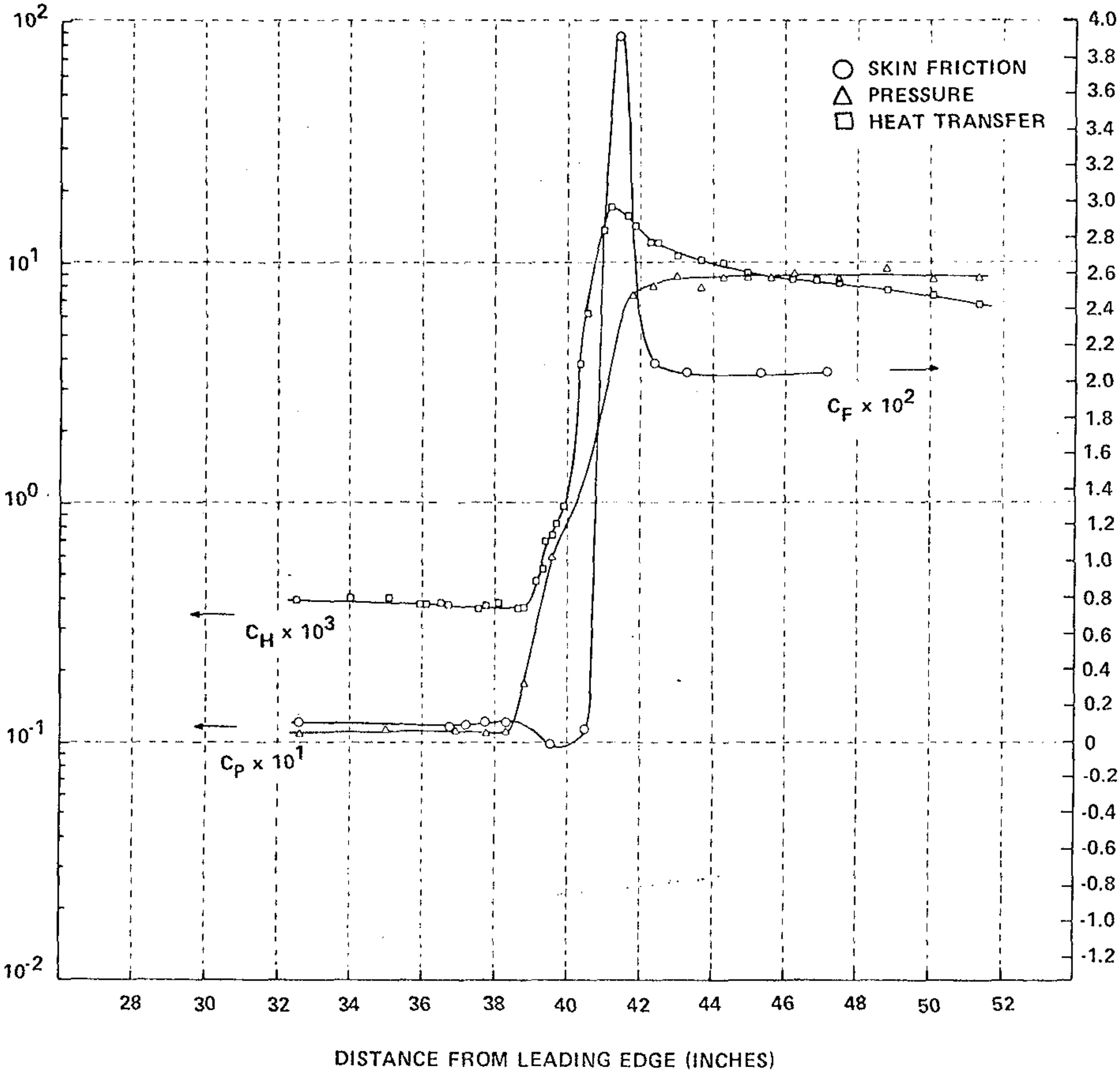


Figure 14a PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS FOR WEDGE-INDUCED SEPARATED FLOWS ($M = 13$ $Re_L = 17 \times 10^6$ $\theta_{WEDGE} = 36^o$)

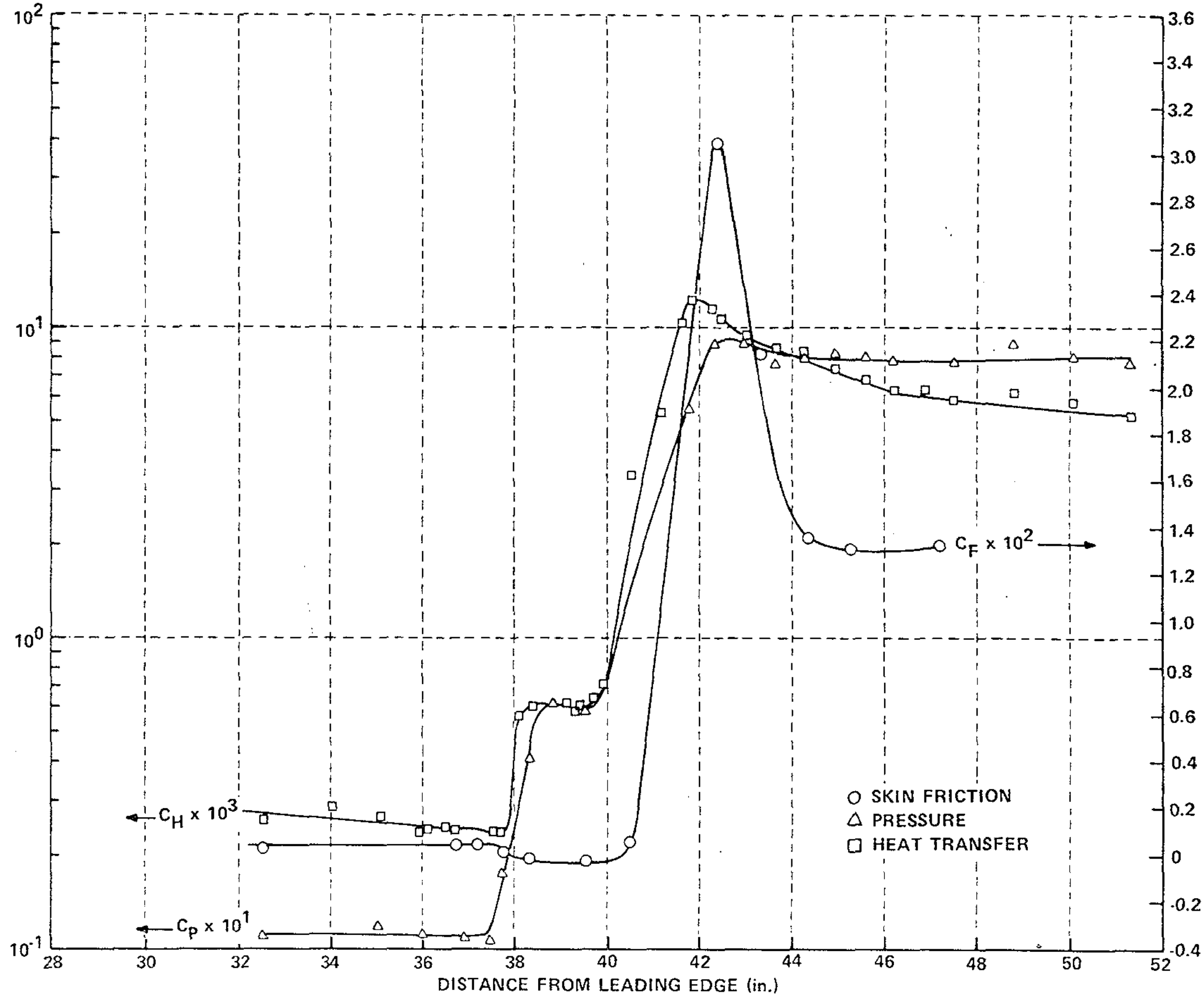


Figure 14b PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTION IN WEDGE-INDUCED SEPARATED FLOW ($M = 11.3$ $Re_L = 33 \times 10^6$ $\theta_{WEDGE} = 36^o$)

