C.P. No. 462
(20,593)
A.R.C. Technical Report



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# On Boundary-Layer Transition Wires

*by*

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1959
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C.P.No.462

# On Boundary-Layer Transition Wires


- By -

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Communicated by Prof. J. H. Preston

3rd December, 1958

## SUMMARY


This report discusses the effect of a single spanwise wire upon the downstream position of boundary-layer transition. Arguments, based on physical reasoning, lead in the simplest case to experimental results being expressible in terms of two-dimensionless groups. The effects of free-stream turbulence, pressure gradient and Mach number upon transition very close to the wire are separately discussed. Transition downstream of the wire is also investigated and a criterion is advanced for the largest protuberance in the form of a wire that, in a specified way, does not effect transition.


## 1. Introduction

Interest in the effect of a protuberance upon boundary-layer transition is largely due to the desire to provoke transition at a specified position on wind-tunnel models and to the need to know the biggest protuberance that has no effect upon the position of transition.

Transition can be effected by a single wire fixed to the surface and aligned transversely to the flow. This method has the advantages of easy and reproducible manufacture and also provides a simple model for experiment and analysis. It is this means of provoking transition that is discussed here.

## 2. Transition at the Wire-Zero Pressure Gradient - Incompressible Flow - Low Stream Turbulence

### 2.1 Existing criteria

Several criteria have been given for the wire diameter k, necessary to advance transition to the wire position in incompressible flow.

Fage and Preston investigated the effect of such a wire upon transition on a body of revolution[1] and as a result suggested the critical value,

$$\frac{u_k \cdot k}{\nu} = 400, \qquad \ldots(1)$$

where/

where $u_k$ is the velocity in the undisturbed boundary layer at the wire position and at a height equal to the wire diameter $k$.

Since their paper several authors have discussed this form of criterion. For instance, Hama, Long and Hegarty[2*] found from their experiments that

$$\frac{u_k k}{\nu} = 200$$

whilst Klebanoff, Schubauer and Tidstrom[4] obtained values within the range

$$200 < \frac{u_k k}{\nu} < 300.$$

In Smith and Clutters' experiments[3] they found that

$$150 < \frac{u_k k}{\nu} < 370$$

and they suggested the average value of

$$\frac{u_k k}{\nu} = 300.$$

If it is assumed that the wire height $k$, is sufficiently small compared with the undisturbed boundary-layer thickness, $\delta_0$, then we can write

$$u_k = k \left[ \frac{\partial u}{\partial y} \right]_{y=0} .$$

Also

$$\tau = \mu \left[ \frac{\partial u}{\partial y} \right]_{y=0}$$

$$= \tfrac{1}{2}\rho U^2 \frac{a_1}{R_{x_k}^{\frac{1}{2}}}$$

where $$R_{x_k} = \frac{U \cdot x_k}{\nu}$$

$U$ = undisturbed stream velocity

$x_k$ = distance of the wire from the leading edge

and $a_1$ has the value 0·66412.

Eliminating/

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*As reported in Ref. 3.

Eliminating $\left[\frac{\partial u}{\partial y}\right]_{y=0}$ between these two expressions leads to,

$$\frac{u_k \cdot k}{\nu} = \frac{a_1}{2} \frac{R_k^2}{R_{x_k}^{\frac{1}{2}}} . \qquad ...(2)$$

Substituting from Fage and Preston's criterion, equation (1) gives,

$$R_k = 35 R_{x_k}^{\frac{1}{4}} . \qquad ...(3)$$

which is, with slight difference in the constant, the criterion due to H. C. Garner as quoted by Pankhurst and Holder[5].

Alternatively noting that

$$R_{\delta_0} \equiv \frac{U \cdot \delta_0}{\nu} = 5 \cdot 27 \, R_{x_k}^{\frac{1}{2}}$$

and substituting into equation (3) leads to,

$$R_{\delta_0} = 0 \cdot 43 \cdot 10^{-2} \cdot R_k^2$$

which appears to be the criterion given graphically by Bryant and Garner[6].

Tani and Hama gave[7], as the result of experiments on a flat plate, a criterion which can be expressed,

$$\frac{U \cdot k}{\nu} \equiv R_k = 90 \, R_{x_k}^{\frac{1}{8}} .$$

Fage and Preston's results[1] have been interpreted by Bryant and Batson[8] to give the criterion

$$R_k = 600 \cdot$$

Anscombe quotes some results due to Davison[9], which are found to approximate to

$$R_k = 1500 .$$

Potter gives a correlation of experimental results[10] which results in

$$R_k = 730$$

whilst Tani and Sato's analysis[11] gives the value

$$R_k = 840 .$$

Thus there are basically the three criteria, $\frac{u_k \cdot k}{\nu}$ = constant, $R_k$ = constant, and Tani and Hama's criterion. However it is readily verified that the eleven different versions quoted can give greatly differing values for the necessary wire diameter.

A/

A criterion is now derived which is found to be of the form $R_k$ = constant; qualified, however, by the meaning of the statement that transition occurs at the wire position.

