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**Aerospace Research Laboratories**

# RESEARCH ON HYPERSONIC FLOWS

S. M. BOGDONOFF
FOR THE STAFF OF THE GAS DYNAMICS LABORATORY
PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

Contract No. AF 33(615)-1079
Project No. 7064

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# FOREWORD

This final report is a summary of a program of theoretical and experimental research on hypersonic flow conducted by the Gas Dynamics Laboratory of the Department of Aerospace and Mechanical Sciences at the James Forrestal Campus of Princeton University, Princeton, New Jersey. This study was sponsored by the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force, under contract AF 33(615)-1079. The work reported herein was accomplished on Project 7064, at the Hypersonic Research Laboratory, ARL, R. H. Korkegi, Director.

This report covers work performed during the period September 1963 to September 1966.

# ABSTRACT

During the three year period, September 1963 to September 1966, the Gas Dynamics Laboratory of Princeton University has been engaged in a series of research programs of basic application to hypersonic flight. These studies were experimentally centered around the Princeton Helium Hypersonic facilities developed under previous ARL support. Research in the four basic areas of interest, lifting surfaces, separated flows, boundary layers, and viscous interactions have been undertaken. Summaries of the researches which have been completed are presented as well as the pertinent results. Studies still in process are outlined and preliminary results presented.

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# LIST OF SYMBOLS

## Cavity Flows

| | |
|---|---|
| $L$ | length of cavity |
| $m_i$ | mass injection rate |
| $q$ | local heat transfer rate |
| $q_{cone}$ | heat transfer rate on the basic cone surface |
| $T_w$ | temperature of the model wall |
| $\tilde{x}$ | wetted length along a generator of axisymmetric cavity model with origin at reattachment point. Positive sense downstream. |
| $\epsilon_S$ | height of separation shoulder above reattachment shoulder, measured perpendicular to basic cone surface. |

## Flat Plate Studies

| | |
|---|---|
| $C_D$ | nose drag coefficient |
| $h$ | heat transfer coefficient |
| $H_\infty$ | total specific enthalpy at the free stream conditions |
| $H_w$ | total specific enthalpy at the initial wall temperature |
| $K_\epsilon$ | $M^3 C_D \epsilon\, t/x$ parameter controlling the inviscid bluntness effect |
| $M$ | Mach number |
| $Nu_{\infty,x}$ | Nusselt number based on surface distance |
| Po | stagnation pressure |
| $Re_{\infty,t}$ | Reynolds number based on leading edge thickness and free stream conditions |
| St | Stanton number |
| $t$ | leading edge thickness |
| $x$ | surface distance from the leading edge |

| | |
|---|---|
| $\beta$ | $\chi_e K_\epsilon^{-2/3}$ |
| $\gamma$ | ratio of specific heats |
| $\Gamma$ | $\epsilon\gamma^{-\frac{1}{2}} (0.664 + 1.73\ H_w/H_\infty)\ (K_\epsilon/\chi_\epsilon)^3 M^3\ St$ |
| $\epsilon$ | hypersonic density ratio limit $(\gamma-1)/(\gamma+1)$ for a perfect gas |
| $\bar{\chi}$ | free stream viscous interaction parameter |
| $\chi_\epsilon$ | $\epsilon(0.664 + 1.73\ H_w/H_\infty)\bar{\chi}$ |
| $P$ | surface pressure |
| $P_\infty$ | free stream pressure |
| $\alpha$ | angle of attack |
| $N_{S\infty}$ | Stanton number based on free stream conditions |
| $Y_s$ | distance of shock from surface |
| $\Delta_P$ | $P - P_1$ |

## Delta Wings

| | |
|---|---|
| $P_c$ | pressure based on cone value |
| $\Lambda$ | sweep angle |
| $\bar{\chi}_c$ | viscous interaction parameter based on concial values |

## Wakes

| | |
|---|---|
| D | diameter of cylinder |
| $P_{t_2}$ | measured pitot pressure |
| $P_{t_o}$ | stagnation pressure |
| x | downstream distance measured from center of cylinder along wake centerline |
| Y | distance normal to centerline |

## Mass Transfer Studies

| | |
|---|---|
| $\dot{m}$ | mass injected in microslugs per second |
| $p$ | measured static pressure |
| $p_c$ | pressure on a cone without blowing |

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# I. INTRODUCTION

Since September 1963, the Gas Dynamics Laboratory of the Aerospace and Mechanical Sciences Department of Princeton University has carried out a continuing program of basic research of fundamental problems of hypersonic flight. These primary experimental studies have made use of a group of helium facilities which were developed from the first helium hypersonic wind tunnel built in the early 1950's with the support of the Aeronautical Research Laboratory of the USAF. The facilities cover a Mach number range from about 10 to 20 at Reynolds numbers, which extend as high as one million per inch, provide a unique capability for studying basic fluid mechanical problems. The tunnels run for relatively long periods of time (of the order of ten minutes) so that detailed pressure distributions and boundary layer surveys can be made. Operation in a transient mode permits detailed heat transfer results to be obtained. During the past year, some modifications of the basic system were required due to difficulties with the high pressure storage tanks, and there was some curtailment of the experimental research during this time. However, new tanks have been installed and operation during the last six months has been at a level considerably higher than previously obtained. The two basic helium tunnels have been extended, with the help of another contract, to a third facility which has been primarily associated with wake studies and uses a magnetic suspension system.

The research programs have covered a series of basic studies which have been carried out consecutively and concurrently over the past three years. These studies have been aimed at specific problems associated with the four fundamental areas of research under the subject contract. (1) Aerodynamics of lifting surfaces (2) Separated flow research, (3) Fundamental boundary layer phenomena (4) Research on viscous interactions. These fundamental areas have been covered in a series of five research programs: (1) the flow over cavities. This covers a specific separated flow phenomenon and includes studies of the pressure and heat transfer distributions for such separated flows as well as the effect of mass injection. (2) studies of flat plates. This study includes flows over flat plates at angle of attack with primary emphasis on problems associated with leading edge effects. It includes heat transfer as well as pressure distributions and shock shapes so that the effect of the viscous or inviscid interaction at the leading edge can be evaluated over the downstream body. (3) exploratory studies of delta wings. To study the application of fundamental hypersonic viscous and inviscid theories to realistic bodies, a series of delta wings have been examined to provide information on the accuracy of prediction of the characteristics of lifting surfaces under hypersonic conditions. (4) the study of wakes. The separated flow study has applications to base pressure prediction and the major interest in wakes has stimulated research in this area. Some studies on spheres and cones supported by the magnetic suspension systems have been carried out in association with another contract but primary studies have been made on the wakes behind cylinders. Some theoretical work in this area has also been undertaken. (5) mass transfer. The laboratory has embarked on the first of a series of long range fundamental studies associated with mass transfer. These studies have taken three different directions; the study of direct mass injection into a boundary layer on a cone, the inverse problem of the removal of mass from a hypersonic boundary layer, and some exploratory studies on whether realistic ablation investigations can be made under the conditions available in the present facilities.

Several of the above studies have been completed and the results published.

Several papers have been presented at national and international meetings. Many of the researches are not complete and results are not yet available or are only in the form of theses, preliminary reports and internal memoranda. It is hoped that continued support will permit these studies to be completed and final reports published.

The following sections of this report present first a few brief comments on the facility development. The completed research studies are briefly outlined and somewhat more detailed information is presented on the studies which have been undertaken and on which only preliminary results have been obtained. A complete list of all of the papers, reports and memoranda which have been generated under this contract can be found in Appendix I.

## II. FACILITY DEVELOPMENT

The main facilities of the laboratory associated with the present program are the two helium tunnels previously described in Reference 1. The three inch tunnel covers a range of Mach numbers from about 8 to 20 with a Reynolds number per inch varying from about 2 to 15 x $10^5$. The second facility, put into operation just before the inception of the present contract, has a six inch diameter test section and operates primarily at a Mach number of 16 over a range of Reynolds numbers from about 8 x $10^4$ to 18 x $10^4$. Both facilities are part of a closed loop system which stores the helium at high pressures (of the order of 2500 psi), throttles this high pressure helium to the desired stagnation pressure during a run, and through the use of a special steam ejector, recovers the helium in an atmospheric balloon after it passes through the test section. The helium then passes through a purifier and a pumping system to be returned to the tanks. This closed loop system has been working extremely well, with a make-up requirement of the order of 5% of the total helium passing through the system. A common heater is provided which keeps the temperature in each stagnation chamber constant during the test period which may be as long as ten minutes. By precharging the settling chambers to the desired stagnation pressure and then removing a specially designed plug which closes the throat, quick starting of the tunnels can be obtained to permit transient heat transfer measurements to be made. During the past period, a third leg to the helium system has been evolved in cooperation with ONR contract No. Nonr 1858(37). A six inch helium tunnel (a carbon copy of the original six inch tunnel) has been constructed and installed in a vertical position. This installation has been coupled with a magnetic suspension system which provides the ability to support simple models up to the order of an inch or an inch and a half in diameter without any physical supports. Both spheres and sharp and blunted cones have been tested in sizes varying from less than a half an inch to somewhat larger than one inch. The work in this facility is primarily supported under the ONR contract, but the tunnel operates as one of the three parallel test systems of the closed helium loop. The work going on in this facility directly complements the wake studies discussed in further detail later in this paper.

During the period of this contract, no major effort has been spent on facility development. The primary addition to the test capability has been the design and operation of a mass injection and suction system which has permitted us to accurately monitor gas flows of the order of microslugs per second. This precision is required since the boundary layer which we are examining has a total mass flow of the order of 25 microslugs and absolute control of the injection or suction rates is required (both numerically and with time) if the final results of the program are to be analyzed. The specific details of this technique and the methods used in the mass injection study have been detailed in Internal Memorandum 6 (Appendix I,7).

With the exception of the requirement to replace the high pressure tanks, little time has been spent on the extension of the capability of the helium facilities. The present facilities provide relatively high Reynolds number, hypersonic flow for reasonable periods of time. Extension of the present range to considerably higher Mach numbers or to considerably higher or much lower Reynolds numbers has not been attempted under the subject contract, although such capabilities are available.

## III. RESEARCH RESULTS

### 1. Cavity Flows

The cavity flow program was a part of a more complex program of separated flows. The primary studies of laminar hypersonic cavity flow was mostly completed under a previous contract and the main emphasis under the subject contract was to extend this work to the effects of mass injection. The models used were designed to be as simple as possible (geometrically) to permit the maximum correlation of theory and experiment. The models were all axially symmetric cones at zero angle of attack with annular cavities. With this geometry, the problem of non two-dimensionality did not arise. (A photograph of the models used, showing the perforated cavity walls through which the mass was injected, is shown in Figure 1).

The test program was carried out in the three inch helium hypersonic wind tunnel, He-1, at a free stream Mach number of about 12, with a few tests included at a free stream Mach number of about 20. Detailed pressure distribution and heat transfers on the wall were obtained for mass injection rates which varied from zero to about 1/3 of the total mass in the boundary layer (measured at the same station on the cone without a cavity). In addition, various modifications of the body downstream of the cavity including the shape of the end of the cavity and the alignment of the wall were studied to evaluate the effect of the downstream conditions on the overall phenomena. Mass injection was found to significantly decrease the heat transfer to the reattachment surface, Figure 2, and this decreased heat transfer was noticed some considerable distance downstream of the cavity, Figure 3. Depression of the rear surface of the cone (below the level of the basic cone) also affects the heat transfer to a considerable degree, Figures 2 and 3 ( $\epsilon_s$ depression of rear surface, L length of cavity). Full details of this study were published (Appendix I,9) and constitute the first detailed study made of the effect of mass injection on a hypersonic separated flow. The conclusions of this study might be briefly summarized as follows: mass injection into the cavity can change, in a major way, the distribution of heat transfer and pressure, particularly around the reattachment point. For the "optimum" mass injection rate, a pressure distribution could be obtained which exhibited minimal disturbances in the reattaching region. The relatively small quantities of mass injected had a pronounced effect on reducing the heat transfer rate in the vicinity of the reattachment region. Injection of a mass flow of about 10% of that in the original boundary layer reduced the heat transfer rates near the reattachment point by a factor of three. Geometry changes could also be used to reduce the heat transfer rate at the reattachment point, but the effect was not as powerful as that of mass injection. It is important to note that the heat transfer rates downstream of the cavity reattachment region were also reduced by injecting mass into the cavity. Although there had been serious question as to whether mass injection could be carried out without the flow becoming turbulent, no evidence of this was found in the present study. Transition without mass injection occurred far downstream on the body and mass injection appeared to change this transition point only by a small amount.

2. Flat Plate Studies

The study of the flow over a flat plate has concentrated primarily on trying to detail the effects of viscous and inviscid interactions on the flows. To this end, the flat plate studies have included wide variations in the leading edge Reynolds number and angle of attack to provide the widest possible set of conditions to check the few theories which are available. Three "first phase" studies have been completed (Appendix I,6,11,15), and a review of the rarefied problem outlined in Appendix I,14. The first study examined the effect of leading edge Reynolds number on the local heat transfer coefficient on a flat plate at a Mach number of about 12. The leading edge Reynolds number was varied from about 193 to 18,850, a range which covers purely viscous to the inviscid bluntness regime. The study found that for $Re_{\infty t}$ less than about 800, bluntness had little effect on the local heat transfer coefficient. Some typical heat transfer results illustrating this point are shown in Figure 4(a-e). The effect of nose shape was also briefly examined by comparing a square and a hemicylindrical nose of the same total dimensions. It was found that the local heat transfer coefficient varies as $C_D^n$ where $n$ is .15 for helium and .19 for air. This disagrees with the value of 1/3 predicted by Cheng and his co-workers. The comparison of the results with theory shows that Cheng, et. al.[2] yields fair agreement in the viscous regime and good agreement in the inviscid bluntness regime. Oguchi's theory[3] predicts local heat transfer coefficients which are low by a factor of two and Bertram and Feller's methods[4] yield fair agreement with the experiments, but it is necessary to know the pressure distribution before one can calculate the local heat transfer. Comparison of the experiments with several of the theories are shown in Figure 5(a-c). Agreement with air data for the same leading edge Reynolds number and Mach number was excellent. This study complements a previous study which detailed the pressure distributions over a plate at similar conditions.

The study of leading edge Reynolds number effects was extended to the case of angles of attack at a Mach number of 16.35. The detailed pressure distribution phase has been completed. These studies were carried out in the six inch helium tunnel at low stagnation pressures so that the leading edge Reynolds number could be dropped as low as 20. For these conditions, it was found that the pressure distribution and the shock wave coordinates were in good agreement with the predictions of strong interaction theory at zero angle of attack. A closed form solution was obtained which closely predicts the pressure distribution and shock wave shape as the angle of attack varies between 0 and 12°. For blunt plates (leading edge Reynolds number greater than about 2000) the measured pressures were considerably below the predicted values of Cheng near the leading edge, but agree with his predictions downstream. Furthermore, the pressure distributions downstream of the leading edge were higher than the values predicted by the blast wave analogy and the sonic wedge method. Typical pressure distributions for sharp and blunt plates vs angle of attack are shown in Figures 6(a,b), and some representative schlieren photographs are shown in Figure 7. Correlation of the results for both sharp and blunt plates at angle of attack is given in Figures 8 and 9. The companion study to determine the detailed heat transfer distributions which go with the above pressure distributions is still underway and has not been completed. It is hoped that this work will continue under further Aerospace Research Laboratory support and that a full paper including all of the results will be presented in the near future.

An additional study, at a Mach number of 10 in air, has also been completed, covering leading edge Reynolds numbers from about 115 to over 14,000. For this study, complete shock shape and pressure and heat transfer distributions over the plate have been obtained and compared with existing measurements and the various theories. This study was limited to zero angle of attack and was carried out primarily to extend the range of the previous experiments. Some typical results are shown in Figures 10-12. For low leading edge Reynolds numbers, the pressures were well predicted by the second order weak interaction theory with a first order correction for the pressure gradient. For large leading edge Reynolds numbers (above 7000) the slope of the pressure distribution was in good agreement with the predicted blast wave solution but the magnitude of the actual pressures was not. Similar to the cases described above, for leading edge Reynolds numbers less than about 2000, no change in the local heat transfer rate was noted for leading edge modifications. In this range, the data were correlated by using the hypersonic viscous parameter. For leading edge Reynolds numbers larger than about 2000, the data correlated reasonably well using the bluntness parameter as suggested by Cheng.

With the completion of the present heat transfer studies, it should be possible to correlate a complete set of results covering the range from Mach numbers of about 10 to 20 including leading edge thicknesses which vary from leading edge Reynolds numbers of the order of 20 to almost 20,000 (fully viscous to bluntness controlled).

### 3. Delta Wings

Several reports on delta wing studies were completed just prior to the present contract. This work was extended to a study of flat delta wings at angle of attack, Appendix I,4. The delta wings used at sweep back angles of 60 and 70° and had leading edge thicknesses which varied from .005 to .030 inch. The angle of attack of the model was varied from 0 to 50°. Using pressure measurements, schlieren photography and oil streak studies, details of the flow were examined and the results correlated with various interaction parameters evaluated using conical flow properties. It had been thought that there would be a region of angle of attack where a leading edge would no longer affect the flow. However, within the range of the tests carried out, the leading edge always affected the overall flow. The "high angle of attack" region was found to be approximately 40° for a 70° delta wing; and leading edge bluntness was found to have a definite effect on the spanwise pressure distribution. Unfortunately, angles of attack high enough to give a valid comparison with the concept of spanwise strip theory could not be reached because of tunnel blockage problems and limitations on model size. At low angles of attack, the flow along the centerline was affected by bluntness up to an angle of attack of approximately 10°. An increase in apex bluntness caused an increase in pressure along the centerline. The variation of pressure along the centerline at angle of attack agrees with the tangent cone approximation for angles of attack in which the local value of viscous interaction parameter is small. The flow streak studies show the changes in the three dimensionality of the boundary layer flow as the angle of attack is increased, Figure 13 (a,b). Some typical results showing the effect of angle of attack on the centerline pressure distribution and a correlation of the effect of sweep on the boundary layer induced pressure field is shown in Figures 14 and 15. Continuations of this study could not be carried out because of the limitation on angle of attack. Using very small models, the angle of attack was still limited to the order of 50° before complete tunnel flow breakdown occurred. It is, however, still very important to get the full range of angle of attack from zero to 90° to better define the limitations of the three classical angle of attack regions which occur in possible practical applications of delta wings Considerably larger equipment is required to carry out these studies, however, and further work along this line was discontinued because of this limitation.

