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PRINCETON UNIVERSITY, AERONAUTICAL ENGINEERING LAB., N.J. (REPORT NO. 182)

A PRELIMINARY STUDY OF REYNOLDS NUMBER EFFECTS ON BASE PRESSURE AT M= 2.95

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USN CONTR. NO. N6-ORI-270

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UNITED STATES NAVY

Office of Naval Research
Mechanics Branch, Mathematical Sciences Division

and

UNITED STATES AIR FORCE

Office of Air Research

(Contract N6-ori-270, Task Order #6,

Project Number NR 061-049)

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By

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Report No. 182

June 12, 1951

ACKNOWLEDGEMENT

The present study is part of a program of theoretical and experimental research on viscous effects in supersonic flow being conducted by the Department of Aeronautical Engineering, Princeton University. This research is sponsored jointly by the Office of Naval Research (U.S.N.), Mechanics Branch, Mathematical Sciences Division, and by the Office of Air Research (U.S.A.F.).

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SUMMARY

A preliminary study was carried out to determine the effect of Reynolds number on the base pressure of a simple cone-cylinder body of revolution. Tests were made at $M = 2.95$ over a range of Reynolds numbers from 0.6×10^6 to 18×10^6. The body was tested in the smooth condition and with transition fixed by several different roughness bands. On the basis of these tests, the following conclusions were reached:

1) The variation of base pressure with Reynolds number is characterized by three distinct regions:

   a) A "laminar" region where the free wake appears to be laminar and where increases in Reynolds number give very large decreases in base pressure,

   b) A "transitional" region where transition from laminar to turbulent flow seems to be occurring in the free wake and where increasing Reynolds number causes a leveling off from the laminar region and then a sharp increase in base pressure,

   c) A "turbulent" region where the boundary layer on the rear of the body is turbulent and where increasing Reynolds number results in a slow but steady decrease in base pressure.

2) Extrapolation of data in regions a) or b) of 1) will not give valid results at higher Reynolds numbers. For the body tested, data above 6×10^6 is needed to predict base pressures accurately at high Reynolds numbers.

3) The use of transition bands of the type tested on the body at low Reynolds number gave results which could not be correlated with data obtained on the smooth body at high Reynolds number. The base pressure depends critically on the ratio of band thickness to body diameter.

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Introduction:

The problem of predicting the pressure on the blunt base of a body of revolution traveling at supersonic speeds has not been susceptible to theoretical treatment. Several investigators have made experimental studies of the problem in supersonic wind tunnels and, more recently, by free-flight tests of missiles. The results obtained have, however, severe limitations which greatly restrict the application to more general problems or other configurations. The wind tunnel tests are limited in many cases to Reynolds numbers below about 4×10^6. Some higher Reynolds number tests (over 10×10^6) have been carried out at the lower supersonic speeds, M = 1.5 and 2.0. Few of the supersonic tunnels have any appreciable Reynolds number range. In some cases, an attempt to obtain the effect of variable Reynolds number has been made by varying the length of the test body. This increase in body length introduces two variables which are not directly part of the Reynolds number effect: first, the pressure distribution over the body changes; and second, the boundary layer thickness increases as the effective Reynolds number increases. For a given body, increasing the Reynolds number by increasing the density or the model size decreases the thickness. Both of these effects may have a considerable influence on the base pressure. Actual missiles or airplanes operate over a wide range of Reynolds numbers, $1 - 80 \times 10^6$, and Mach numbers from 1 to perhaps 6 or 7. It is perhaps possible to cover this range by free-flight tests, but the results are confined almost entirely to bodies which are fin-stabilized. The fins and the details of the fin-body function and position may have a considerable effect on the base pressure.

There are no wind tunnels presently available which can cover the entire flight Reynolds number range at any given Mach number. The standard technique is to roughen the model to get high effective Reynolds number for low test Reynolds number. The question thus arises as to what is the value of the effective Reynolds number, i.e., what is the free-flight Reynolds number which corresponds to the roughened model test? There are several general methods of applying the roughness or transition strip but no way of predicting the corresponding flight Reynolds number. If the characteristic which is being studied reaches a constant value at high Reynolds numbers, then the problem is simplified provided the method of producing the transition or roughness band has no effect on the final value observed.

The only results which are available over a wide Reynolds number range are those shown by D. Chapman of the NACA in Reference 1. Using two wind tunnels, Chapman was able to get tests from a Reynolds number of about 0.4×10^6 to 10×10^6 at a Mach number of 2.0. The results show a very sharp decrease in base pressures as the Reynolds number is increased from the lowest values, a leveling off, and then a sudden increase in base pressure at about Re $= 5 \times 10^6$, with approximately uniform pressures up to 10×10^6. The schlieren photographs verify that the flow over the rear of the body is laminar for the initial phase and turbulent for the final phase. The base pressure increases slightly with increasing Reynolds number once the turbulent region is established. The turbulent results at $M = 1.5$ show a greater increase than those shown at $M = 2.0$.

In an attempt to establish the transition region and to study more completely the results at high Reynolds numbers, a series of tests have been carried out in the Princeton 4" x 8" Variable Density Blow-Down

Supersonic Tunnel. A simple cone-cylinder body was studied at a Mach number of approximately 3 over a Reynolds number range from about 600,000 to 18,000,000, based on body length. The effect of several transition bands was also studied in an attempt to evaluate the effective Reynolds number of a body with fixed transition.

NOTATION

D	body diameter, inches
L	body length, inches
Re	Reynolds number based on body length
P_b	base pressure, psf
P_1	static pressure in the free flow ahead of the model, psf
M	Mach number (free stream)

Experimental Apparatus:

a) Supersonic Tunnel:

A complete description of the design and operation of the 4" x 8" tunnel used in these experiments will be available in a report to be issued in the near future. For completeness, however, a brief description follows: the tunnel is of the blow-down type using a tank system of 1000 cubic feet at 250 atmospheres as the driving power. A regulator system between the tunnel and the tanks allows the stagnation pressure in the tunnel to be varied at will between approximately 50 psia (minimum operating pressure for the M = 3 nozzle used) and 500 psia. The settling chamber is provided with three 40-mesh screens and there is a contraction ratio of approximately 80 to the nozzle throat. Stagnation temperature and pressure are recorded at the same time as data on the model is taken. The test section is 4 inches wide by 8 inches high and is provided with 9 inch diameter windows which are $2\frac{1}{2}$ inches thick. A conventional off-axis schlieren system using a onemicrosecond Chapman-Ioberg spark at 15,000 volts was used to take the schlieren photographs within a few seconds of the other data recording

The tests consisted of runs of several minutes during which time the stagnation pressure was set, two sets of data recorded. This procedure was repeated until the stagnation pressure could no longer be held constant due to low pressure in the storage tanks. The check of the two consecutive sets of data at the same stagnation pressure showed if the tunnel and instrumentation had reached equilibrium conditions. If the tests did not check, re-runs were made. The tunnel is not provided with a heater so that there is no control of the stagnation temperature. During a typical run the stagnation temperature varied approximately 10 - 15°F per minute.

Calibration of the tunnel showed a variation of about 1% in Mach number along the tunnel center line over the length of approximately 8 inches in which the model was tested. Complete surveys will be given in the wind tunnel report noted previously. The tunnel also showed a shift in Mach number due to stagnation presuure changes, varying from approximately 2.94 at low pressure to 2.96 at high pressures. The mean value over the eight inches was used for each pressure in the calculations but, since the variation was small, all results are labeled as $M = 2.95$.

b)
b) Models:

The models were supported on a sting carried in a central body which spanned the tunnel, Fig. 1. During starting, the larger models were retracted into a supporting strut downstream of the test section. Once the flow was established, the model was moved forward into the test section free from any effects of the downstream supports. All models and sting systems were constructed to the geometry shown in Fig. 2. These models were used to cover the range of Reynolds numbers with considerable overlap. The models were of .25, .50, and 1.0 inch diameter and were all constructed of paper laminate Micarta. This was done to eliminate any heat transfer effects to or from the model due to the drift in stagnation temperature. The tests, therefore, correspond to equilibrium conditions over the body. The models were finished in a high speed precision lathe using a sharp tool and no attempt was made to polish the surface after this operation.