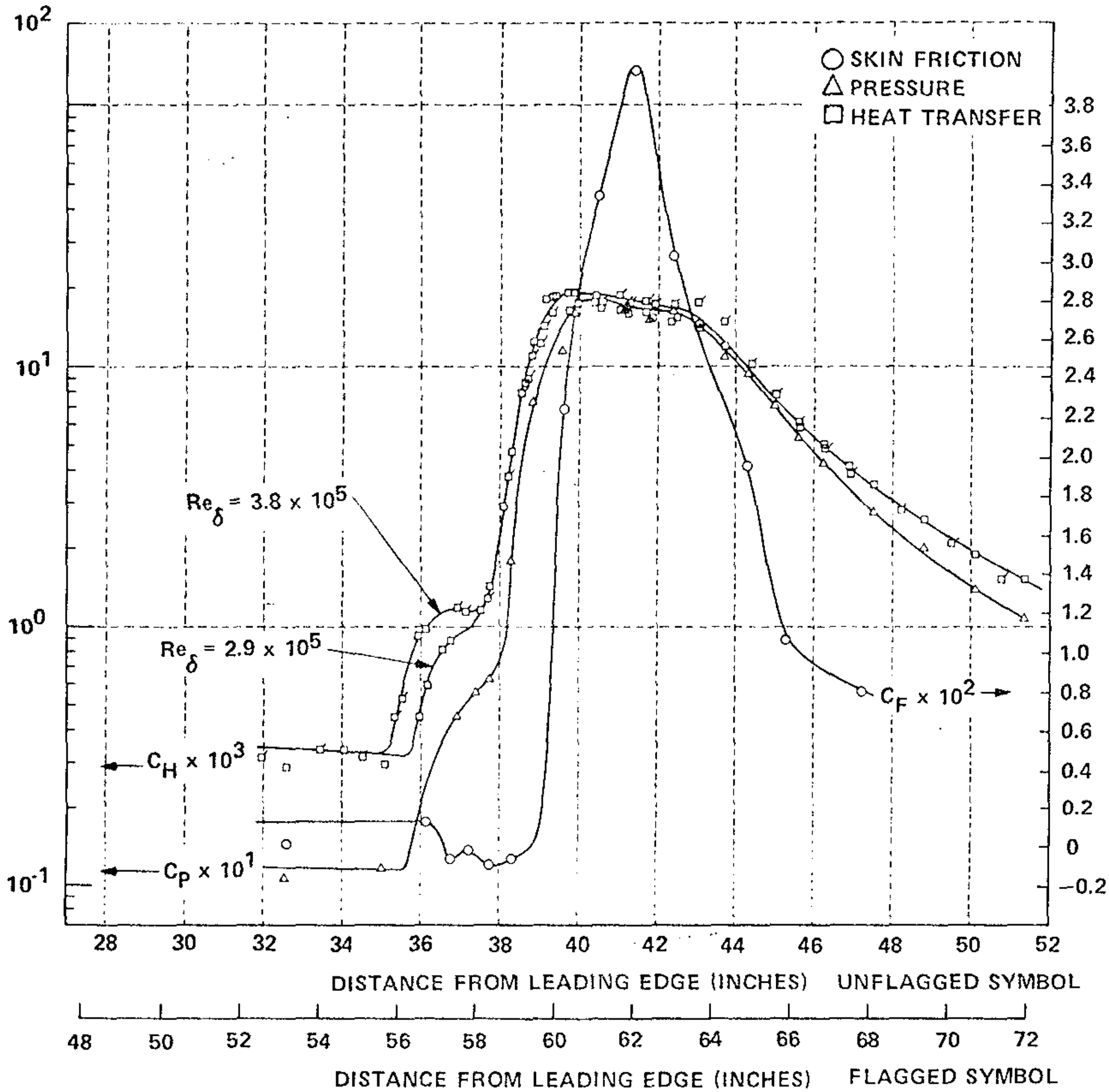


Figure 15a VARIATION OF INTERACTION LENGTH WITH REYNOLD NUMBER FOR SHOCK-INDUCED FLOWS ($M = 13$ $Re/FT = 4.7 \times 10^6$ $\theta_{SHOCK} = 20^o$)

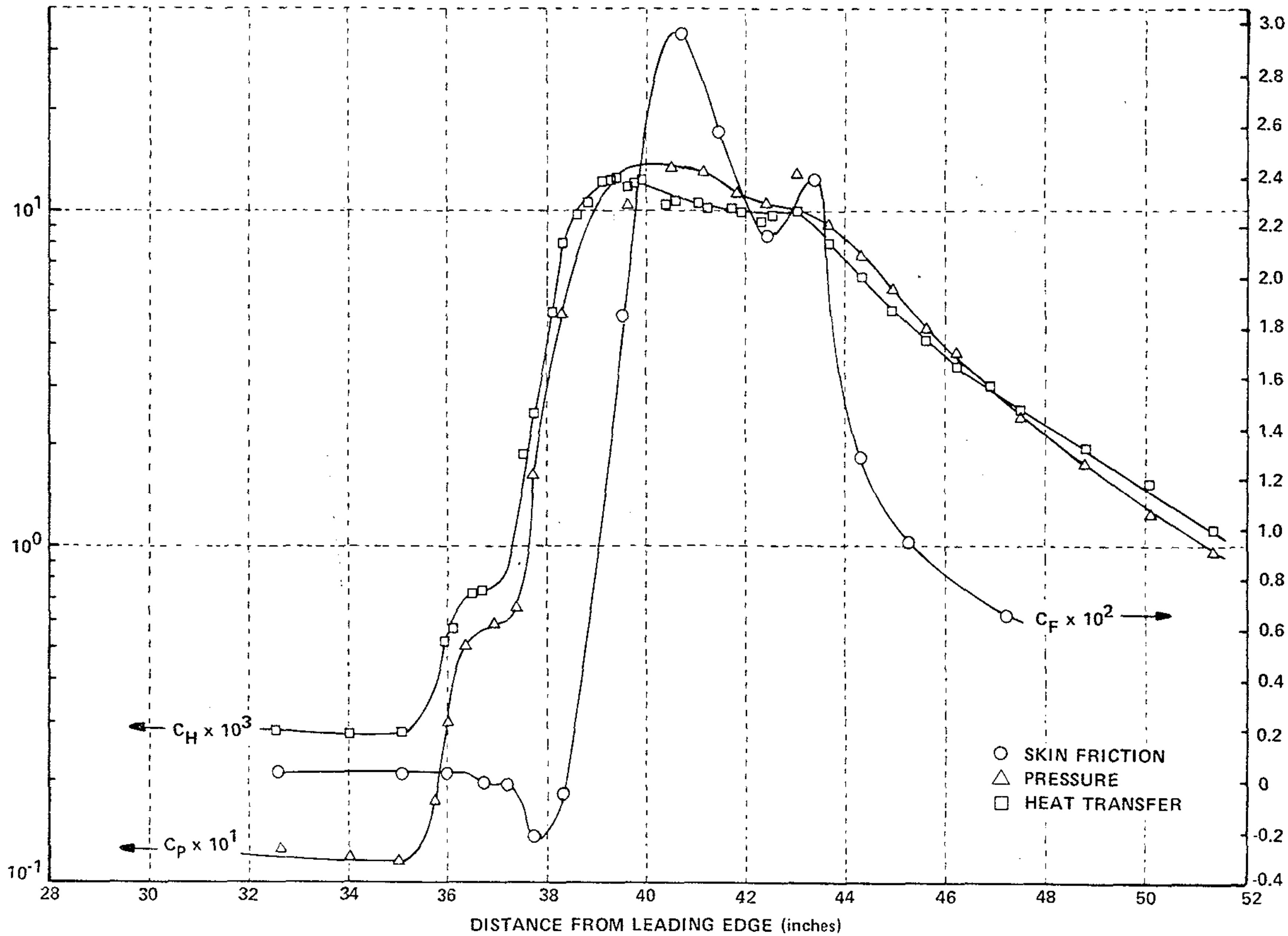


Figure 15b PRESSURE, HEAT TRANSFER AND SKIN FRICTION DISTRIBUTIONS IN SHOCK-INDUCED SEPARATED FLOW ($M = 11.3$ $Re_L = 33 \times 10^6$ $\theta_{SHOCK} = 17.6^o$)