## 4. Wakes

Wake studies under the present contract have been restricted to some specific tests where results at very high Mach numbers might add to the general understanding of the phenomena. For two dimensional wakes behind cylinders, excellent detailed results are available for Mach numbers of 3.7 and 5.8 from the work of Kendall[7] and McCarthy.[8] However, the primary interest in wakes is at hypersonic speeds and there was some question as to whether the results at these lower speeds might be appropriately extended to much higher Mach numbers. In an attempt to provide such data, a two dimensional circular cylinder was examined at a Mach number of 16 in the 6 inch helium tunnel, Appendix I,10. Cylinder diameters of 1/8" and 3/16" were used giving a Reynolds number variation of 10,000 to 25,000 based on free stream conditions. The first part of the study, detailed pitot pressure surveys, was carried out starting one diameter downstream of the body and extending to 80 diameters. Some typical results are shown in Figures 16 to 19. For the range of conditions tested, the profiles in the far wakes at the same non-dimensional station (same $\frac{x}{d}$ ) are similar. Following from this, the longitudinal variations of centerline pitot pressure and the pitot pressure at the wake edge were both found to be independent of Reynolds number. It was also found that the rate of growth obtained in this investigation is approximately 0.6 (Figure 19). This value compares reasonably well with the rates of growth found at lower free stream Mach numbers by Demetriades[9], Kendall[7], and Murman and Hurlburt[10] testing in air. However, the rates of growth derived from McCarthy's data[8] were considerably less than those noted above. There also appears to be no dependence of the rate of wake growth on either Mach number or Reynolds number. On the basis of total head surveys alone, it seems impossible to determine transition. By comparing the profiles obtained in the present study with those presented by McCarthy, it is believed that transition may occur within the wake lengths examined. However, no longitudinal pressure variation or discontinuity was found within the length of the present surveys. A rather important indication of the effect of diffusion taking place between the outer inviscid wake and the inner viscous wake can be obtained by plotting the quantity called the pitot amplitude, Figure 20. The pitot amplitude shows an exponential decrease with increased $x/d$ . It has been stated that the amplitude of the pitot variation across the wake diminishes as the fluctuations become more regular and hence a direct measure of the fluid mixing is obtained. In the present experiment the mixing appears to take place at the same rate irrespective of the Reynolds number, and this independence of Reynolds number has not been indicated by results from other workers at lower Mach numbers.

Although the details of the pitot pressure surveys serve to form a basis for examining the wake behind the cylinder, another measurement is needed if the static pressure, velocity and temperature are to be calculated. Studies are still under way in an attempt to get such information. The conventional static pressure tube cannot be used because of major corrections and scale problems, and attempts to use hot wires have not been completely successful to date. Further work in this area is required to provide point physical characteristics throughout the wake region.

With the support of the Advanced Research Projects Agency and the Office of Naval Research, wake studies similar to that discussed for the cylinder are being carried out for axially symmetric bodies in the vertical helium tunnel using a magnetic suspension system. The problems of two dimensionality and end effects have been eliminated by the added complication of magnetically supporting the models. This technique, however, has proved to be an extremely successful one and spheres and cones are being flown with regularity in a major program of detailed wake studies. First results on the study of wakes of support free spheres at a Mach number of 16 in helium has been presented at an AIAA meeting, Appendix I,12. Current studies are aimed at the flow field behind cones, which is a considerably simpler body because of the lack of external entropy gradients caused by the strong bow shock. Evaluation of the effects of nose bluntness and shoulder bluntness are being carried out as well as detailed measurements in the wake to provide local physical conditions.

### 5. Mass Transfer Studies

With the advent of the "mass injection in cavity" study noted earlier, the laboratory has embarked on a major long range study of fundamental effects of mass transfer on hypersonic laminar boundary layers. This important phenomenon is of direct application to problems of cooling hypersonic vehicles and, in one form, as ablation. It is the only current practical approach to the solution of reentry problems. The studies which have been undertaken are exploratory and have taken on three different directions. First, a study of transpiration on a discrete section of a $10^{\circ}$ half angle cone. This geometry was chosen in an attempt to get a direct comparison between transpiration cooling and mass transfer to a separated cavity flow which covers the same dimension on the same cone. Using porous materials of carefully chosen uniform properties, mass has been injected into the laminar boundary layer on the basic cone and details of the resulting pressure distribution and boundary layer profiles have been obtained. In contrast to the cavity injection, any injection into the boundary layer on the basic cone causes major modification of the external flow field. Variations of the injection rate cause major changes in the pressures on the portion of the cone downstream of the porous section, Figures 21 and 22. Mass injected into the cone causes a decrease in the pressure downstream of the porous section, which, in practice, would result in a destabilization of the cone. The added mass at the beginning of the porous region causes a shock wave to propagate out into the flow, and the sudden end to the porous section results in a readjustment in the boundary layer displacement thickness which generates a rather strong expansion which causes the decrease in the pressure over the downstream section of the cone. Detailed survey of this phenomena has been undertaken as a preliminary to changes in the geometry which will permit the injected mass to cause smaller disturbances in the external flow and hopefully increase the efficiency of the injected mass. Problems of making detailed surveys within the region in which the mass is injected are currently being studied to get a detailed profile of the mixing which occurs. On the basis of the measurements thus far, transition does not occur on the porous section nor over the downstream region which has been studied. A complementary study to the above program has been the use of suction on the same basic cone. Rather small amounts of suction will cause major changes in the thickness of the boundary layer to occur since the lower part of the hypersonic boundary includes only a small fraction of the total mass in the boundary layer. Again, the emphasis in these studies are the detailed examination of the boundary layer profiles to get a better understanding of the hypersonic laminar boundary layer in the regions of mass injections and strong pressure gradients. Considerable further work on both of these programs has yet to be undertaken before a significant understanding of the flow can be obtained. The results are being compared with theoretical calculations of rather limited applicability.

As a preliminary to performing tests under direct ablating conditions, an exploratory study has been carried out to determine the key parameters involved in model designs for hot facilities for such tests. Theoretical predictions and experimental studies of ablation have been carried out in a hot nitrogen stream developing a stagnation enthalpy of about 1000 Btu per pound. Teflon, napthalene and paradichlorobenzine models have been examined by using photography and temperature history of the models. Data from these histories were then put in the form of parametric functions of time. The analysis found materials which satisfy certain thermal conditions for ablation tests in a low energy nitrogen tunnel are possible. The validity of the thermal and ablative parameters which govern ablation was established by cross checking the ablation performance of different model configurations. With the validity of the ablation tests established, thermal data such as thermal diffusivity and heat vaporization may be derived from the analysis of the experiments.

The study provides a background necessary for the design of future ablation experiments.

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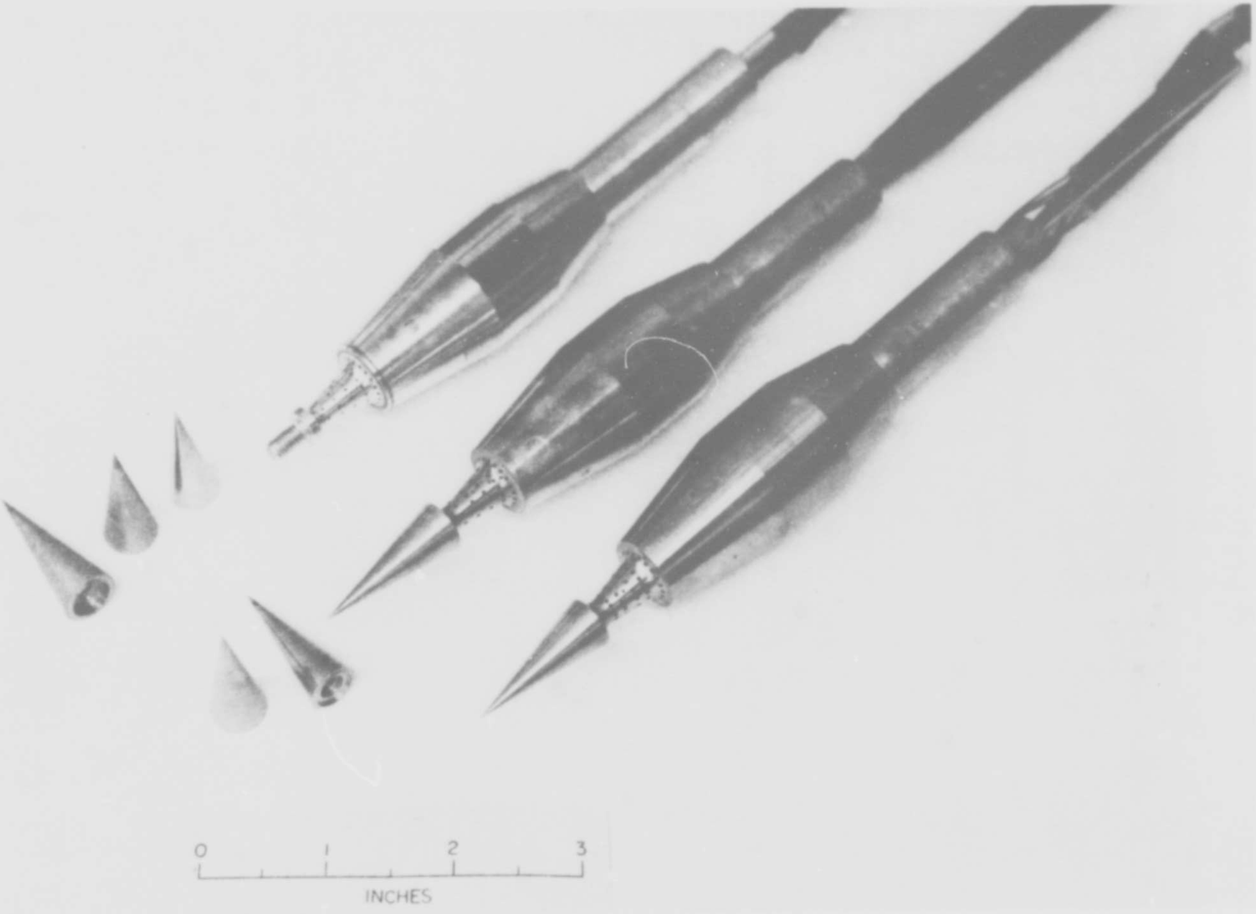


Figure 1. Wind-tunnel models. From left to right, heat transfer model, pressure model B and pressure model A.

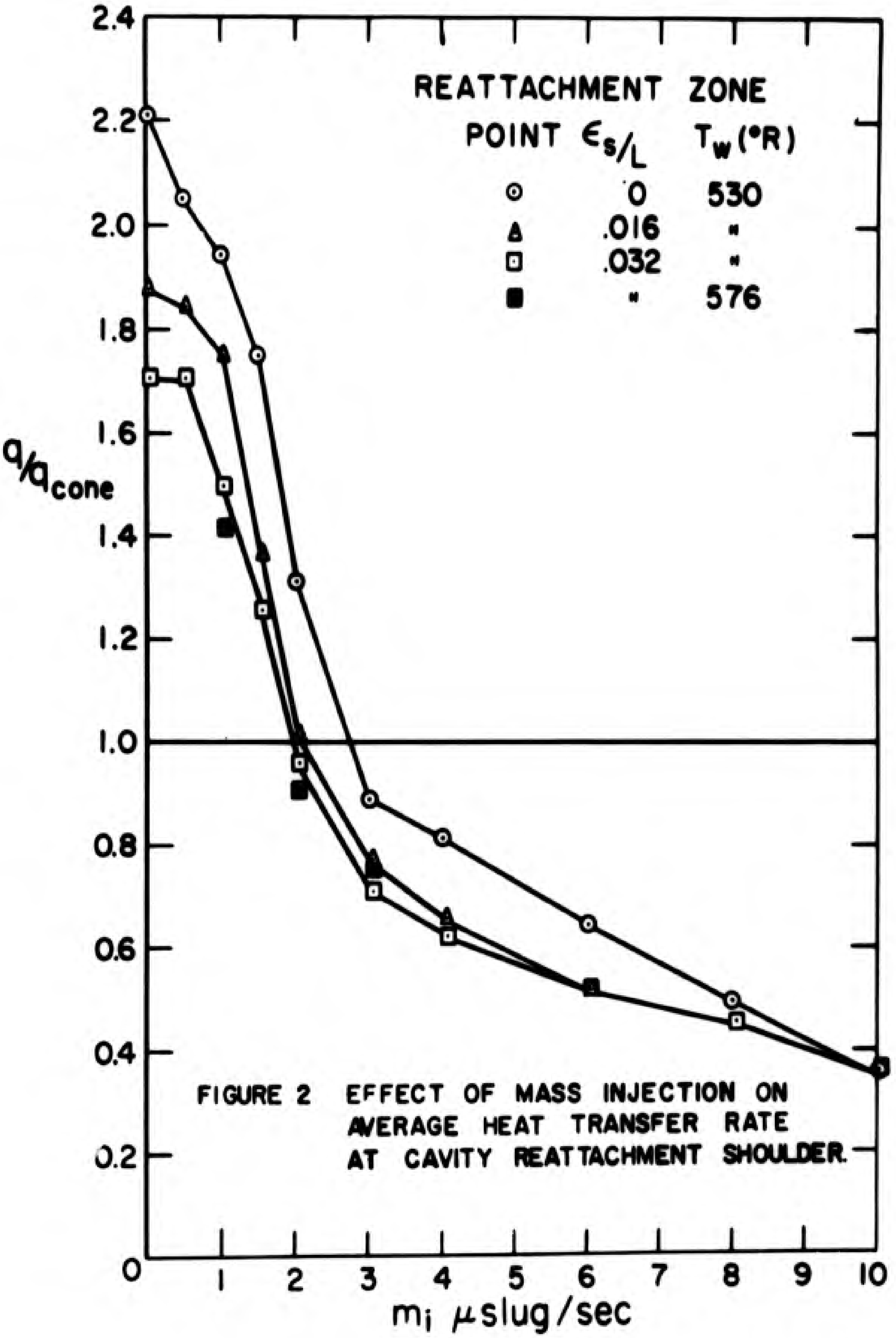


FIGURE 2 EFFECT OF MASS INJECTION ON AVERAGE HEAT TRANSFER RATE AT CAVITY REATTACHMENT SHOULDER.

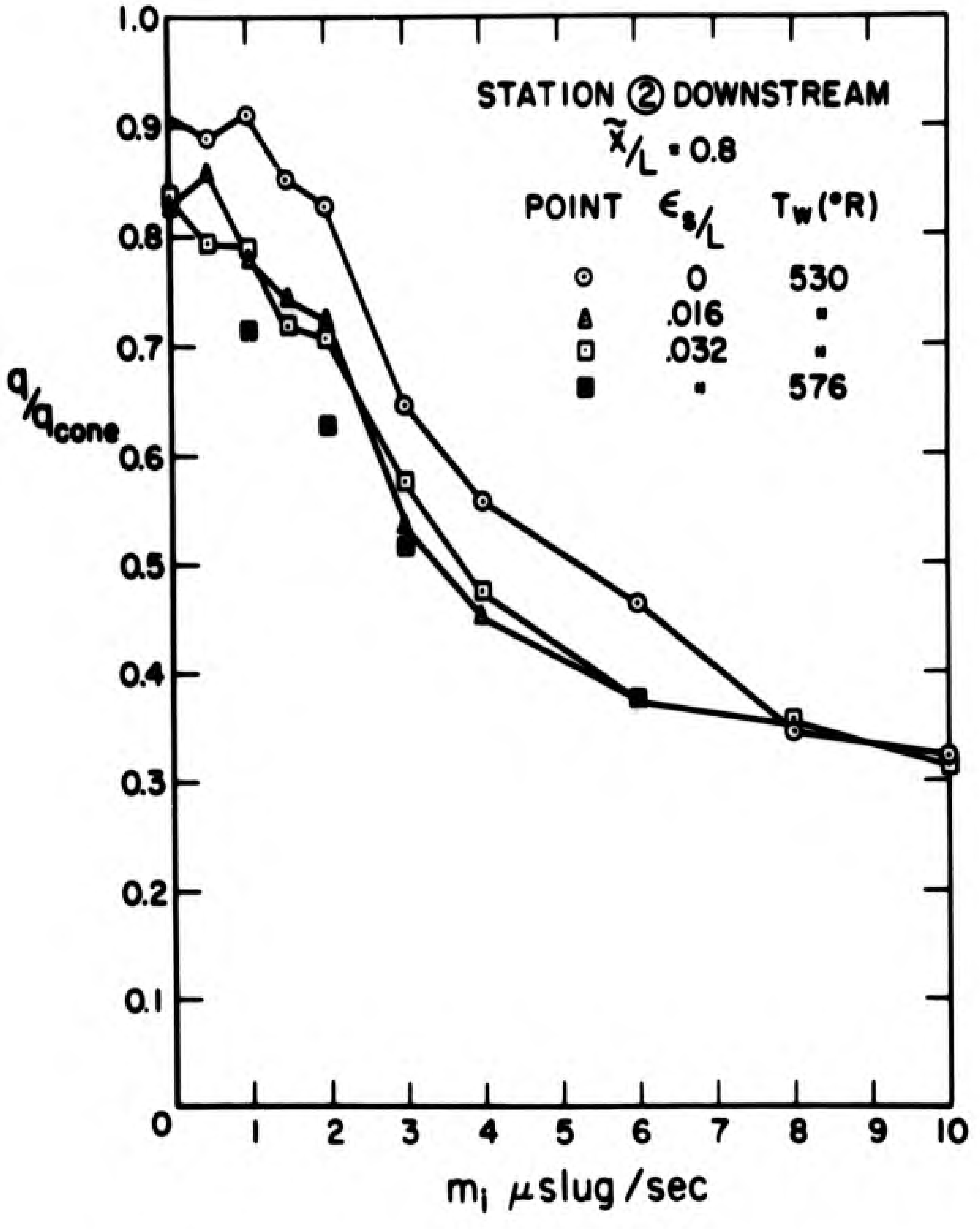


FIGURE 3 EFFECT OF MASS INJECTION ON HEAT TRANSFER RATE AT DOWNSTREAM STATION (2).