The base pressure was obtained by drilling 4 holes in the base of the two larger models half way between the sting surface and the outside surface of the model. The holes were connected together inside the model and a single passage led out through the hollow sting support. For the .25 inch diameter model, only two holes were used because of the size limitation. On the 1.00 inch diameter model sting, a small collar which pressed against the model base was used to aid in model-sting aligment, but tests without the collar showed no effect on the base pressure.

Experimental Results and Discussion:

a) Smooth Model Tests:

The results of tests of the three models, all geometrically similar and in a smooth condition, are shown in Fig. 3. The base pressure is presented in coefficient form as the ratio of the measured base pressure to the free stream static pressure ahead of the model. The general shape of the curve below a Reynolds number of approximately 6×10^6 is similar to that obtained in the only other comparable study, D. Chapman's results at $M = 2.0$. Representative schlieren photographs over the Reynolds number range are shown in Figures 4a and 4b.

In the Reynolds number range from 0.6 to 1.0×10^6, the base pressure dropped very sharply in a manner similar to Chapman's results.

The schlieren photographs show a typical "laminar" wake region downstream of the base characterized by the sharp free boundary layer and the absence of any trailing shock for a considerable distance from the wake pattern. There must be a compression fan arising from the turning of the wake flow along the sting, but these waves do not coalesce to form a shock for some distance. As the Reynolds number is increased, the base pressure decreases rapidly to a minimum near 1.0×10^6 while the schlieren photographs show a shortening of the wake region and a moving in of the trailing shock, although the free boundary layer still seems to be laminar. A tentative explanation, difficult to substantiate from the recorded data or schlieren photographs, is that transition from a laminar to turbulent free jet is occurring at the wake-sting junction. The turbulent free boundary layer can probably sustain a higher pressure ratio than the laminar layer and so gives a lower base pressure. At Reynolds numbers above 1.0×10^6, the flow has developed the characteristic "turbulent" formation with the free jet showing definite "fuzziness" of the free boundary layer and a strong trailing shock approaching very close to the edge of the wake pattern. Further increases in Reynolds number make no significant changes in the wake pattern even though the base pressure increases sharply at about 3×10^6 and then decreases slightly at high Reynolds numbers. The region from $1 - 3 \times 10^6$ is probably characterized by transition of the free laminar layer to turbulent in the wake region before the occurrence of the trailing shock. The region above 3×10^6 is tentatively associated with transition to turbulent boundary layer on the body moving forward as the Reynolds number increases. Theoretical studies of this phenomena in two, as well as three, dimensions are now underway at the Supersonics Laboratory.

Chapman observed an almost uniform base pressure region from $Re \approx 5 \times 10^6$ before the sharp increase but nothing comparable was obtained from these tests. Considerable difficulty was experienced in getting consistent data in the transition region from Re = 1.0 - 3.5 x 10^6, although the model seemed to be in good condition. No attempt was made to polish the model before each test. Most of the tests fell between the dotted curves shown in Fig. 3 with the few that fell outside this region shown on the figure. A large percentage of the tests clustered around the solid line shown on the figure, but only representative tests are shown to indicate the degree of the scattering. This transition region would naturally be influenced by body finish and air stream turbulence level and, therefore, direct comparison of the results with those of Chapman is not completely valid.

In the high Reynolds number region, where presumably the boundary layer flow over the body is primarily turbulent, a small but steady decrease in base pressure is observed beyond a Reynolds number of 6 x 10^6. This is again in agreement with the trends obtained from Chapman's tests at M = 1.5 and 2.0 for turbulent boundary layers. At M = 1.5 the base pressure increased considerably with increasing Reynolds number, at M = 2.0, the curves are almost flat, and at 2.95 from the tests reported herein, the base pressure decreases with increasing Reynolds number. Further increases in Mach number would be expected to show greater decreases with increasing Reynolds number if the trend shown in these tests continues.

b) Tests of Models with Roughness:

The experimental equipment permitted the attainment of fairly high Reynolds numbers where the boundary layers naturally were turbulent. A few tests were made to evaluate the commonly used expedient of fixing transition to simulate high Reynolds numbers, and to examine whether or not the roughness /or band/ or its relative height is the true variable.

The .25 inch and 1.00 inch diameter models were used for these tests. Transition was fixed after the cone-cylinder juncture by a band of masking tape 0.10 inches wide placed on the body as shown in Fig. 2. Thickness was varied by using one or more layers of the tape which was about 0.007 inches thick. The results of the four series of tests which were carried out are shown in Fig. 5 and some typical schlieren photographs are shown in Figs. 6a and 6b. The high base pressures at low Reynolds numbers associated with laminar flow are, as expected, not obtained. The results obtained are, however, not related in any simple way to the data obtained at higher Reynolds numbers for natural transition. Depending on the degree of roughness, below about 5×10^6 the roughness tests may fall above or below the smooth body data. The actual data depends quite critically on the ratio of transition band height to body diameter, t/D. Below 1×10^6, the addition of roughness gave base pressures considerably below those obtained in the smooth condition. Between $1 - 3 \times 10^6$, (the "transition" region), the rough tests gave base pressures above the smooth values but approached the smooth values as the roughness was increased. Above 3×10^6, the addition of roughness gave lower base pressures than the smooth models for all cases tested. The decrease in pressure depended on the thickness of the band. The tests of the .25 inch diameter and 1.00 inch diameter body with bands of approximately the same t/D ratio gave comparable results in the range where the tests overlapped. The tests of the 1.00 inch model with t/D = .023 and .045 came together above about 15×10^6 and appear to approach a constant value of about .37 for p_b/p_1. Further tests are needed to verify this, and tests at considerably higher Reynolds numbers for a smooth body are needed to show if such is the case for natural transition also.

Logically, there seems to be little real reason to hope that the addition of roughness will completely simulate high Reynolds number flows. The base pressure problem is, as has been stated by several investigators, essentially a mixing problem. The dead air region behind the blunt base must mix with the supersonic free stream through a layer which is the detached boundary layer from the body. The process must be a function of the thickness as well as the character of this layer. The attainment of high Reynolds numbers by natural means results in a turbulent boundary layer which is quite thin. The introduction of a transition band will undoubtedly result in turbulent boundary layers, but considerably thicker than the natural turbulent layer. At the same time, the roughness tests show that thickening the layer gives decreasing base pressures, the same effect as caused by increasing the Reynolds number. The results are not explainable by any of the present theories.

c) Effect of Sting Diameter and Length:

Chapman made a fairly complete study of the effect of support sting diameter and length at $M = 2.9$ in Reference 1. For laminar flow, ratios of support diameter to body diameter below .6 and ratio of support length to body diameter over 2.8 gave no effect on base pressure. For turbulent flows, the ratio of support length to body diameter of over 2.8, also gave no effect. However, for ratios of support diameter to body diameter from .6 down to .3 (the smallest tested) the base pressure is still rising slightly. For the configuration used in these tests, a ratio of support diameter to body diameter of .25 and a length to body diameter ratio of 3.9, it seems reasonable to assume that the results obtained are, at most, only slightly affected by the support system.

Conclusions

Preliminary tests were made at $M = 2.95$ of a simple cone-cylinder body of revolution over a range of Reynolds numbers from 0.6×10^6 to

18×10^6. The body was tested in the smooth condition and with transition fixed by several different roughness bands. On the basis of these tests, the following conclusions were reached:

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References

1. Chapman, Dean R.: An Analysis of Base Pressure at Supersonic Velocities and Comparison with Experiment, N.A.C.A. T.N. #2137, (1950).