2.2 Reasoning leading to present criteria

Consider the flow along a flat plate, when transition is so much advanced by the presence of the wire that it is predominantly due to the wire and negligibly due to "natural" causes, such as tunnel turbulence. Furthermore it is postulated that the boundary-layer flow downstream of the wire depends mainly on the flow conditions at the wire and is little affected by its previous history.

Hence one writes,

$$(x_T - x_k) = f_1(k, \delta_k)$$

where $x_T$ and $x_k$ are distances from the plate leading edge of the positions of transition and of the wire, and $\delta_k$ is the boundary-layer thickness immediately behind the wire. Or by dimensional analysis,

$$\frac{x_T - x_k}{\delta_k} = f_2\left(\frac{k}{\delta_k}\right). \qquad \ldots(5)$$

If $\delta_0$ is the boundary-layer thickness at the wire position in the absence of the wire, then similarly,

$$\delta_0 = f_3(k, \delta_k)$$

or,

$$\frac{\delta_0}{\delta_k} = f_4\left(\frac{k}{\delta_k}\right).$$

Then substitution into equation (5) gives,

$$\frac{x_T - x_k}{\delta_0} = f_5\left(\frac{k}{\delta_0}\right) \qquad \ldots(6a)$$

or replacing $\delta_0$ by $\delta_0^*$, the displacement thickness,

$$\frac{x_T - x_k}{\delta_0^*} = f_6\left(\frac{k}{\delta_0^*}\right). \qquad \ldots(6b)$$

This latter step is only permissible in the incompressible flow case; for in the later discussion we exclude the density $\rho$ as a variable affecting the problem and in the compressible flow case use of the displacement thickness introduces $\rho$ as a further variable.

Provided that there is no interaction with a supersonic mainstream flow, the effect of moderate Mach number $M$, upon equation (6a) might be small; for though $\delta_0$ increases rapidly with $M$ the boundary-layer profile when scaled to a common value of $\delta_0$ is not greatly distorted. So as $x_T \to x_k$ equation (6a) might be little affected. We can also write[12]+,

$$\frac{\delta_0}{x_k} = \frac{5 \cdot 270}{R_{x_k}^{\frac{1}{2}}} \qquad \ldots(7a)$$

and/

+The convention, used in Ref. 12, of putting $y = \delta_0$ when $u_k/U = 0 \cdot 995$ is adopted.

and for incompressible flow,

$$\frac{\delta_0^*}{x_k} = \frac{1 \cdot 721}{R_{x_k}^{\frac{1}{2}}} \qquad \ldots(7b)$$

where $$R_{x_k} = \frac{U \cdot x_k}{\nu}$$

and C is a function of Mach number. Substituting equation (7a) into equation (6a) gives,

$$\left(\frac{x_T}{x_k} - 1\right) \frac{R_{x_k}^{\frac{1}{2}}}{5 \cdot 27C} = f_5 \left[\frac{k}{5 \cdot 27C} \frac{R_{x_k}^{\frac{1}{2}}}{x_k}\right]. \qquad \ldots(8)$$

Assuming that the unknown function in equation (6a) can be written in the form,

$$f_5\left(\frac{k}{\delta_0}\right) = K\left(\frac{k}{\delta_0}\right)^n \qquad \ldots(9)$$

then equation (8) becomes

$$\left(\frac{x_T}{x_k} - 1\right) \frac{R_{x_k}^{\frac{1}{2}}}{5 \cdot 27C} = K\left[\frac{k}{x_k} \frac{R_{x_k}^{\frac{1}{2}}}{5 \cdot 27C}\right]^n = K\left[\frac{R_k}{R_{x_k}^{\frac{1}{2}}} \frac{1}{5 \cdot 27C}\right]^n.$$

Now the experimental results illustrated in Fig. 3 of Ref. 7 show that for incompressible flow, $x_T/x_k$ is independent of $x_k$ depending only upon U and k. Thus

$$n = -1$$

and so, $$\frac{x_T}{x_k} - 1 = K \frac{27 \cdot 8C^2}{R_k}. \qquad \ldots(10)$$

This gives the result that transition occurs at the wire, where $x_T = x_k$ when $R_k = \infty$, whilst a plot of $1/R_k$ against $x_T/x_k$ should give a linear variation. Also, for any specified value of $x_T/x_k$ the variation of $R_k$ with Mach number is such that

$$R_k = C^2 \times \text{constant}. \qquad \ldots(11)$$

### 2.3 Experimental support for present criterion

This form of correlation is illustrated by a plot in Fig. 1 of some of the results of Ref. 7 for a flat plate and in Fig. 2 of some of the results of Ref. 1 for an axisymmetric body. Both these sets of results, particularly the latter, lend support to the result that as $x_T \to x_k$ then $1/R_k \to 0$. The latter results also support the predicted linear variation but in both cases there is a kink at a value of $x_T/x_k$ in the region of 1·1; the slope of the curve

changing/

changing but regaining the linearity at higher values of $x_T/x_k$. This might be explained by the results of Liepmann and Fila[13] and of Tani and Sato[11]. The former investigated, in detail, the flow pattern behind a semi-circular wire. Their results showed that the wake behind the wire could take up either of two distinct shapes dependent upon the Reynolds number. The change appeared to take place at about $x_T/x_k > 1 \cdot 14$.