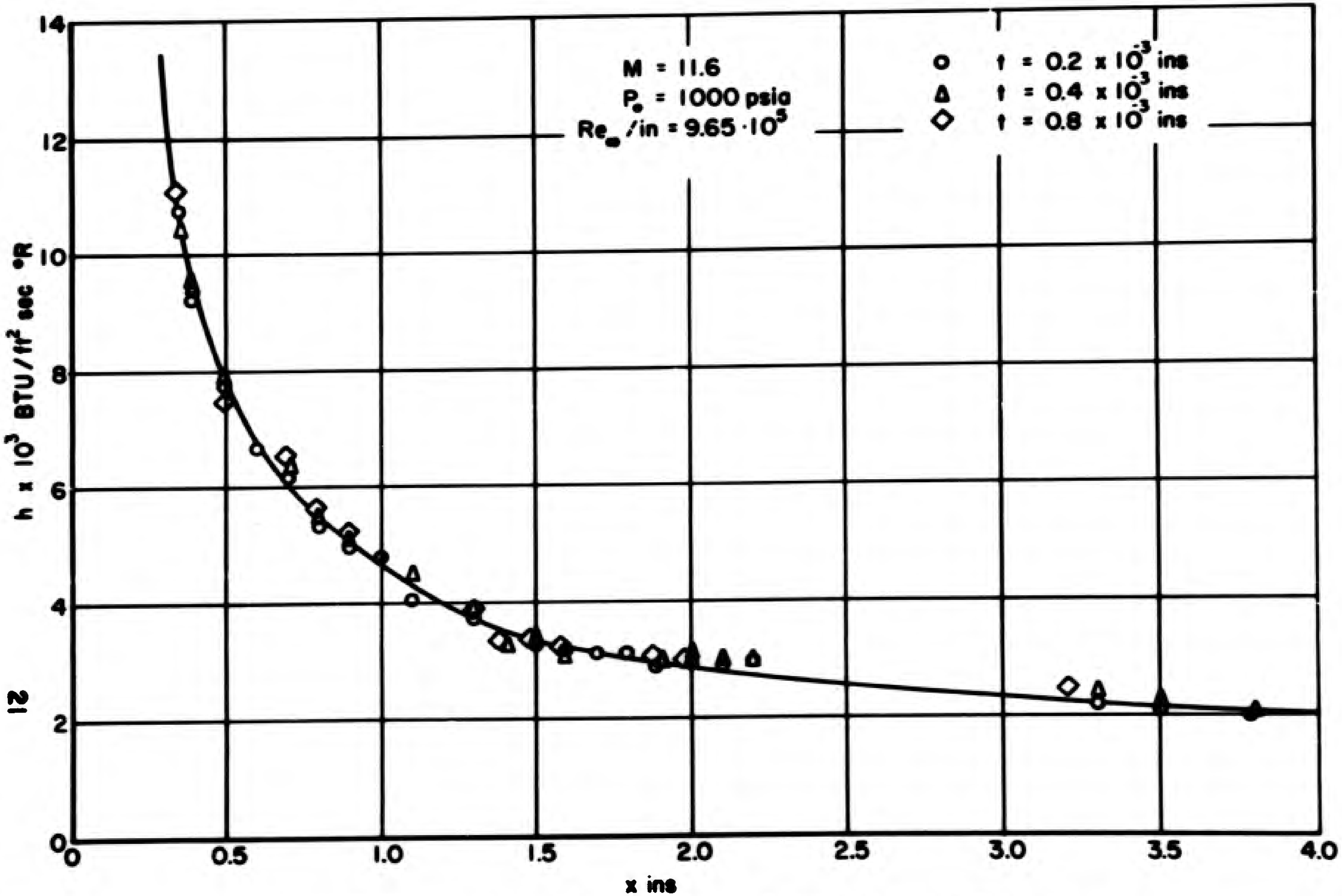


FIGURE 4(a) LOCAL HEAT TRANSFER COEFFICIENT.

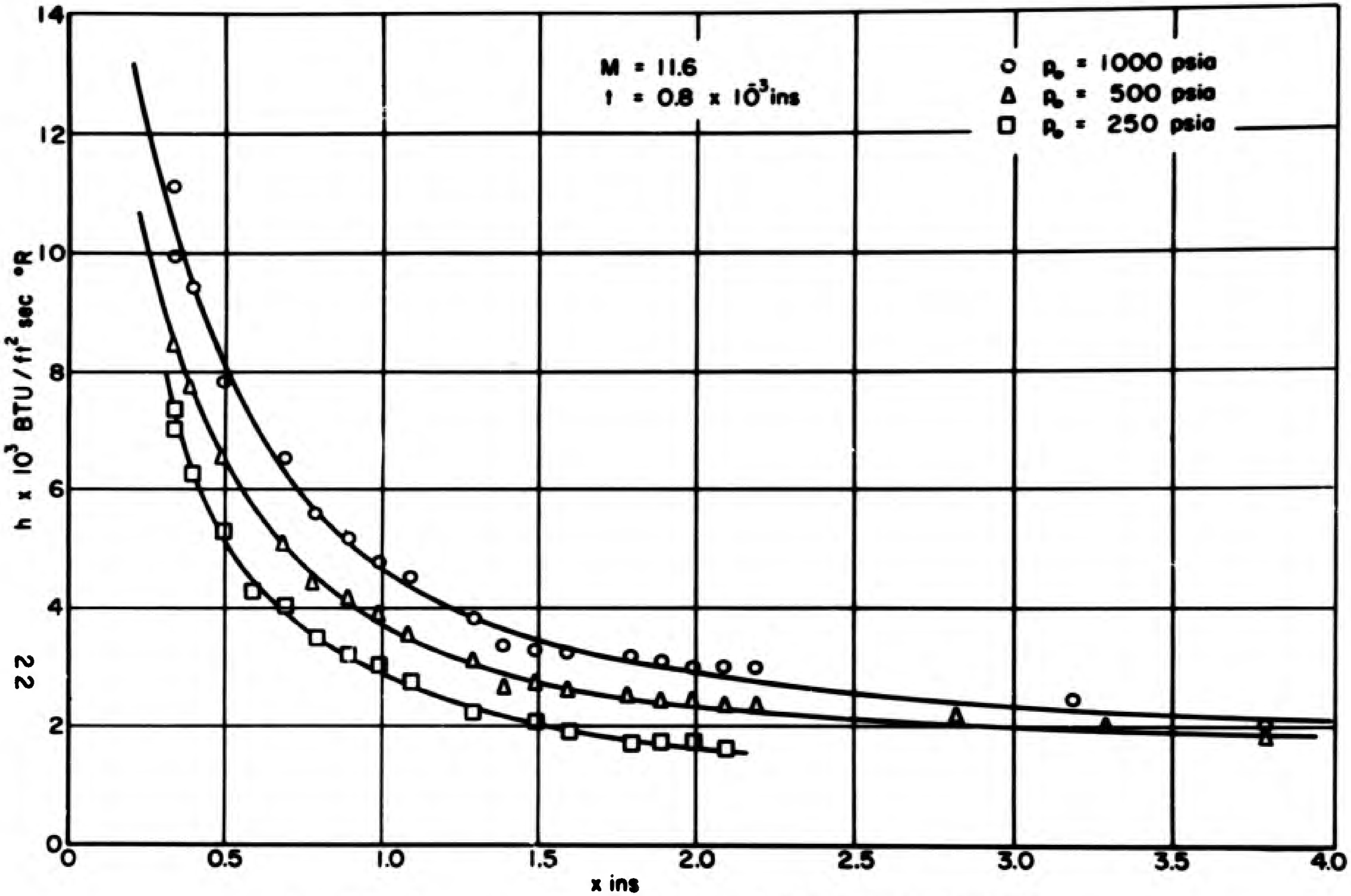


FIGURE 4(b) LOCAL HEAT TRANSFER COEFFICIENT

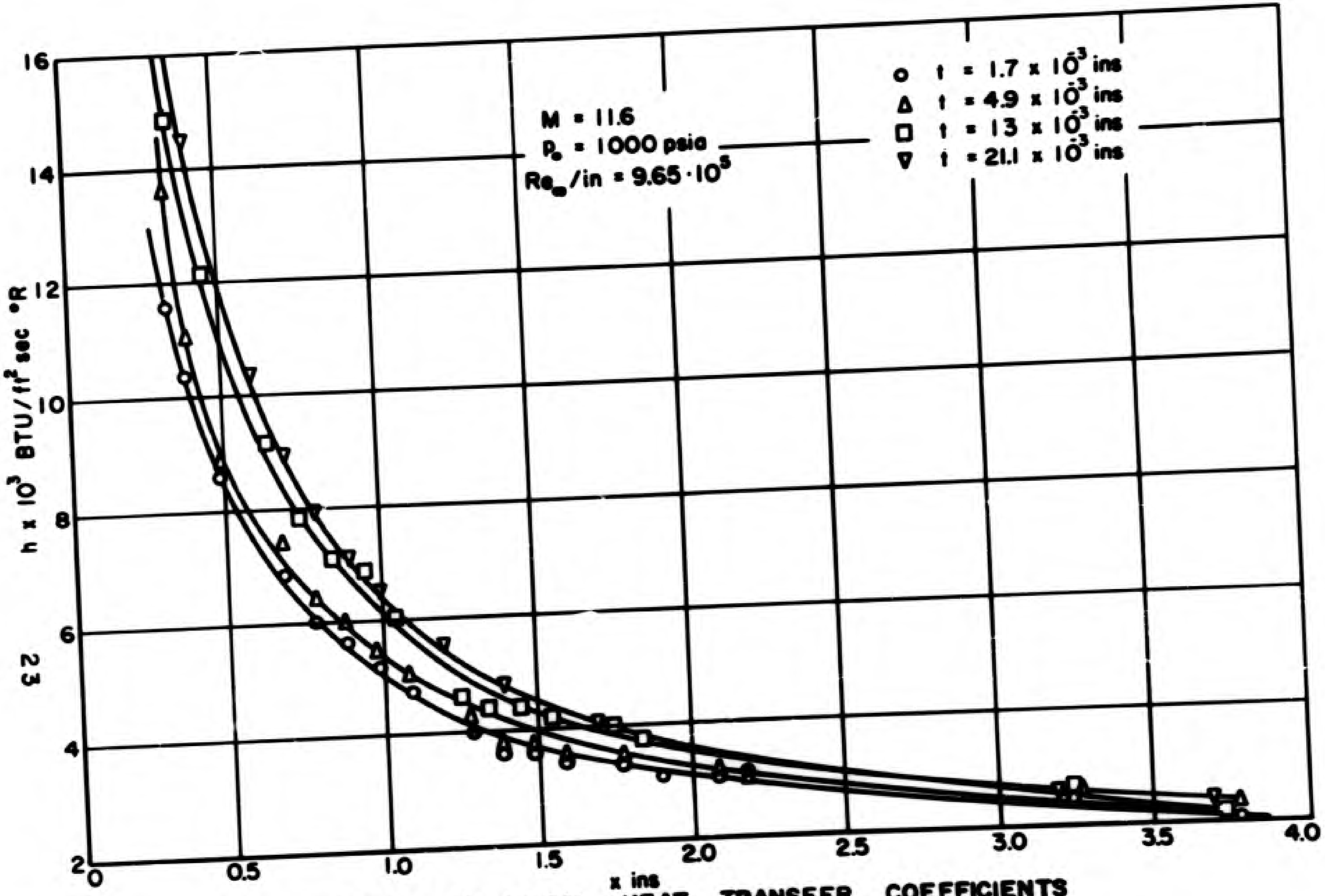


FIGURE 4(c) LOCAL HEAT TRANSFER COEFFICIENTS

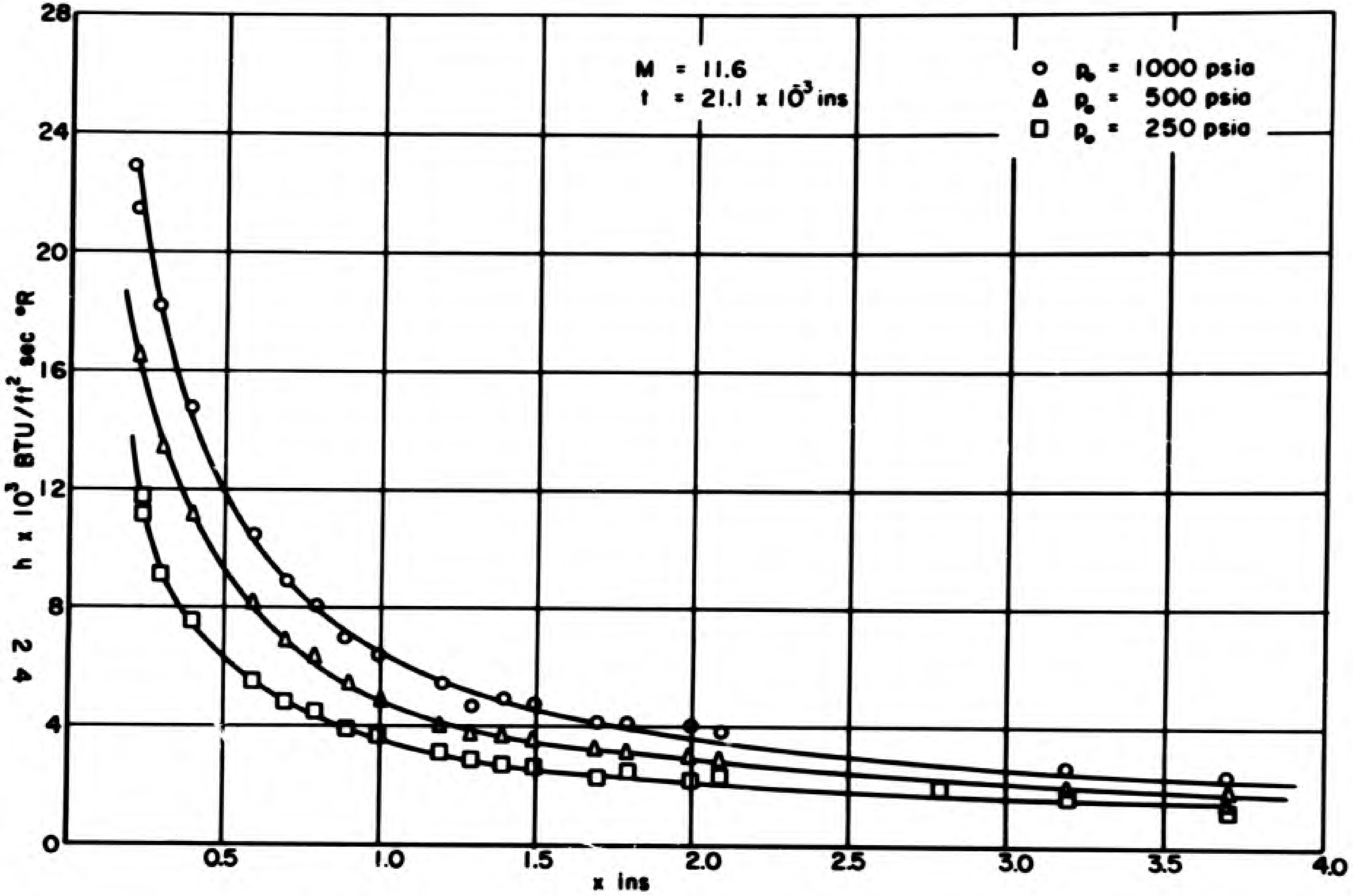


FIGURE 4(d) LOCAL HEAT TRANSFER COEFFICIENTS

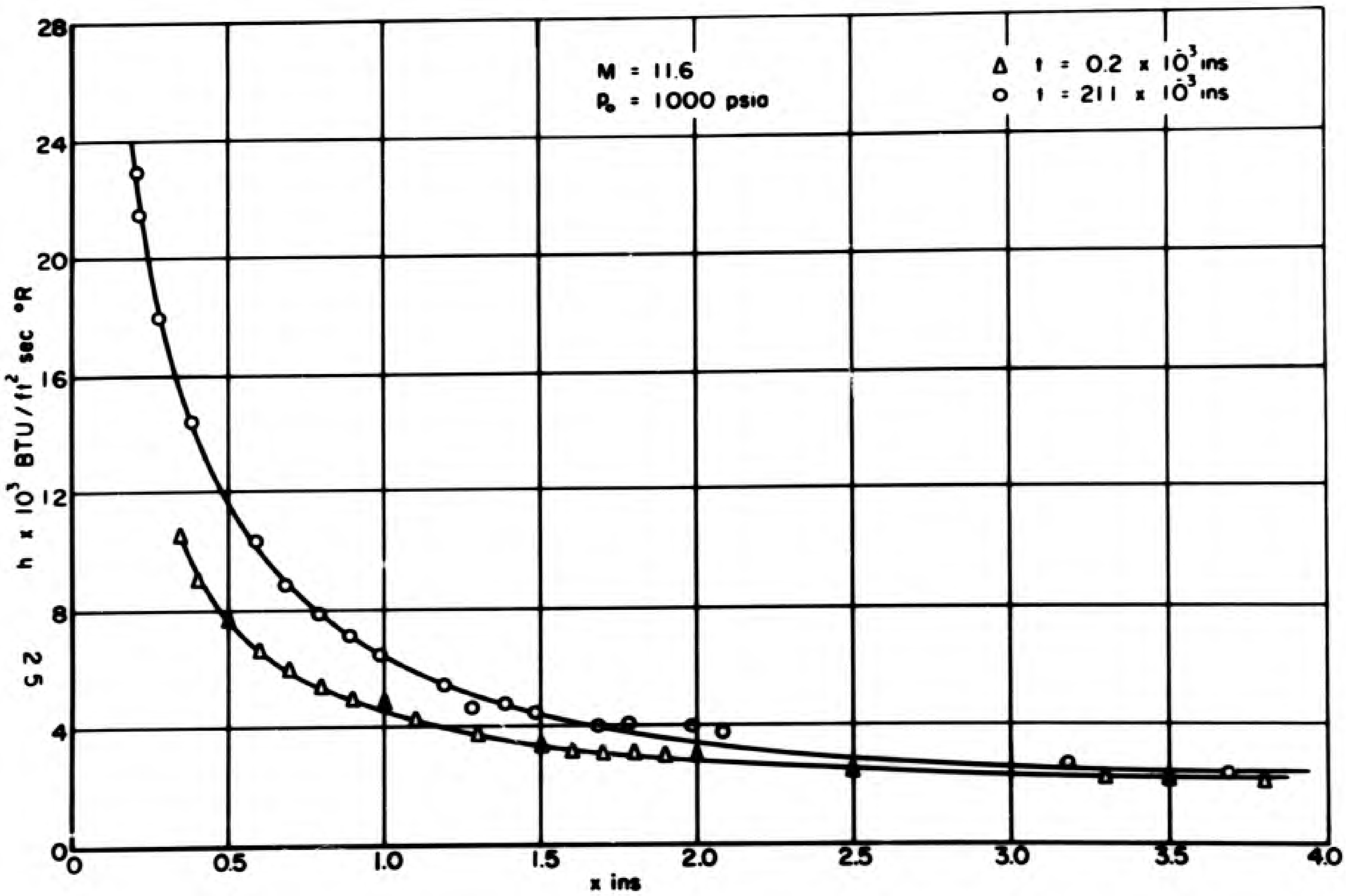


FIGURE 4(e) LOCAL HEAT TRANSFER COEFFICIENTS

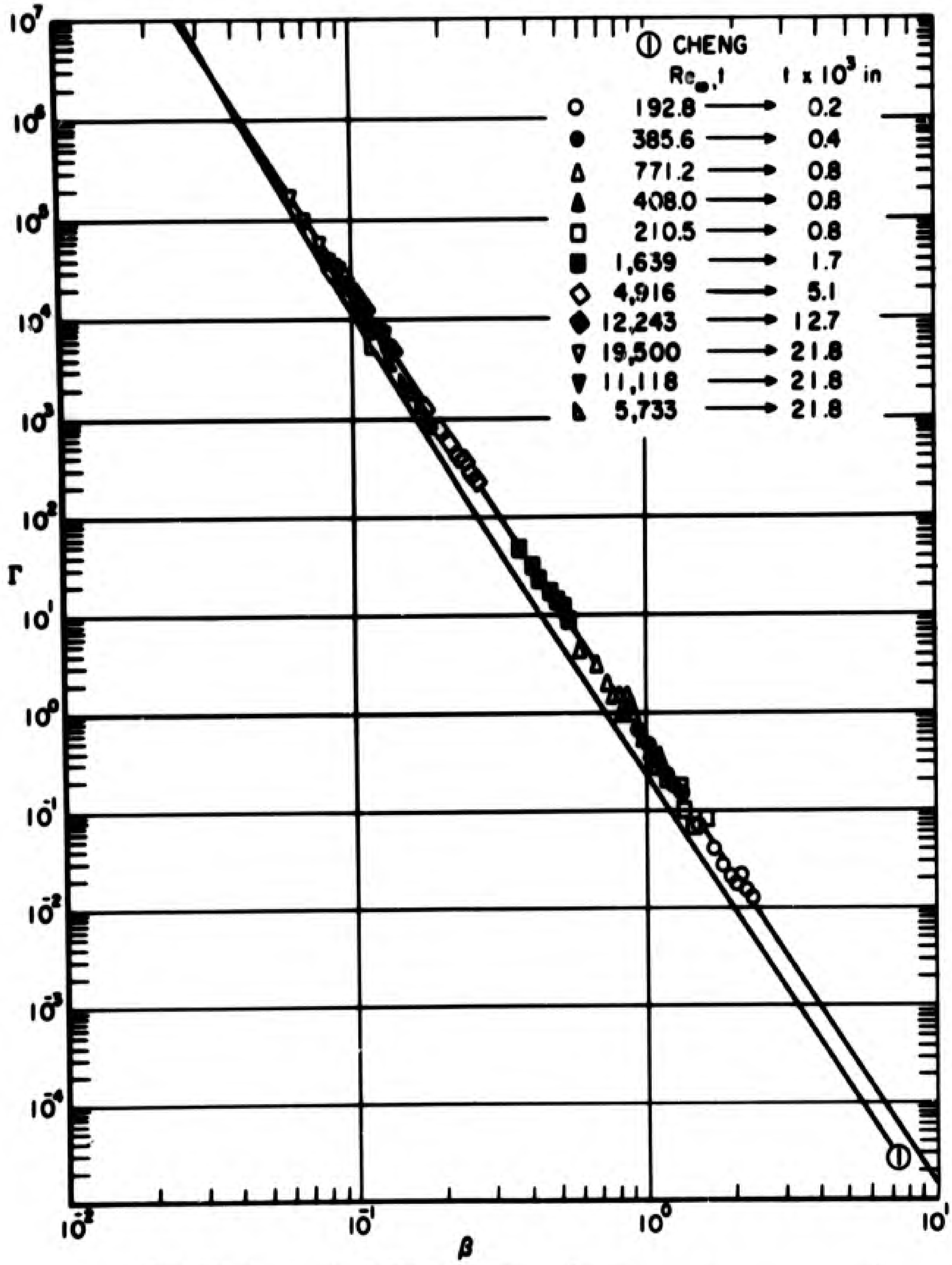


FIGURE 5(a) COMPARISON WITH CHENG, et. al.