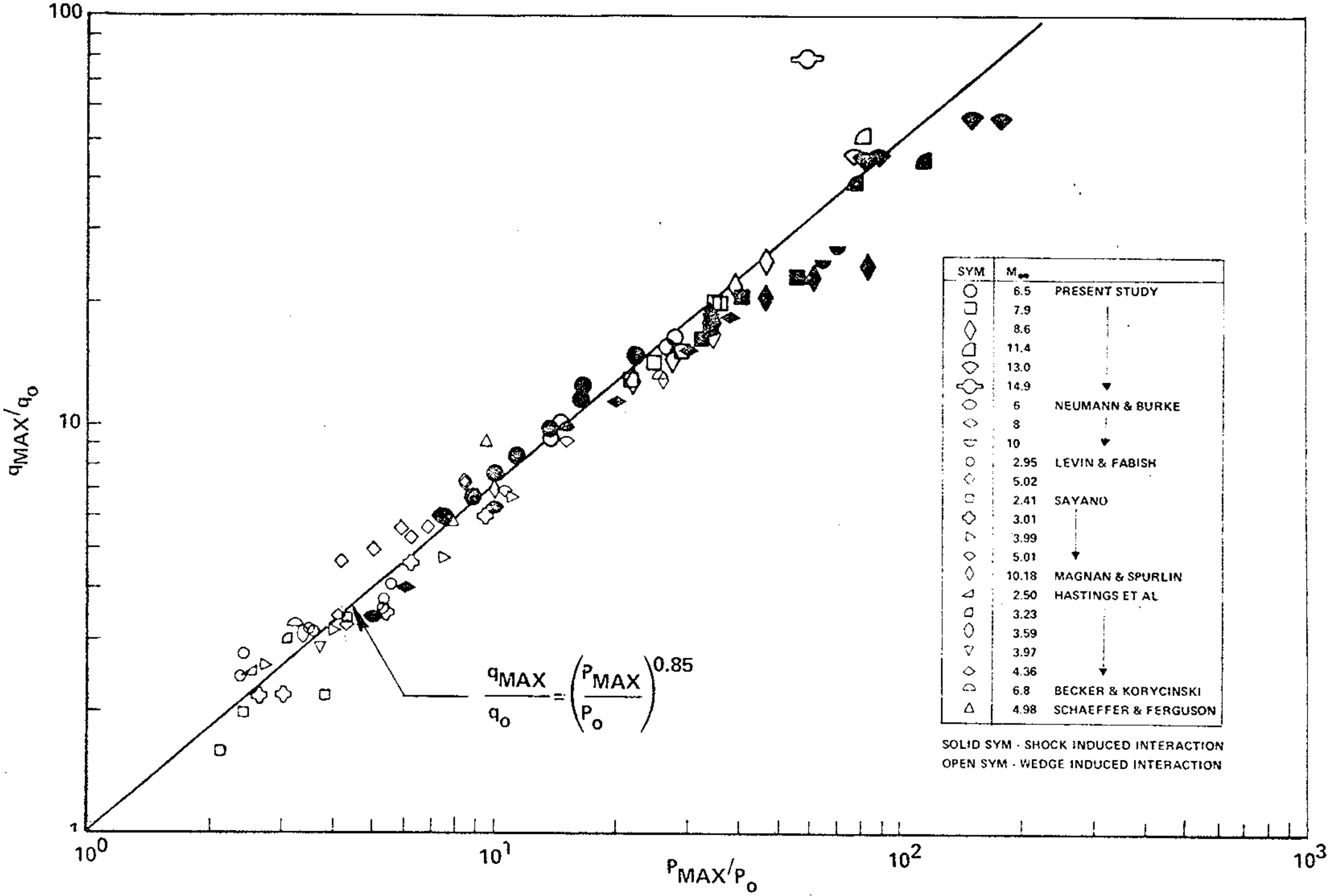


Figure 16 CORRELATION OF MAXIMUM HEATING IN WEDGE – AND EXTERNALLY GENERATED SHOCK-INDUCED TURBULENT SEPARATED FLOWS

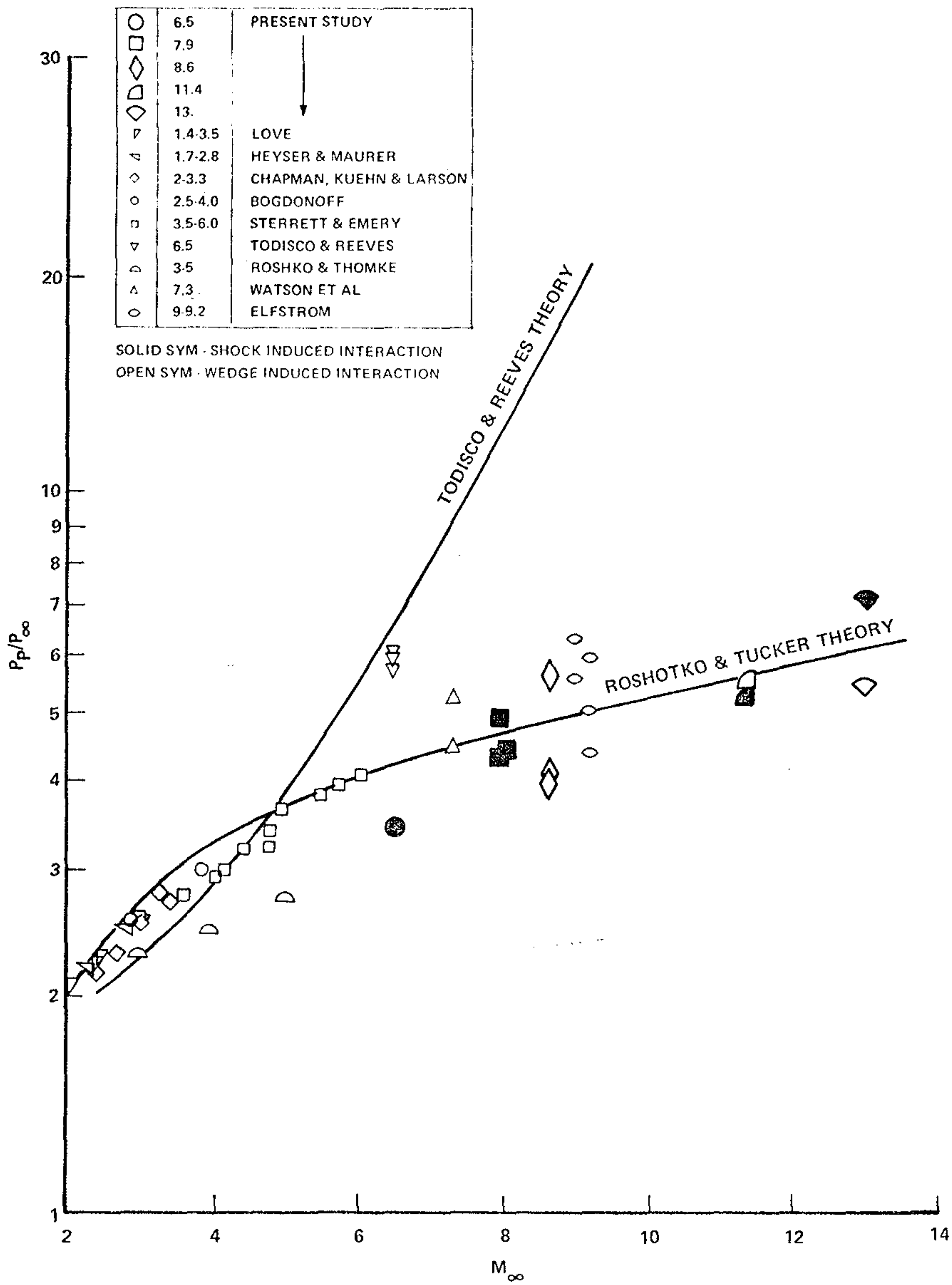


Figure 17 CORRELATION OF PLATEAU PRESSURE MEASUREMENTS IN WEDGE – AND SHOCK – INDUCED TURBULENT SEPARATED REGIONS

