NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4388

EFFECTS OF NOSE ANGLE AND MACH NUMBER ON TRANSITION ON CONES AT SUPERSONIC SPEEDS

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SUMMARY

An investigation has been made to determine the transition characteristics of a group of smooth, sharp-nosed cones varying from 10° to 60° in included apex angle over a Mach number range from 1.61 to 2.20 and a range of tunnel Reynolds number per foot from about 1.5×10^6 to 8×10^6. The tests were made at zero angle of attack and with zero heat transfer.

The results indicate that the general level of transition Reynolds number varied between 6×10^6 and 8×10^6 when based on surface distance and local flow conditions just outside the boundary layer, and between 900 and 1,000 when based on boundary-layer momentum thickness and local conditions outside the boundary layer. Increasing the cone angle caused a moderate decrease in distance transition Reynolds number, together with a consequent decrease in momentum transition Reynolds number. Changes in Mach number and unit tunnel Reynolds number had little or no effect on the transition Reynolds numbers. When transition occurred within 15 to 20 percent of the model length from the base there usually was a drop-off in transition Reynolds number.

INTRODUCTION

The study of boundary-layer transition is of continuing importance in the design of supersonic and hypersonic airplanes and missiles. The state of the art is still such that recourse must be had to experimental data in making estimates of transition Reynolds numbers. While a large body of experimental data is now available for study, there is still a lack of data wherein some of the parameters are varied in a systematic manner and the results are obtained in a single facility in which the apparent turbulence level and local flow irregularities are small. This investigation was undertaken to fulfill some of the need for such results.

The tests were made in the Langley 4- by 4-foot supersonic pressure tunnel, in which past tests have indicated a relatively low level of

effective turbulence and local flow irregularity. Four basic cones were used, with included apex angles of 10°, 27°, 45°, and 60°. The test Mach numbers were 1.61, 1.82, 2.01, and 2.20, and the tunnel unit Reynolds number range varied from about 1.5×10^{6} to 8×10^{6}. An additional cone nearly twice as long as the basic cones was also tested at a Mach number of 2.01. All cones had sharp noses with a diameter or thickness of 0.002 inch, and all tests were made with the models at zero angle of attack and with zero heat transfer. Transition was determined by means of schlieren photography.

SYMBOLS

M	Mach number
R	Reynolds number
s	surface distance from apex

Subscripts:

tr	transition
∞	free stream
l	local conditions outside boundary layer
θ	boundary-layer momentum thickness

APPARATUS AND METHODS

Wind Tunnel

This investigation was conducted in the Langley 4- by 4-foot supersonic pressure tunnel, which is a rectangular, closed-throat, single-return type of wind tunnel with provisions for the control of the pressure, temperature, and humidity of the enclosed air. Flexible nozzle walls were adjusted to give the desired test-section Mach numbers of 1.61, 1.82, 2.01, and 2.20. During the tests the dewpoint was kept below -20° F at atmospheric pressure; therefore the effects of water condensation in the supersonic nozzle were negligible.

Models

The models used in this investigation (fig. 1) consisted of three 24.00-inch sharp-nose cones with apex angles of 10°, 27°, and 45°, one 17.50-inch cone whose apex angle measured 60°, and one 40.00-inch cone whose apex angle measured 10°. All models were constructed of steel and were polished to a mirrorlike finish, which past experience indicates to be representative of a surface roughness of less than 5 microinches root-mean-square. The noses of the cones were approximately 0.002 inch in diameter or thickness. A photograph of the models is presented as figure 2. It should be mentioned that the base of the 60° cone was modified by cutting down and beveling in order to get an effective decrease in the area ratio so that the tunnel would start, at least, at the highest test Mach number. All models were sting mounted for the test, the lengths of the short and long stings being $4\frac{1}{2}$ and $10\frac{1}{2}$ inches, respectively. Some of the models were made in two parts. Care was taken that the joint between the parts was faired smooth.

Tests

All tests were conducted with the models at zero angle of attack. The tests were conducted at mean Mach numbers of 1.61, 1.82, 2.01, and 2.20, but the 45° and 60° cones were tested only at the higher Mach numbers because of tunnel choking. For all test Mach numbers and cone angles the nose shock was always attached. Calibrations of the test-section flow have indicated that local variations of Mach number are smaller than 0.02 for Mach numbers of 1.61, 1.82, and 2.01. No calibration has been made for a Mach number of 2.20.

Tests were made by starting at low tunnel stagnation pressures and advancing to the higher pressures. Tunnel stagnation pressure varied from about 800 to 4,300 lb/sq ft, which corresponds to a range of tunnel Reynolds number per foot from about 1.5×10^{6} to 8×10^{6}. The tunnel stagnation temperature varied from about 95° to 130° F. Whenever data were to be recorded the tunnel was brought to the desired pressure and held there for a period of time that, judging from past experience, was sufficient to insure equilibrium conditions. Light flashes of approximately 4 microseconds' duration were used to record the location of transition by means of schlieren photography. From three to ten pictures, with an average of six, were taken at each tunnel pressure. Since equilibrium conditions existed at the time of recording the data, there was no transfer of heat.

Some difficulty was encountered with sandblasting effects on the models at the higher tunnel stagnation pressures because of particles

flying through the tunnel. This sandblasting resulted in either model pitting or the raising of small protuberances which could have affected transition. Where it was believed that the data might be affected, the models were repolished and reruns were made. Subsequent analysis indicated that all the data obtained on the cones with the sharp (0.002 inch) noses were free of any effects of sandblasting.

Data Reduction

Location of transition was determined by examination of the schlieren photographs by two or more readers. The transition locations determined by the different readers were then averaged at each tunnel stagnation pressure and the average value was treated as a single test point. In most instances the differences in the transition locations determined by the various readers were negligible. Boundary-layer momentum thickness was computed by the method of reference 1. Mangler's transformation (ref. 2), which gives the general relationship between two-dimensional and axially symmetrical boundary layers, was employed to reduce the flat-plate calculations to those for a conical body. Flow conditions on the cone surfaces were obtained with the aid of the tables in reference 3, with the assumption that no boundary layer was present.