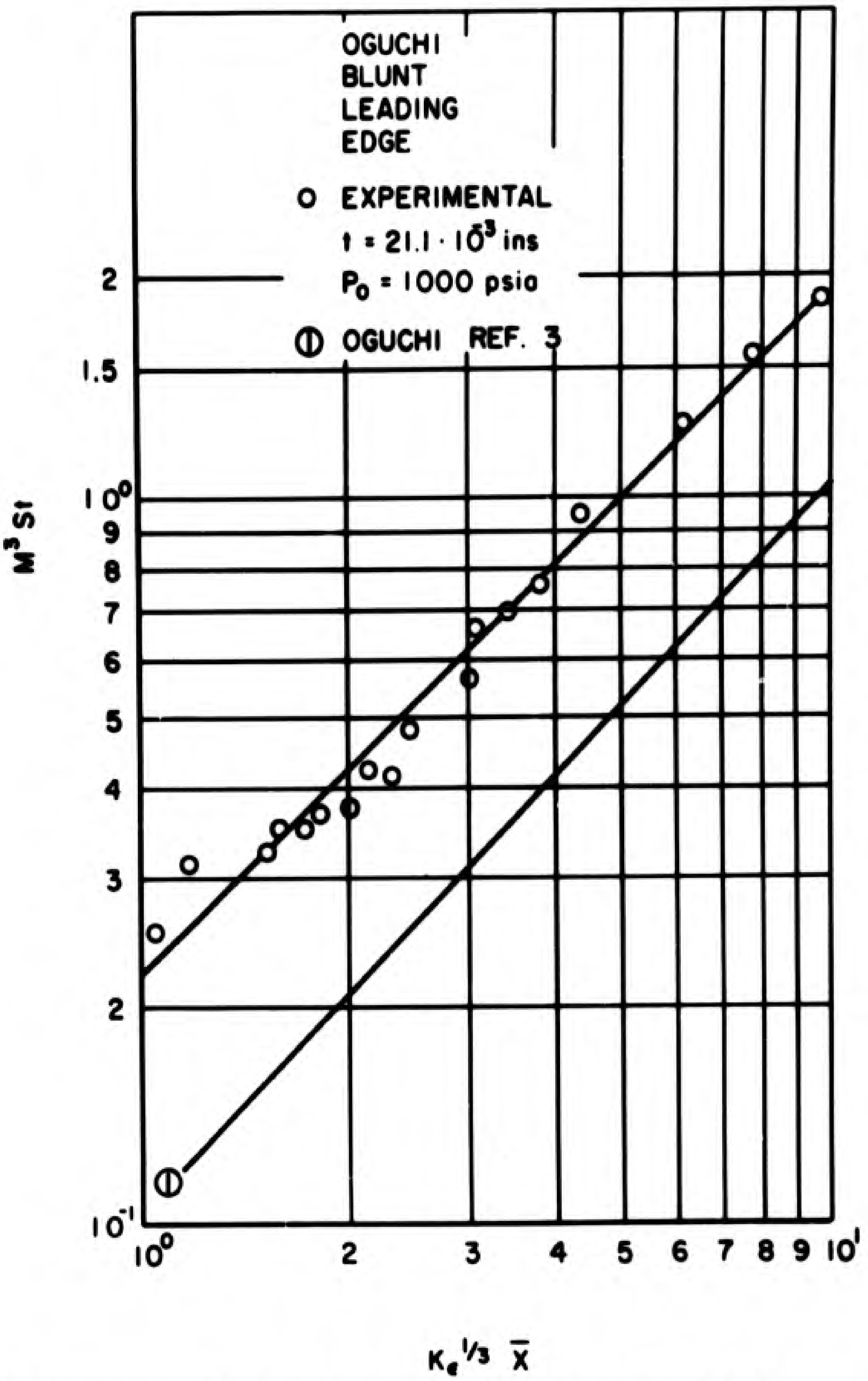


FIGURE 5(b) COMPARISON WITH THEORY BY OGUCHI.

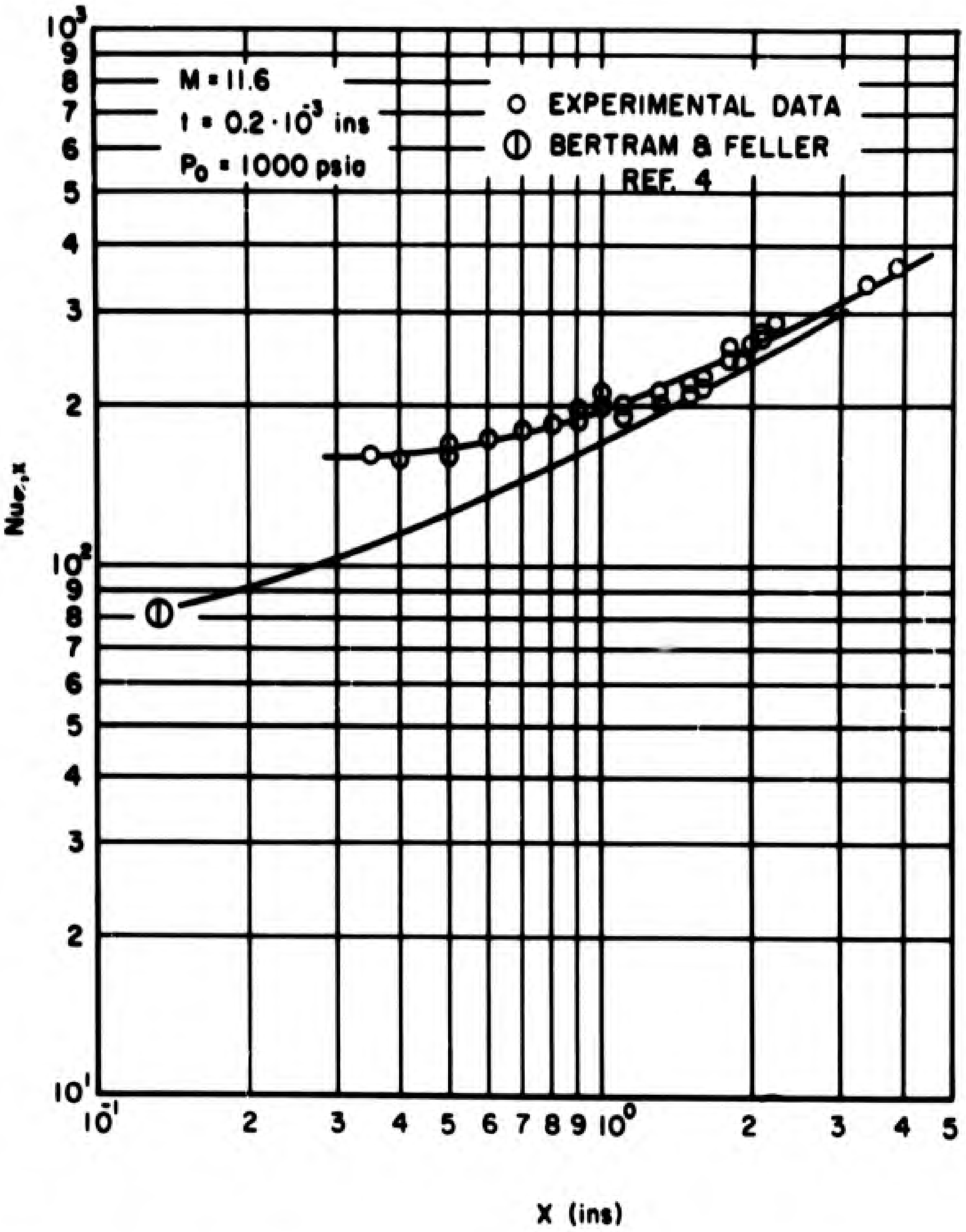


FIGURE 5(c) COMPARISON WITH METHOD BY BERTRAM & FELLER.

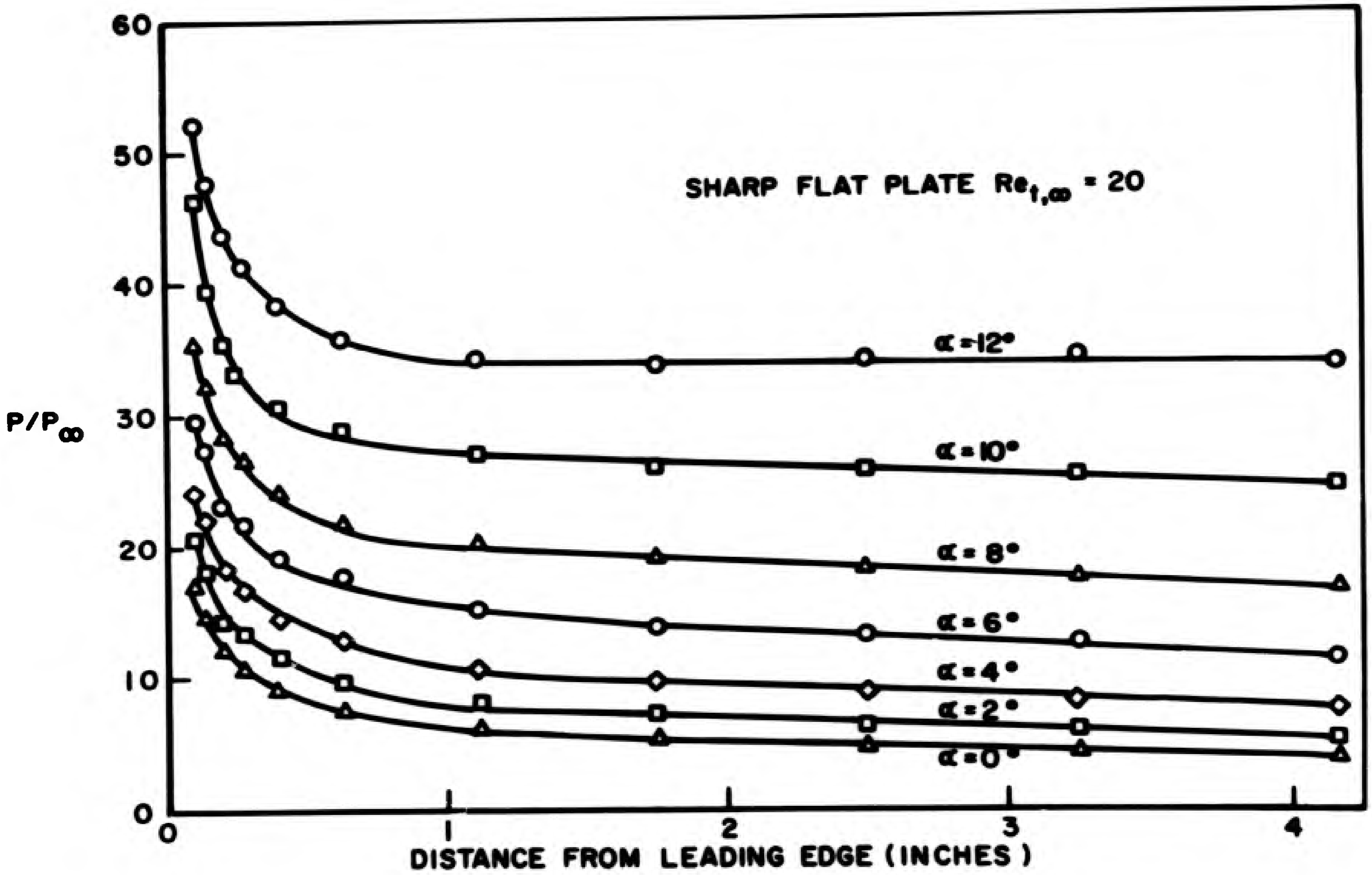


FIGURE 6(a) PRESSURE DISTRIBUTION ON A FLAT PLATE AT $M_\infty = 16.35$, $t = 0.001$ INCHES, AT VARYING ANGLES OF ATTACK.

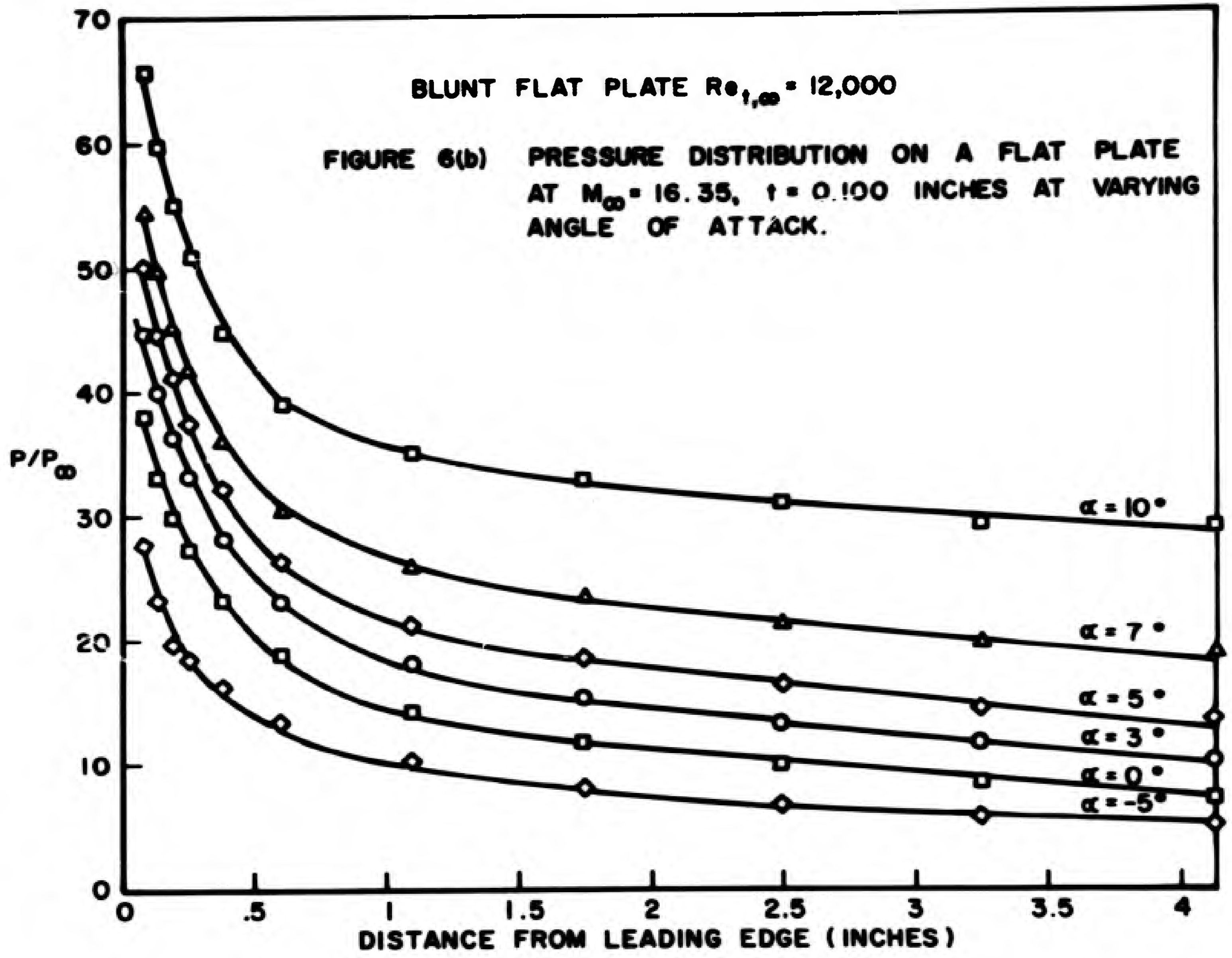


FIGURE 6(b) PRESSURE DISTRIBUTION ON A FLAT PLATE AT $M_\infty = 16.35$, $t = 0.100$ INCHES AT VARYING ANGLE OF ATTACK.