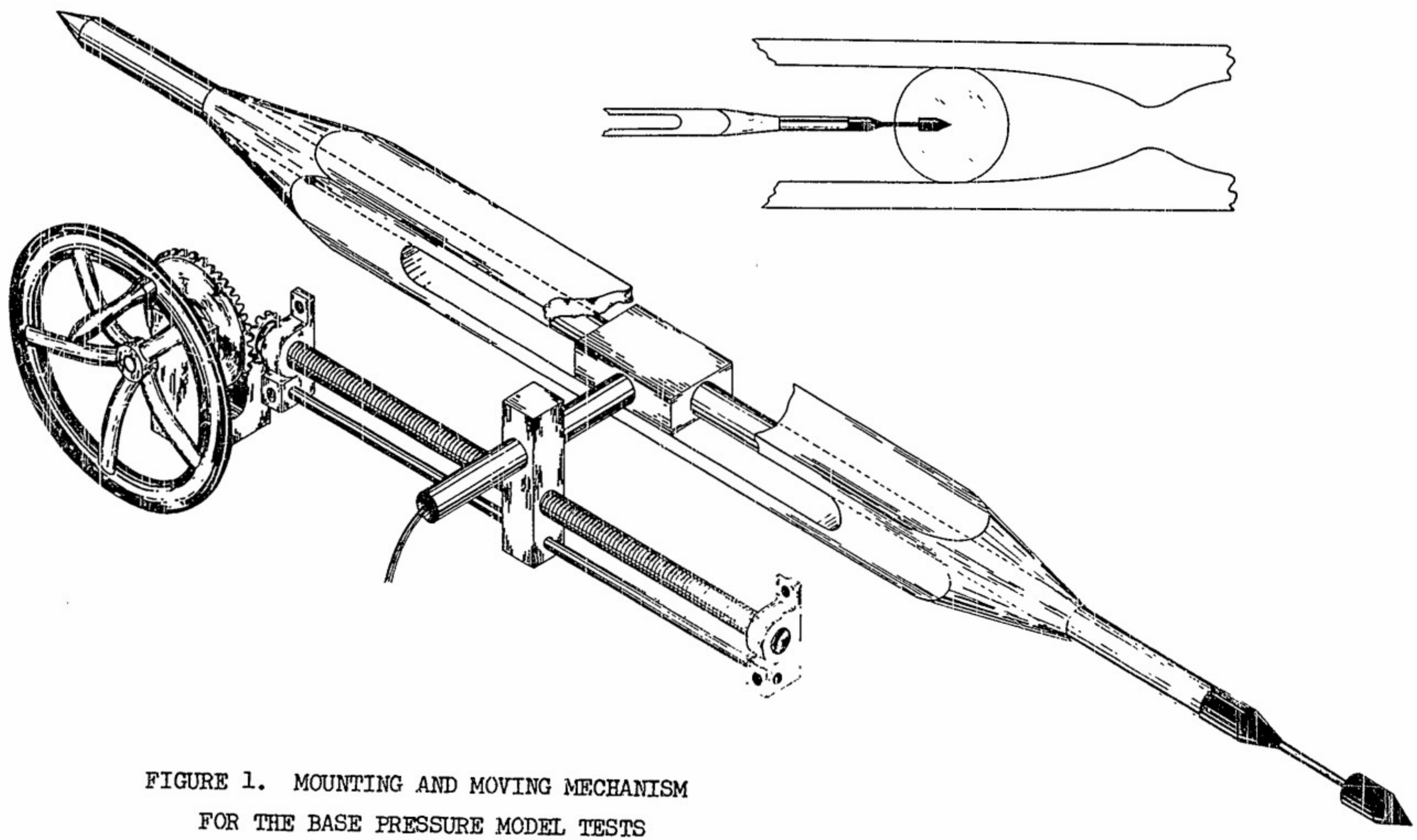


FIGURE 1. MOUNTING AND MOVING MECHANISM
FOR THE BASE PRESSURE MODEL TESTS

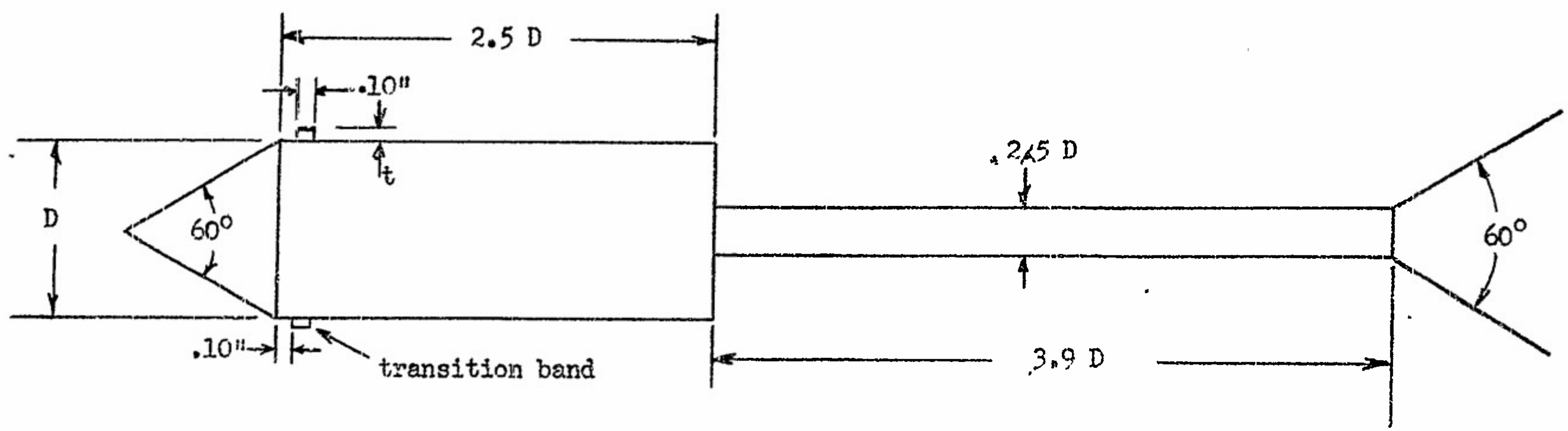


FIGURE 2. GEOMETRY OF CONE-CYLINDER TEST BODY AND SUPPORT.