RESULTS AND DISCUSSION

General Remarks

Before the quantitative aspects of the transition phenomena are discussed, a few remarks will be made about the qualitative results of the investigation. First, the transition phenomena were unsteady, the transition front oscillating perhaps as much as 10 percent forward or rearward of its average location. The greatest unsteadiness usually occurred when transition was located on the last 15 or 20 percent of the model length. In addition, a number of bursts of turbulence just ahead of or merging with the main transition point were discerned in the schlieren photographs. These bursts were discounted in establishing the location of the main front. Examination of the available photographs did not reveal any reliable evidence of any bursts of turbulence very far ahead of the average transition location; hence it appears that, no matter what the point of origin, the bursts sustained their main growth in a relatively short region just ahead of the average front.

Transition Reynolds Number

The quantitative results of this investigation, with a few exceptions, are presented as functions of local Reynolds number at various

local Mach numbers because the local flow conditions on the surface of the cone behind the nose shock and just outside the boundary layer are fundamental to the problem. For convenience in cross referencing, the free-stream Mach numbers usually are also included.

The location of the average transition point along the model surface as a function of local Reynolds number per foot for the various cone angles is presented in figure 3. Included in each plot are two lines, a long-dash line indicating the slope corresponding to a constant transition Reynolds number and a short-dash line indicating model surface length. Data presented in this figure, particularly that from the most forward transition locations investigated to about 80 to 85 percent of model length, showed fairly good agreement with the slope for constant transition Reynolds number. When transition occurs farther rearward, a dropoff in transition Reynolds number generally occurs. In figure 3(a), at $M_\infty = 2.01$, the 40-inch 10° cone shows a dropoff at a lower unit local Reynolds number than the 24-inch 10° cone; however, the dropoff occurs at about the same 80- to 85-percent station on both models. This result suggests that transition near the model base may be affected by the turbulence in the separated wake at the base. The fact that transition could be affected as far ahead of the base as 15 or 20 percent of the model length when the subsonic portion of the boundary layer is so thin doesn't appear to be reasonable. The possibility exists that the extent of the forward influence may be connected in some way with the increased oscillation of the transition front near the base of the model that was mentioned previously. Calculations show that the decrease in transition Reynolds number occurs at about the same distance forward of the base on both cones when the distance is expressed as a multiple of the boundary-layer thickness. Another possibility is that there may be some heat transfer within the model material near the base because of the difference between the recovery temperatures on the model surface and the model base due to separated flow at the base.

Another point that should be mentioned is that the tests of the 40-inch 10° cone were made specifically to determine whether changes in unit Reynolds number had any effect on transition Reynolds number. Hence a larger number of schlieren photographs at a larger number of tunnel pressures were obtained for the 40-inch model than for the 24-inch models. A comparison of these experimental results, exclusive of those for the last 5 to 10 inches, with the slope for constant transition Reynolds number leads to the same conclusion as was derived for the shorter models. The effect of tunnel pressure on transition was small, if it existed at all, when the last 15 or 20 percent of the model length was neglected.

Variations of $R_{s,tr}$ with unit local Reynolds number are presented in figure 4. The general level of $R_{s,tr}$ is about 6×10^6 to 8×10^6 exclusive of the results for the last 15 to 20 percent of the model

lengths. This is a higher level than that obtained in most supersonic wind tunnels (see refs. 4 and 5) and suggests that the results are relatively free of tunnel turbulence effects and local flow irregularities. The data also indicate a decrease in $R_{s,tr}$ with an increase in cone angle. At $M_\infty = 2.20$ this decrease amounts to about 1.5×10^6 for an increase in cone angle from 10° to 60°. The results suggest that this effect may be stronger at the lower Mach numbers (compare 10° and 27° cones over the Mach number range) but more data are required to establish this point definitely. There appears to be little if any effect of Mach number on the results, a result somewhat in contradiction to the indications of most other wind-tunnel investigations that $R_{s,tr}$ decreases with Mach number. (See refs. 5 to 8.)

Figure 5 shows variations of the momentum transition Reynolds number $R_{\theta,tr}$ with R_l per foot, with cone angle and Mach number as parameters. A composite plot of $R_{\theta,tr}$ as a function of local unit Reynolds number, with either cone angle or Mach number identified, is presented as figure 6 for greater ease in making comparisons. The range of $R_{\theta,tr}$ extended from about 900 to 1,000 and remained fairly constant; $R_{\theta,tr}$ had only a slight tendency to decrease with increase in cone angle. Again there is little or no effect of Mach number.

For the sake of general interest, the transition results are plotted against unit tunnel Reynolds number in figure 7. There do not seem to be any significant changes from figure 6.

SUMMARY OF RESULTS

An investigation has been made to determine the transition characteristics of a group of cones varying from 10° to 60° in included apex angle over a Mach number range from 1.61 to 2.20 and a range of tunnel Reynolds number per foot from 1.5×10^6 to 8×10^6. The results indicate that:

1. The general level of transition Reynolds number varied between 6×10^6 and 8×10^6 when based on surface distance and local flow conditions just outside the boundary layer, and between 900 and 1,000 when based on boundary-layer momentum thickness and local conditions.

2. Increasing the cone angle caused a moderate decrease in distance transition Reynolds number together with a consequent decrease in momentum transition Reynolds number.

3. Changes in Mach number and unit tunnel Reynolds number had little or no effect on the transition Reynolds number.

4. When transition occurred within 15 to 20 percent of the model length from the base there usually was a dropoff in transition Reynolds number which may be connected with the turbulence in the separated wake or with heat transfer within the model material near the base because of the difference between the recovery temperatures on the model surface and the model base due to separated flow at the base.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 2, 1958.