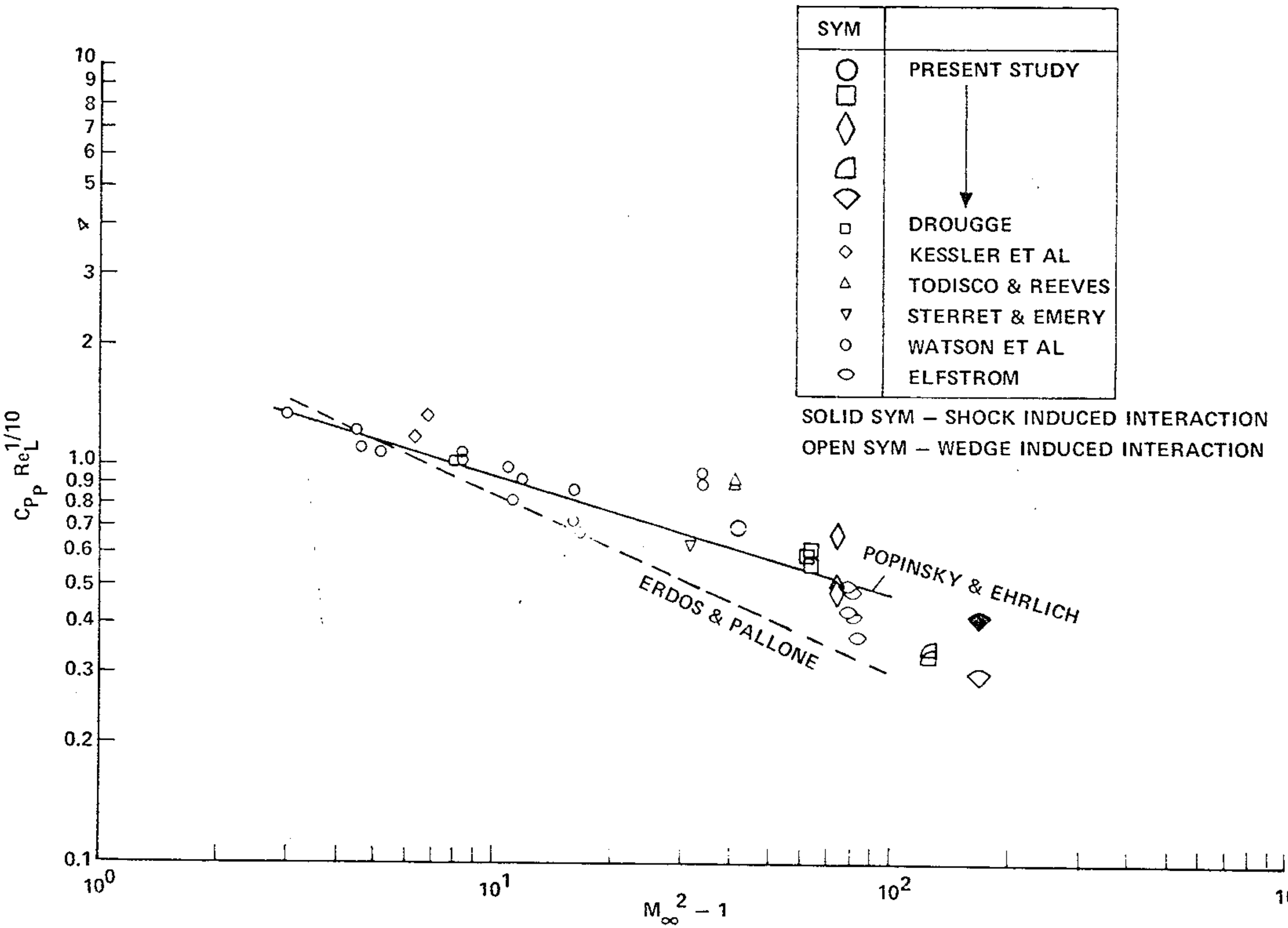


Figure 18 CORRELATION OF PLATEAU PRESSURE MEASUREMENTS IN WEDGE – AND SHOCK-INDUCED TURBULENT SEPARATED REGIONS

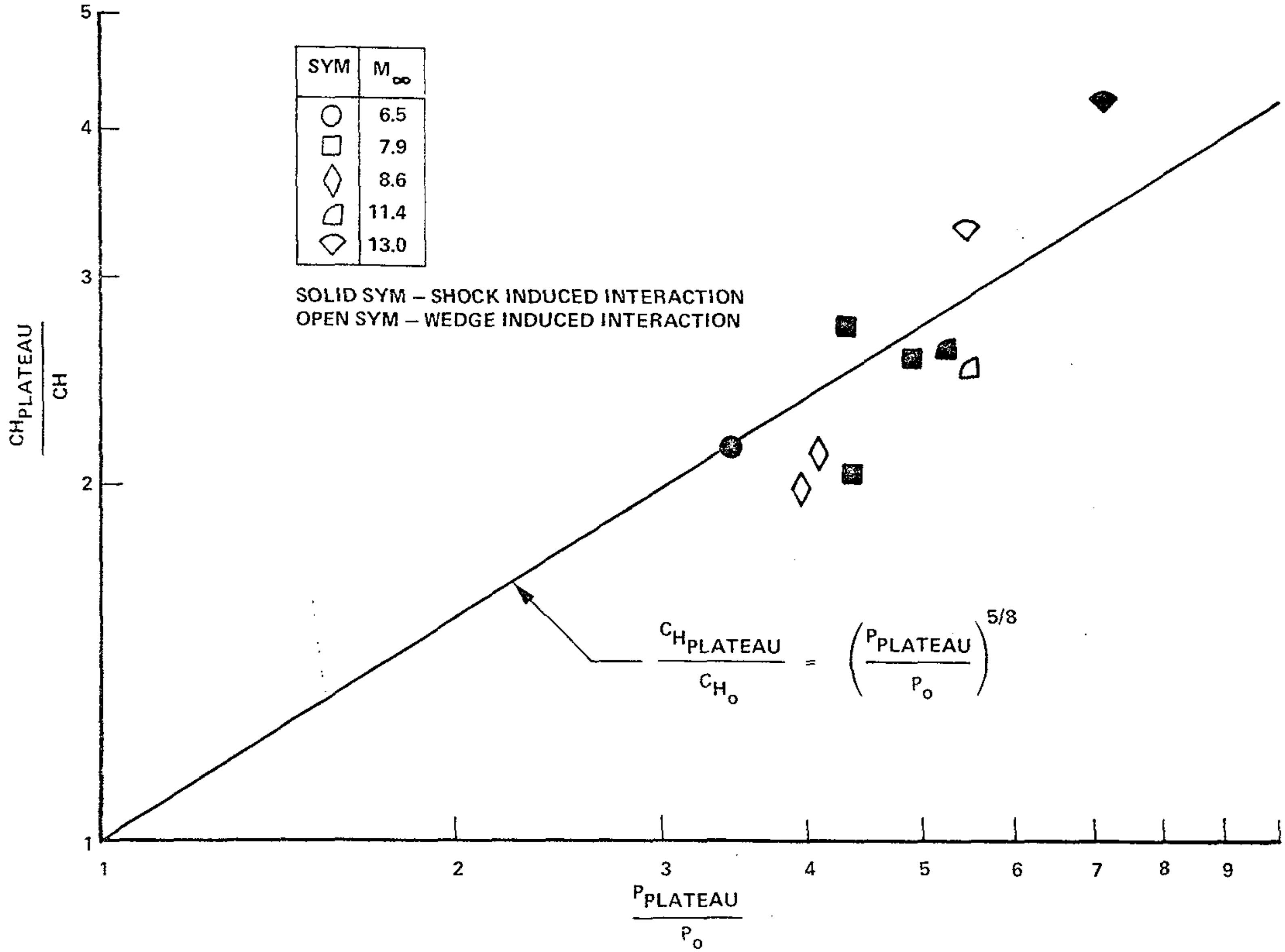
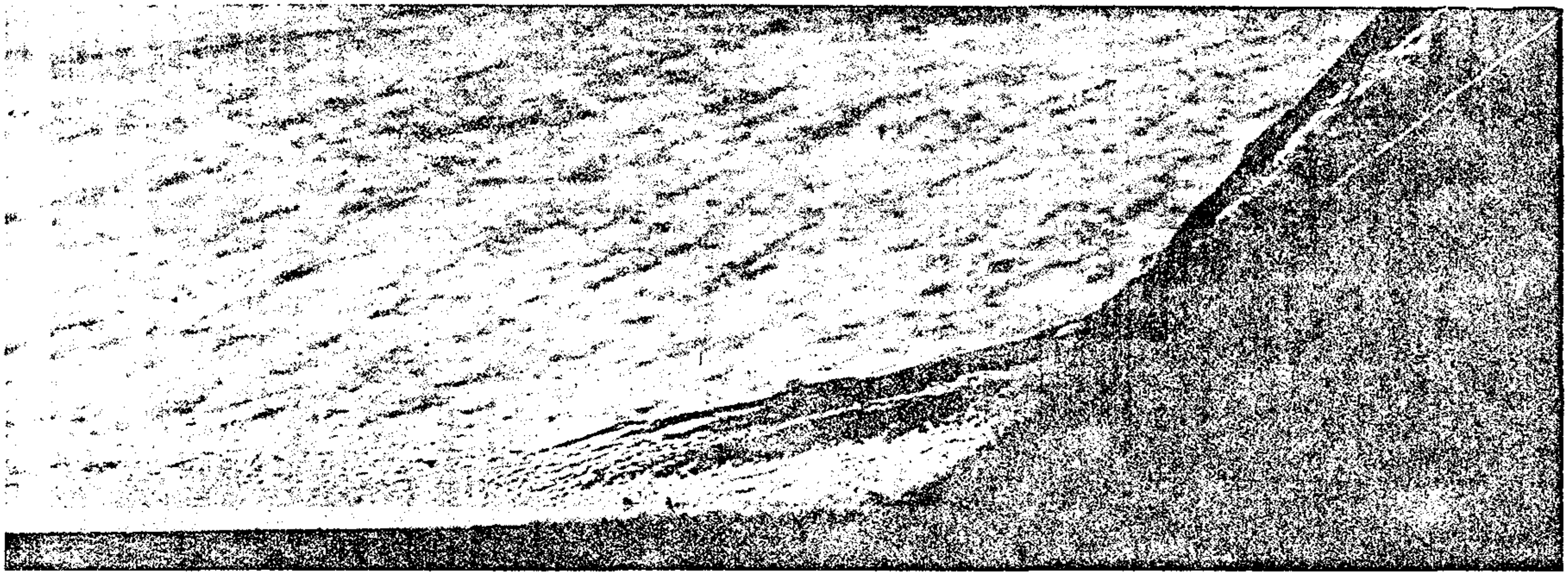
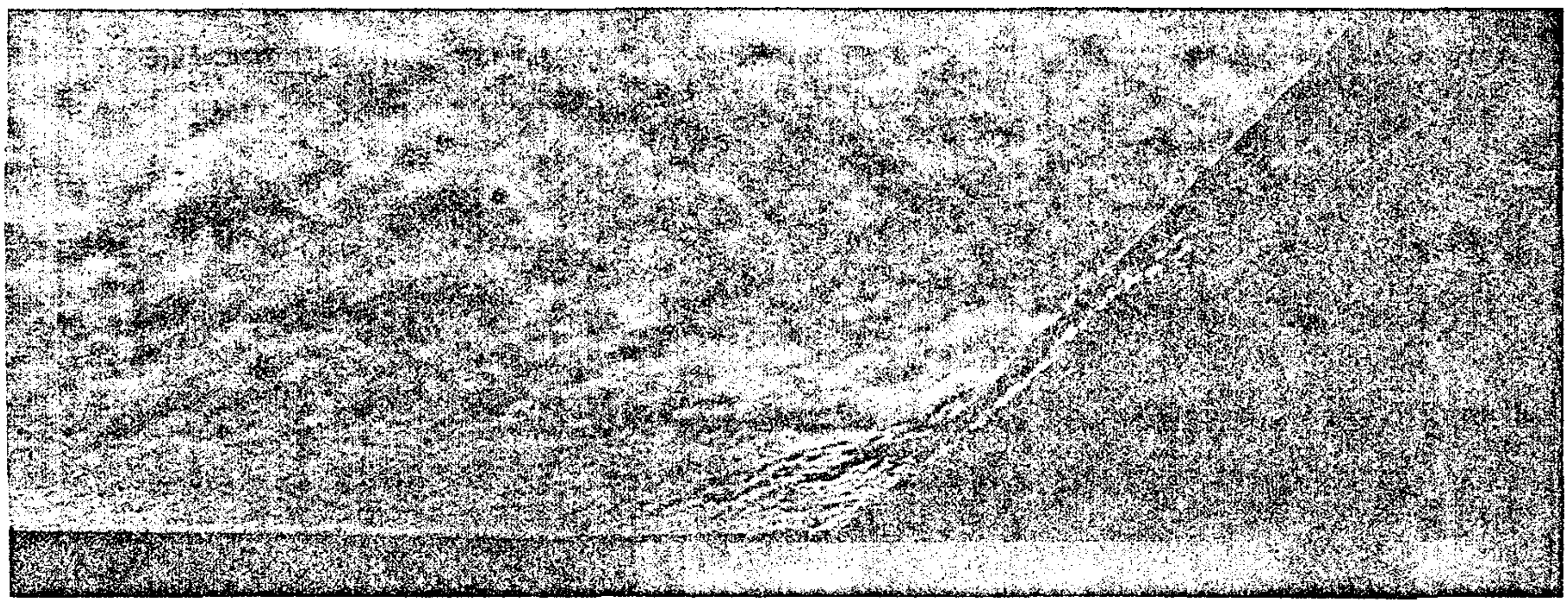