Tani and Sato, in their experiments, were also able to distinguish between two types of flow. In one, transition occurred in the laminar boundary layer whilst still separated from the upper surface of the wire, whilst in the other transition occurred in the boundary layer downstream of where it reattached to the plate surface. The dividing point between the two régimes appeared at about $1/R_k = 1 \cdot 33 \cdot 10^{-3}$+. Thus this change of flow pattern might be expected to affect equation (9).

The transition positions given in Fig. 1 were deduced from observations with a surface pitot tube. It seems likely from inspection of Liepmann and Fila's results[13] that, for the first linear portion of the curve from the point $x_T = x_k$ such a method would give a position slightly downstream of where the separated layer reattached to the surface; whilst for the second linear portion of the curve beyond the change in slope it would give a position corresponding to the beginning of transition. On the other hand the transition positions given in Fig. 2 were observed by use of dye filaments in a water flow. The kink in this curve might correspond to the division of flow régimes observed by Tani and Sato.

The term "transition at the wire", as used here, can now be given its necessary qualification. A choice of wire Reynolds number has to be made such that the streamwise length of the wake is satisfactorily small. Fage and Preston[11] adopted the values occurring at the sharp kinks in their curves. These discontinuities do not appear in Tani and Hama's result (Fig. 1) and so values are taken from an extrapolation of the second linear portion of the curve to the point $x_T = x_k$. This is illustrated by the points "A" in Figs. 1 and 2.

Dryden has pointed out[14] that the problem involves the five variables, $x_T$, $x_k$, k, U and $\nu$ which can be described by two fundamental units. Hence the problem is controlled by three dimensionless groups. In his original analysis of the results of Tani, Hama and Mituisi[15] Dryden was able to correlate using the groups $R_{x_T}$ and $k/\delta_0^*$. In fact for these results only two groups are involved because for the experiments $x_T$ was a constant thus reducing the variables to four in number and hence the dimensionless groups to two. Thus these results are also found to correlate just as well on the present basis using $R_k$ and $x_T/x_k$++. Smith and Clutter have since observed that for five variables a third dimensionless group is significant in a plot of $R_{x_T}$ and $k/\delta_0^*$ (Ref. 3).

In/

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+The three experimentally determined points correspond to values of $R_k$ of 756, 749, and 641.

++There is no difficulty here if the variables are chosen as being U, $\nu$, k, $x_T/x_k$; $x_T$ being a constant.

In the later results of Tani, Iuchi and Yanamoto[16] which were for a low turbulence flow, $x_T$ is reintroduced as a variable. Even though five variables are again involved it is found that correlation was obtained on the present basis of using only $R_k$ and $x_T/x_k$. This is illustrated in Fig. 3 where except for two points whose special significance is discussed later, all the values lie on one curve. The third dimensionless group could be taken as $k/x_k$ and correspondingly numbered values are attached to the points. No systematic variation with $k/x_k$ is apparent and so the problem is reduced to one in two dimensionless groups.

From the extrapolation in Fig. 3 we thus have that when $x_T = x_k$, $1/R_k = 1 \cdot 21 \cdot 10^{-3}$ or $R_k = 826$.

2.4 Effect of wire on boundary-layer thickness

The corresponding values of the boundary-layer momentum thickness immediately behind the wire are of interest. For, expressed as a Reynolds number $R_{\theta_k}$, and with transition at the wire they become values of the transition Reynolds number $R_{\theta_T}$. Following Preston's analysis[17] values of $R_{\theta_k}$ can be computed. He points out that the drag of a wire adds to the downstream momentum thickness by an amount

$$\Delta R_\theta = \tfrac{1}{2} C_D \left( \frac{u_k}{U} \right)^2 R_k \qquad \ldots(12)$$

where the drag coefficient $C_D$ he quotes from the work of Sacks[18] as having the experimental value of 0·75. Without the wire the momentum thickness has the value

$$R_{\theta_0} = a_1 R_{x_k}^{\frac{1}{2}}. \qquad \ldots(13)$$

Thus immediately behind the wire,

$$R_{\theta_k} = a_1 R_{x_k}^{\frac{1}{2}} + \tfrac{1}{2} C_D \left( \frac{u_k}{U} \right)^2 R_k. \qquad \ldots(14)$$

In the usual boundary-layer nomenclature[20], $u_k/U \equiv f'$ and $f'$ is a function of $\eta$ where here,

$$\eta \equiv \frac{R_k}{R_{x_k}^{\frac{1}{2}}}. \qquad \ldots(15)$$

Thus

$$\frac{R_{\theta_k}}{R_k} = \frac{a_1}{\eta} + \tfrac{1}{2} C_D f'^2$$

$$= f(\eta). \qquad \ldots(16)$$

This is plotted in Fig. 4 with an auxiliary scale of $R_{x_k}$ when $R_k = 826$. The results given in Fig. 3 show that $R_k = 826$ for the range $0 \cdot 67 \leqslant R_k/R_{x_k}^{\frac{1}{2}} \leqslant 1 \cdot 34$ whilst further results given by Schubauer and

Klebanoff[4]/

Klebanoff[4] and analysed by Potter[10] extend this range to 2·4. The minimum value of $R_{\theta_T}$ occurs when the wire is right at the leading edge, i.e., when $R_{x_k} = 0$. If $R_k = 826$ right up to this point then the corresponding minimum $R_{\theta_T} = 309$. This value is close to the value of 320 which has been suggested by Preston[17] as being the minimum possible value of $R_\theta$ for a fully developed turbulent boundary layer. There is thus evidence that for transition at the wire $R_k = 826$ for the range $0 \leqslant R_{x_k} \leqslant 1 \cdot 53 \cdot 10^6$.

