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TECHNICAL NOTE

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INVESTIGATION BY SCHLIEREN TECHNIQUE OF METHODS OF FIXING FULLY TURBULENT FLOW ON MODELS AT SUPERSONIC SPEEDS

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INVESTIGATION BY SCHLIEREN TECHNIQUE OF METHODS OF FIXING FULLY TURBULENT FLOW ON MODELS AT SUPERSONIC SPEEDS

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SUMMARY

An investigation has been made of the effectiveness of two-dimensional wire and three-dimensional granular-type roughnesses for fixing transition on a 27° cone at a free-stream Mach number of 2.20. One height of each type of roughness was investigated over a free-stream Reynolds number per foot range of about 1.0×10^{6} to 7.0×10^{6}. The tests were made at an angle of attack of 0° and with essentially zero heat transfer.

The results indicate that, within the Reynolds number per foot range investigated, both two-dimensional wire and three-dimensional granular types of roughness caused large forward movements of transition at constant Reynolds number per foot; however, the forward movement with increase in Reynolds number per foot was very slow for the two-dimensional wire roughness and transition never reached the roughness location as it did with the three-dimensional granular roughness. An extrapolated value of the roughness Reynolds number (based on roughness height and flow conditions at the outer edge of the roughness) for the first appearance of forward movement from the smooth-cone case for the three-dimensional granular roughness was in good agreement with the value of about 600 for the first appearance of turbulent bursts obtained on a similar cone by the hot-wire technique. The range of values of roughness Reynolds number for which a fully turbulent boundary layer existed in the vicinity of the roughness element was about 4,500 to 6,500.

INTRODUCTION

The fixing of transition on models in a wind tunnel so that the flow over the model is turbulent is of utmost importance in the study of lift-drag ratios of airplane and missile configurations in supersonic flow. In order to make tests at wind-tunnel Reynolds numbers and to correct the results to estimated flight Reynolds numbers, transition must be fixed at the proper place on the model to obtain turbulent boundary-layer characteristics. For this reason, it is desirable to establish a criterion for determining the fixing of transition on models for wind-tunnel testing.

One method of fixing transition on a model is to attach grains of roughness at the desired transition location. Reference 1 gives a criterion for the first initiation of turbulent bursts. There is, however, an interval between the Reynolds number at which there is the first initiation of bursts and the Reynolds number at which a fully developed turbulent boundary layer exists in the vicinity of the roughness. The latter is important in the determination of conditions for which turbulent heat-transfer and skin-friction characteristics are obtained. Reference 1 has indicated that the interval in Reynolds number is small at subsonic speeds. Unpublished tests conducted in the Langley 4- by 4-foot supersonic pressure tunnel indicated a larger interval at supersonic speeds and suggested a need for more research to clarify this possibility.

The purpose of the present experiments was to make a preliminary investigation to shed additional light on this problem. The tests were conducted on a 27° cone at a free-stream Mach number of 2.20. One height of two-dimensional wire roughness and one height of three-dimensional granular roughness were investigated over a free-stream Reynolds number per foot range of about 1.0×10^6 to 7.0×10^6 at an angle of attack of 0°.

SYMBOLS

M	free-stream Mach number
s	surface distance from apex
R_k	Reynolds number based on roughness height and local flow conditions at top of roughness
R_l	Reynolds number based on transition distance and local flow conditions outside the boundary layer
R_θ	Reynolds number based on boundary-layer momentum thickness and local flow conditions outside the boundary layer.

Subscript:

tr	transition

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 tunnel with provisions for the control of the pressure, the temperature, and the humidity of the enclosed air. The investigation was conducted at a free-stream Mach number of 2.20. During the tests the dewpoint was kept below -20° at atmospheric pressure to insure that the effects of water condensation in the supersonic nozzle were negligible.

Model

The model used in this investigation (fig. 1) consisted of a sting-mounted 24.00-inch nose cone whose apex angle measured 27°. The model was constructed of solid steel and was approximately 0.002 inch in nose diameter or thickness. Surface roughness of the basic model was less than 5 microinches root mean square.

Two-dimensional roughness was effected by affixing a 0.016-inch-diameter wire circumferentially on the model 6.09 inches from the apex. Maximum roughness height was determined by taking several spanwise measurements along the wire.

Approximate uniformly distributed three-dimensional granular roughness was effected by masking off a 1/4 inch to 3/8 inch strip on the model 6 inches from the model apex. The unmasked area was sprayed with lacquer and finely graded number 60 carborundum grit was sprinkled thereon so that the grit particles were spaced fairly far apart. The grit was then pressed firmly into the lacquer to assure contact with the surface and resprayed. Maximum height of about 0.019 inch for the number 60 carborundum grit was estimated on the basis of the results of reference 1.

Tests

All tests were conducted with the model at an angle of attack of 0° and at a free-stream Mach number of 2.20, which corresponds to a local Mach number of 1.92.

Test procedure consisted of starting at low tunnel stagnation pressures and increasing to the higher pressures. Tunnel stagnation pressures varied from about 700 to 4,300 pounds per square foot, which correspond to a range of tunnel Reynolds number per foot from about 1.0×10^6 to 7.0×10^6 or to a local Reynolds number per foot range from about 1.1×10^6 to 7.9×10^6. The tunnel stagnation temperatures varied from about 90° F to 125° F.