Figure 19 CORRELATION BETWEEN PLATEAU HEAT TRANSFER AND PLATEAU PRESSURE

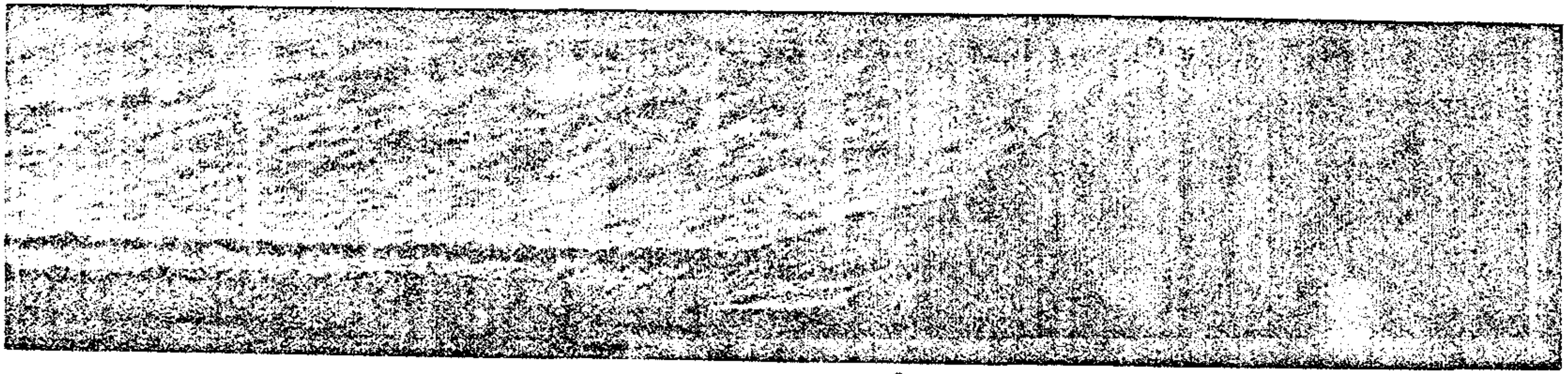


M = 11.30



M = 13.0

Figure 20 MACH NUMBER EFFECTS ON THE SCALE OF THE INTERACTION

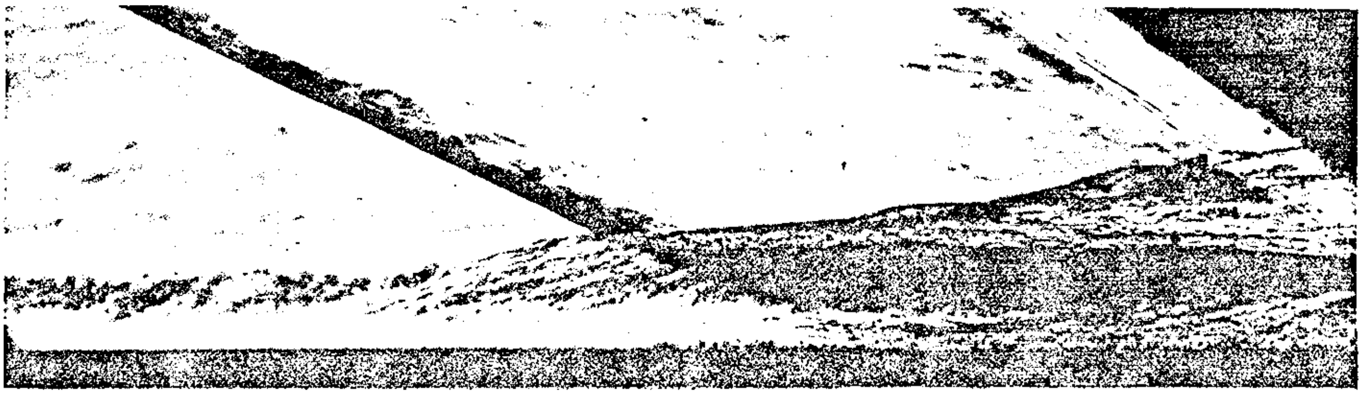


$M = 7.9 \quad R_{e_L} = 36 \times 10^6$

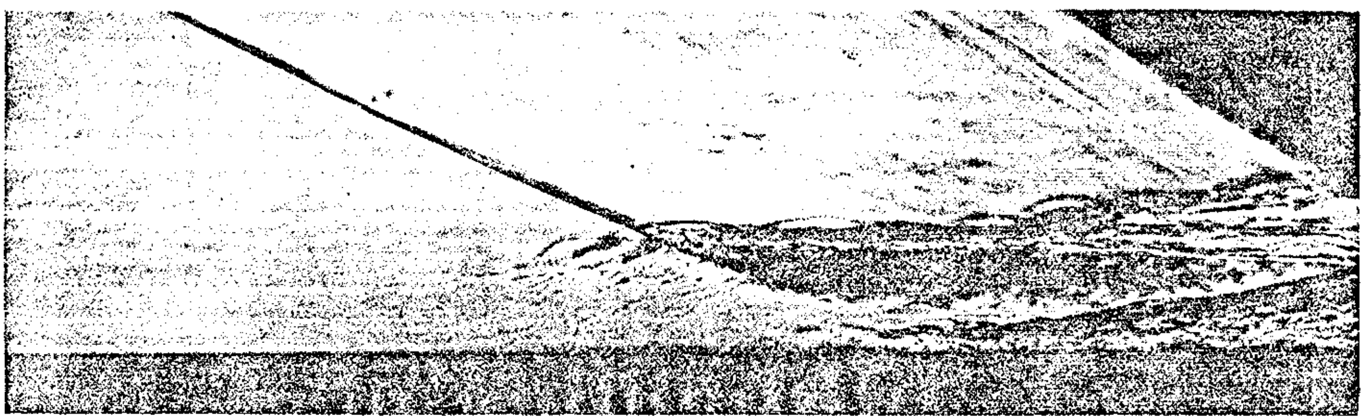
$M = 7.9 \quad R_{e_L} = 22 \times 10^6$

$M = 8.6 \quad R_{e_L} = 22 \times 10^6$

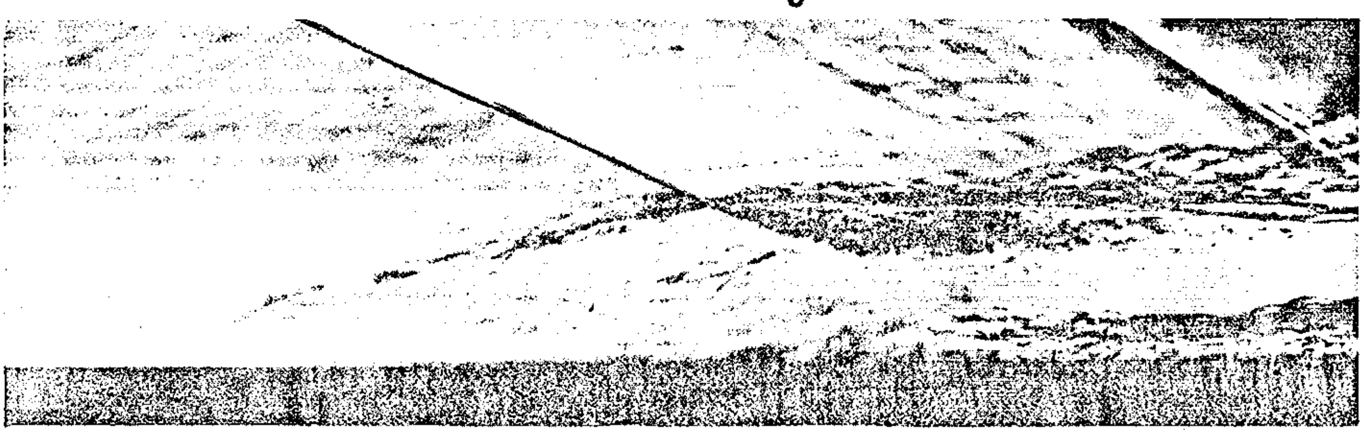
Figure 21 MACH NUMBER & REYNOLDS NUMBER EFFECTS ON THE SCALE OF THE WEDGE-INDUCED INTERACTION REGIONS