There is a difficulty, revealed in Fig. 4, where $R_{\theta_T}$ can have the same value for three values of $R_{x_k}$. In view of the later discussion it does not seem likely that this would occur in practice. It may be that $C_D$ does not remain at the value of 0·75 over the full range of this curve.+

There remains the question as to what occurs as $R_{x_k}$ increases beyond the value $1 \cdot 53 \cdot 10^6$ up to the point where natural transition takes place. Preston has suggested[17] that as well as increasing the boundary-layer thickness a wire adds a disturbance to the flow. If we regard $\Delta R_\theta$ as being indicative of this disturbance, we can, using the value $R_k = 826$, plot $\Delta R_\theta$ against $R_{\theta_T}$. This is done in Fig. 5. The results of Ref. 16 which were plotted in Fig. 3 were obtained in a low turbulent flow for which natural transition took place at $R_{\theta_{NT}} = 1070$. Fig. 5 shows that at this point $\Delta R_\theta$ has a value of 9·7. Thus if $R_k = 826$ over the whole range of $R_{x_k}$ as the wire position is moved towards that for natural transition then $R_{\theta_T}$ rises to 1070; at which point $\Delta R_\theta = 9 \cdot 7$ though the wire is still ahead of the natural transition point. From this point onwards if transition is still to just occur at the wire then $R_{\theta_T}$ stays at the value 1070 whilst $\Delta R_\theta$ and correspondingly $R_k$, decrease to zero. There is support for this suggestion from the data for transition downstream of the wire which is to be discussed later. There is also an interesting parallel case in the effect of free-stream turbulence upon transition where the behaviour is similar. This is shown also in Fig. 5 where values of the turbulence $u'/U$ as taken from Gazeley's review[19] and scaled by the factor 4250, are plotted against $R_{\theta_T}$. A similar effect is apparent in that when $R_{\theta_{NT}}$ is achieved $u'/U$ still has a finite value.

3./

+This value of $C_D$ was obtained from experiments in a turbulent boundary layer with circular cylinders of diameter up to 1/8th of the boundary-layer thickness. For a 1/7th power profile this is for values of $u_k/U$ up to 0·75. This velocity ratio in a laminar boundary layer occurs when $\eta = 2 \cdot 5$.

## 3. Transition at the Wire - Zero Pressure Gradient - Incompressible Flow - High-Stream Turbulence

The present analysis, suggesting that when transition is effected only by the wire, then results can be expressed by the two groups $R_k$ and $x_T/x_k$, has been supported by the experiments of Tani, Iuchi and Yanamoto. Further experiments by them with a stream of turbulence $u'/U$ for which $R_{\theta_{NT}} \simeq 500$, suggest that not only does the new variable $u'/U$ affect the value of $R_k$ but that the third dimensionless group becomes significant. This is shown in Fig. 6. Taking the third group as $k/x_k$, and appreciating the paucity of the data, there is evidence of distinct curves for differing values of $k/x_k$. In addition there is a considerable decrease in the value of $R_k$ for transition at the wire. Fage and Preston's results, obtained in a stream for which $R_{\theta_{NT}} \simeq 490$, also showed a lowering of $R_k$ below the non-turbulent value of 826.

For the low turbulence flow $R_{\theta_T} = 490$ corresponds to a value of $\Delta R_\theta = 54$. Suppose we regard this value of $\Delta R_\theta$ as being indicative of a constant disturbance supplied by the free-stream turbulence. Then compared with the low turbulence case, and at any particular value of $R_{\theta_T}$, the wire now has to supply a smaller disturbance in the form of a $\Delta R_\theta$ lessened by the amount 54. Such a displaced curve is shown in Fig. 5. Values of $\Delta R_\theta$ and $R_\theta$ computed from Fage and Preston's results are, with one exception, seen to form a plausible extrapolation to this curve.+

Values computed from the results of Fig. 6 are also shown in Fig. 5. Only one out of the three results is in agreement with the theoretical curve. A difficulty with both these and the Fage and Preston results is that there is evidence, from a variation in $R_{\theta_{NT}}$, of a variation in free-stream turbulence with tunnel speed.

The effect of the third dimensionless group upon the value of $R_k$ when $x_T/x_k = 1{\cdot}0$ is illustrated in Fig. 7, where the results of Fage and Preston and of Tani, Iuchi and Yanomoto are plotted. The former being for the flow past an axisymmetric body with a rounded nose and the latter for the flow over a flat plate, $x_k$ has not the same significance in both cases and so the third dimensionless group was chosen as $\delta\delta^*/k$.