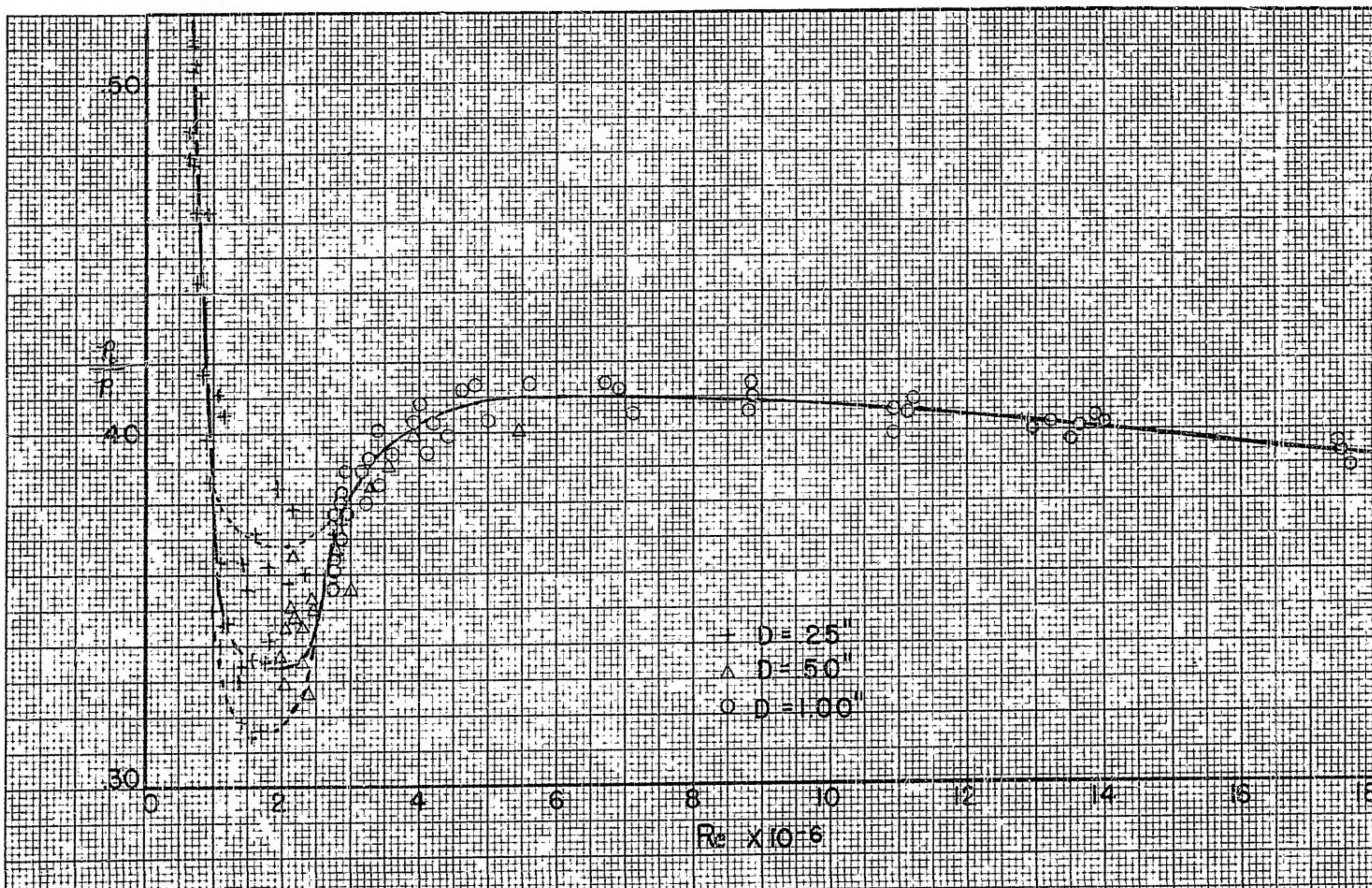
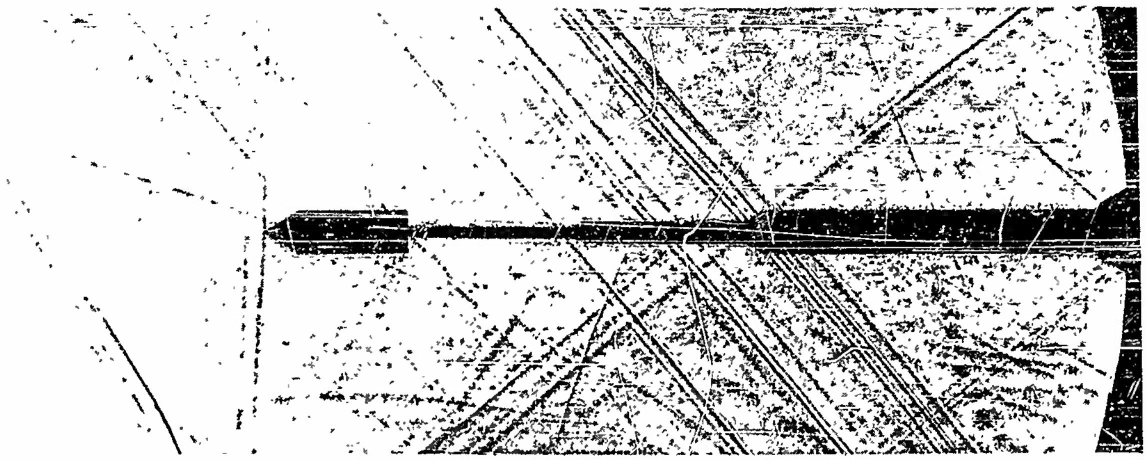


FIGURE 2. THE VARIATION OF BASE PRESSURE COEFFICIENT WITH REYNOLDS NUMBER FOR A SMOOTH MODEL



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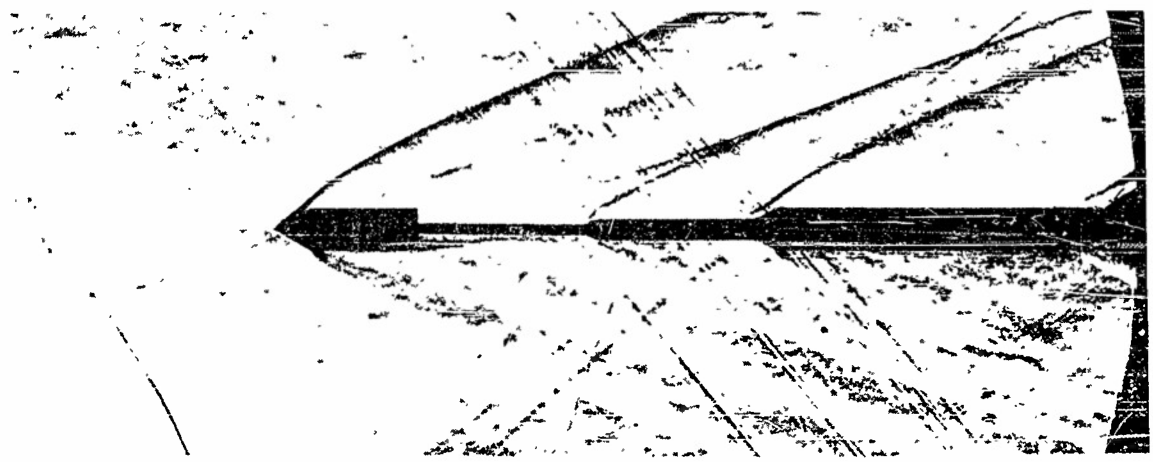
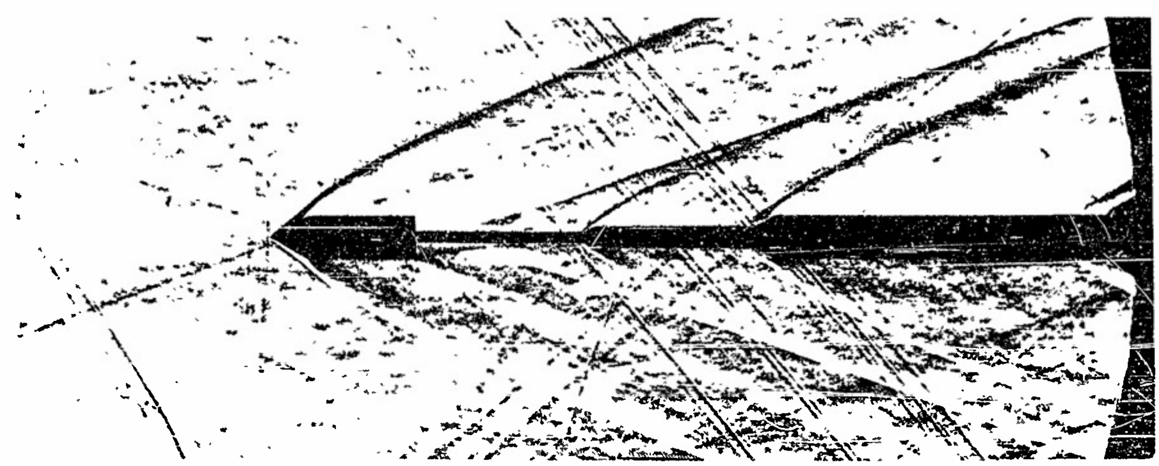
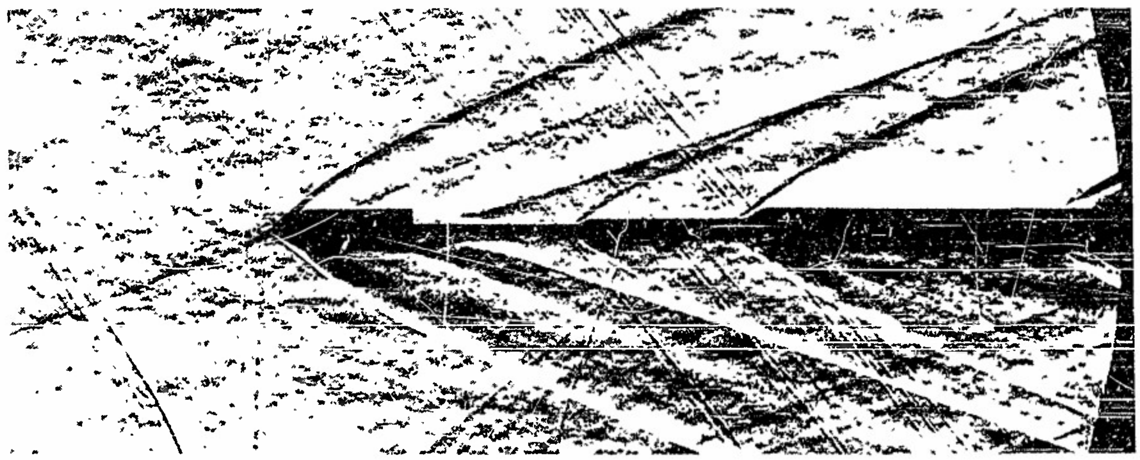