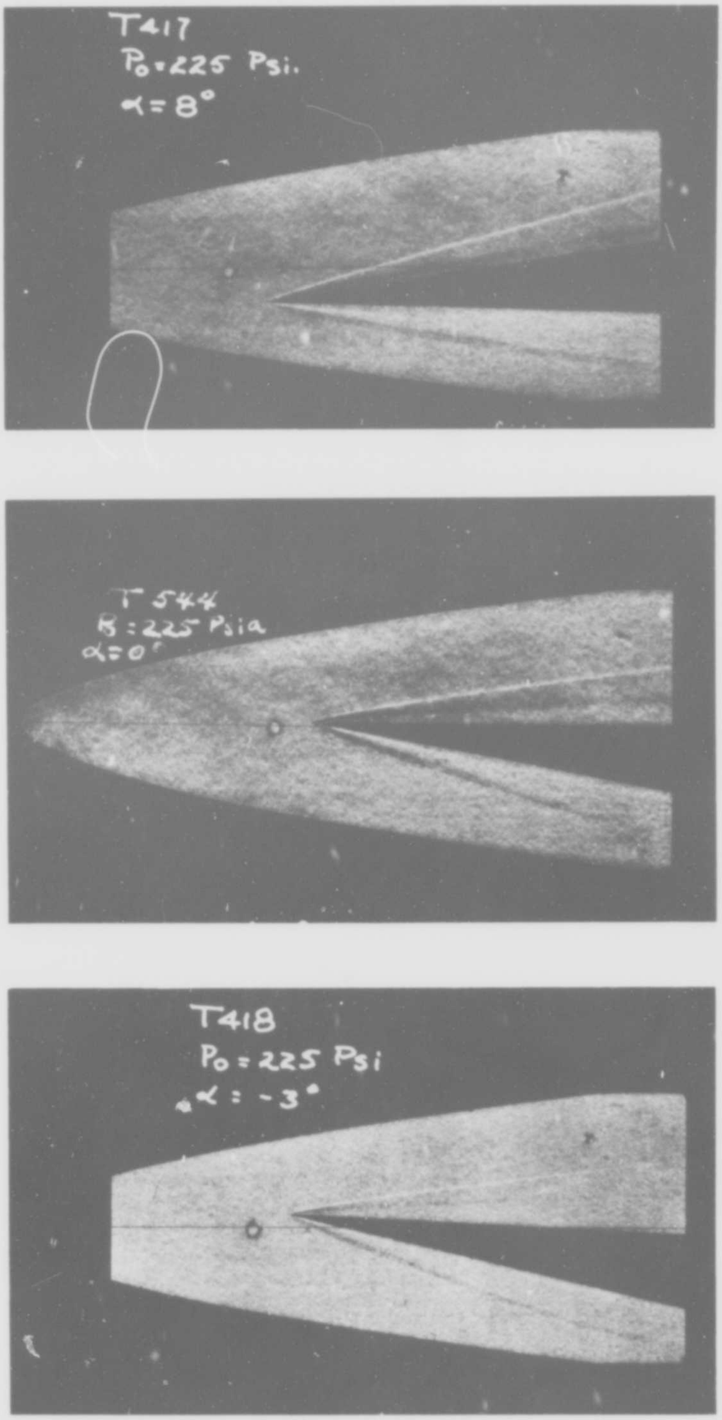


Figure 7(a). Schlieren photographs of flat plates at $M_\infty = 16.3$, t = 0.001 inches, at varying angle of attack.

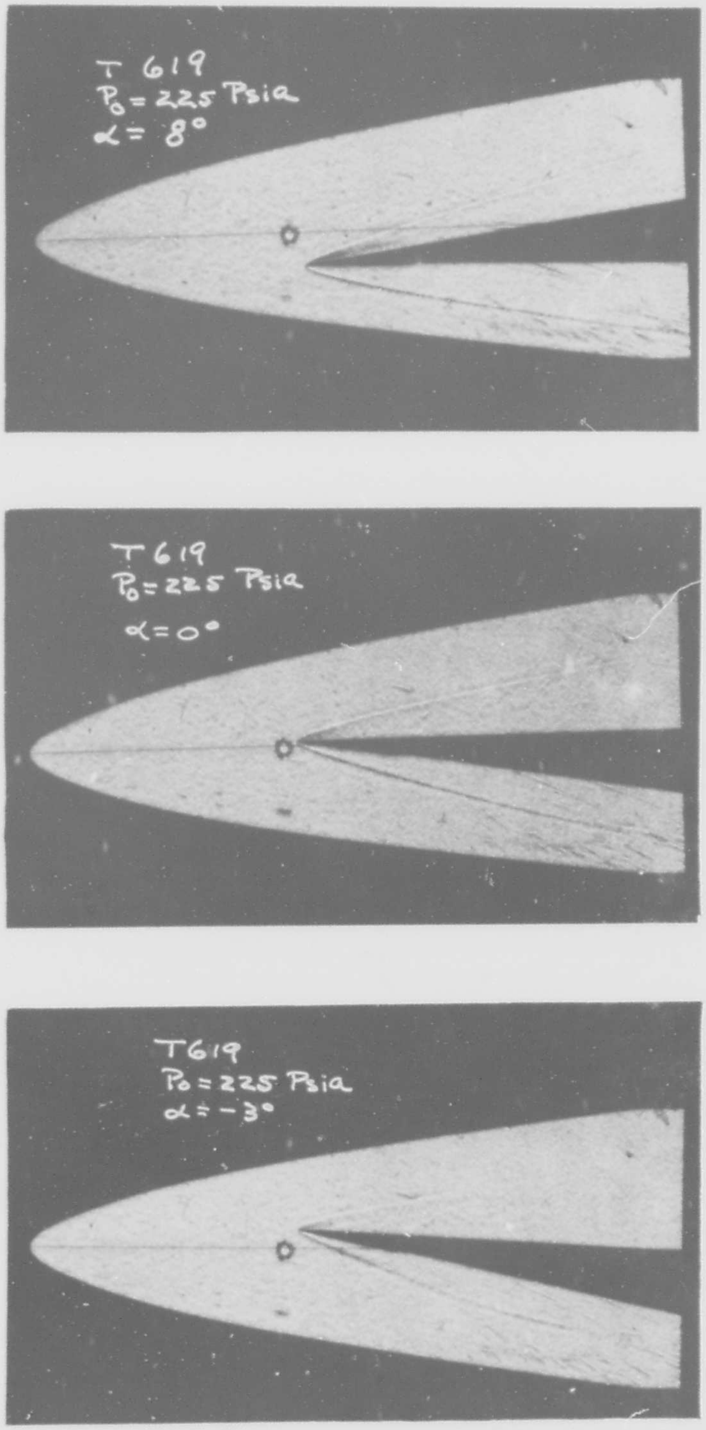


Figure 7(b). Schlieren photographs of flat plate at $M_\infty$ = 16.3, t = 0.014 inches, at varying angle of attack.

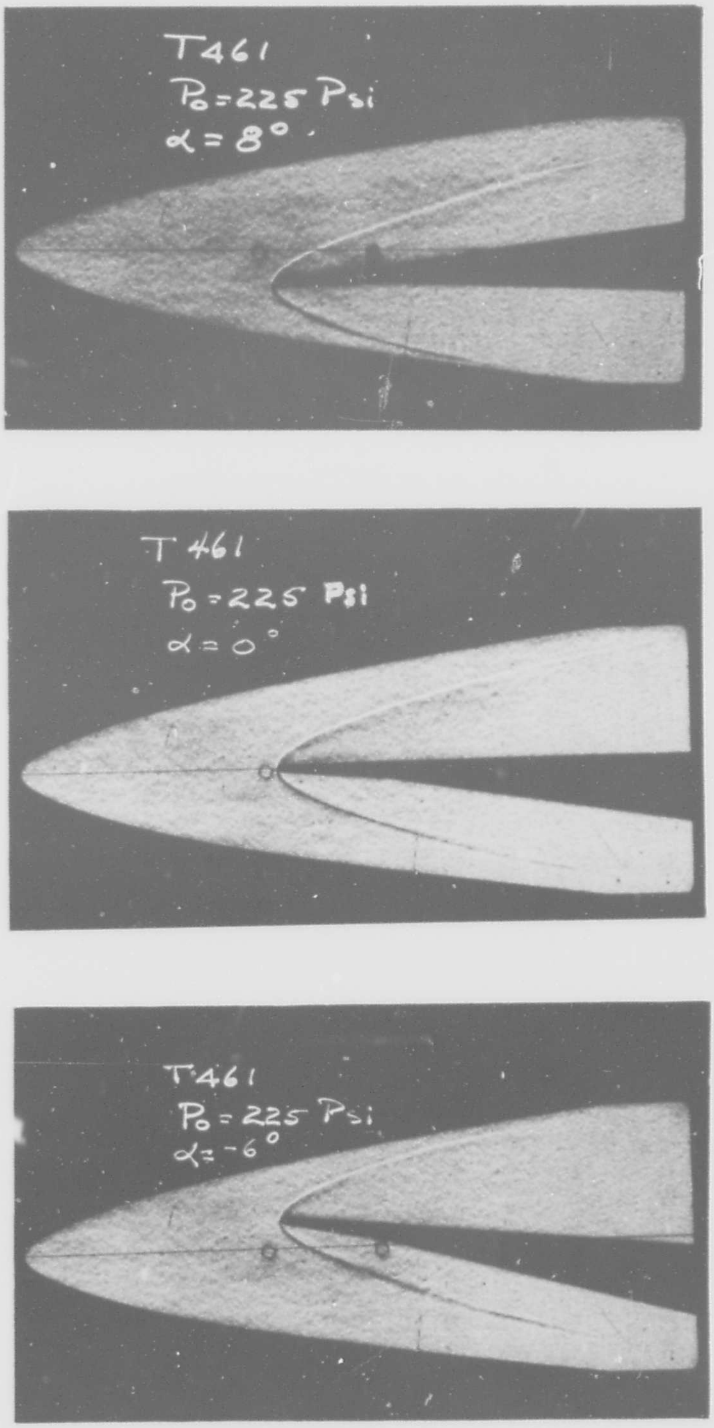


Figure 7(c). Schlieren photographs of flat plate at $M = 16.3$, $t = 0.100$ inches, at varying angle of attack.

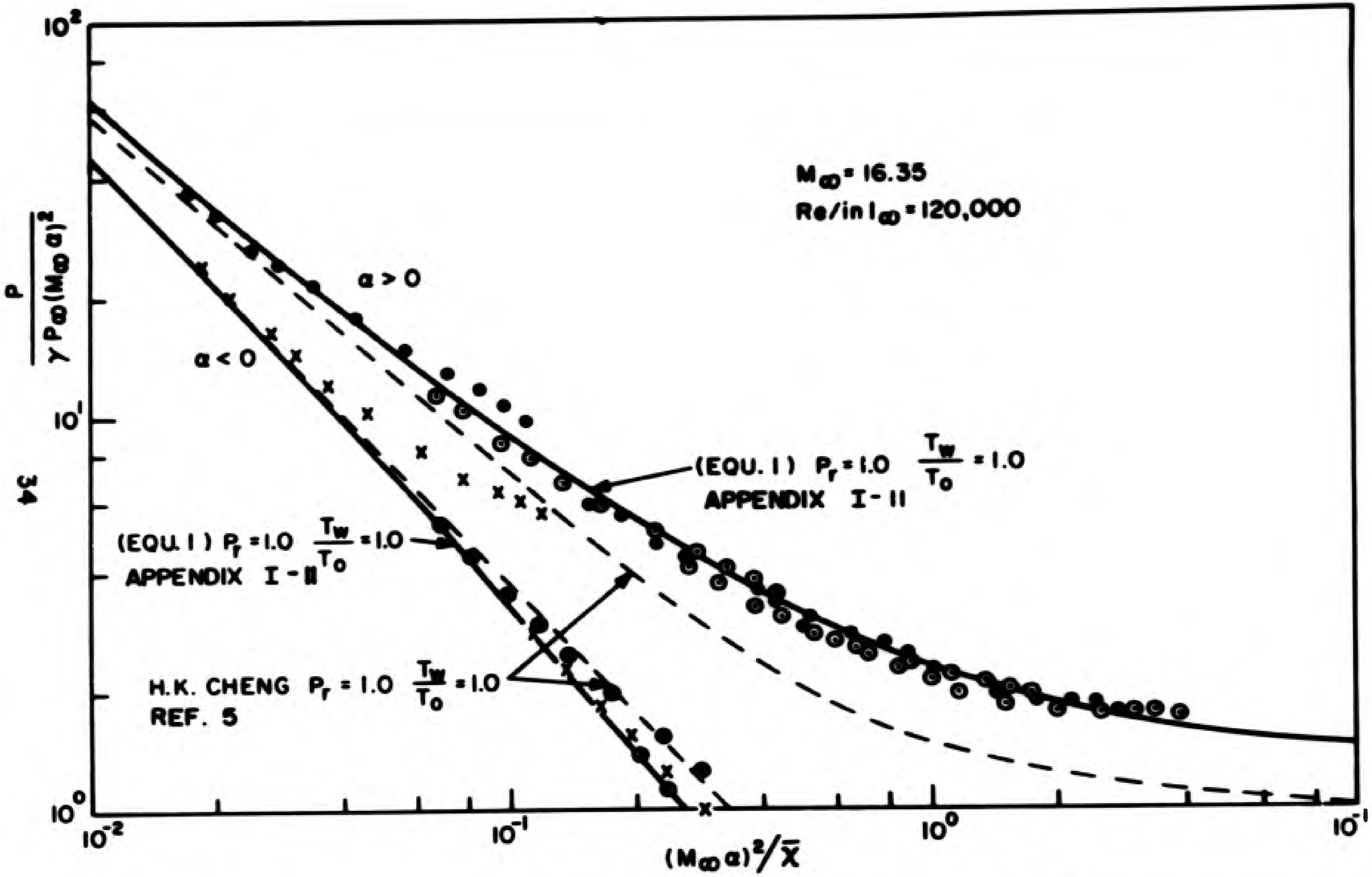


FIGURE 8 CORRELATION OF PRESSURE MEASUREMENTS ON A SHARP FLAT PLATE AT VARYING ANGLES OF ATTACK.

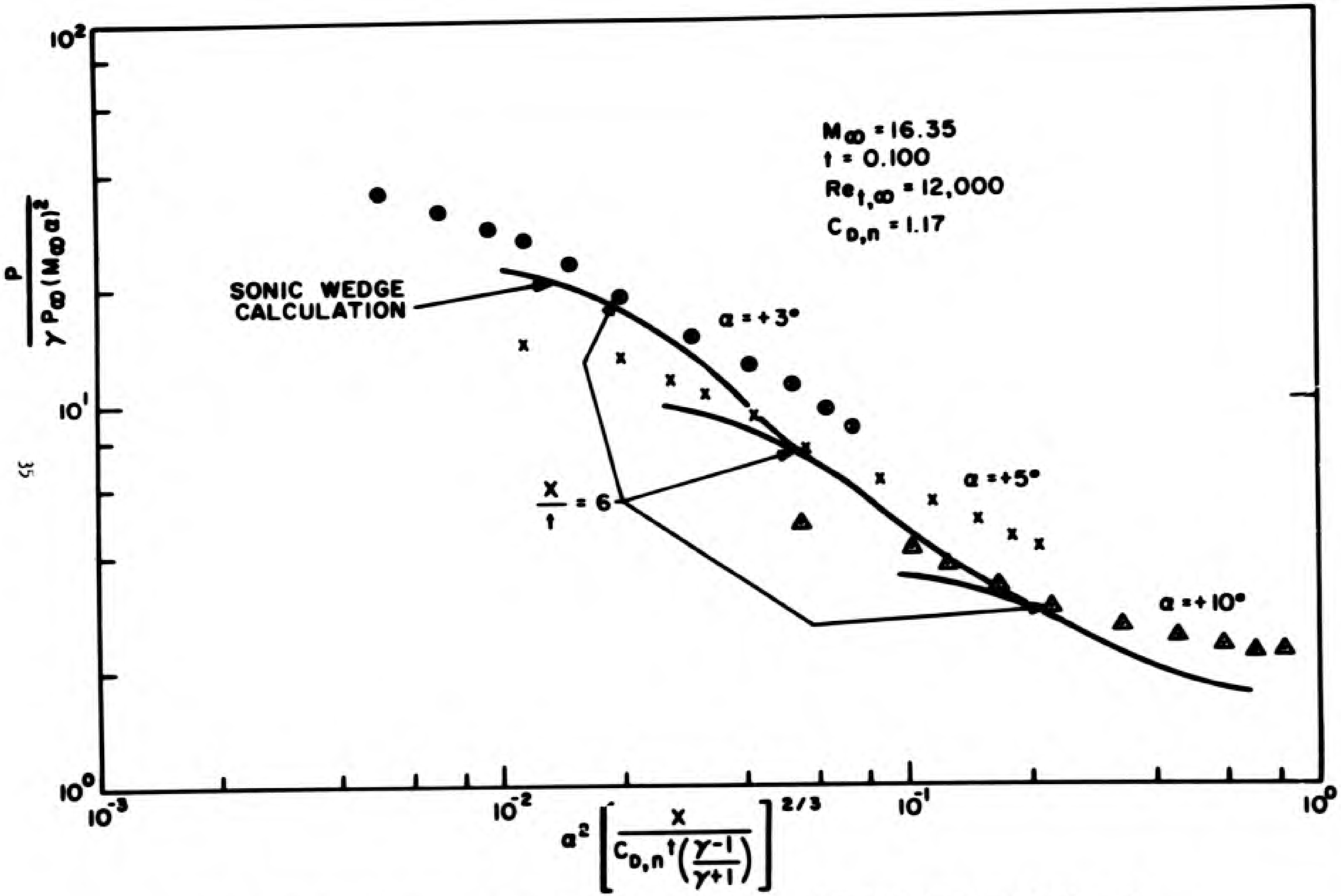


FIGURE 9 CORRELATION OF PRESSURE MEASUREMENTS ON A BLUNT FLAT PLATE AT VARYING ANGLE OF ATTACK.

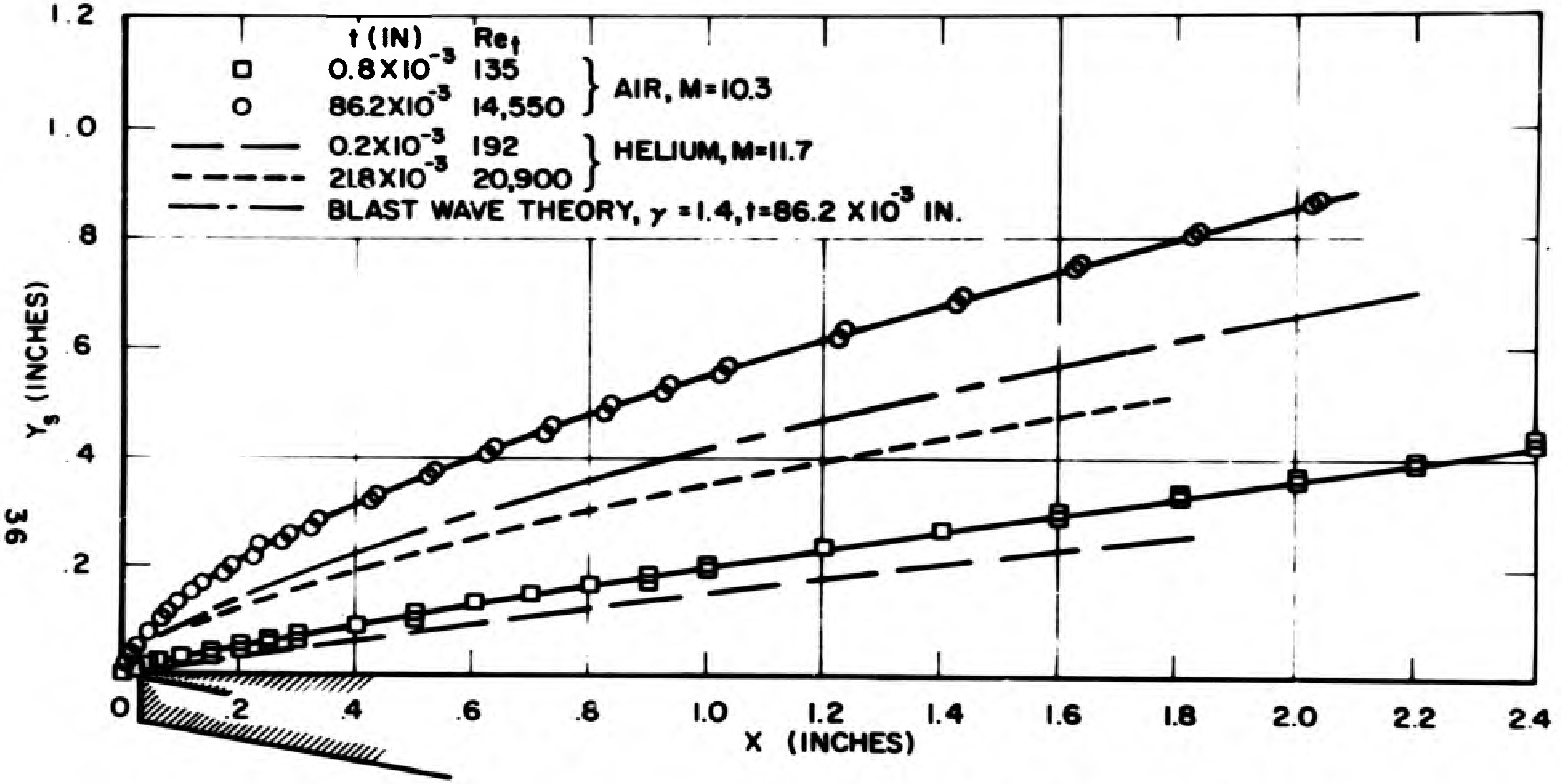


FIGURE 10 SHOCK WAVE SHAPE FOR THE SHARP AND BLUNT LEADING EDGE, FOR AIR AND HELIUM.