There is evidence from this scanty data that as the wire is moved towards the nose, $R_k$ tends towards 860 which is close to the low-turbulence value. This also means that the corresponding minimum value of $R_\theta$, which occurs at the nose, has the value of 322; again a figure close to the minimum suggested by Preston[17].

4./

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+The curve is not extrapolated beyond the point shown for it then goes beyond the range of probable certainty of the value of $C_D$. See previous footnote.

4. Transition Downstream of the Wire

There have been several suggestions advanced for correlating the experimental results for transition occurring downstream of the wire. Potter has suggested a relation[10] which can be written,

$$\frac{1}{R_k} = \frac{1}{780}\left(\frac{x_T}{x_k}\right)^{\frac{1}{2}}$$

whilst Tani and Sato[11] suggest in effect,

$$\frac{1}{R_k} = \frac{1}{840}\left(\frac{x_T}{x_k}\right)^{\frac{1}{2}}.$$

Tani, Hama, and Mituisi have suggested a correlation[15] which can be expressed,

$$\frac{1}{R_k} = \frac{R_{x_k}^{-1/8}}{90}\left(\frac{x_T}{x_k}\right)^{\frac{1}{2}}.$$

The first two of these are plotted in Fig. 3 and are seen to give high values compared with the experimental values for low-turbulence flow. The third is seen to include the third dimensionless group which can be taken as $R_{x_k}$ and thus is faulty on this score.

The previous arguments advanced to explain both the linear variation of $1/R_k$ against $x_T/x_k$ and also the fact that the third dimensionless group was of no significance, relied on the assumption that transition was effected only by the wire. In fact as $x_T$ approaches the value for natural transition the third dimensionless group will become of significance. If we take $R_{x_k}$ as this third group, then each line of constant $R_{x_k}$ will branch off from the common straight line to its own vertical asymptote as $x_T$ approaches the value for natural transition. A theoretical derivation of such curves is given in the Appendix. To compute them it is necessary to assign a value to $R_{\theta_T}$ Fig. 5 presents a relation between $\Delta R_\theta$, which is suggested as being indicative of the disturbance given to the boundary layer, and $R_{\theta_T}$ when transition occurs at the wire. If the value of $R_{\theta_T}$ is solely dependent upon $\Delta R_\theta$ and is quite independent of where transition occurs compared to where the wire introduces its disturbance; then we can use the relation between $\Delta R_\theta$ and $R_{\theta_T}$, obtaining with transition at the wire, as a universal relation.

Two curves, thus computed, for $R_{x_k} = 0{\cdot}5 \cdot 10^6$ and for $R_{x_k} = 1{\cdot}5 \cdot 10^6$ are drawn in Fig. 3. In computing them an upper limit of $R_\theta = 1070$ was applied for $0 \leqslant \Delta R_\theta \leqslant 9{\cdot}7$. In the case of $R_{x_k} = 1{\cdot}5 \cdot 10^6$ this leads to the branching up of the curve to its

vertical/

vertical asymptote shown. We thus now have an explanation for the two points which lie above the experimental straight line variation and which are shown to be in reasonable agreement with this theoretical curve. In the case of $R_{x_k} = 0{\cdot}5 \cdot 10^6$ the theoretical curve is found to fall away from the experimental values. However from the series solution to these curves, equation (29) as derived in the Appendix, we have by differentiation and putting $\eta = \eta'$

$$\frac{d\left(\frac{x_T}{x_k} - 1\right)}{d(\eta'/\eta)} = 3 + 3b_1\eta'^3 + \frac{9a_1 C_D}{8}\eta'^3 + \ldots .$$

Now experiments have shown that the third dimensionless group, which can be represented by $R_{x_k}$ or hence by $\eta'$, is of no significance. In the above expression the only term independent of $\eta'$ is the first and this gives,

$$\frac{d(\eta'/\eta)}{d\left(\frac{x_T}{x_k} - 1\right)} = \frac{1}{3} \qquad \ldots(17)$$

which is the straight line shown in Fig. 3. It gives an excellent representation of the experimental results.

## 5. Transition at and Downstream of the Wire - Streamwise Pressure Gradient

Tani, Iuchi and Yamamoto extended their experiments[16] to include the effects of streamwise pressure gradient. This introduces a further non-dimensional group which is chosen as the Pohlhausen parameter,

$$\lambda^* \equiv \frac{\delta_0^{*2}}{\nu}\frac{dU}{dx}$$

where values are evaluated at the wire position.

The results, for low turbulence flow, are found to correlate well on the basis of plots of $1/R_k$ against $x_T/x_k$. For this case $R_k$ was computed using the local stream velocity at the wire position. As for the zero pressure gradient case, linear variations were obtained and the third dimensionless group was not significant. Two examples are shown in Fig. 8 for the two extreme gradients; $\lambda^* = 0{\cdot}073$ and $0{\cdot}35$. There is seen to be an effect of pressure gradient upon both the value of $R_k$ for transition at the wire and upon the slope of the curve. Values of $R_k$ for transition at the wire obtained from these and similar plots are shown in Fig. 9. There is seen to be a good correlation illustrating a decrease in the value of $R_k$ for transition at the wire as the pressure gradient becomes more favourable. Correspondingly from equation (12) there is a decrease in the minimum possible value of $R_0$ for a turbulent boundary layer as was predicted by Preston[17].