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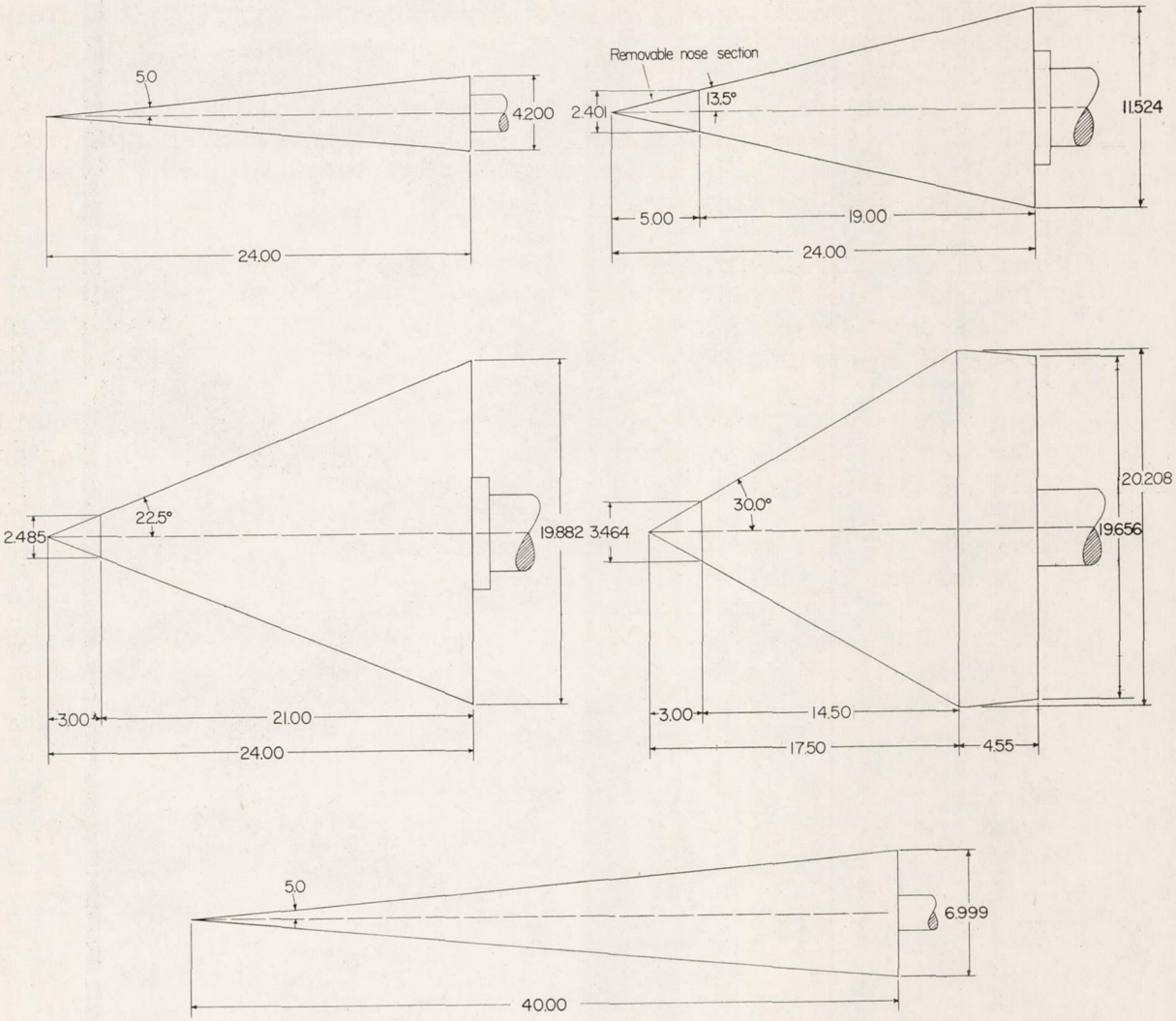


Figure 1.- Sketch of models. All dimensions are in inches unless otherwise indicated.