$R_e = .688 \times 10^6$

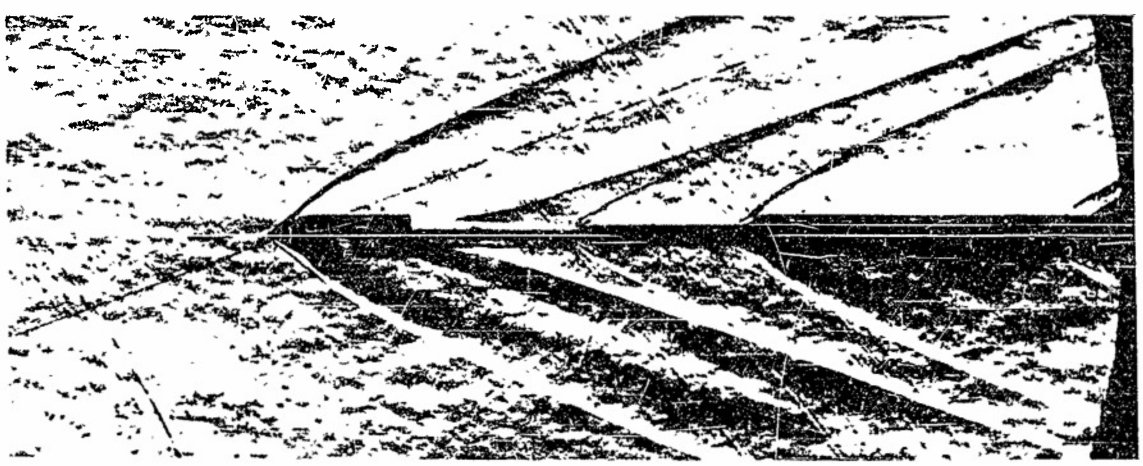


$R_e = .826 \times 10^6$

FIGURE 4 a). SCHLIEREN PHOTOGRAPHS OF SMOOTH BASE PRESSURE MODEL, D = .25", M = 2.95, FOR A RANGE OF REYNOLDS NUMBERS

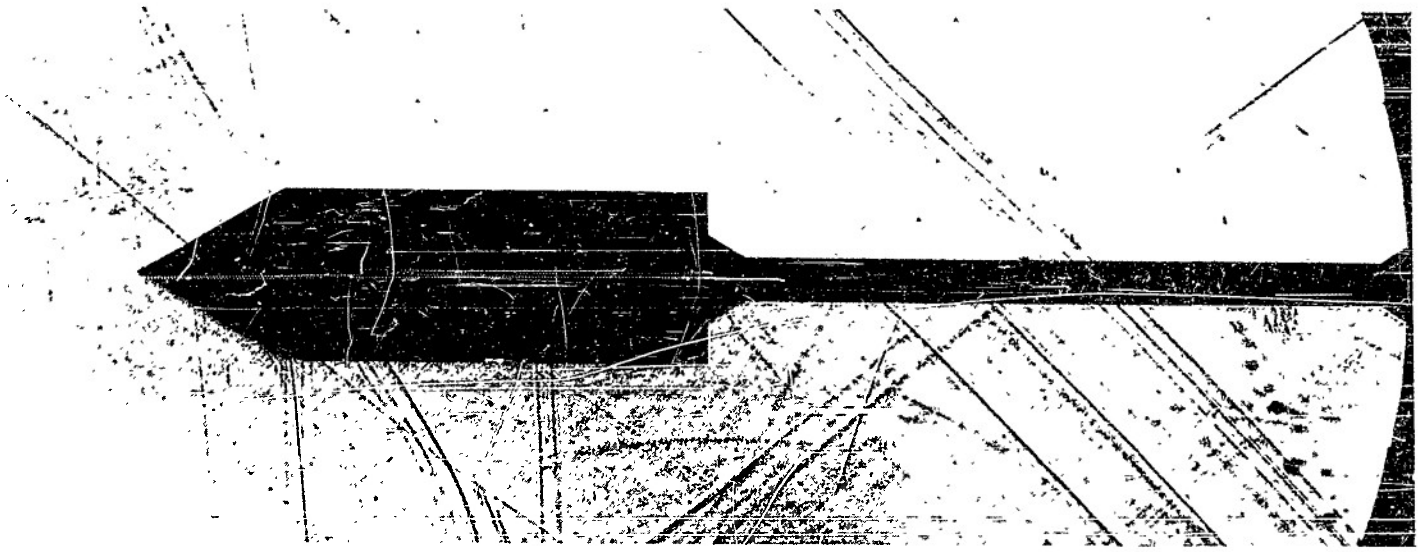