The location of transition for the fully developed turbulent flow was determined by means of schlieren photography. 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 approximate equilibrium conditions and thereby assure zero L
heat transfer. Light flashes of approximately 4 microseconds' duration 7
were used to photograph the schlierens. From 3 to 10 pictures, with an 6
average of 6, were taken at each tunnel pressure. 1

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. For the most part scatter did not exceed ±4 percent. Figure 2 presents typical schlieren photographs. Estimated location of transition is represented by a vertical line. Boundary-layer momentum thickness for local conditions on the model and no heat transfer was computed by the method of reference 2. Mangler's transformation (ref. 3) 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 surface were obtained with the aid of the tables in reference 4 with the assumption that no boundary layer was present.

RESULTS AND DISCUSSION

Transition Distance

The location of the average transition distance s_{tr} along the model surface is presented in figure 3 as a function of local Reynolds number per foot. Included in the plot is a horizontal dashed line indicating total model surface length and a horizontal dotted area indicating the location of the roughness elements.

The data indicate that transition was near the base of the smooth model at a local unit Reynolds number of 3.5×10^6 and moved forward to a distance of 12.2 inches from the model apex at a unit Reynolds number of about 7.5×10^6. When two- or three-dimensional roughness was added, there was a sharp decrease in transition distance measured from the cone apex for a given local unit Reynolds number. For the three-dimensional granular roughness, transition moved forward with increase in local Reynolds number per foot and reached the roughness location at a local unit Reynolds number range of 3.0×10^6 to 4.0×10^6. The two-dimensional wire roughness transition moved forward with the same characteristic trend but at a slower rate, particularly at the higher values of Reynolds number per foot, and never reached the roughness location. As has been found in previous investigations, transition movement to the vicinity of roughness is very slow and it does not appear that the use of two-dimensional wire roughness is an effective method of fixing transition on models at a desired location.

Roughness Reynolds Number for Transition

Reynolds number based on estimated roughness height (using results of ref. 1 as criteria), and local flow conditions at the top of roughness is presented as a function of local unit Reynolds number for the three-dimensional granular roughness in figure 4. A vertical band of cross hatching indicates the range of local unit Reynolds numbers at which transition has moved up to the roughness location. It should be noted that this transition band which was determined by the schlieren technique does not indicate the same transition phenomena as is indicated by the hot-wire technique. The hot-wire technique indicates the first appearance of turbulent bursts while the schlieren technique indicates the merging of a number of bursts into what appears to be a solid front where the boundary layer is fully turbulent.

The data indicate a variable R_k which is closely linear when plotted on log-log paper. The value of R_k for transition at the roughness ranges from about 4,500 to 6,500 depending upon the exact value of Reynolds number that is chosen. This range of values is considerably higher than the value indicated for initial turbulent bursts and thereby suggests that it cannot be assumed that transition will always move rapidly to the roughness element after the initial burst of turbulence.

Momentum Transition Reynolds Number

Although the parameter $R_{\theta,tr}$, the transition Reynolds number based on boundary-layer momentum thickness and local flow conditions outside the boundary layer, is not a criterion generally associated with fixing transition with roughness, it is of interest and has been computed for the three-dimensional granular and the two-dimensional wire roughnesses. It is presented as a function of local Reynolds number per foot in figures 5 and 6. Included in each figure is a dotted area indicating the range of momentum transition Reynolds numbers for the smooth cones reported in reference 5.

Smooth-cone $R_{\theta,tr}$ values fall in the range of 800 to 1,000 in the local unit Reynolds number range of about 1.5×10^6 to 8.0×10^6. Data for $R_{\theta,tr}$ for three-dimensional granular roughness at first showed a dropoff with increase in local unit Reynolds number until a minimum of about 400 was reached and then the data increased until it coincided with the R_θ for the roughness location in the unit Reynolds number range of about 3.0×10^6 to 4.0×10^6.

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The values of $R_{\theta,tr}$ for the two-dimensional wire roughness showed a similar dropoff with local unit Reynolds number until a minimum value of slightly lower magnitude was reached and then increased so as to approach the values for R_θ for the roughness location tangentially at a much slower rate than for the granular roughness. Whether it is significant that the minimum values of $R_{\theta,tr}$ for both types of roughnesses tested were nearly the same and occurred in about the same range of unit Reynolds number, near 1.5×10^6, as yet is not known.

Although the present tests were not made at a low enough Reynolds number range to gain an insight into what actually happens, it appears that, if the curve of $R_{\theta,tr}$ for the three-dimensional granular roughness model (fig. 5) were extrapolated, it would rise sharply and merge with the momentum thickness transition Reynolds number for the smooth cone in the range of unit Reynolds number of 0.8×10^6 to 1.0×10^6. This intersection of the transition curve of the smooth-cone data with the three-dimensional granular roughness cone data would then indicate the Reynolds number per foot for the first forward movement of the transition front from that of the smooth-cone location and should correspond to the first appearance of turbulent bursts from the roughness as indicated in the hot-wire technique. On the basis of this assumption an average value of unit Reynolds number of 0.9×10^6 would result in an extrapolated value of 600 to 700. This is in excellent agreement with the results of reference 1. It should be noted that the Reynolds number per foot increase from the estimated first appearance of turbulence to the movement of transition to the roughness location corresponds to an increase in Reynolds number per foot by a factor of 3 to 4.