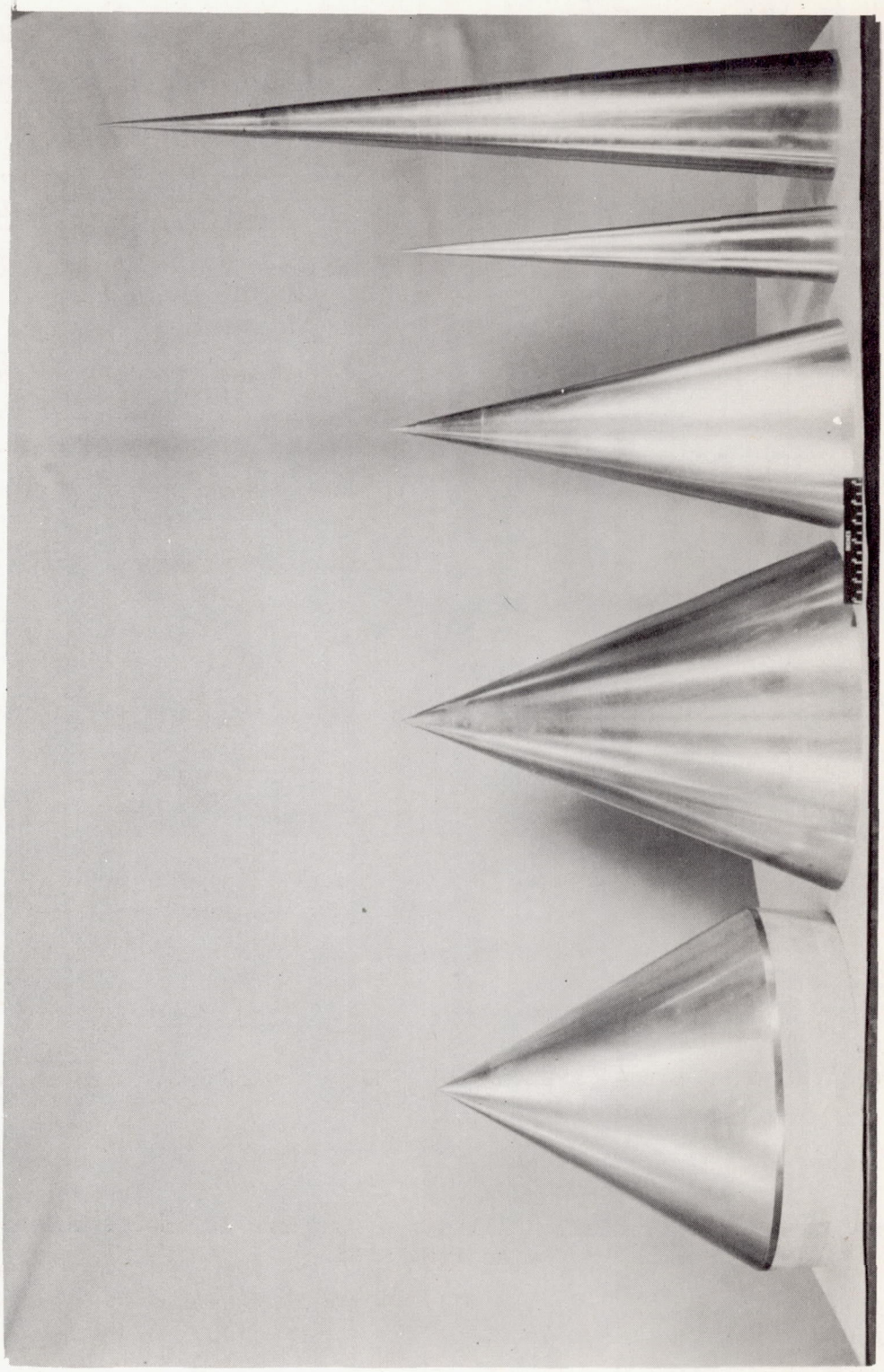
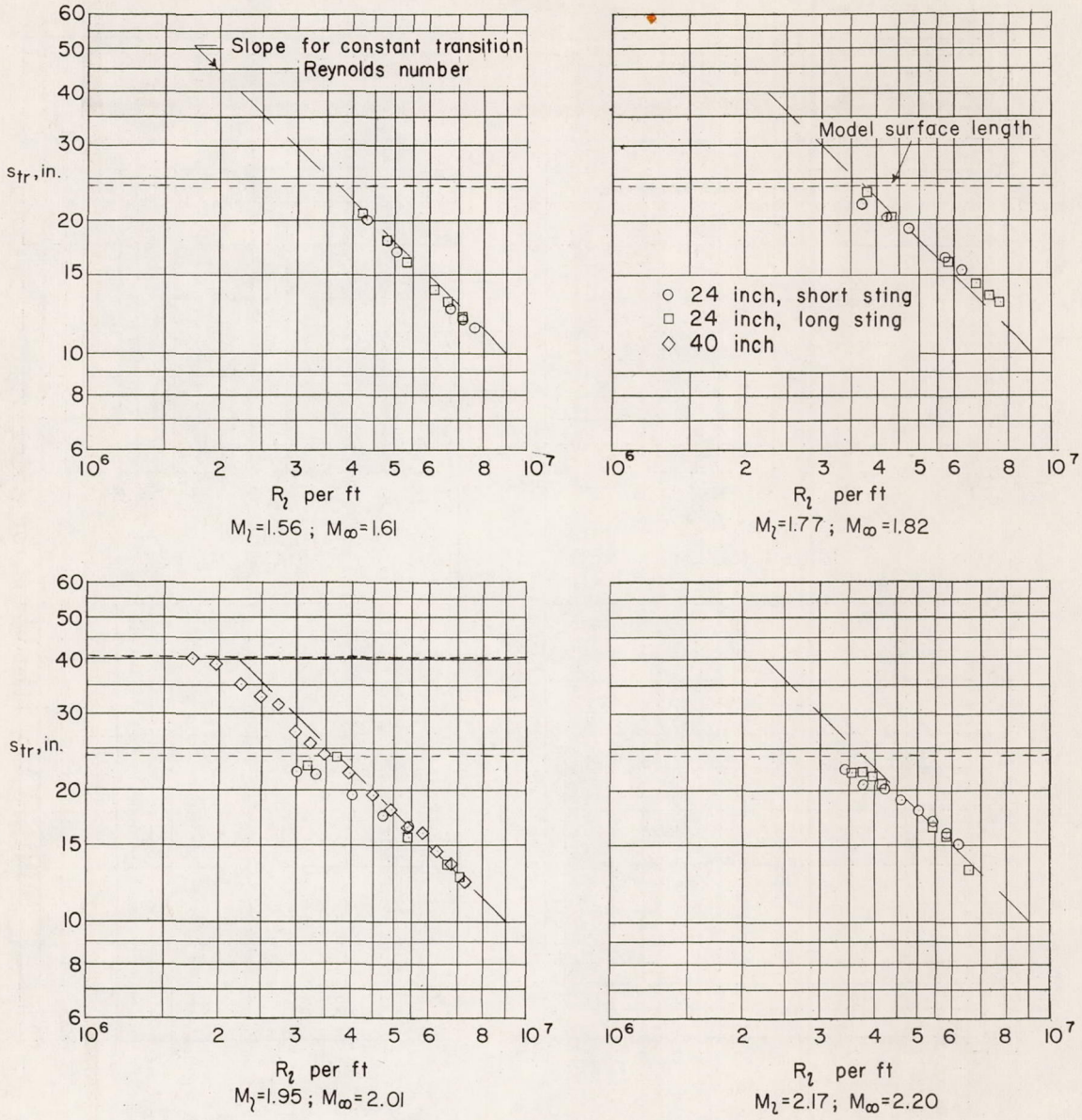
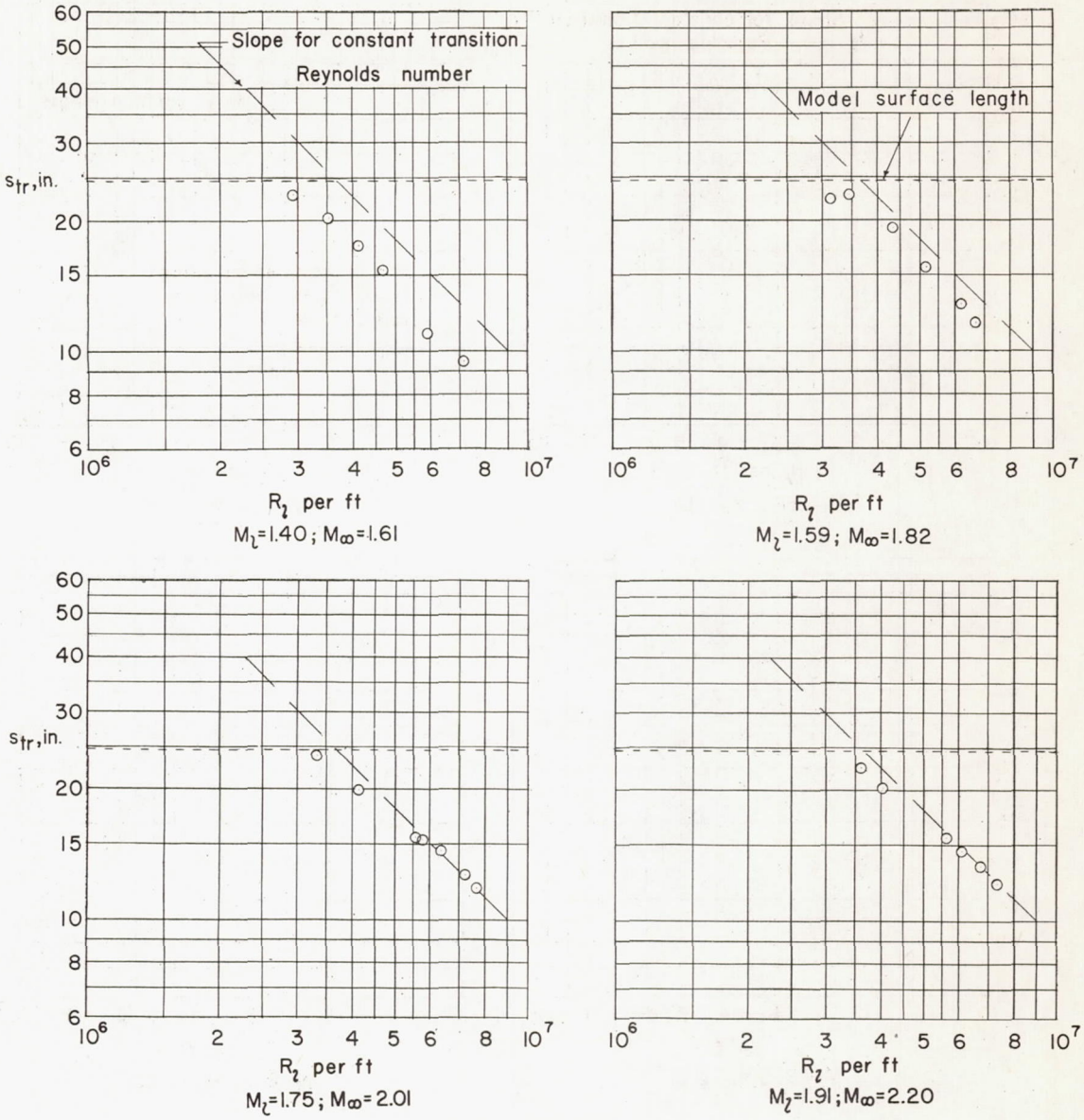