$R_e = 2.14 \times 10^6$



$R_e = 4.18 \times 10^6$

FIGURE 4 a). CONCLUDED



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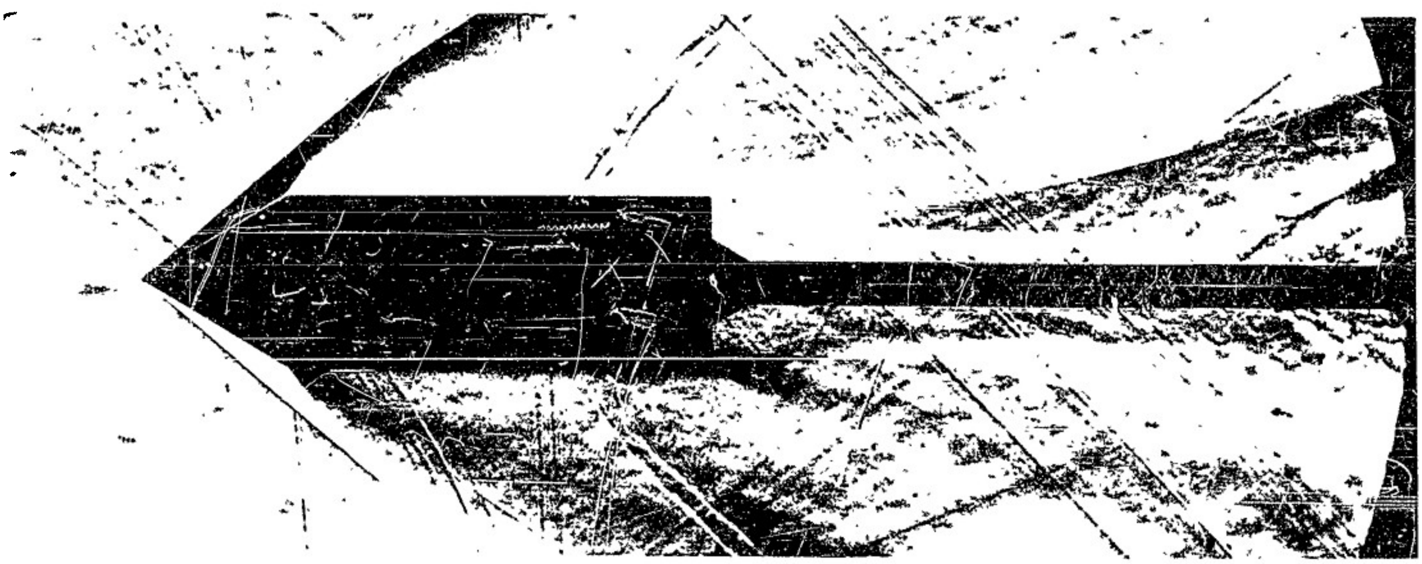
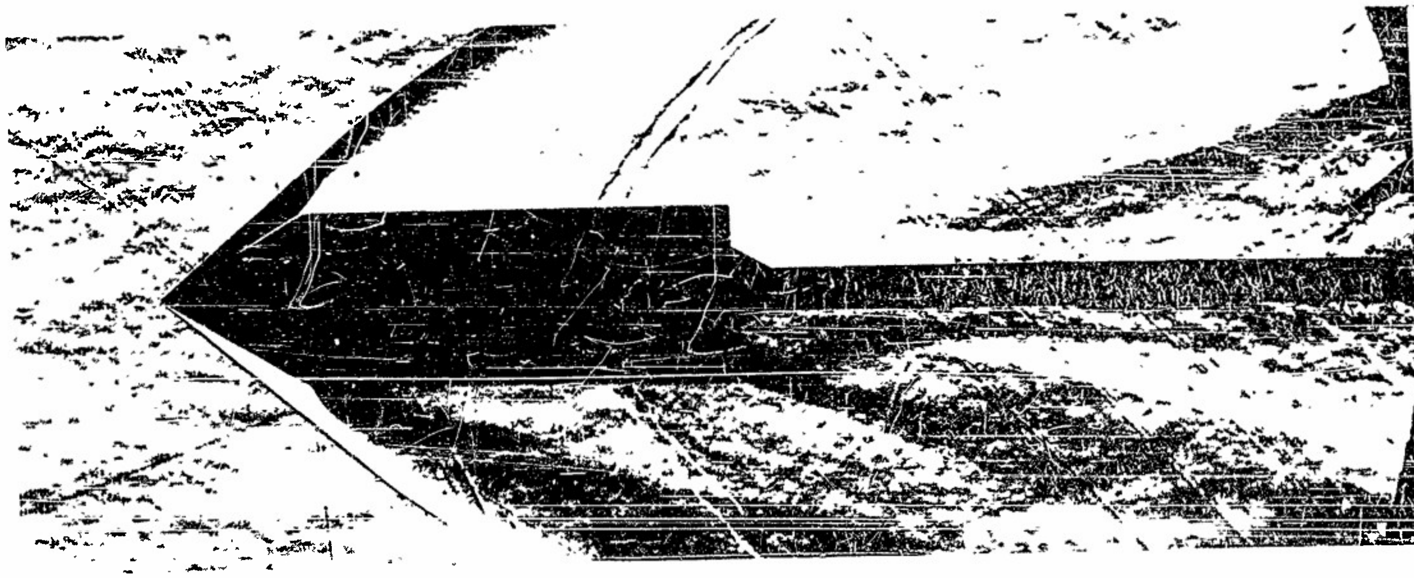
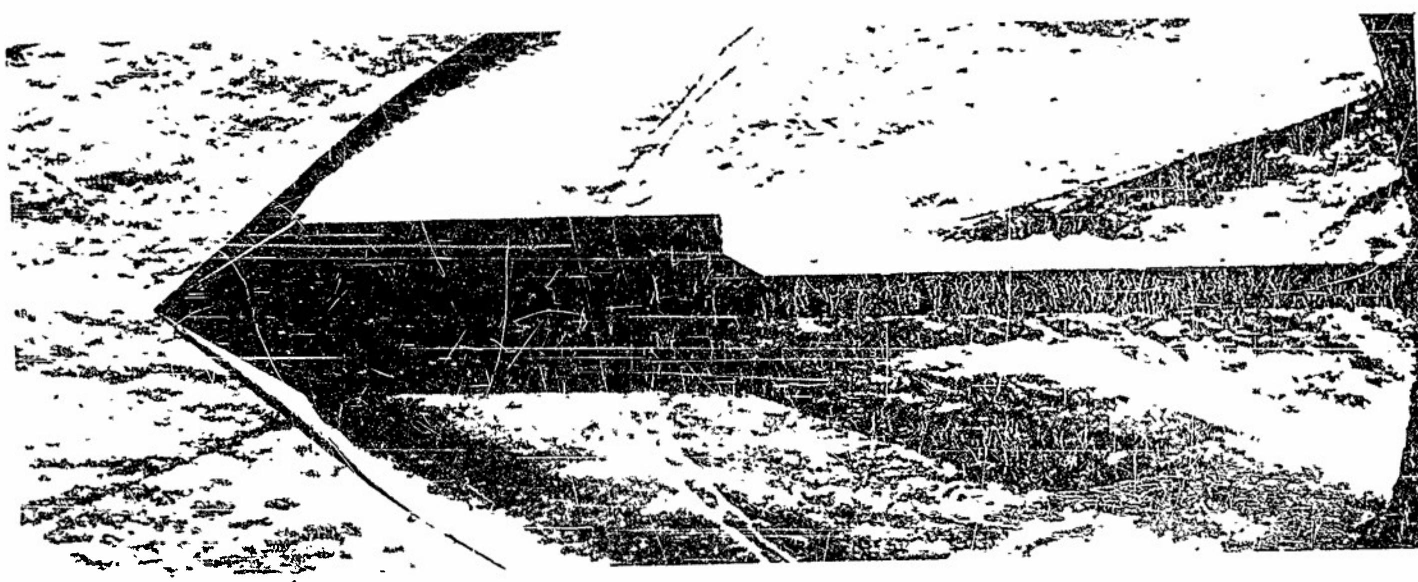