Because some supersonic results obtained in the Langley 4- by 4-foot tunnel do indicate the rapid forward movement of transition to the roughness location after the first appearance of turbulent bursts, it appears that further research should be done to resolve the reasons for the differences.

CONCLUSIONS

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An investigation has been made of the effectiveness of two-dimensional wire and three-dimensional granular type roughnesses for fixing a fully turbulent boundary layer on models at supersonic speeds. The results indicate:

1. Within the range of Reynolds number per foot investigated, both two-dimensional wire and three-dimensional granular types of roughness caused large forward movements of transition at constant Reynolds number per foot; however, the forward movement with increase in Reynolds number per foot was so slow for the two-dimensional wire roughness that it does not appear to be desirable for fixing transition on models.

2. An extrapolated value of roughness Reynolds number (based on the roughness height and flow conditions at the outer edge of the roughness) for the first appearance of forward movement of transition from the smooth-cone case for the three-dimensional granular roughness was in good agreement with the value of about 600 for the first appearance of turbulent bursts obtained on a similar cone by the hot-wire technique.

3. Roughness transition Reynolds number for which a fully turbulent boundary layer existed in the vicinity of the roughness element was found to be in the range of 4,500 to 6,500.

4. Additional investigation is needed to establish the magnitude of the interval between the Reynolds number per foot at which there is initiation of turbulent bursts and the Reynolds number per foot at which a fully developed turbulent boundary layer exists in the vicinity of the roughness element.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 14, 1959.

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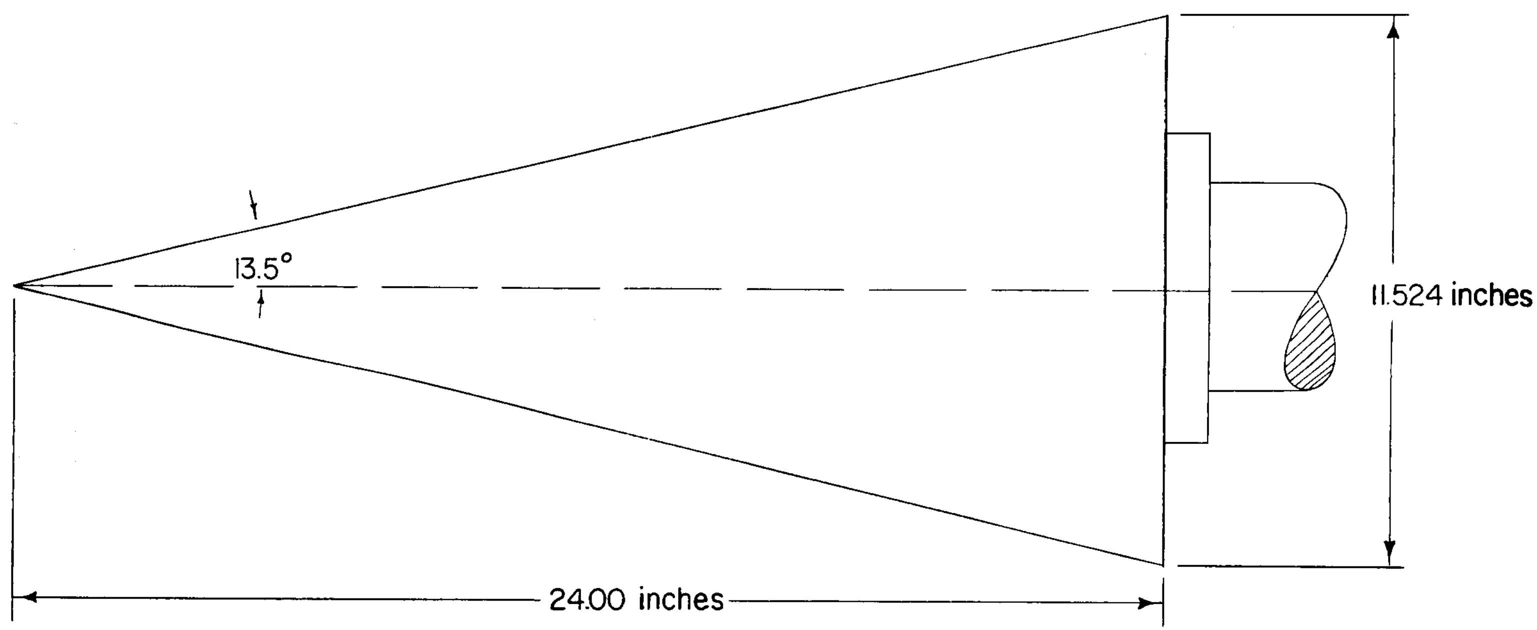
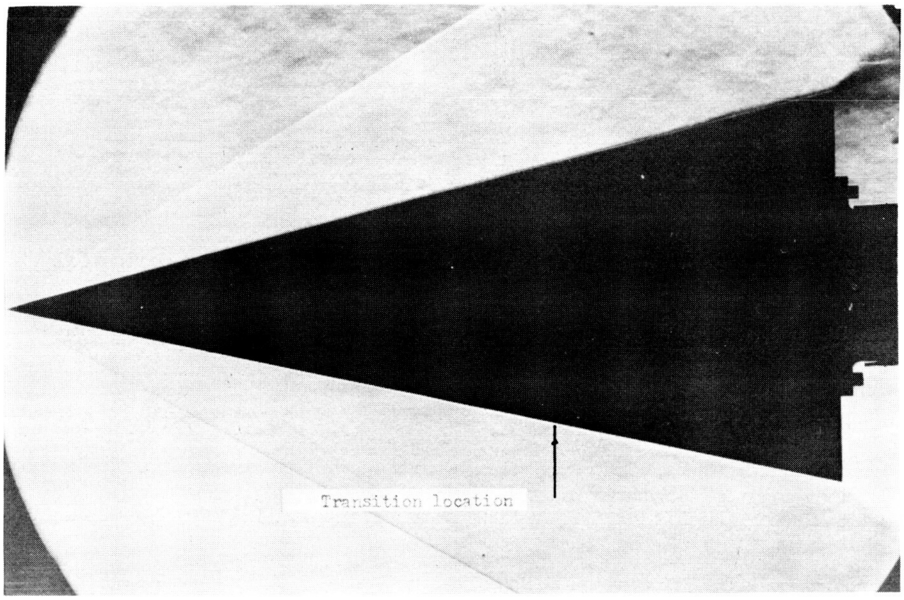
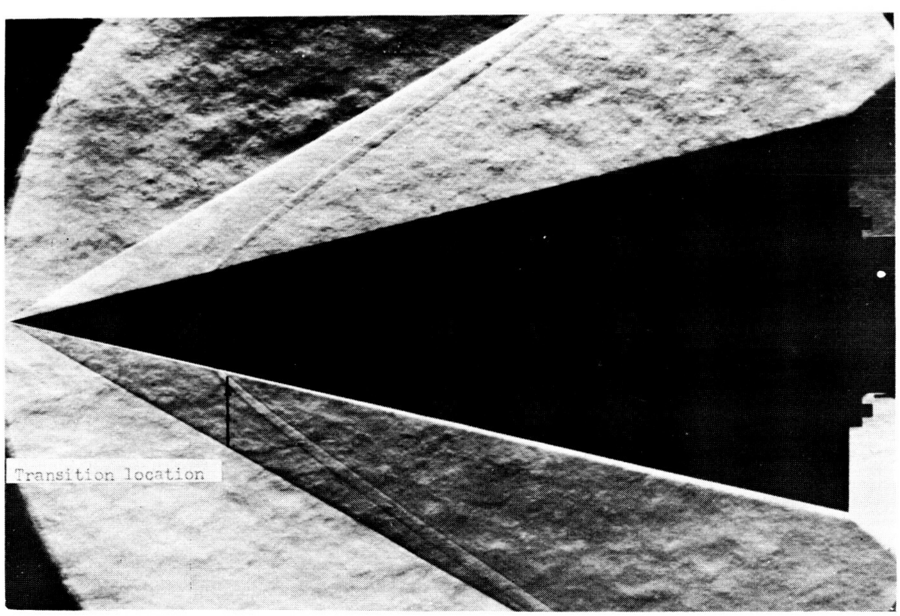