$M_\infty = 11.3$ $R_{e_L} = 33 \times 10^6$



$M_\infty = 13.0$ $R_{e_\delta} = 2.9 \times 10^5$ $R_{e_L} = 33 \times 10^6$



$M_\infty = 13.0$ $R_{e_\delta} = 3.8 \times 10^5$

Figure 22 MACH NUMBER AND REYNOLDS NUMBER EFFECTS ON THE SCALE OF THE SHOCK-INDUCED INTERACTION REGIONS

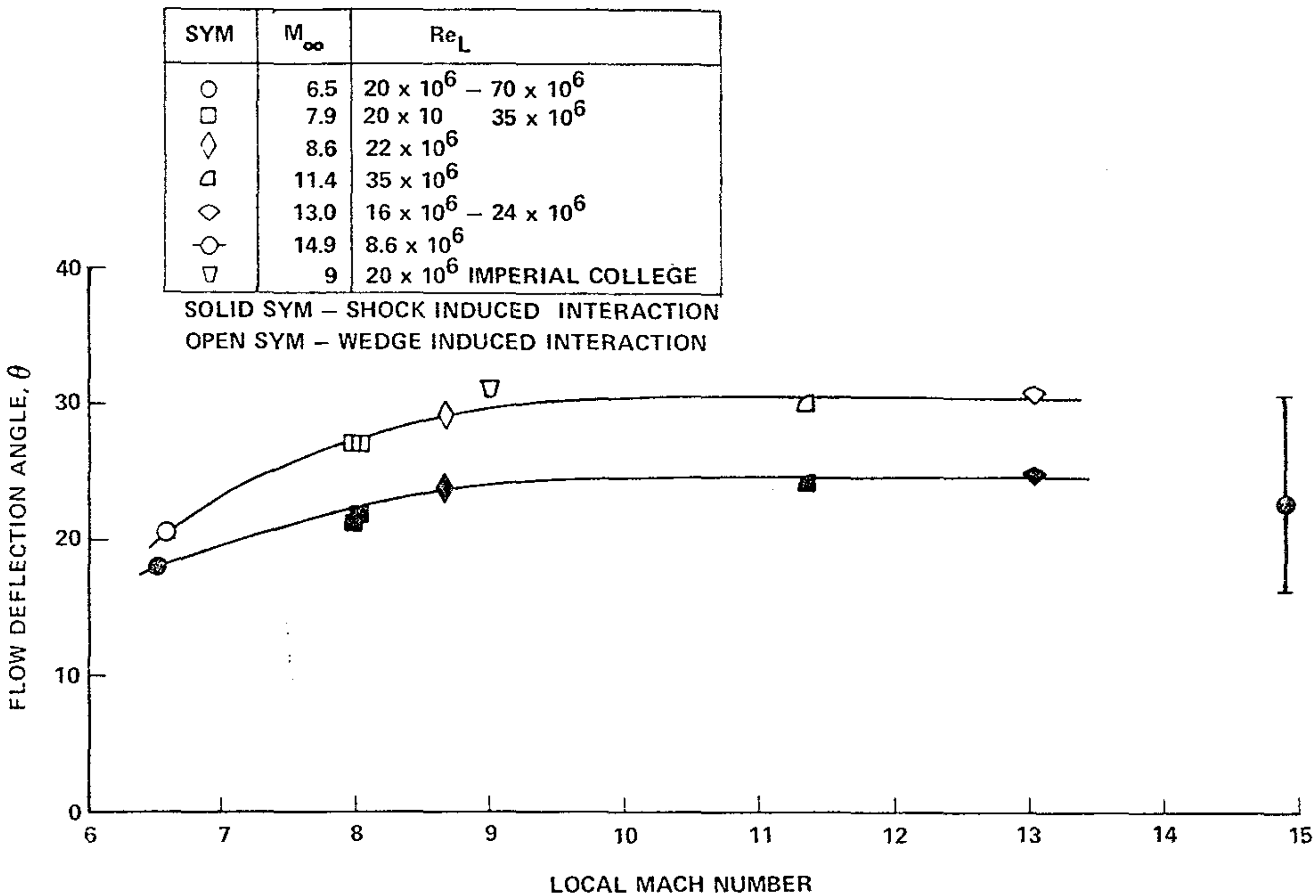


Figure 23 FLOW DEFLECTION ANGLE TO INDUCE INCIPIENT SEPARATION OF A HYPERSONIC TURBULENT BOUNDARY LAYER

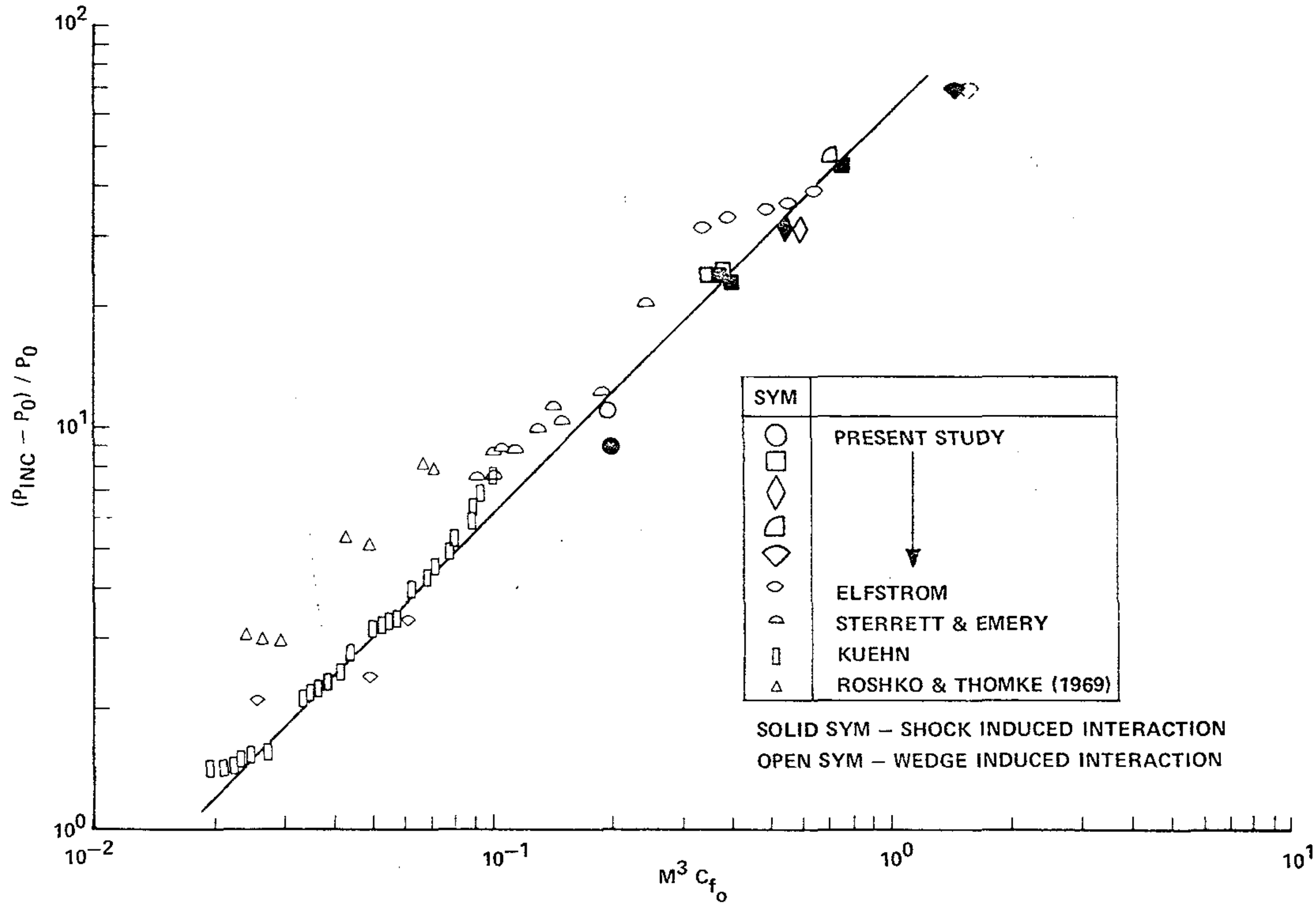


Figure 24 CORRELATION OF INCIPIENT SEPARATION CONDITIONS FOR WEDGE–AND SHOCK–INDUCED TURBULENT INTERACTION REGIONS

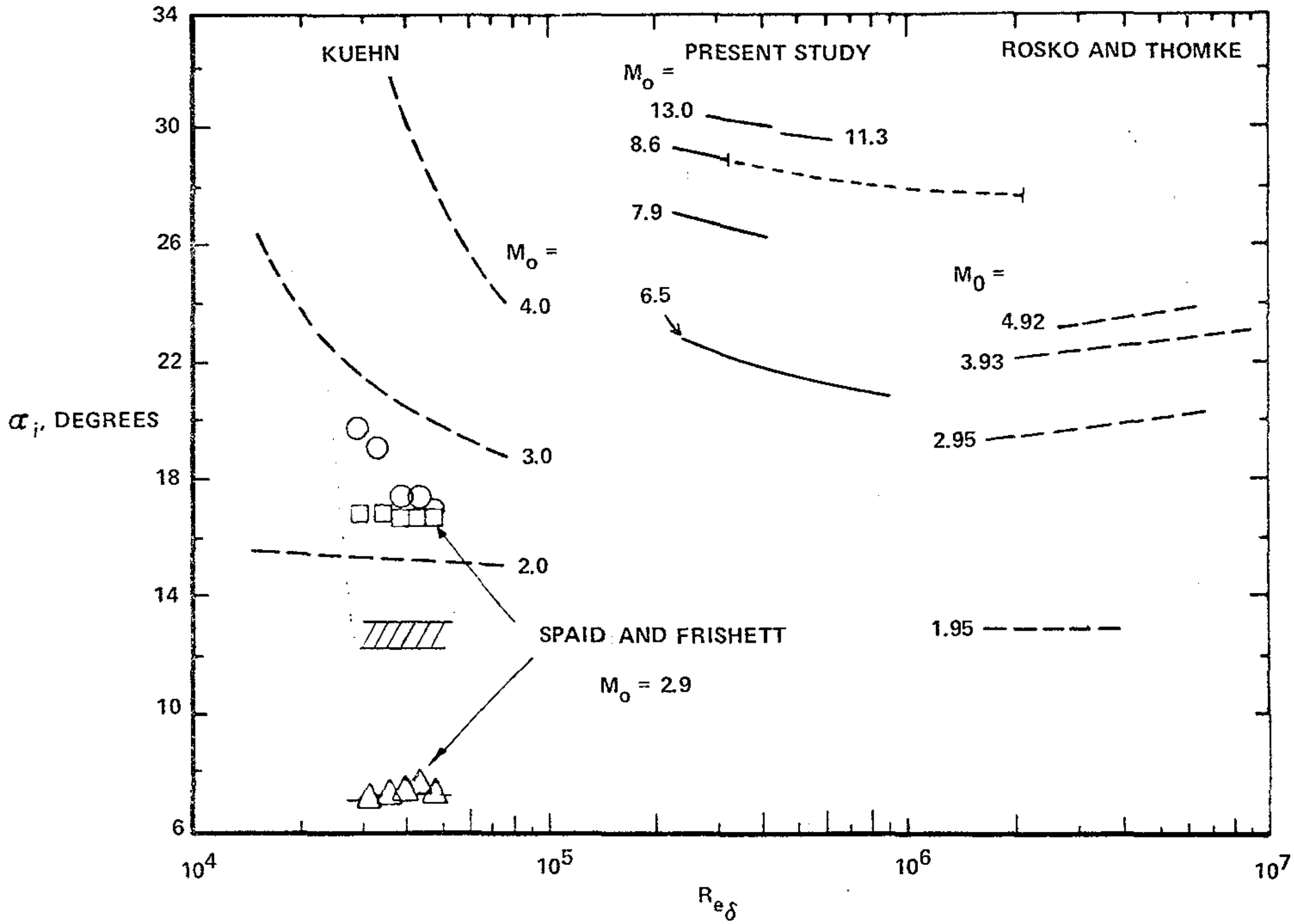


Figure 25 WEDGE ANGLE TO INDUCED INCIPIENT SEPARATION

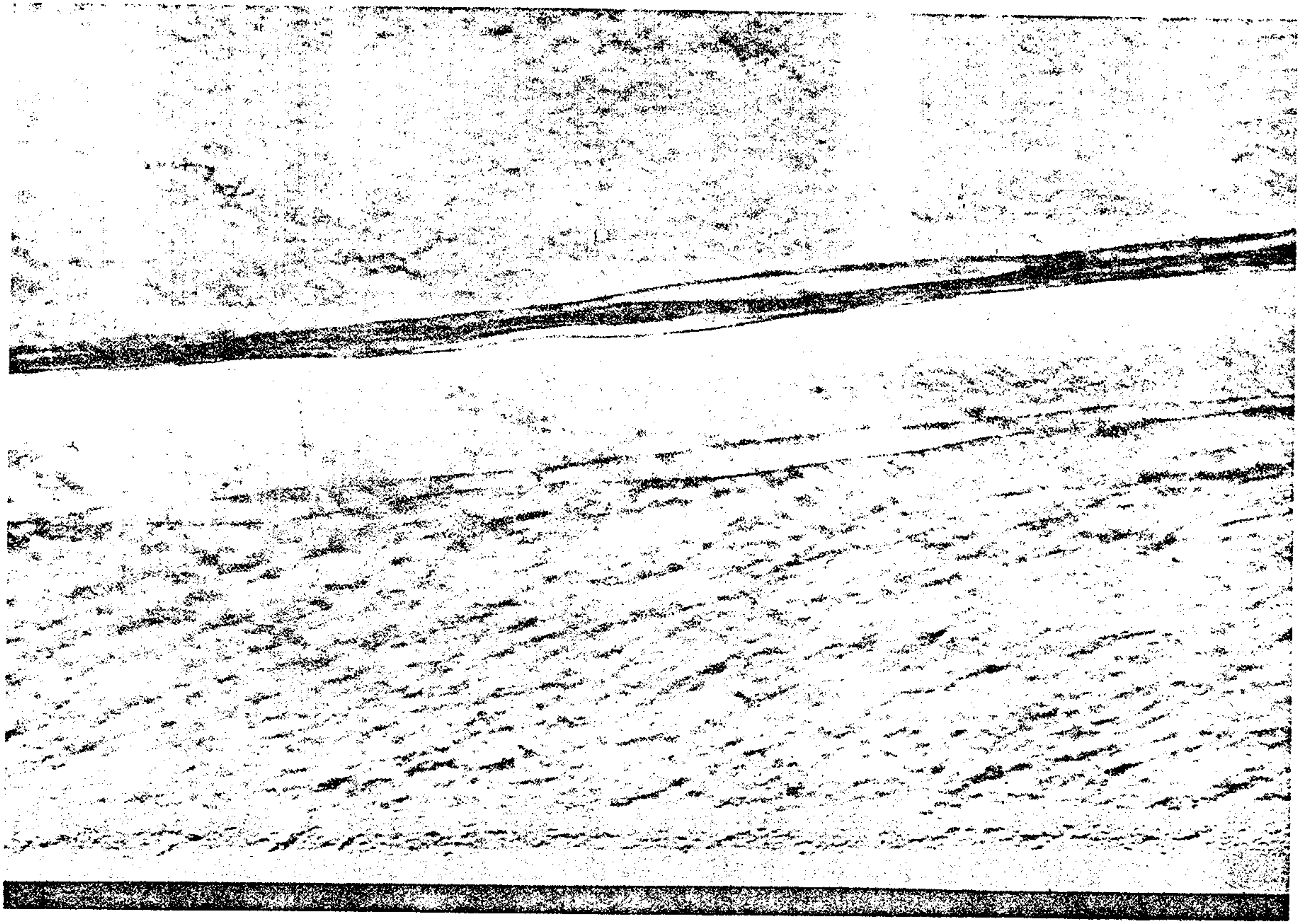


Figure 26 A TURBULENT BOUNDARY LAYER OVER A FLAT PLATE
($M = 11.3$ $Re_L = 34 \times 10^6$)