$R_e = 2.77 \times 10^6$

FIGURE 4 b). SCHLIEREN PHOTOGRAPHS OF SMOOTH BASE PRESSURE MODEL, D = 1.00", M = 2.95, FOR A RANGE OF REYNOLDS NUMBERS



$R_\theta = 4.48 \times 10^6$



$R_\theta = 13.19 \times 10^6$

FIGURE 4 b). CONCLUDED

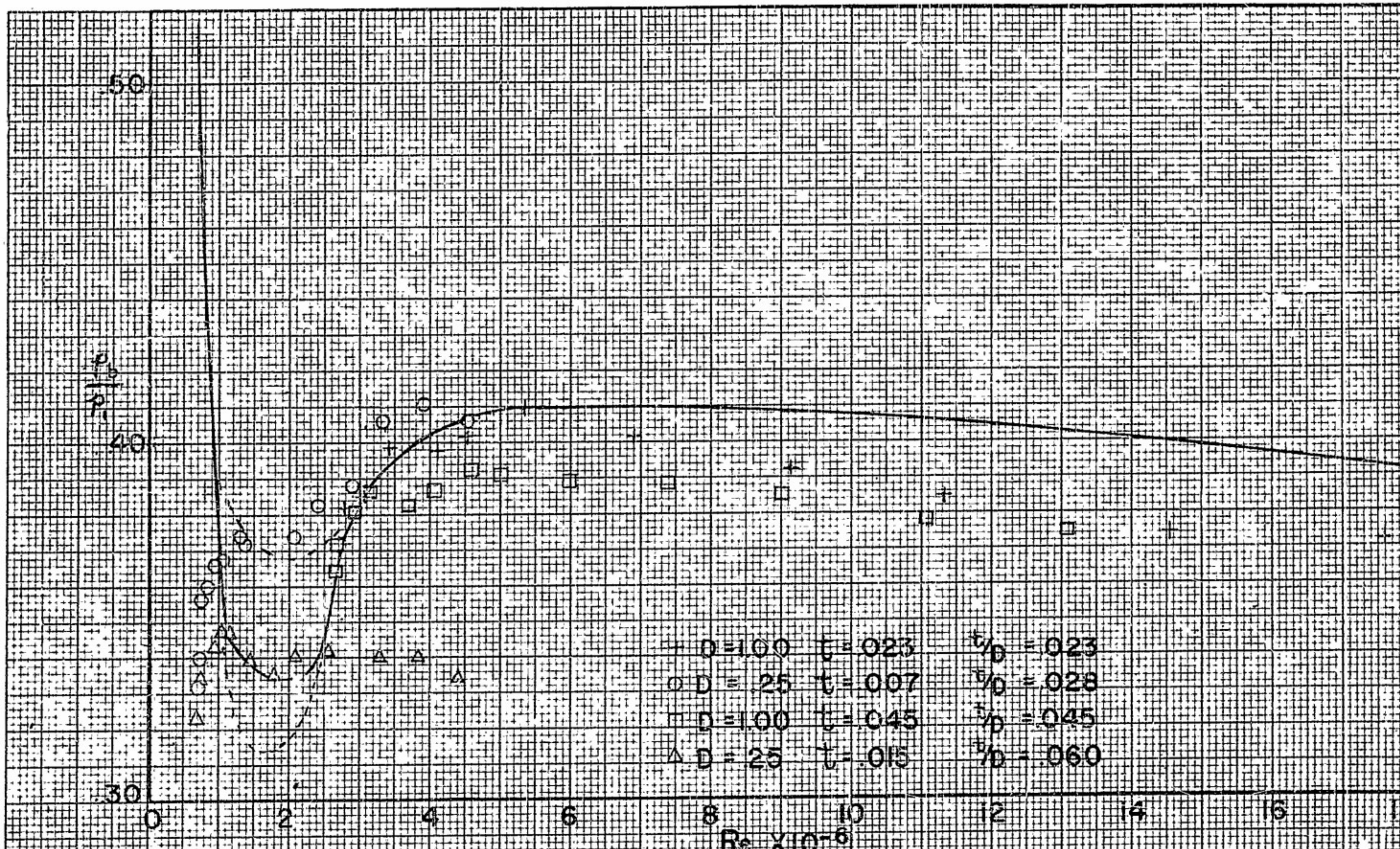
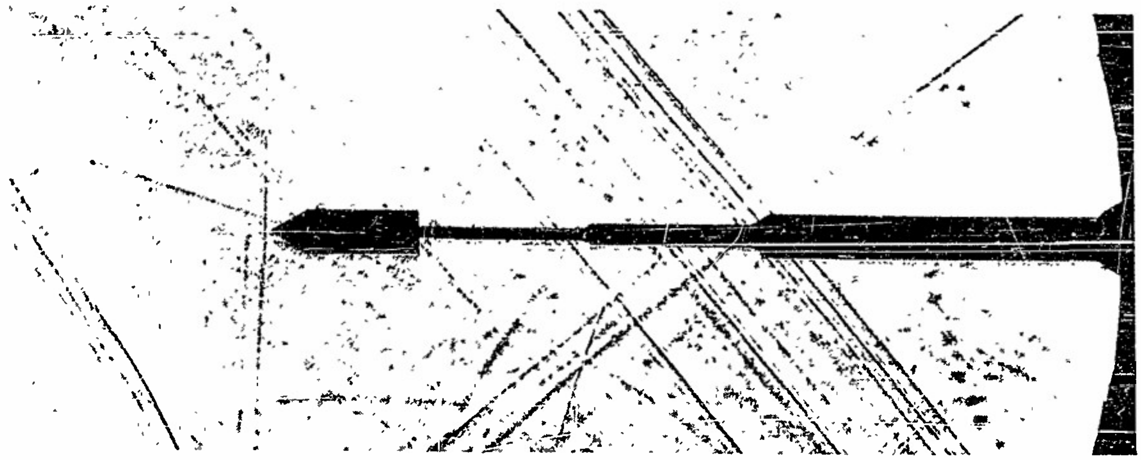


FIGURE 5. THE VARIATION OF BASE PRESSURE COEFFICIENT WITH REYNOLDS NUMBER FOR SEVERAL TRANSITION STRIP THICKNESSES



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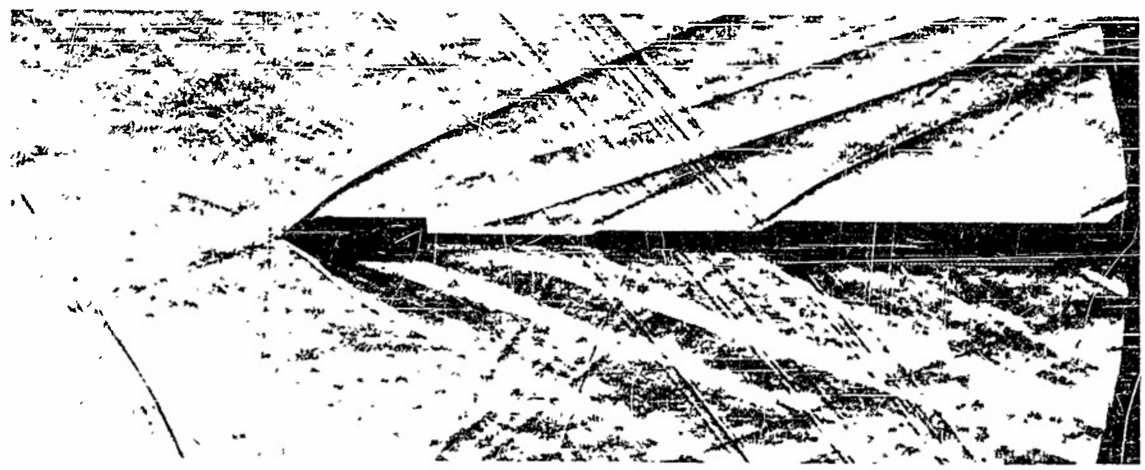
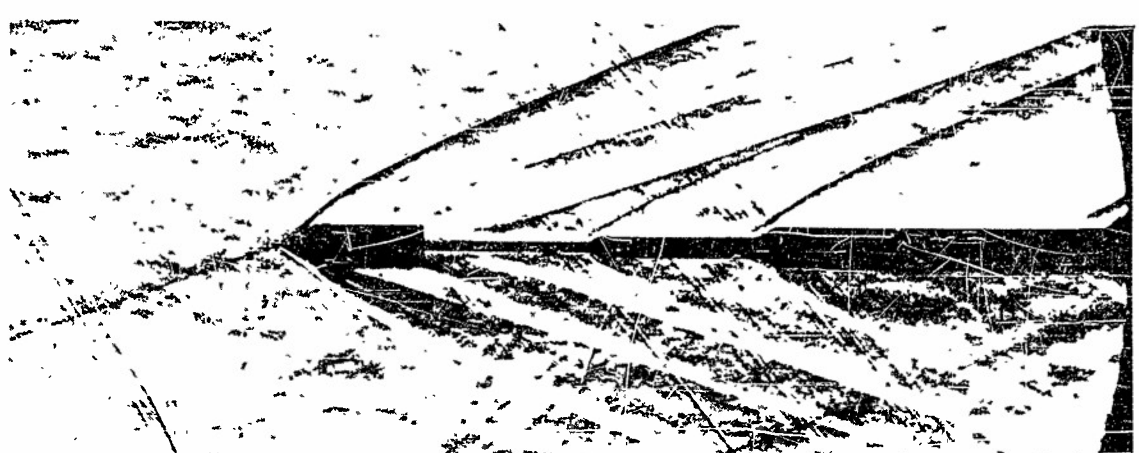
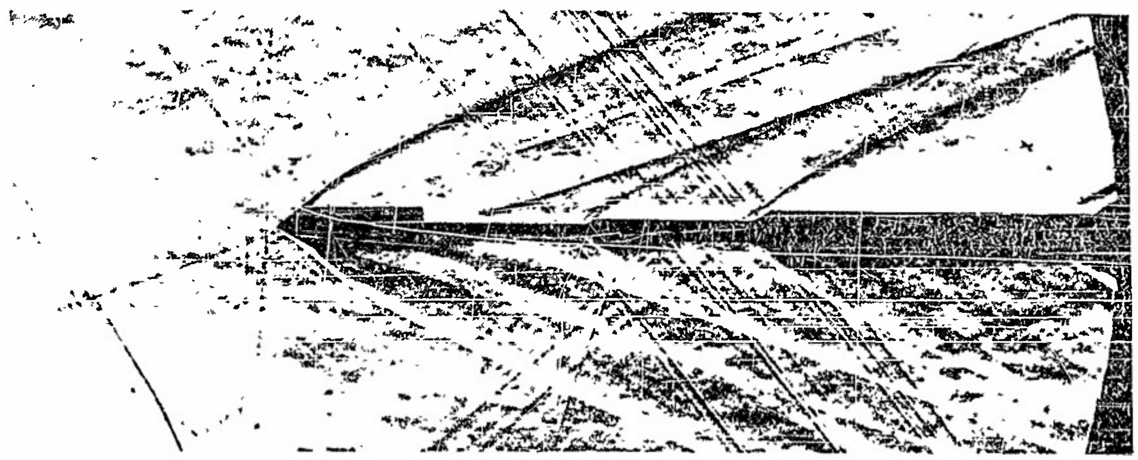