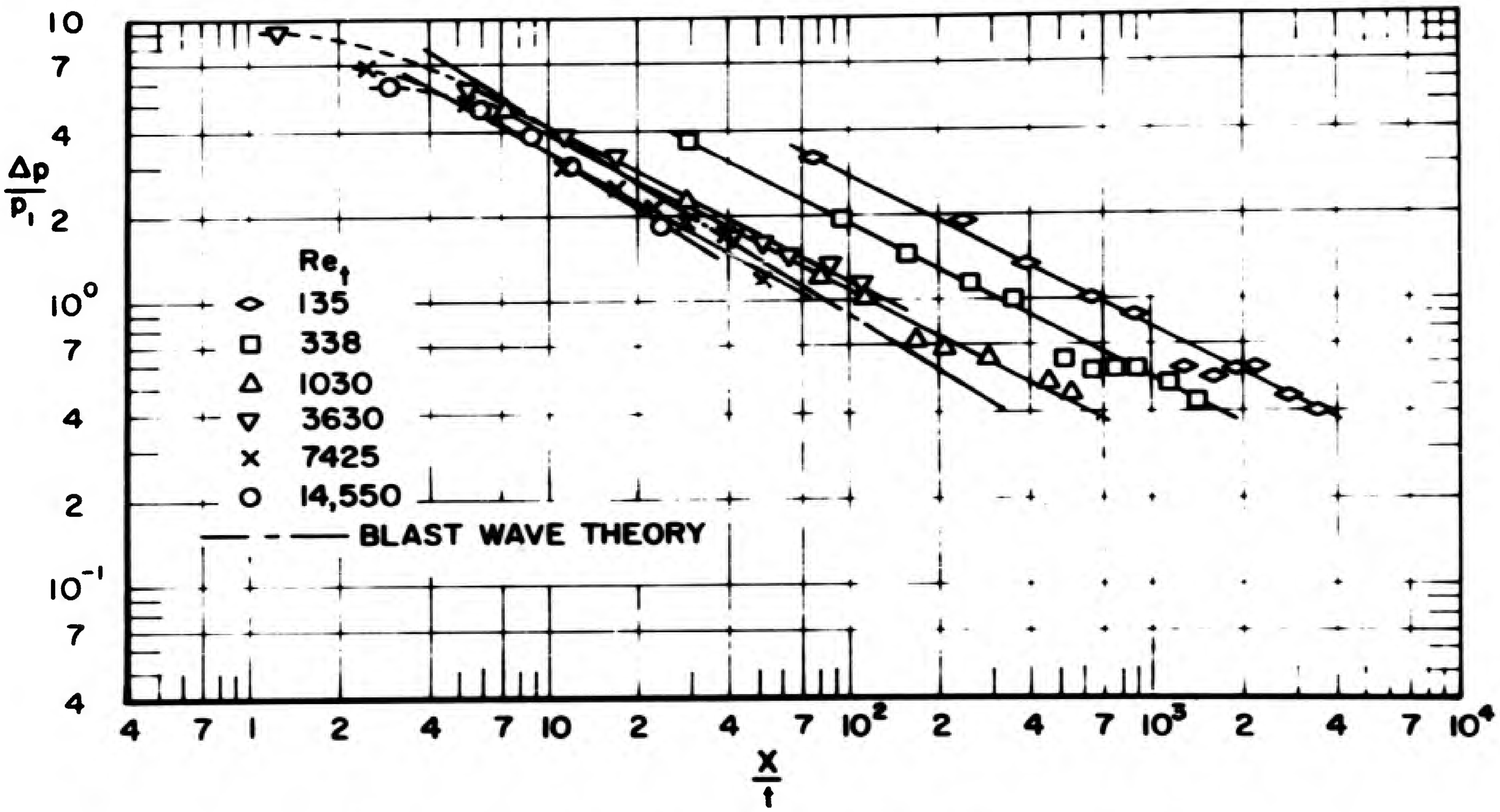


FIGURE II CORRELATION OF THE PRESSURES USING THE DIMENSIONLESS PARAMETER x/t.

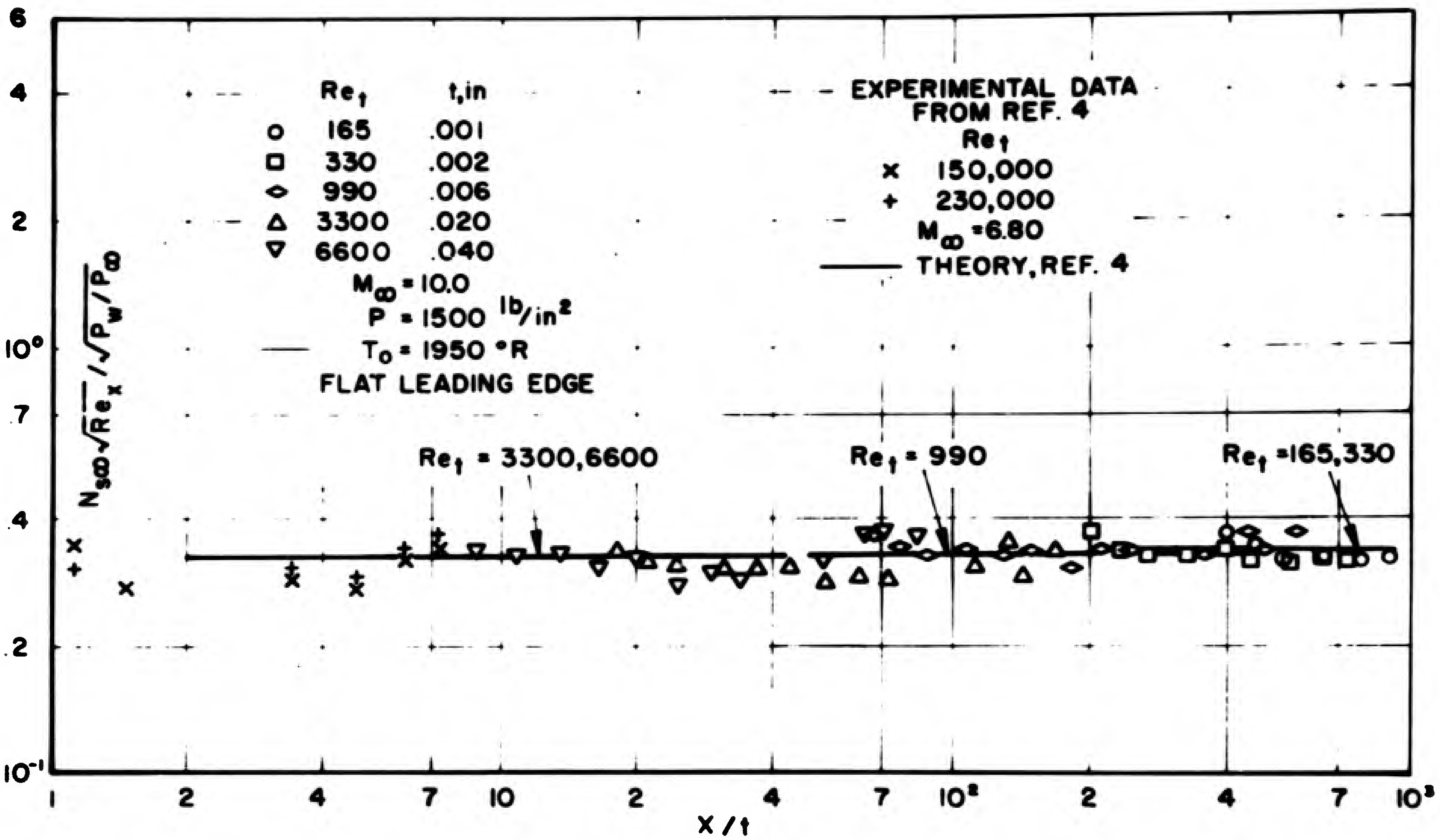
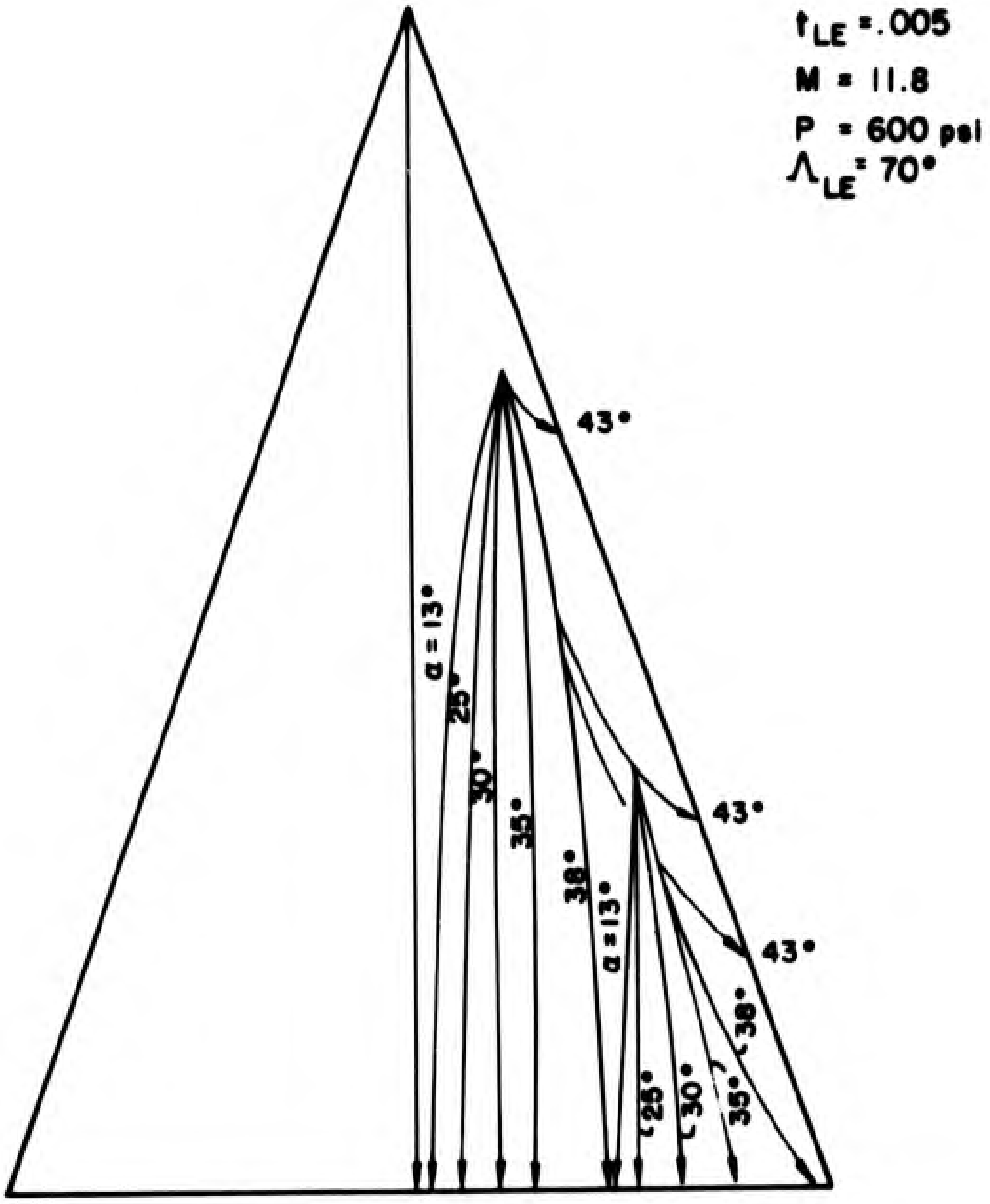


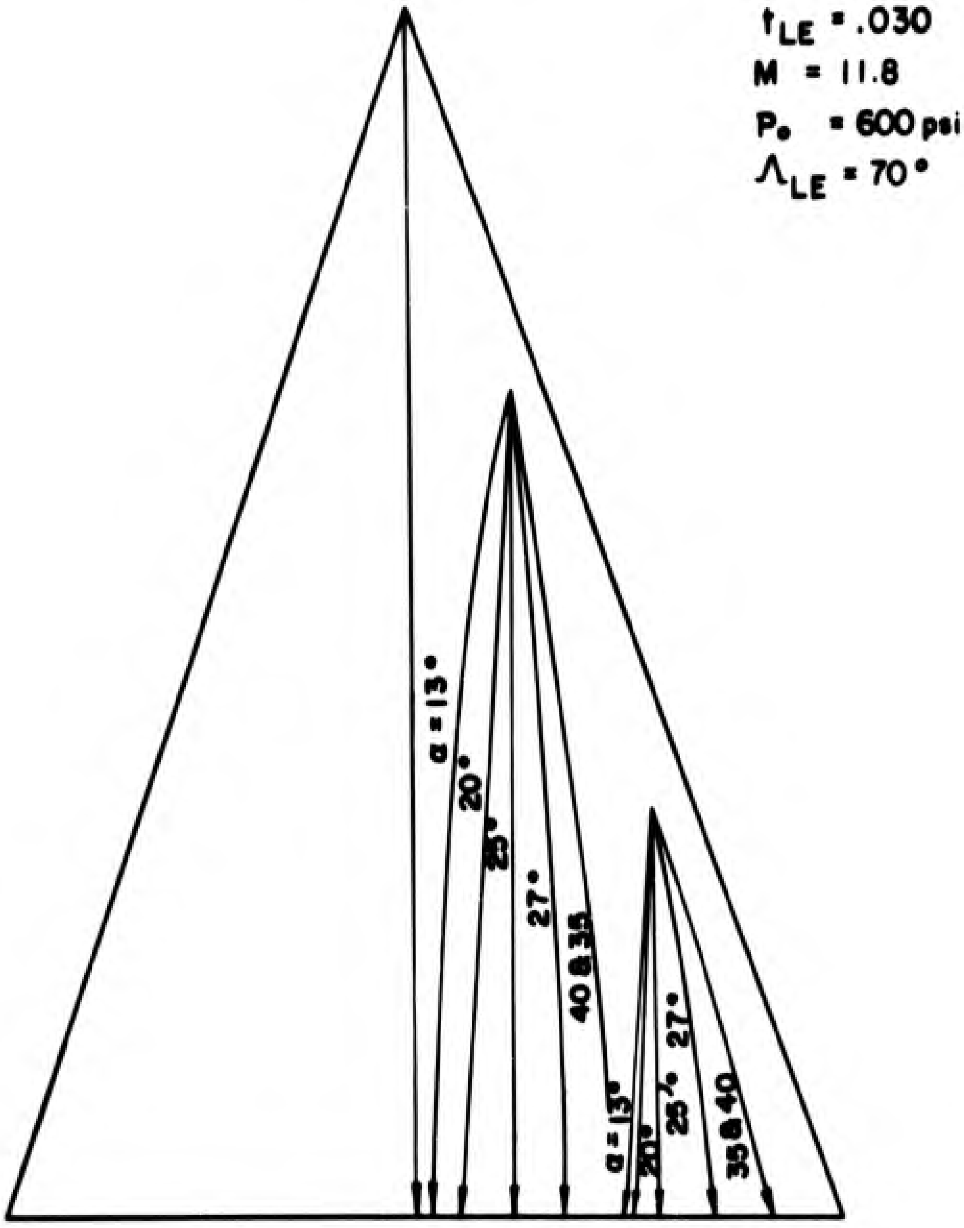
FIGURE 12 HEAT TRANSFER CORRELATION FOR THE VARIOUS LEADING EDGE THICKNESSES $P_0 = 1500$ PSIA



PLAN VIEW COMPRESSION SIDE

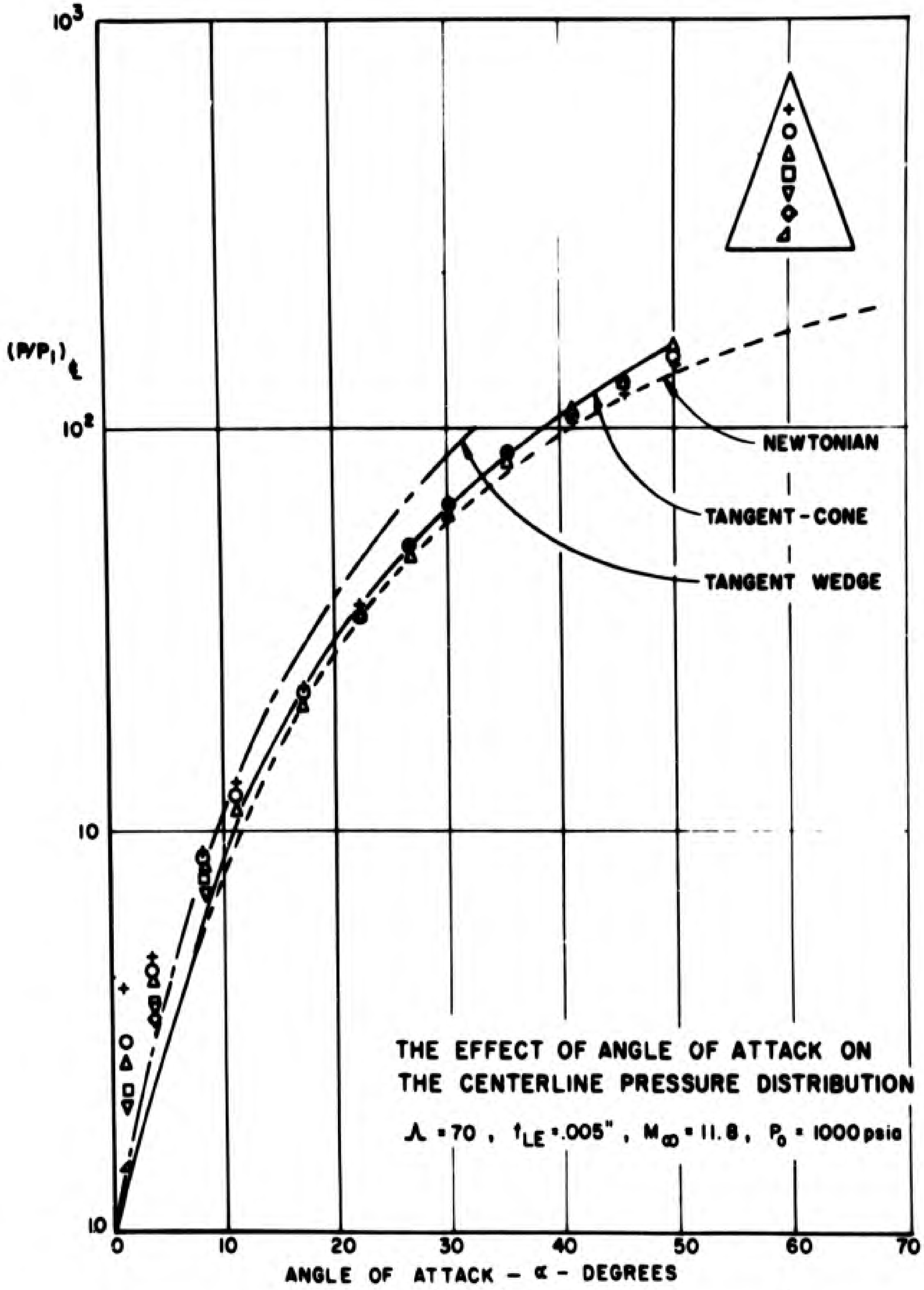
COMPOSITE SKETCH OF OIL FLOW PHOTOGRAPHS AT VARIOUS ANGLES OF ATTACK.