Figure 2.- Photograph of models. L-57-5603



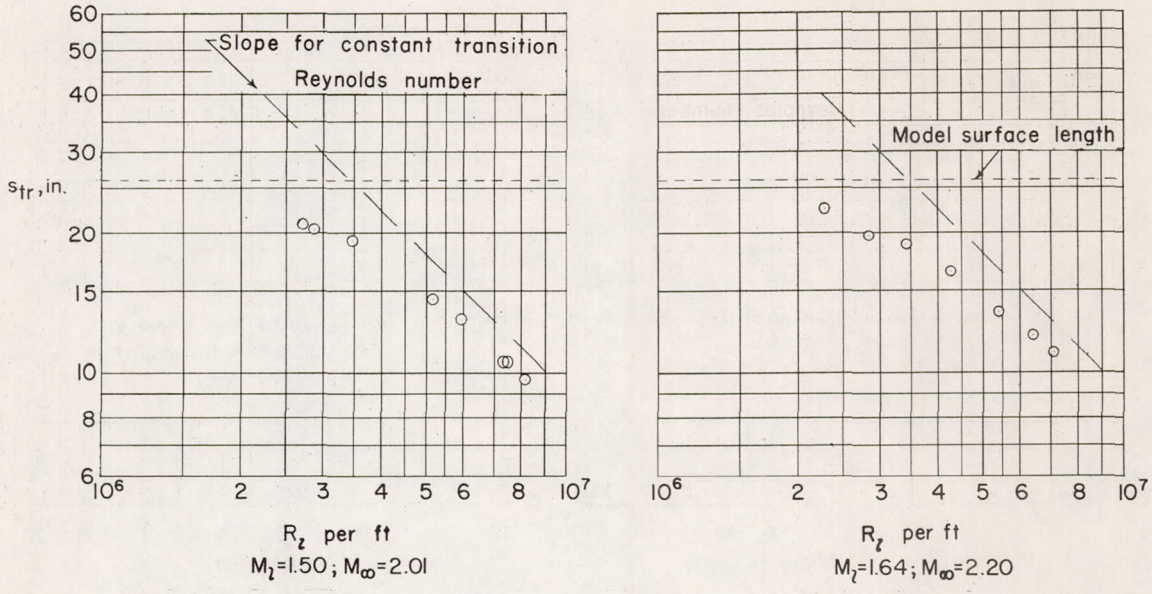
(a) 10° cone.