$R_\theta = .817 \times 10^6$

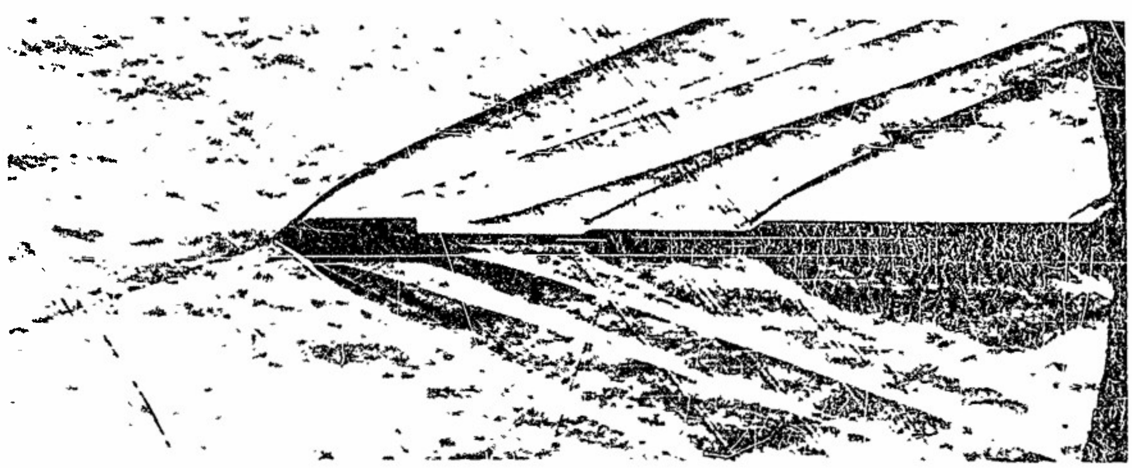


$R_\theta = 1.20 \times 10^6$

FIGURE 6 a). SCHLIEREN PHOTOGRAPHS OF BASE PRESSURE MODEL WITH TRANSITION STRIP, D = .25", t = .007, M = 2.95, FOR A RANGE OF REYNOLDS NUMBERS

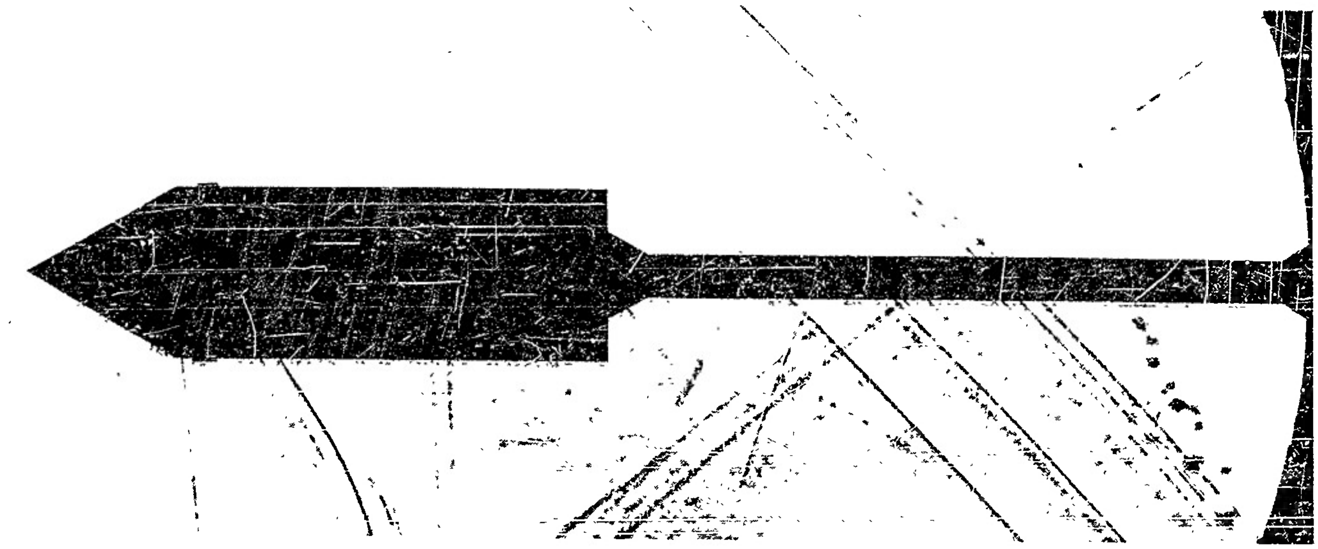


$R_{\theta} = 1.61 \times 10^{6}$



$R_{\theta} = 2.04 \times 10^{6}$

FIGURE 6 a). CONCLUDED



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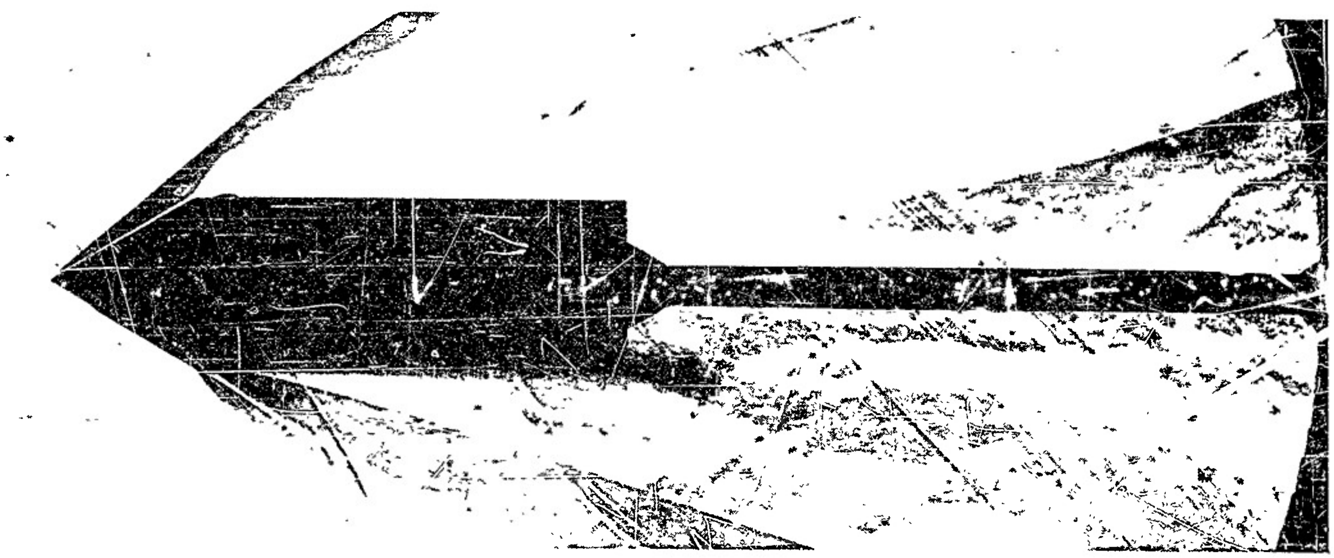

$R_\theta = 2.74 \times 10^6$

FIGURE 6 b). SCHLIEREN PHOTOGRAPHS OF BASE PRESSURE MODEL WITH TRANSITION STRIP, D = 1.00", t = .023, M = 2.95, FOR A RANGE OF REYNOLDS NUMBERS

$R_e = 5.28 \times 10^6$

$R_e = 17.54 \times 10^6$

FIGURE 6 b). CONCLUDED