Fage and Preston's experiments which were done in a turbulent stream[1] were also extended to cover the effect of pressure gradients.

Corresponding/

Corresponding values from their results are also plotted in Fig. 9. Bearing in mind that the scatter at $\lambda^* = 0{\cdot}0$ has been attributed to turbulence making the third dimensionless group significant, it is seen that except for two points the correlation is good. Like the low turbulence results there is seen to be a decrease in $R_k$ with increase in favourable pressure gradient though now the variation is greater.

## 6. Transition at the Wire - Effect of Subsonic Mach Number

It has already been suggested that equation (10) might apply to compressible flow thus leading to equation (11) as being applicable when transition is at the wire. Using the results of Ref. 12 this latter equation has been plotted in Fig. 10, scaled so as to pass through $R_k = 826$ at $M = 0{\cdot}0$. The previously discussed results for transition at the wire in incompressible flow conditions are plotted.

For high subsonic Mach numbers Gamble has carried out tests upon an aerofoil with a 25° sweep back angle[20]. The results, shown plotted in Fig. 11, are found to correlate quite well when the Reynolds number $R_k$ was based on the local stream velocity at the wire position. The stream Mach number at the wire position varied from 0·89 to 1·09. For transition at the wire Fig. 11 gives $R_k = 746$ which is plotted in Fig. 10.

Also plotted are the results of some experiments by the writer+ upon a 4% thick aerofoil with a 60° leading-edge sweep back angle and the result of some experiments by Seban, et al[21] for an elliptic cylinder. Though these results are not for a flat plate boundary layer, they do, to some degree, confirm that up to $M = 1{\cdot}0$ there is little effect upon $R_k$ for transition at the wire.

## 7. Transition at the Wire - Effect of Supersonic Mach Number

Tests have been performed by Luther[22] with wires of various sizes at a fixed position upon cone-cylinder bodies of revolution and for various Mach numbers. Except for the smallest wire size the correlation of his results was found to be fair as is illustrated by the plot of one case in Fig. 12. In this figure results for positions towards the rear of his model can be excluded as there is an indication that there is some upstream influence from the base. The values of $R_k$ shown in this figure were based upon the undisturbed free-stream conditions but the value for transition at the wire was converted to that based upon local conditions at the wire; it is plotted in Fig. 10 together with other values obtained from Luther's work and also some values obtained by the writer.

Except for two points that are discussed later, Fig. 10 shows that equation (11) underestimates the rise of $R_k$ at supersonic Mach number. It is known that at supersonic speeds a shock wave is formed due to the presence of the wire[23]. Hence the wire has a wave drag. Thus the wire resistance has not only to provide the $\Delta R_\theta$ necessary to advance transition to itself but has also to provide this wave drag.

Thus in the absence of a wave drag we have a wire Reynolds number given by equation (11), $R_{k_1}$ say, producing a $\Delta R_\theta$ as given by equation (12), of

$\Delta R_\theta$/

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+Performed in a 4 in. × 4 in. wind tunnel.

$$\Delta R_\theta = \tfrac{1}{2}C_D f_1'^2 R_{k_1}.$$

If we write the wave drag coefficient as

$$C_{D_W} \equiv \frac{D_W}{\frac{1}{2}\rho U^2 k}$$

then with wave drag existing, and a wire Reynolds number $R_{k_2}$, say,

$$\Delta R_\theta + \tfrac{1}{2}C_{D_W} R_{k_2} = \tfrac{1}{2}C_D f_2'^2 R_{k_2}.$$

Thus to produce the same $\Delta R_\theta$ the wire size is increased in the ratio,

$$\frac{R_{k_2}}{R_{k_1}} = \frac{f_1'^2}{f_2'^2 - \frac{C_{D_W}}{C_D}}$$

or towards the leading edge as $f_1' = f_2' \to 1 \cdot 0$

$$\frac{R_{k_2}}{R_{k_1}} = \frac{1}{1 - \frac{C_{D_W}}{C_D}}. \qquad \ldots(18)$$

An approximate estimate of the wave drag of blunt bodies can be obtained by Moeckel's method[24]. At $M = 4 \cdot 0$ this method gives a wave drag for a circular cylinder of $C_{D_W} = 1 \cdot 5$. We are only concerned with a half of the wave thus reducing this to $C_{D_W} = 0 \cdot 75$. In addition the external flow is past a shape that the boundary layer makes effectively less blunt than a circular cylinder. If we guess the shape as being a half sine wave of thickness chord ratio of $0 \cdot 5$ then linearised theory gives for this shape a $C_{D_W} = 0 \cdot 5$ at $M = 4 \cdot 0$. Scaling the wave drags obtained by Moeckel's method to give the value $0 \cdot 5$ at $M = 4 \cdot 0$ and then substituting into equation (18), with $C_D = 0 \cdot 75$ as before gives the values shown as the full line in Fig. 10. It is clear from its derivation that the scale of this line is in doubt but comparison with the experimental points shows that it supplies an explanation for the experimental values of $R_k$ in the supersonic range being so much higher than the values given by equation (11).