Figure 3.- Surface distance to transition point as a function of R_l per foot for cones with sharp noses.

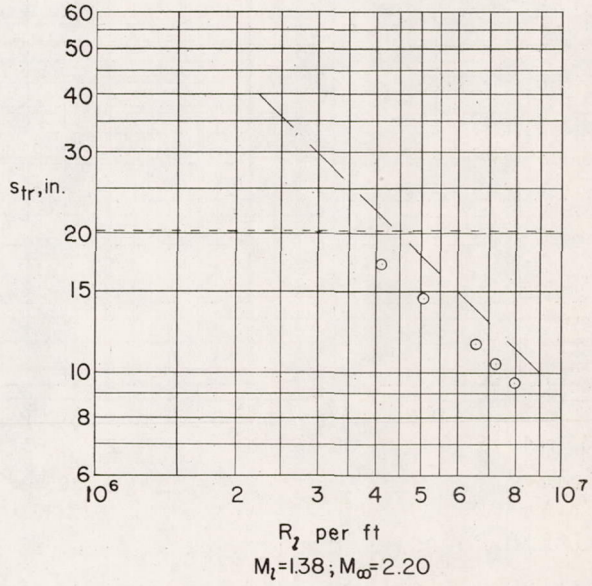


(b) 27° cone.

Figure 3.- Continued.



(c) 45° cone.



(d) 60° cone.

Figure 3.- Concluded.

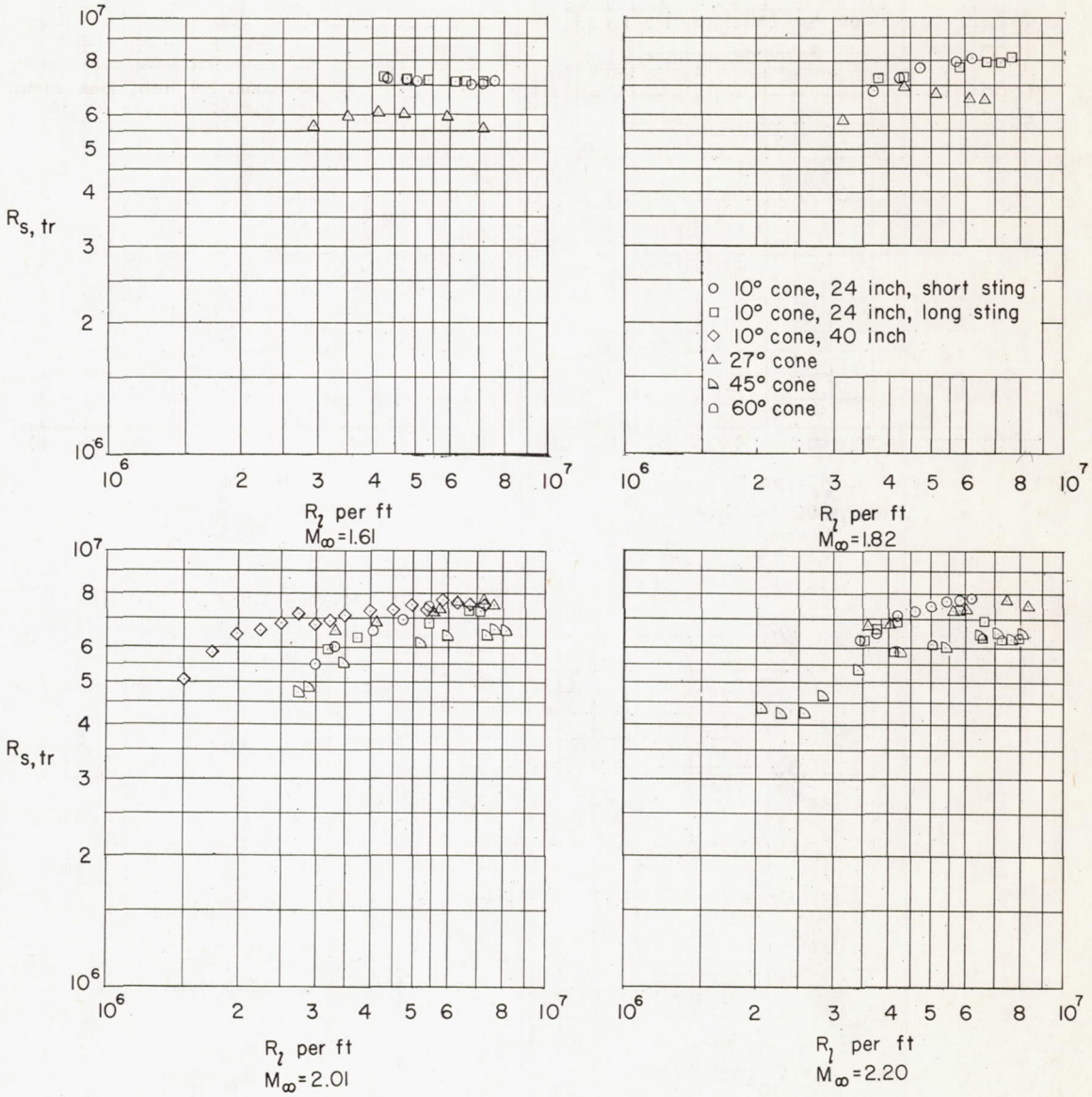


Figure 4.- Transition Reynolds number $R_{s,tr}$ based on surface distance and local conditions outside boundary layer, as a function of R_l per foot.