Figure 1.- Sketch of model.



(a) Three-dimensional granular roughness. R_l per foot = 1.21×10^6.



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(b) Three-dimensional granular roughness. R_l per foot = 3.37×10^6.

Figure 2.- Typical schlieren photographs showing location of transition. Parts (a) and (d) are different schlieren photographs at the same R_l per foot.

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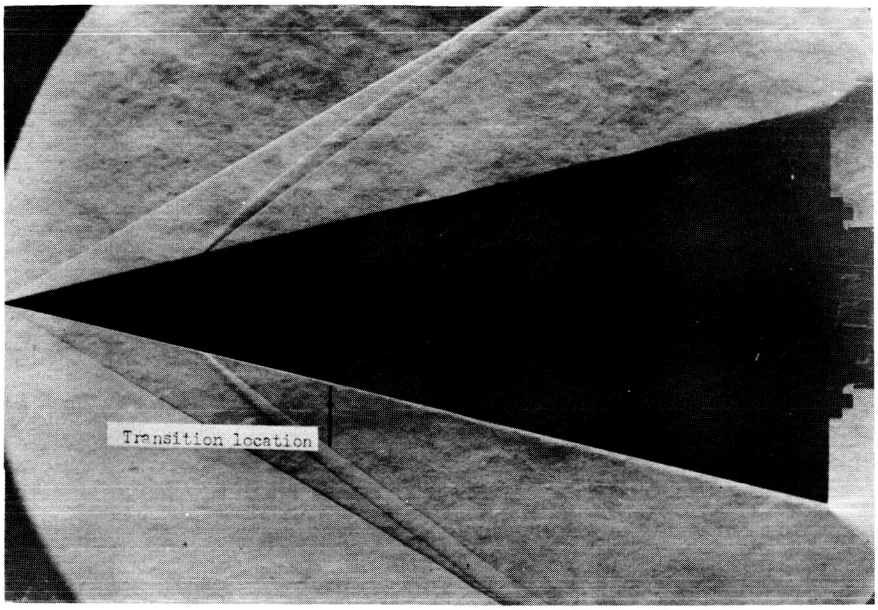
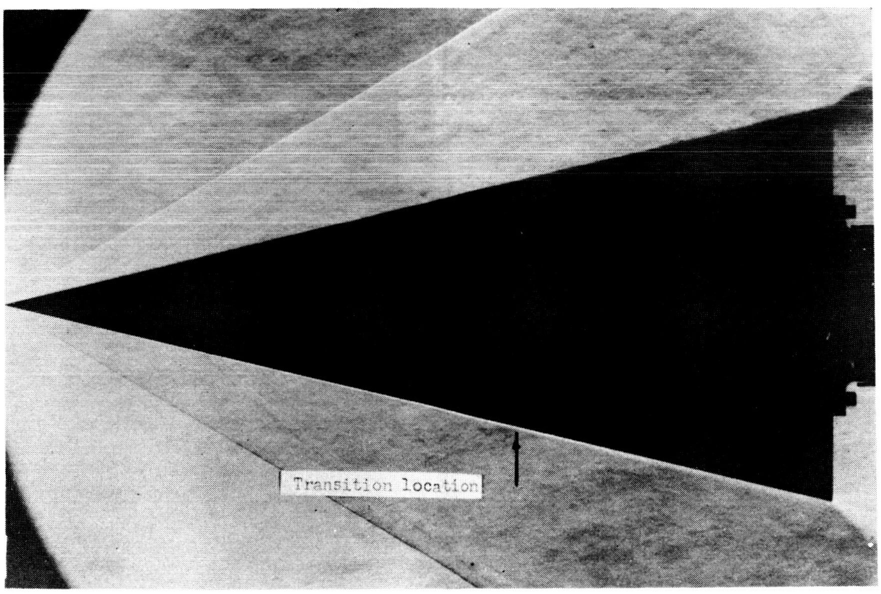