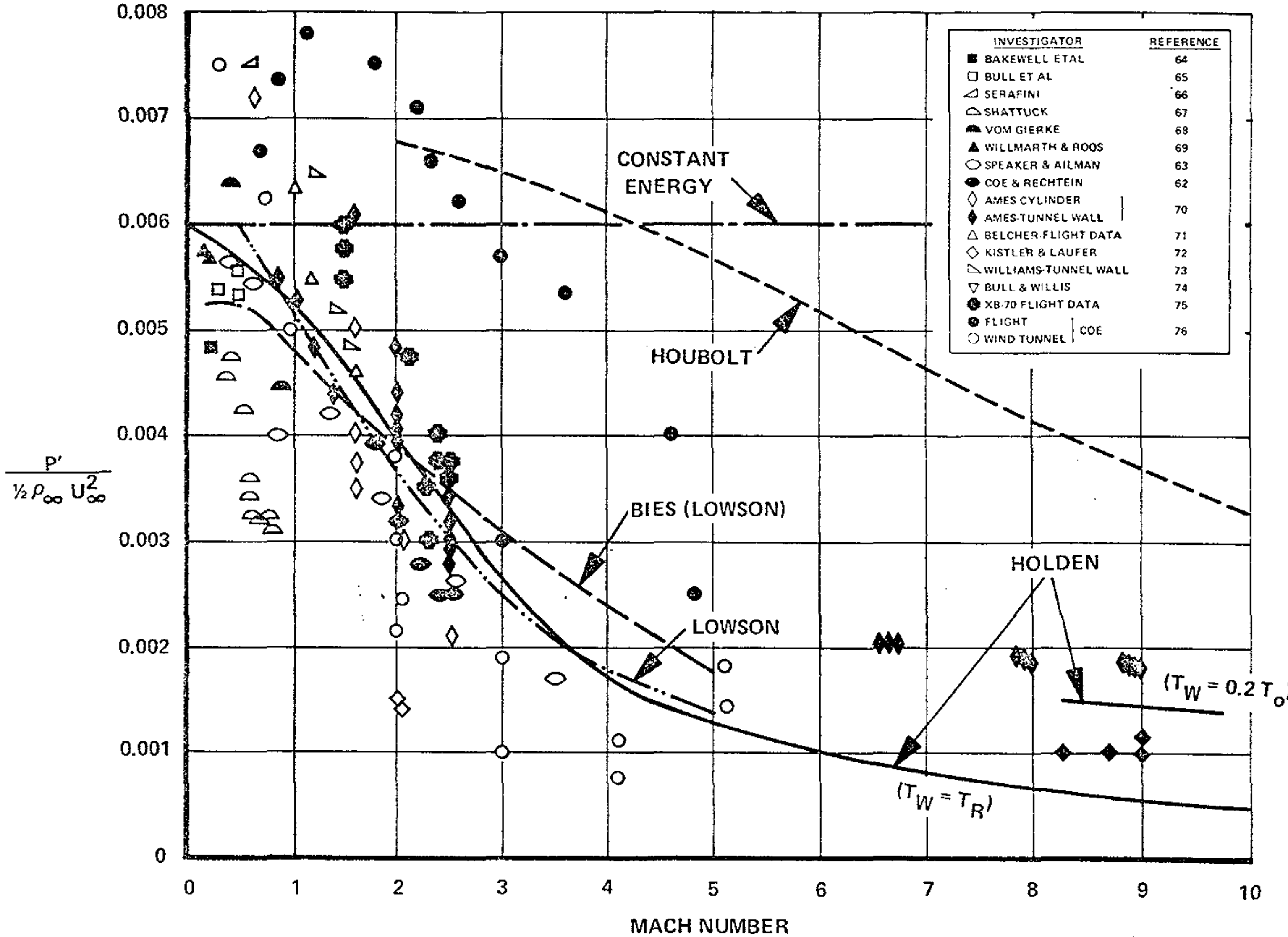


Figure 27 CORRELATION OF R.M.S. PRESSURE FLUCTUATIONS ON A FLAT PLATE

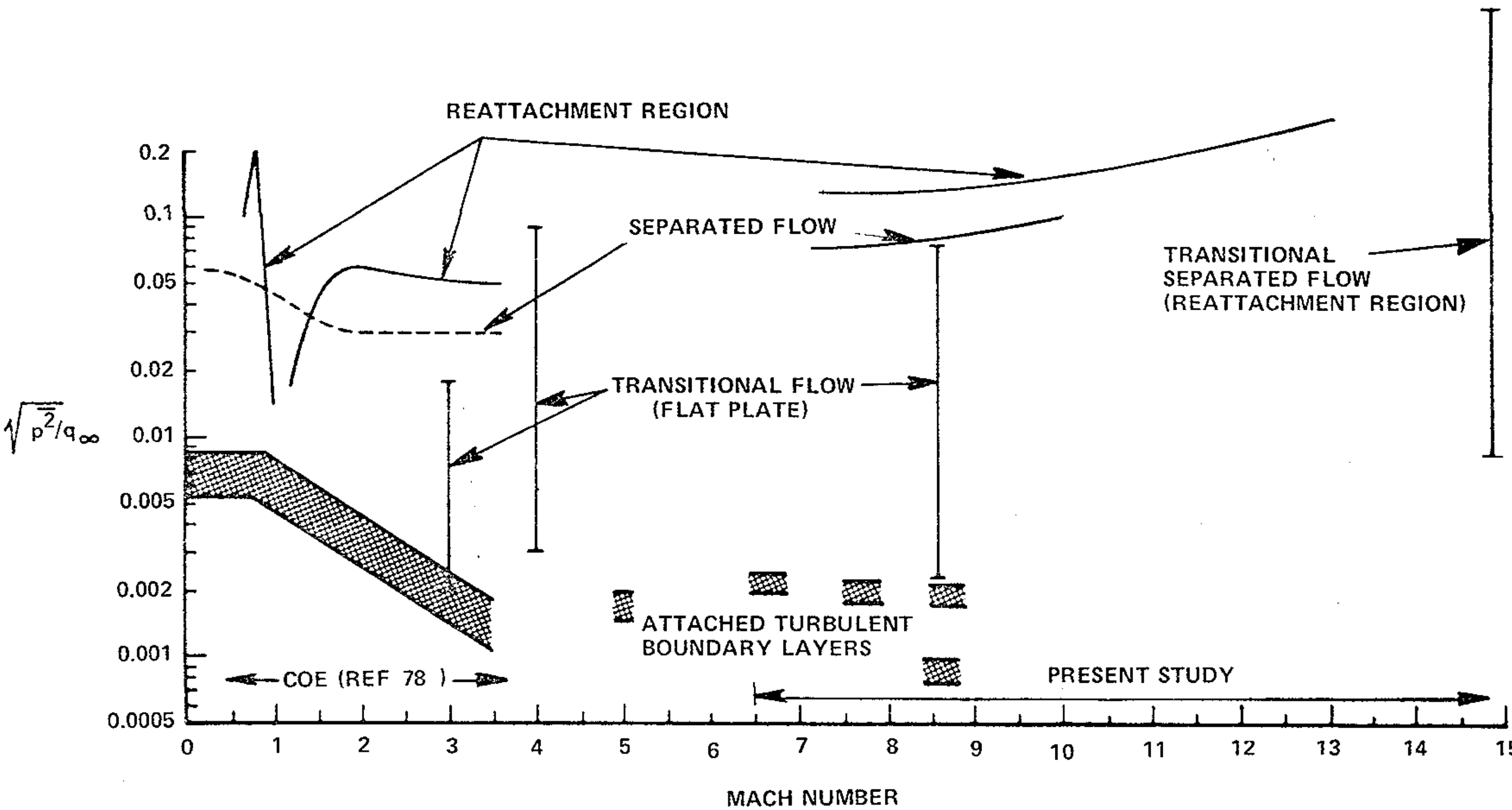
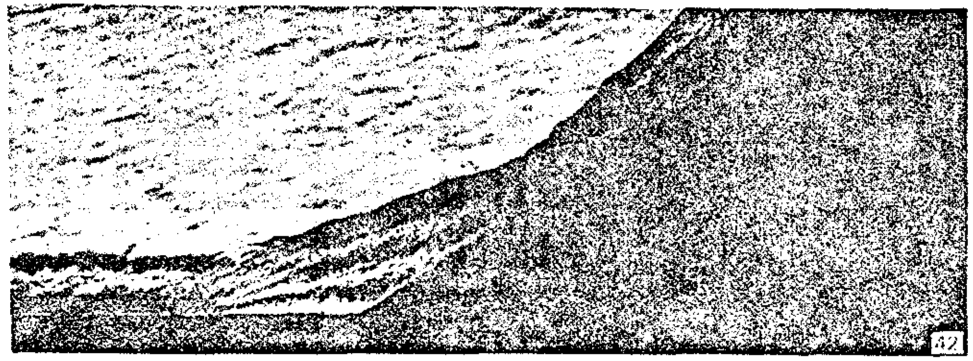
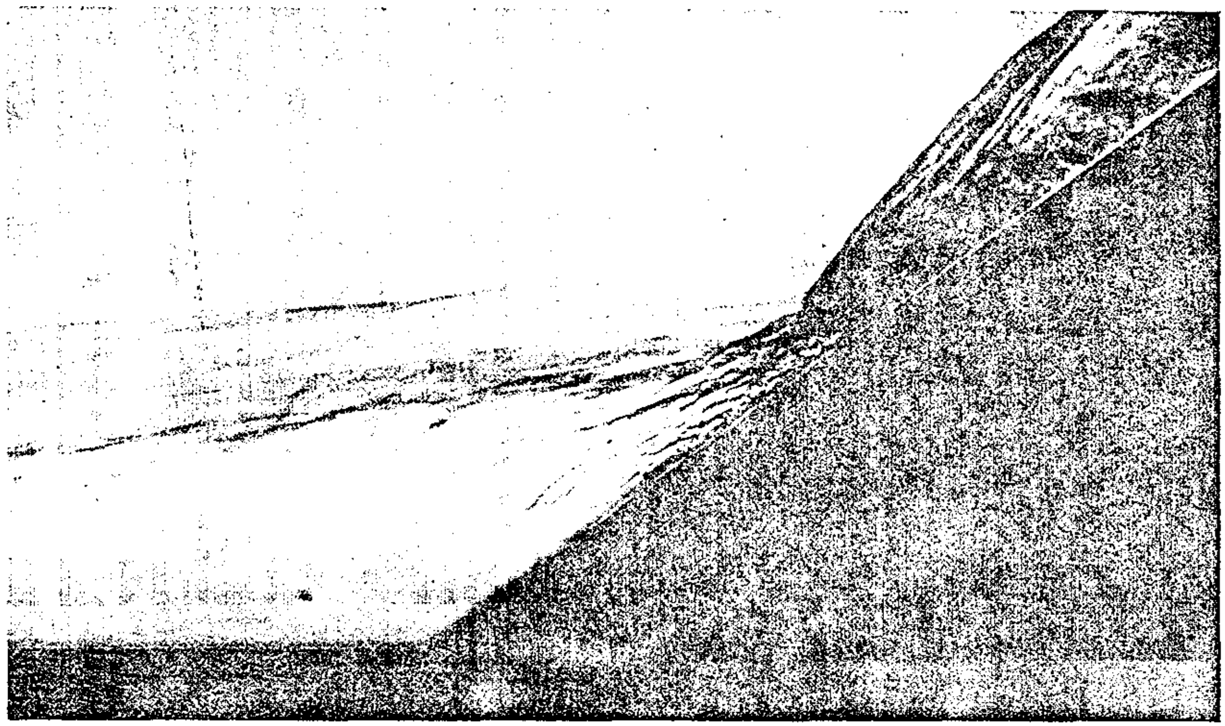


Figure 28 INTENSITY OF TURBULENT PRESSURE FLUCTUATION IN TURBULENT INTERACTION REGIONS