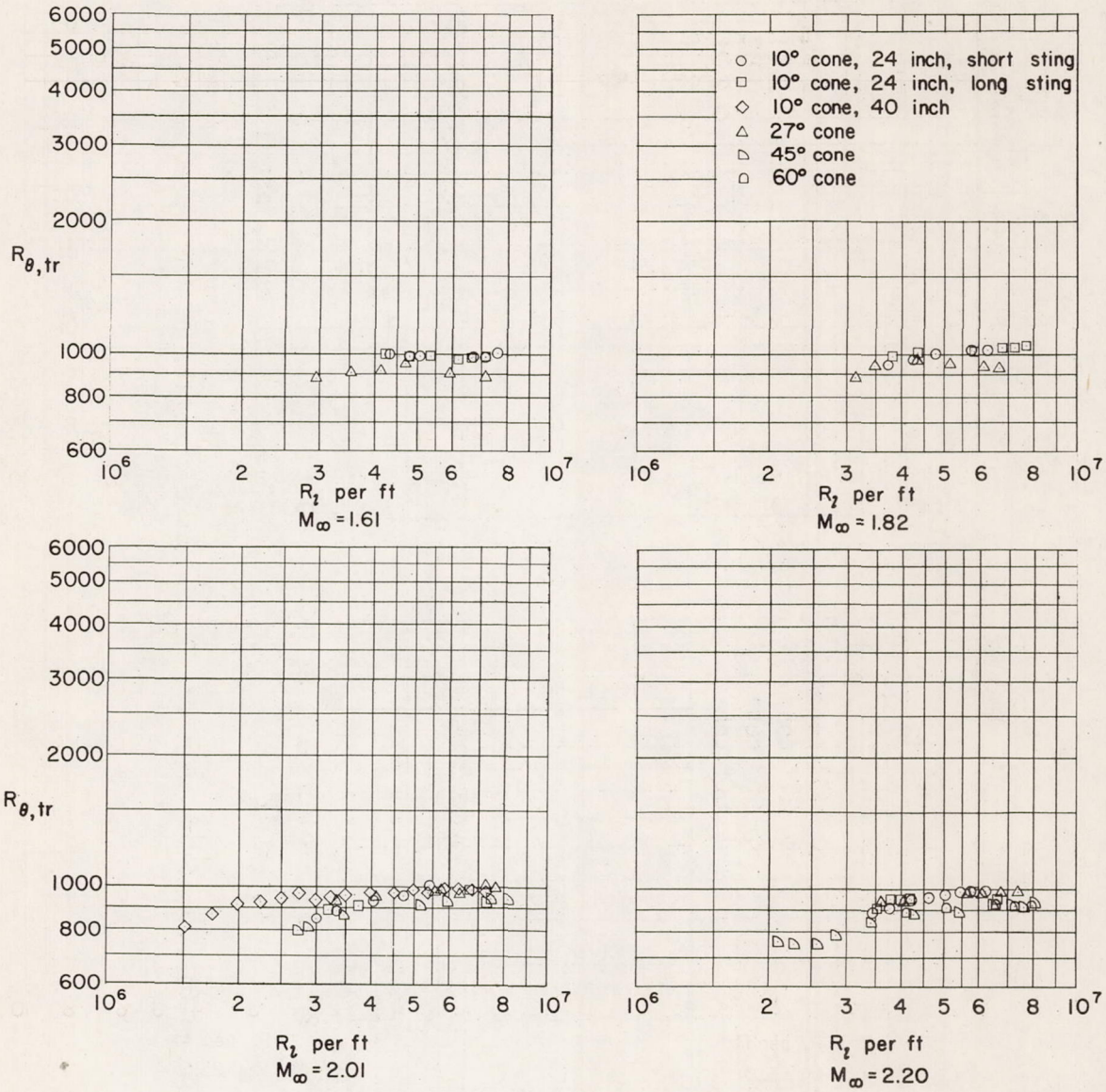


Figure 5.- Transition Reynolds number $R_{\theta,tr}$ based on θ and local conditions outside boundary layer, as a function of R_l per foot.