The experimental points plotted in Fig. 10 that were obtained by the writer were for wires on wings having a 60° leading-edge sweep back. Thus for $M < 2 \cdot 0$ the Mach number normal to the leading edge was subsonic. This may then explain why the two points for $M = 1 \cdot 6$ and $1 \cdot 8$ lie nearer to the curve given by equation (11) than to the curve given by equation (18).

## 8. The Largest Wire Size with no Effect upon Transition

We have the result that for wires not too far upstream of the natural transition point, $R_{\theta_T} = 1070$ for $0 \leqslant \Delta R_\theta \leqslant 9 \cdot 7$. Thus we have from equation (12) that the largest wire size to have no effect upon $R_{\theta_T}$ is given by,

$\Delta R_\theta$/

$$\Delta R_\theta = 9{\cdot}7 = \tfrac{1}{2} C_D \left(\frac{u_k}{U}\right)^2 R_k$$

whilst for $k/\delta_0$ small we have from equation (2),

$$\frac{u_k}{U} = \frac{a_1}{2} \frac{R_k}{R_{x_k}^{\frac{1}{2}}}$$

so that the critical value of $R_k$ is given by,

$$R_k^3 = \frac{8}{a_1^2 C_D} \Delta R_\theta \cdot R_{x_k}$$

$$= 235\, R_{x_k} . \qquad \ldots(19)$$

This relation is given graphically in Fig. 13.

Whilst this gives a value of $R_k$ for no effect upon $R_{\theta_T}$ there will of course be some effect upon $R_{x_T}$; though the theoretical curve of Fig. 3 for $R_{x_k} = 1{\cdot}5 \cdot 10^6$ shows that this effect will be small.

Fig. 3 indicates that for $R_{x_k}$ much below about $1{\cdot}5 \cdot 10^6$ equation (19), which is based upon the relation between $\Delta R_\theta$ and $R_{\theta_T}$ given in Fig. 5, might not hold.

Let us define a critical $R_k$ as being that corresponding to the intercept between the straight line of Fig. 3 given by equation (17), and the appropriate asymptote; for example, point "A" in Fig. 3.

Then,

$$\frac{826}{R_k} = 1 + \frac{1}{3}\left(\frac{R_{x_{NT}}}{R_{x_k}} - 1\right)$$

and from equation (13), taking

$$R_{x_{NT}} = \left(\frac{1070}{a_1}\right)^2 = 2{\cdot}6 \cdot 10^6$$

then the critical $R_k$ is given by

$$R_k = \frac{2{\cdot}5 \cdot 10^3}{\dfrac{2{\cdot}6 \cdot 10^6}{R_{x_k}} + 2} . \qquad \ldots(20)$$

Values are plotted in Fig. 13.

Schiller advanced a criterion for the first appearance of serious disturbances in a laminar flow due to roughness[25]. This

criterion,/

criterion, as further discussed by Goldstein[26], has been suggested by Gazeley[19] as giving a criterion for the first effect upon transition. It is,

$$\frac{u_k \cdot k}{\nu} = 50. \qquad \ldots(21)$$

It has been investigated experimentally by Smith and Clutter[3] who used as a criterion the case when $R_{x_T}$ has been reduced to 95% of its natural value. They found that there was a very large scatter in the values of $\frac{u_k \cdot k}{\nu}$, the range being $40 < \frac{u_k \cdot k}{\nu} < 400$. The lower limit approximates to Schiller's value given by equation (21). This can be written,

$$R_k = 50/f'$$

so that noting equation (15) we can express this as,

$$R_k = f(R_{x_k})$$

and this is plotted in Fig. 13. In comparison with the criterion given by equation (20), Schiller's criterion is found to be unduly stringent at the higher values of $R_{x_k}$ while for more forward positions it does not place a sufficient limitation upon the wire size.

## 9. Conclusions

With a low turbulence, incompressible flow over a flat plate, transition occurs at the wire when the wire Reynolds number based upon the free-stream velocity $Uk/\nu$, is 826.

The effect of stream turbulence is to make this Reynolds number a function of both the degree of turbulence and of wire position (Fig. 7); the effect of compressibility is to make it a function of Mach number (Fig. 10); and the effect of pressure gradient is to make it a function of the Pohlhausen parameter (Fig. 9).

When transition occurs downstream of the wire, then over most of the range, the reciprocal of the wire Reynolds number varies linearly with transition position.