(c) Two-dimensional wire roughness. R_l per foot = 1.33×10^6.



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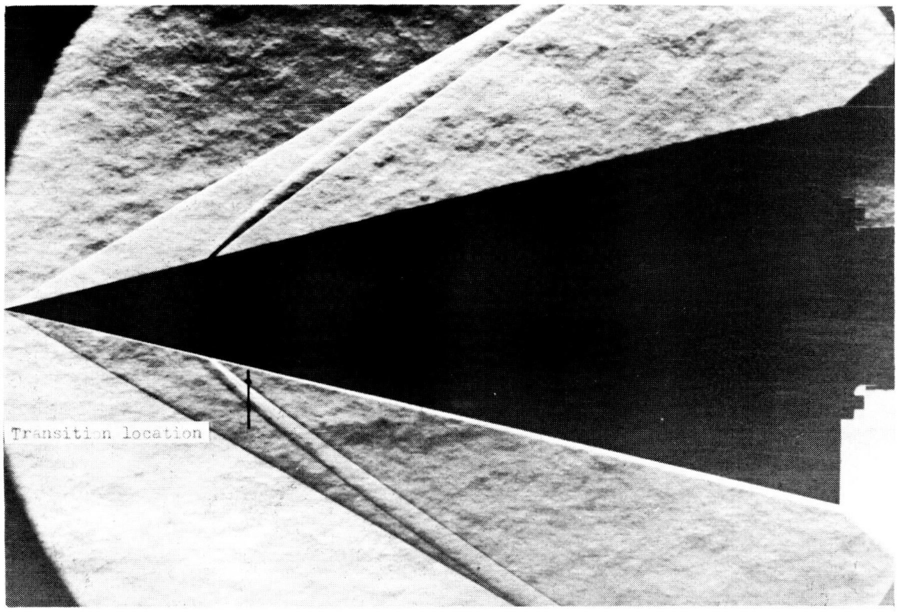
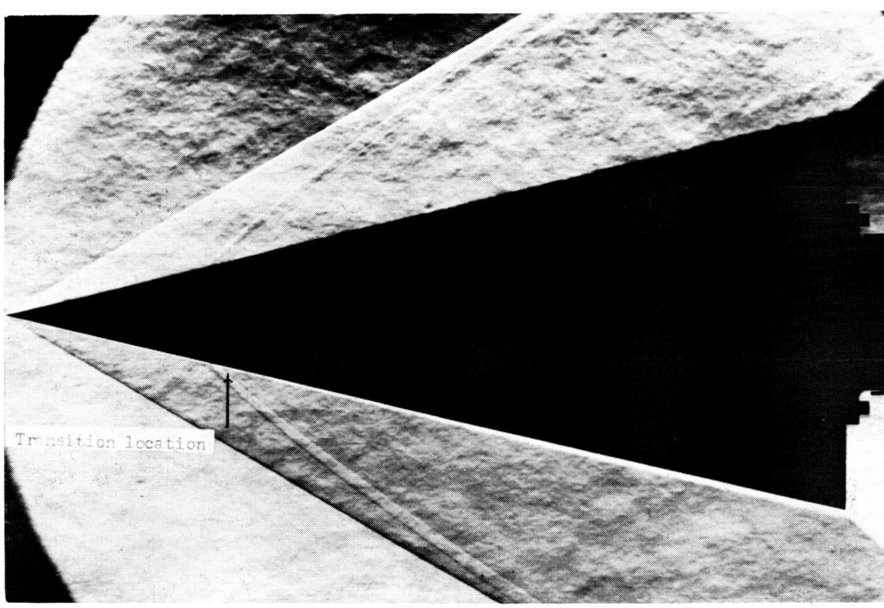
(d) Three-dimensional granular roughness. R_l per foot = 1.21×10^6.