FIGURE 13(a)



PLAN VIEW - COMPRESSION SIDE

COMPOSITE SKETCH OF OIL FLOW PHOTOGRAPHS AT VARIOUS ANGLES OF ATTACK.
FIGURE 13(b)



THE EFFECT OF ANGLE OF ATTACK ON THE CENTERLINE PRESSURE DISTRIBUTION

$\Lambda = 70$, $t_{LE} = .005''$, $M_\infty = 11.8$, $P_0 = 1000$ psia

FIG. 14

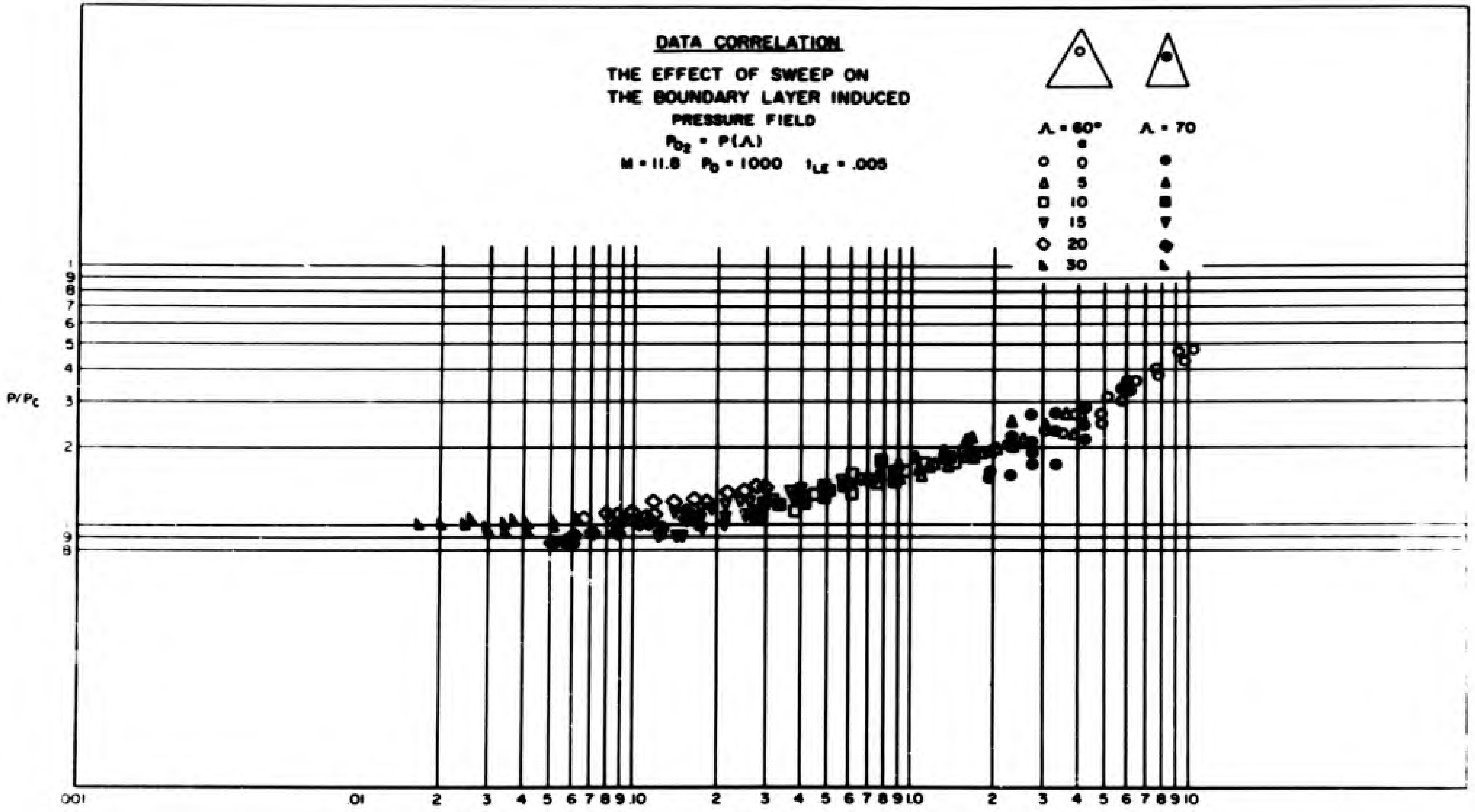

DATA CORRELATION
THE EFFECT OF SWEEP ON
THE BOUNDARY LAYER INDUCED
PRESSURE FIELD
$P_{02} = P(\Lambda)$
$M = 11.8$ $P_0 = 1000$ $t_{LE} = .005$
$\Lambda = 60°$ α $\Lambda = 70$
○ 0 ●
▲ 5 ▲
□ 10 ■
▼ 15 ▼
◇ 20 ◆
◣ 30 ◣
P/P_c
1 9 8 7 6 5 4 3 2 9 8
.001 .01 2 3 4 5 6 7 8 9 .10 2 3 4 5 6 7 8 9 1.0 2 3 4 5 6 7 8 9 10
$\bar{x}_c$

FIGURE 15

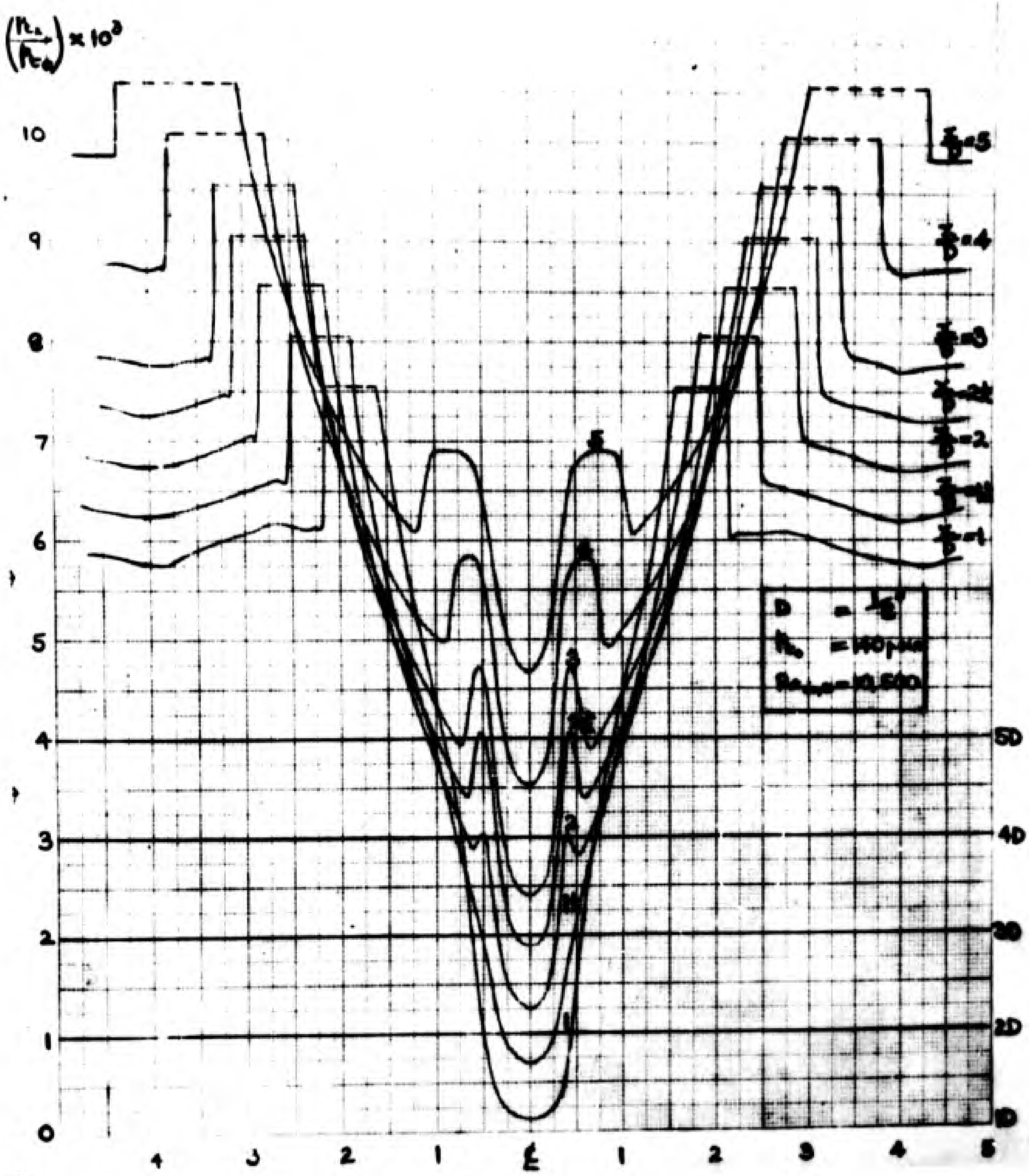


Figure [illegible]. Comparison of the pitot pressure surveys in the near wake.

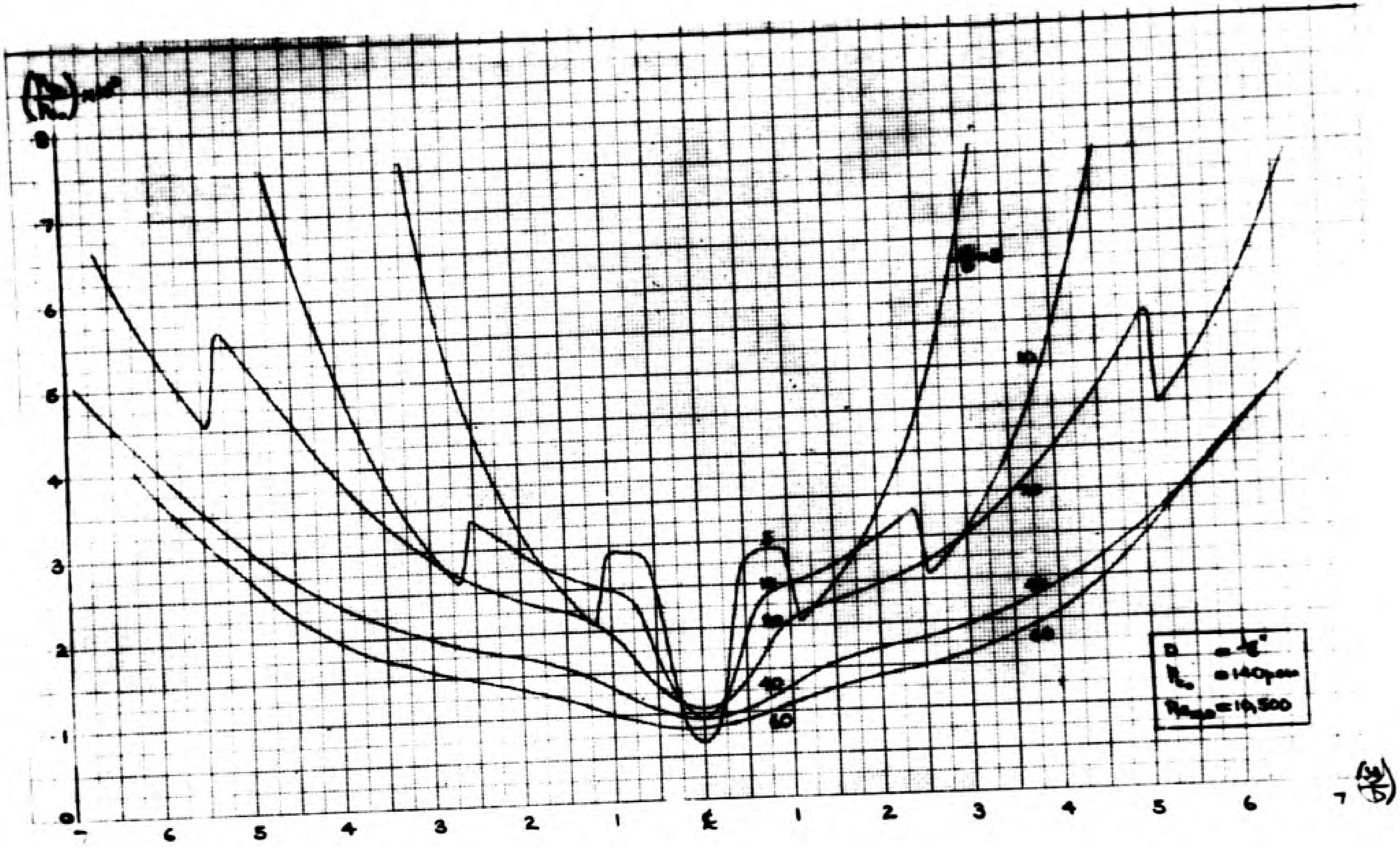


Figure 17. Comparison of the pitot pressure surveys in the far wake.

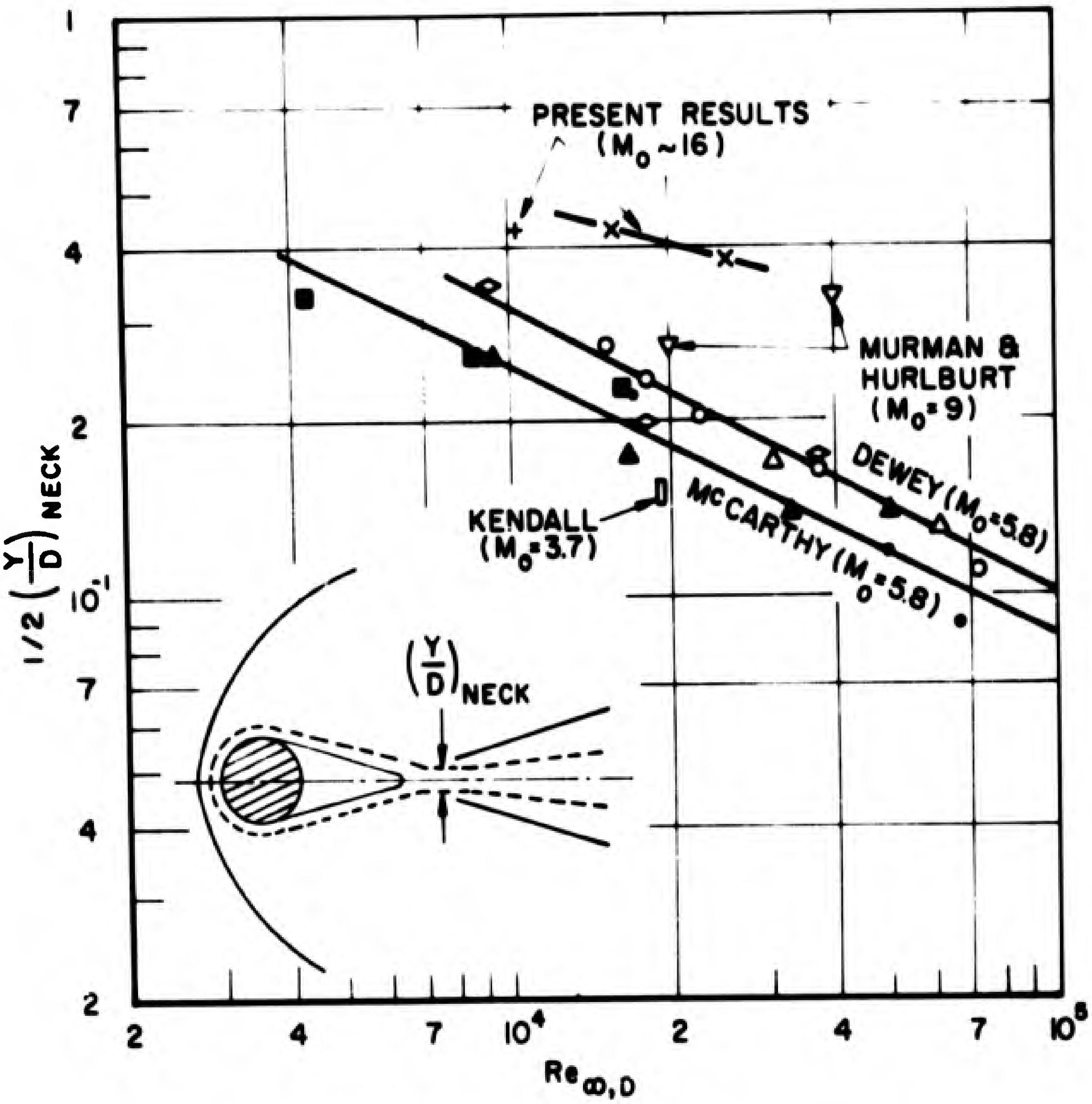


FIGURE 18 COMPARISON OF NECK WIDTHS VERSUS $Re_{\infty,d}$.