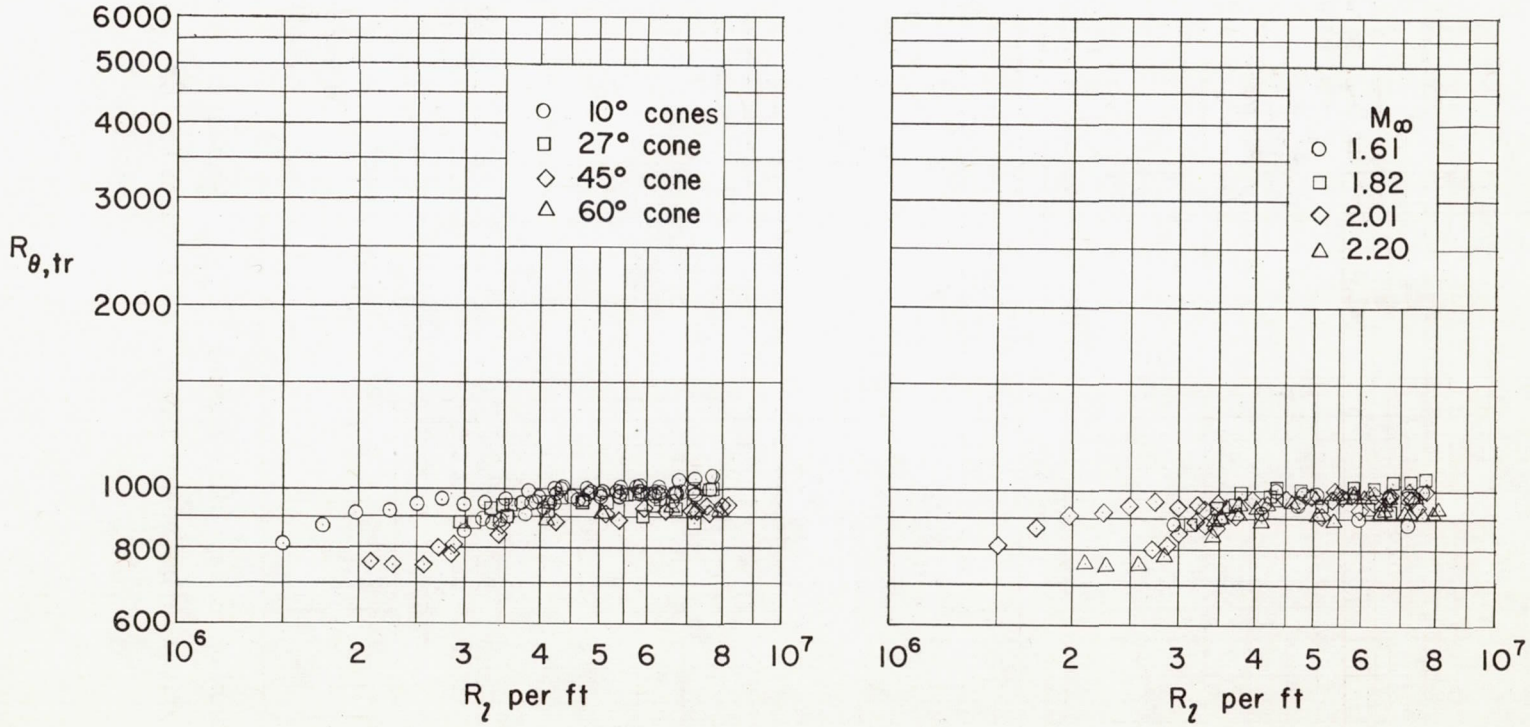


Figure 6.- Composite plot of $R_{\theta,tr}$ as a function of R_l per foot.

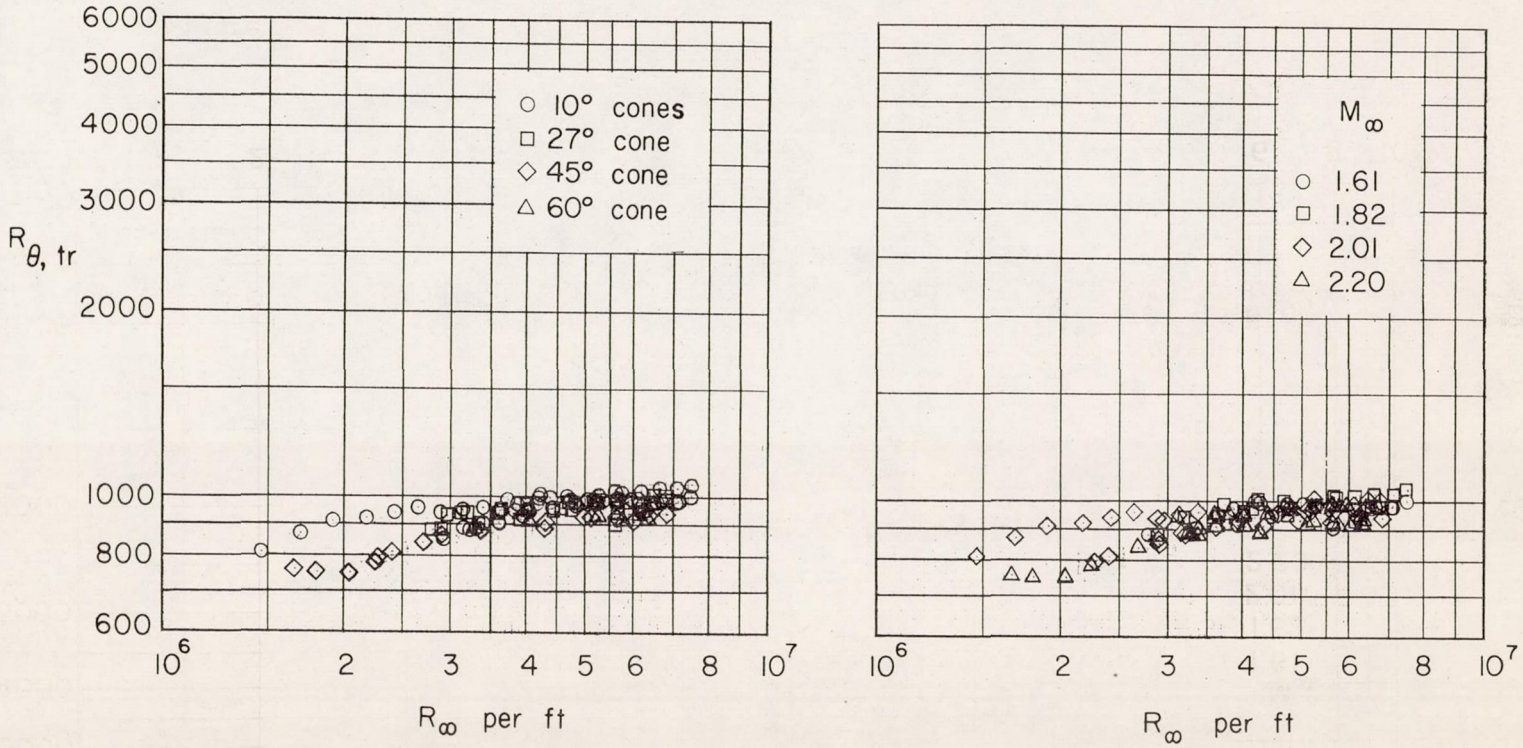


Figure 7.- Composite plot of $R_{\theta,tr}$ as a function of R_∞ per foot.

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