Figure 2.- Continued.



(e) Two-dimensional wire roughness. R_l per foot = 3.57×10^6.



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(f) Three-dimensional granular roughness. R_l per foot = 2.59×10^6.

Figure 2.- Concluded.

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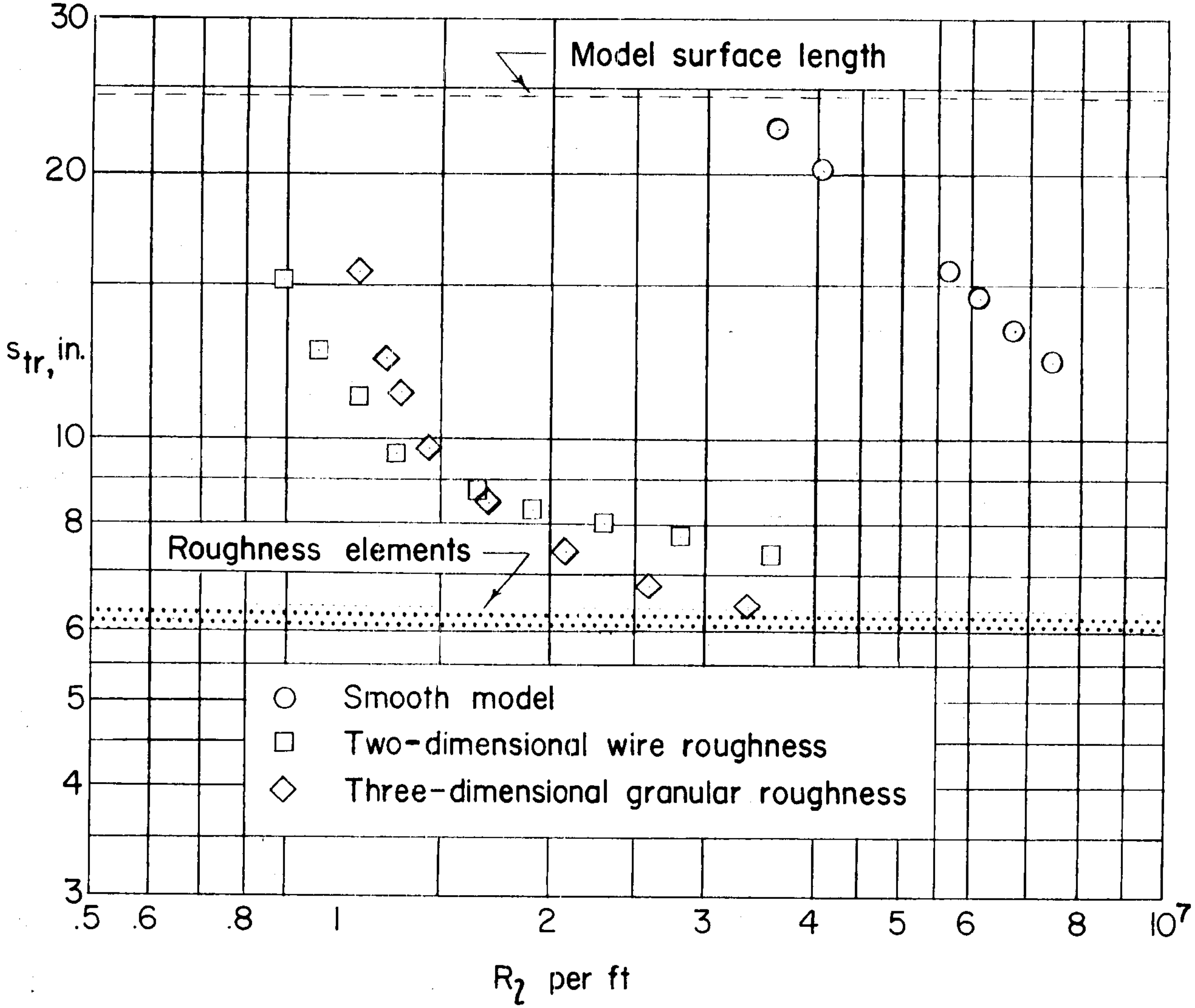

Figure 3.- Surface distance to transition point plotted as a function of R_l per foot. M = 2.20.