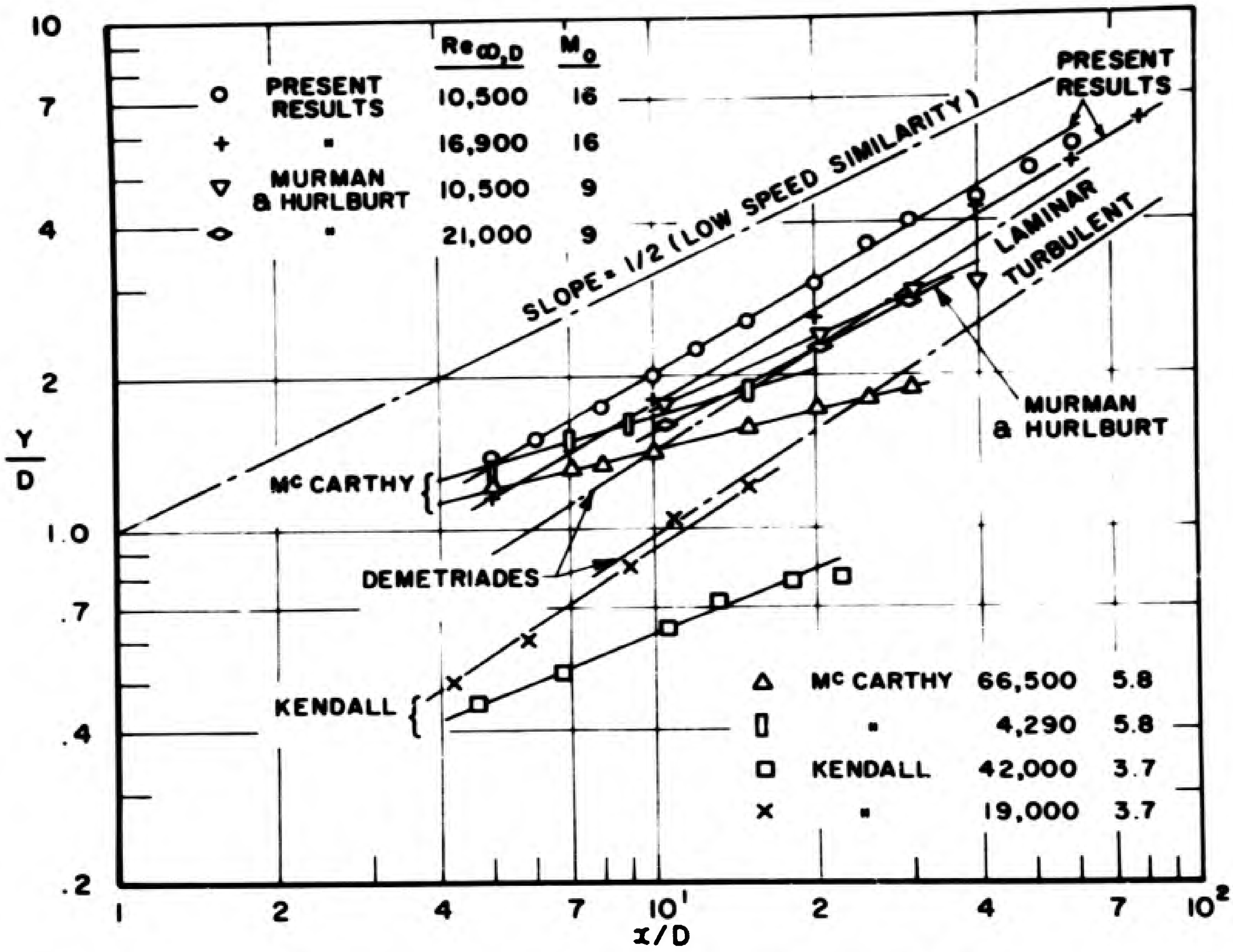


FIGURE 19 COMPAR'SON OF WAKE GROWTHS.

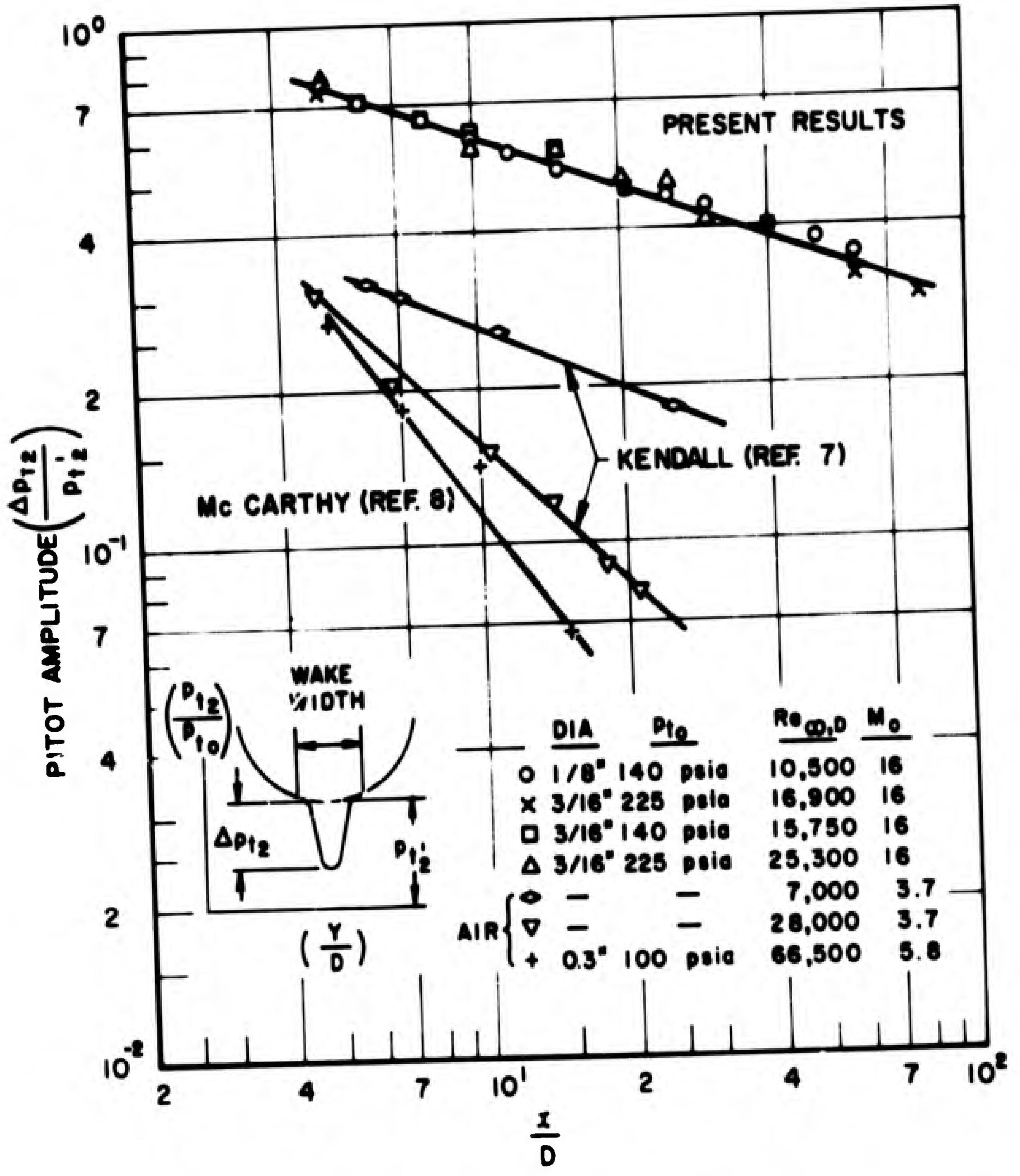


FIGURE 20 COMPARISON OF PITOT AMPLITUDES.

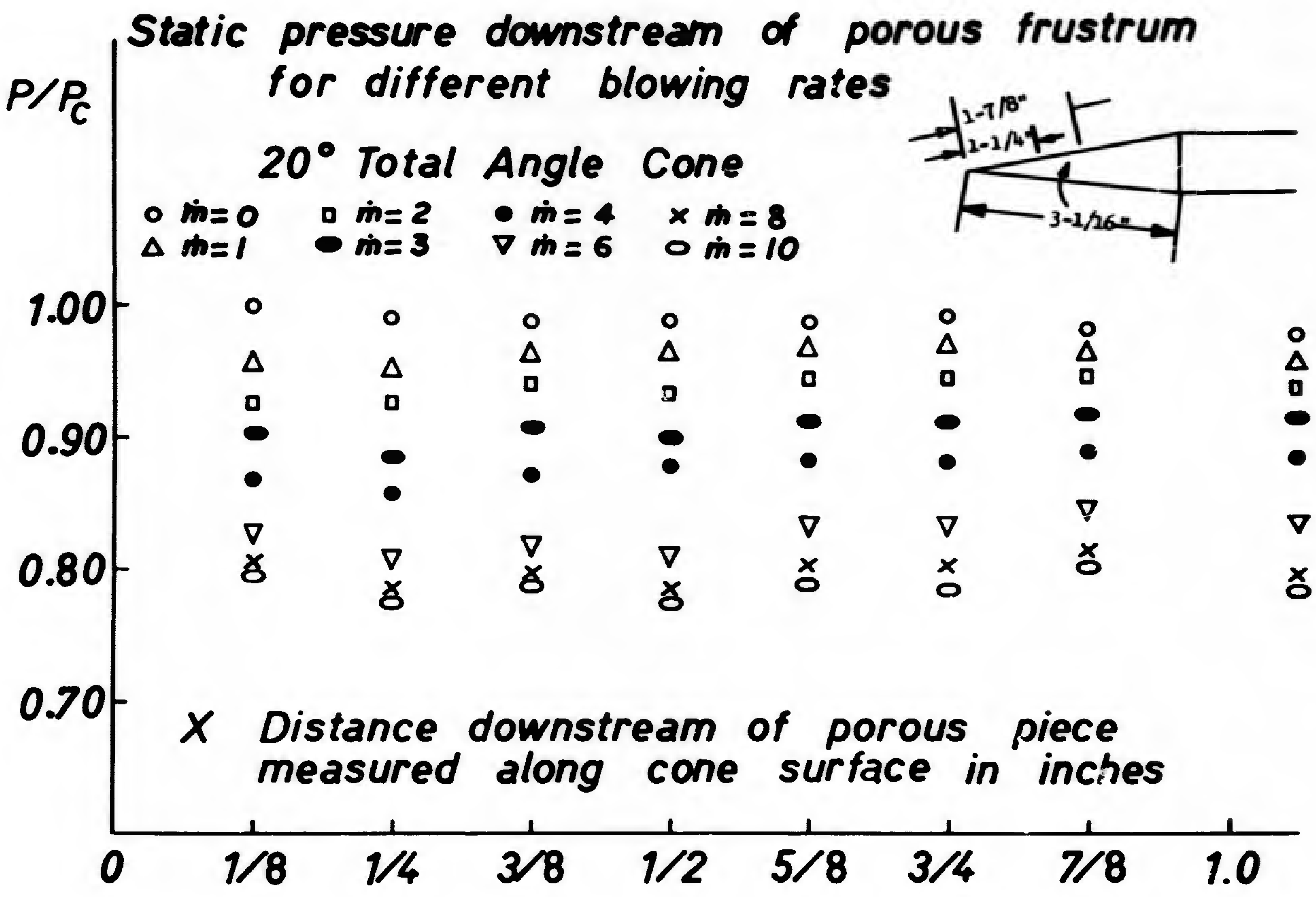

Static pressure downstream of porous frustrum
for different blowing rates
20° Total Angle Cone
○ $\dot{m}=0$
△ $\dot{m}=1$
□ $\dot{m}=2$
● $\dot{m}=3$
● $\dot{m}=4$
▽ $\dot{m}=6$
× $\dot{m}=8$
○ $\dot{m}=10$
1-7/8"
1-1/4"
3-1/16"
$P/P_c$
1.00
0.90
0.80
0.70
X Distance downstream of porous piece measured along cone surface in inches
0
1/8
1/4
3/8
1/2
5/8
3/4
7/8
1.0

Figure 21

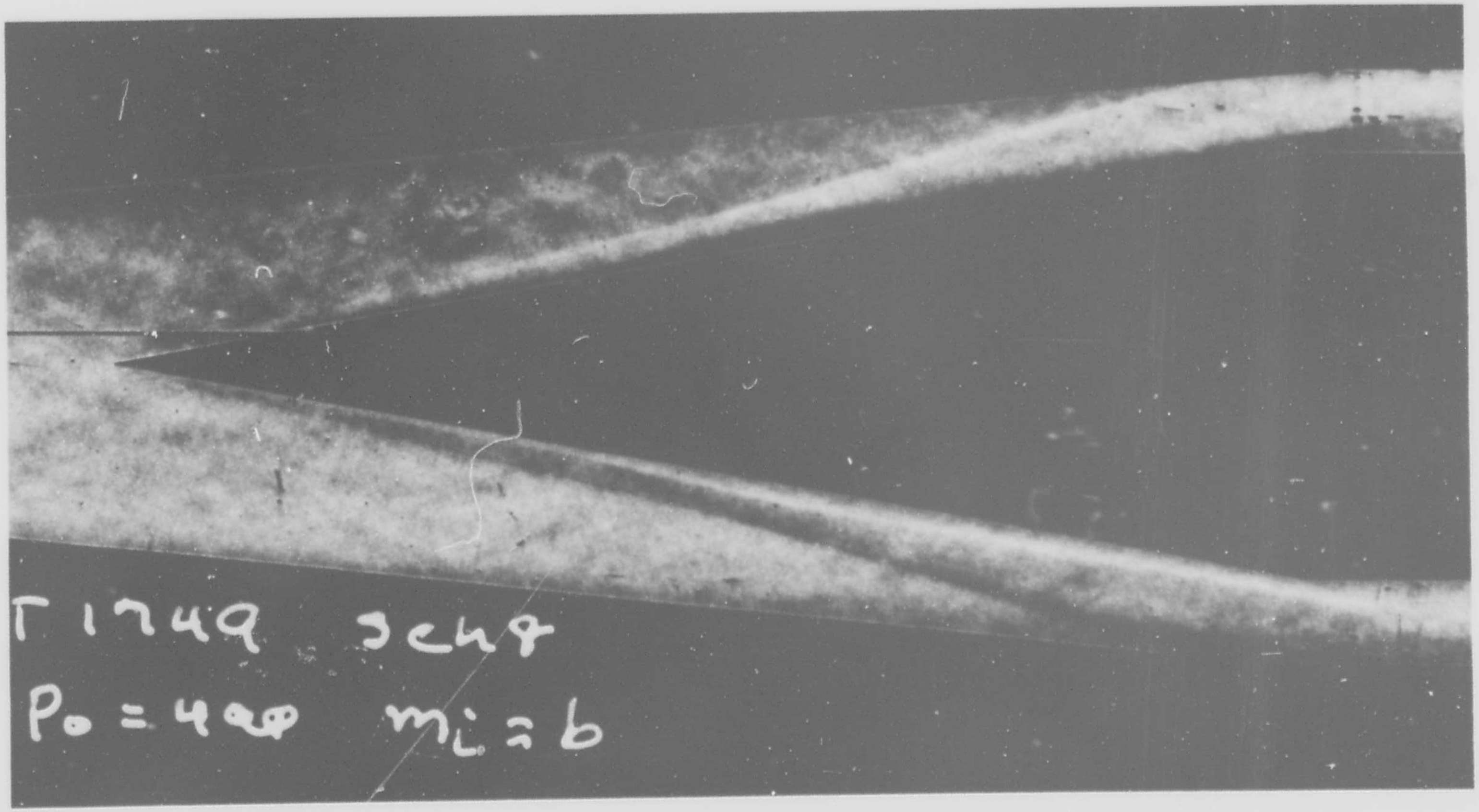


Figure 22. Mass injection on a 10° cone. ($m_i$ = 6 microslugs per second).

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## APPENDIX I

### Papers, Reports, Memoranda Published under the Subject Contract

1. Ledger, J. D., "Experimental Investigation of the Wake of a Circular Cylinder at Mach 16", 1963 (MSE Thesis), Princeton University.
2. Nicoll, K. M., "An Experimental Investigation of Laminar Hypersonic Cavity Flows", 1963 (PhD Thesis), Princeton University.
3. Vollmar, W. R., "An Experimental Study of the Heat Transfer to a Flat Plate at Zero Angle of Attack in a Mach Number 10.0 Air Stream," December 1963 (MSE Thesis), Princeton University.
4. Barber, E. A., "Some Experiments on Delta Wings at Hypersonic Speeds", Princeton University, Aerospace and Mechanical Sciences Report No. 679, January 1964.
5. Nicoll, K. M., "A Study of Laminar Hypersonic Cavity Flows", AIAA Journal, Vol. 2, No. 9, September 1964.
6. Kidani, R. J., "An Experimental Investigation of the Effect of the Leading Edge Reynolds Number on the Heat Transfer Coefficient on a Flat Plate at M = 11.6", October 1964 (MSE Thesis), Princeton University.
7. Nicoll, K. M., "Design Criteria and Experimental Techniques for a Study of a Hypersonic Cavity Flow with Mass Injection", Gas Dynamics Laboratory Internal Memorandum No. 6, December 1964.
8. Nicoll, K. M. and Bogdonoff, S. M., "Experimental Studies of a Specific Cavity Configuration in Laminar Hypersonic Flow", Archiwum Mechaniki Stosowanej, 1, 16 (1964).
9. Nicoll, K. M., "Mass Injection in a Hypersonic Cavity Flow", Princeton University Aerospace and Mechanical Sciences Report No. 714, December 1964, also ARL Report No. 65-90, May 1965.
10. Ledger, J. D., Vas, I. E. and Bogdonoff, S. M., "Hypersonic Studies of Wakes Behind Cylinders, Part I: Pitot pressure measurements at M = 16 in helium", Princeton University, Aerospace and Mechanical Sciences Report No. 739, June 1965.
11. Feldhuhn, R. H., "An Experimental Investigation of the Effects of Leading Edge Reynolds Number and Angle of Attack on the Flow of Helium over a Flat Plate at M = 16.35", Princeton University MSE Thesis, Gas Dynamics Laboratory Internal Memorandum No. 8, July 1965.

12. Vas, I. E., Murman, E. M. and Bogdonoff, S. M., "Studies of Wakes of Support-Free Spheres at M = 16 in Helium", AIAA Journal, Vol. 3, No. 7, July 1965.

13. Shulman, L. M., "Ablation of Flat, Radial and Cone Models in a Low Energy Hypersonic Nitrogen Flow", 1965 (MSE Thesis), Princeton University.

14. Bogdonoff, S. M., "The Sharp Flat Plate in Hypersonic Flow - A Review and Preview", Gas Dynamics Laboratory Internal Memorandum No. 9, October 1965. Also presented at the Symposium on the Advanced Problems and Methods in Fluid Mechanics, Jurata, Poland, September 1-7, 1965.

15. Townsend, J. C., Vollmar, W. R. and Vas, I. E., "The Leading Edge Effect on the Flow over a Flat Plate at M = 10", Princeton University Aerospace and Mechanical Sciences Report No. 767, February 1966.

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Scientific. Final. September 1963 to September 1966

**5. AUTHOR(S)** *(Last name, first name, initial)*

Bogdonoff, S. M. (for the staff of the Gas Dynamics Laboratory)

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**13. ABSTRACT**

During the three year period, September 1963 to September 1966, the Gas Dynamics Laboratory of Princeton University has been engaged in a series of research programs of basic application to hypersonic flight. These studies were experimentally centered around the Princeton Helium Hypersonic facilities developed under previous ARL support. Research in the four basic areas of interest, lifting surfaces, separated flows, boundary layers, and viscous interactions have been undertaken. Summaries of the researches which have been completed are presented as well as the pertinent results. Studies still in process are outlined and preliminary results presented.

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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| lifting surfaces | | | | | | |
| separated flows | | | | | | |
| boundary layers | | | | | | |
| viscous interactions | | | | | | |
| cavity flows | | | | | | |
| flat plate | | | | | | |
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| wakes | | | | | | |
| magnetic suspension system | | | | | | |
| mass transfer | | | | | | |

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