(a) SEPARATED REGION UNSTEADINESS ($M = 6.5$, $R_{e_L} = 4.5 \times 10^6$)



(b) TRANSITIONAL SEPARATED FLOW ($M = 15$, $R_{e_L} = 9.5 \times 10^6$)

Figure 29 SEPARATED REGION UNSTEADINESS IN FULLY TURBULENT AND TRANSITIONAL FLOWS

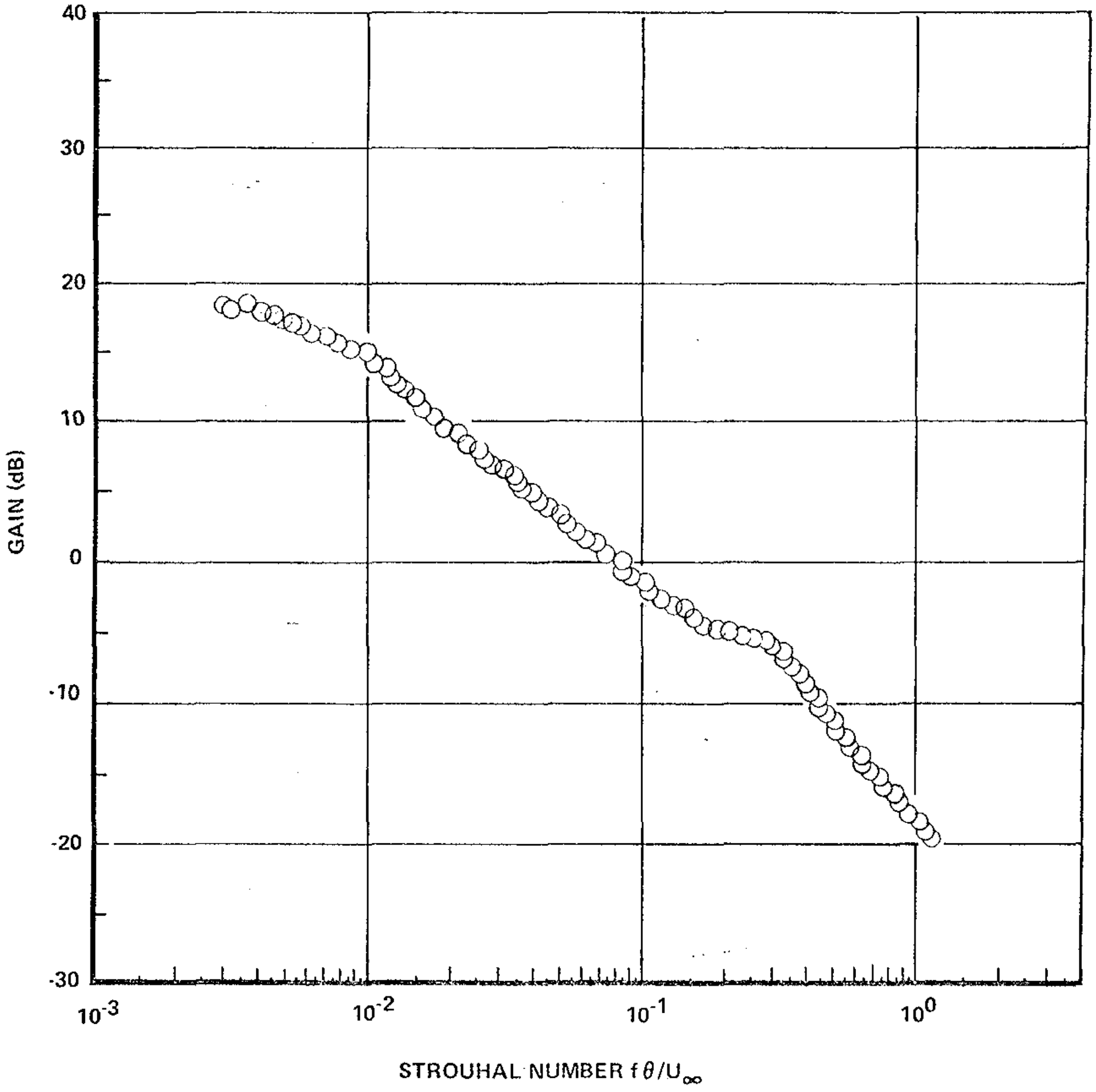


Figure 30 POWER SPECTRUM CLOSE TO REATTACHMENT FOR A SHOCK – INDUCED SEPARATED FLOW ($M = 8.6$, $\theta_{SHOCK} = 20^o$)