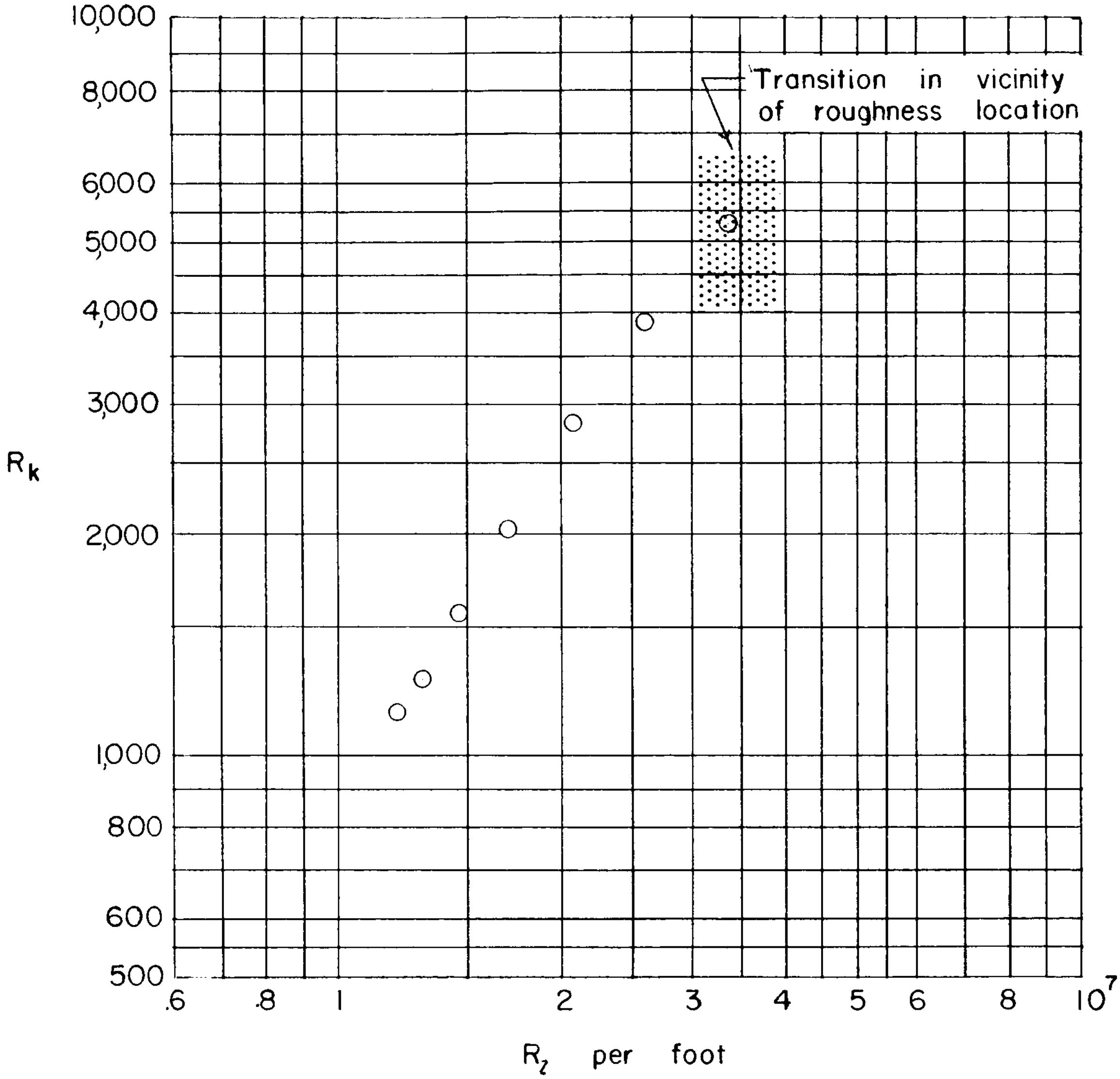

Figure 4.- Reynolds number R_k based on roughness height and local flow conditions at top of roughness plotted as a function of R_l per foot for the three-dimensional granular roughness. M = 2.20.

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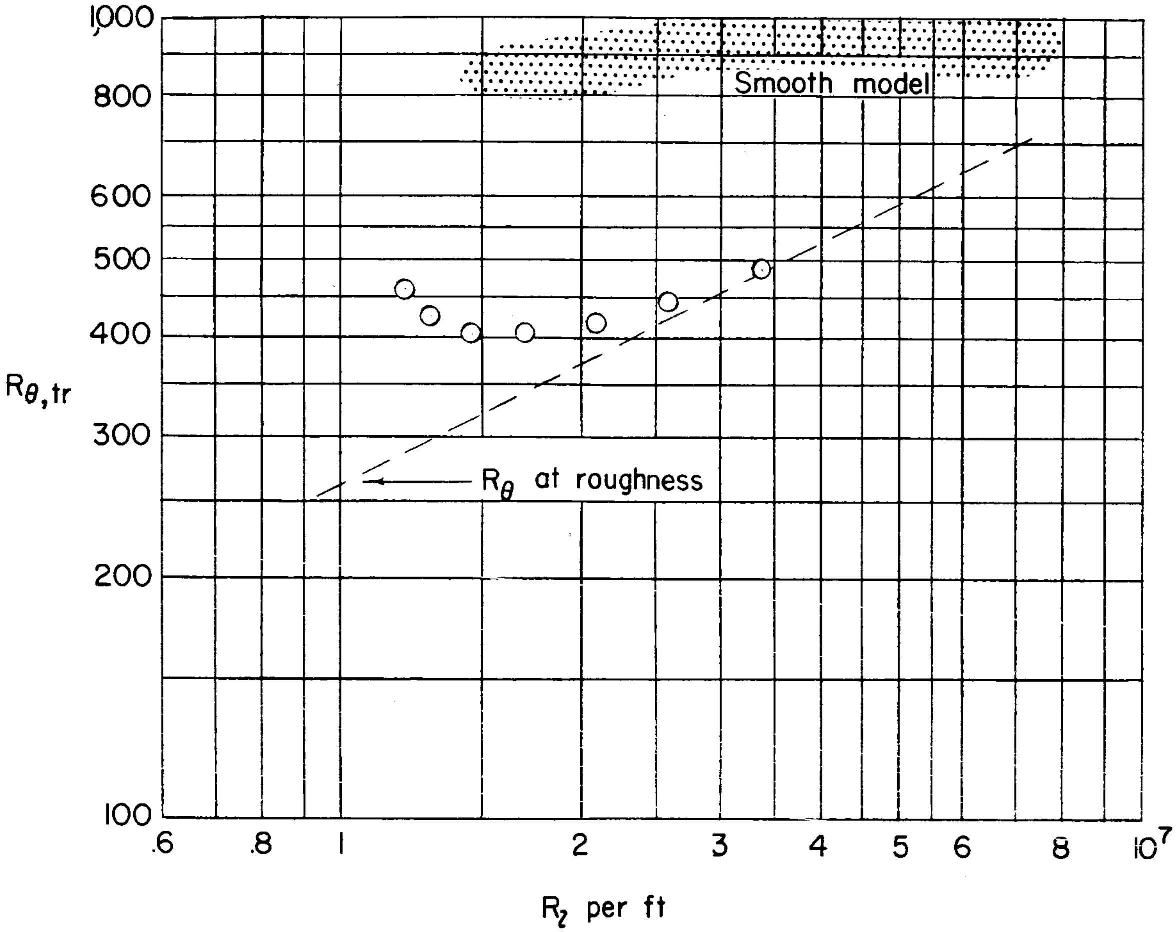

Figure 5.- Transition Reynolds number $R_{\theta,tr}$ based on θ and local flow conditions outside boundary layer plotted as a function of R_l per foot for three-dimensional granular roughness. M = 2.20.

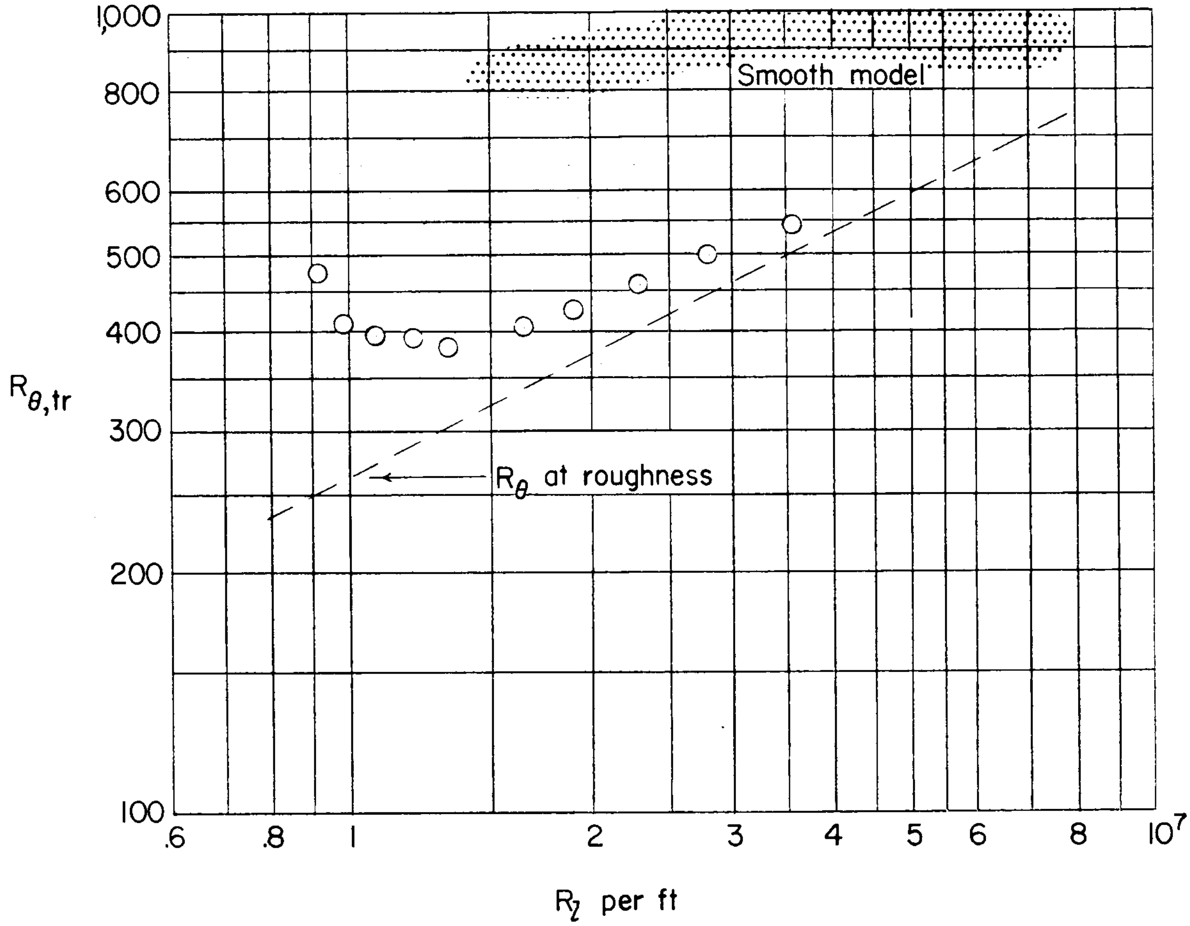

Figure 6.- Transition Reynolds number $R_{\theta,tr}$ based on θ and local flow conditions outside boundary layer plotted as a function of R_l per foot for two-dimensional wire roughness. M = 2.20.

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