## 10. Notation

| | |
|---|---|
| $a_1$ | constant of value 0·66412, equation (13) |
| $b_1, b_2$ | series coefficients, equation (23) |
| $C$ | function of Mach number, equation (7a) |
| $C_D$ | drag coefficient of wire |
| $C_{D_W}$ | wave drag coefficient of wire |
| $D_W$ | wave drag of wire |
| $f'$ | $\equiv u_k/U$ |
| $k$ | wire diameter |

| | |
|---|---|
| $K$ | constant defined in equation (9) |
| $M$ | Mach number |
| $n$ | index defined in equation (9) |
| $R$ | Reynolds number based on velocity $U$ |
| | $R_k \equiv \frac{Uk}{\nu}$; $R_x \equiv \frac{Ux}{\nu}$; $R_\delta \equiv \frac{U\delta}{\nu}$; $R_\theta \equiv \frac{U\theta}{\nu}$ |
| $R_{k_1}$ | wire Reynolds number in the absence of wave drag |
| $R_{k_2}$ | wire Reynolds number in the presence of wave drag |
| $\Delta R_\theta$ | increment in the momentum thickness Reynolds number due to the wire drag |
| $u$ | velocity in the boundary layer |
| $u_k$ | velocity in the boundary layer at the wire position at a height $k$, but in the absence of the wire |
| $u'$ | velocity of turbulence in the mainstream |
| $U$ | velocity just outside the boundary layer at the wire position |
| $x$ | distance along the boundary layer from the leading edge |
| $y$ | distance normal to the surface |
| $\delta$ | boundary-layer thickness |
| $\delta^*$ | boundary-layer displacement thickness |
| $\eta$ | $\equiv R_k/R_{x_k}^{\frac{1}{2}}$ |
| $\eta'$ | value of $\eta$ for transition at the wire and for a specified value of $R_{x_k}$ |
| $\theta$ | boundary-layer momentum thickness |
| $\lambda^*$ | Pohlhausen parameter $\equiv \frac{\delta^{*2}}{\nu}\frac{dU}{dx}$ |
| $\mu$ | coefficient of viscosity |
| $\nu$ | kinematic coefficient of viscosity |
| $\rho$ | density |
| $\tau$ | frictional shear stress |

Suffices

| | |
|---|---|
| $k$ | pertaining to the wire position |
| $NT$ | pertaining to the position of "natural" transition in the absence of the wire |

o pertaining to the wire position but in the absence of the wire

T pertaining to the position of transition

w pertaining to transition at the wire for a specified value of $\Delta R_\theta$, equation (25).

---

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APPENDIX/

APPENDIX

In computing the relation $x_T/x_k = f(1/R_k)$ for a specified value of $R_{x_k}$, firstly values of $R_{\theta_0}$ are obtained from equation (13). From equation (15) $\eta$ then follows as a function of $R_k$ and hence $f'$ can be obtained from the known boundary-layer solution. This latter is tabulated in, for instance, Ref. 27 or for odd and small values of $\eta$ can be computed from,

$$f' = 0{\cdot}33206\eta\,[1 - 0{\cdot}006918\eta^3 + 0{\cdot}6016\cdot10^{-4}\eta^6 + \ldots]. \qquad \ldots(22)$$

It is convenient for later analysis to write this as,

$$f' = \frac{a_1}{2}\eta[1 + b_1\eta^3 + b_2\eta^6 + \ldots.]. \qquad \ldots(23)$$

Then $\Delta R_\theta$ follows from equation (12) and addition to $R_{\theta_0}$ gives $R_{\theta_k}$ that is the momentum thickness Reynolds number immediately behind the wire. This Reynolds number will increase with the boundary-layer development downstream of the wire until it reaches the transition value, $R_{\theta_T}$.

If downstream of the wire the boundary-layer development is expressed by,

$$R_\theta^2 = a_1^2\,(R_x + \text{constant})$$

where the constant specifies a fictitious leading-edge position, then,

$$R_{\theta_T}^2 = a_1^2\,(R_{x_T} + \text{constant})$$

$$R_{\theta_k}^2 = a_1^2\,(R_{x_k} + \text{constant})$$

so noting equation (13) this gives,

$$R_{\theta_T}^2 - R_{\theta_k}^2 = \left(\frac{x_T}{x_k} - 1\right) R_{\theta_0}^2. \qquad \ldots(24)$$

To obtain the value of $R_{\theta_T}$ for use in this equation we note that from equation (12)

$$f_w'^2 = (f'^2 R_k)/R_{k_w} \qquad \ldots(25)$$

where the suffix w indicates the case of transition at the wire for the computed value of $\Delta R_\theta$. Then $\eta_w$ can be obtained from an inversion of the series of equation (22) which is,

$$\eta = \frac{2}{a_1} f' \left[ 1 - \frac{8b_1}{a_1^3} f'^3 + \frac{64}{a_1^6}(4b_1^2 - b_2)\, f'^6 + \ldots. \right] \qquad \ldots(26)$$

or $$\eta = 3{\cdot}0115\, f'[1 + 0{\cdot}13894 f'^3 + 0{\cdot}097920 f'^6 + \ldots.]. \qquad \ldots(27)$$

Then/

Then

$$R_{\theta_T} = [(a_1 R_{k_w})/\eta_w] + \Delta R_\theta \qquad \dots(28)$$

or for $R_{k_w} = 826$

$$R_{\theta_T} = [0\cdot54886 \cdot 10^3/\eta_w] + \Delta R_\theta .$$

Alternatively a series solution may be derived as follows. Substituting equations (15) and (23) into equation (12) gives,

$$\begin{aligned}\Delta R_\theta &= \tfrac{1}{2} C_D R_{x_k}^{\frac{1}{2}} \eta f'^2 \\ &= \tfrac{1}{2} C_D R_{x_k}^{\frac{1}{2}} \frac{a_1^2}{4} \eta^3 [1 + b_1\eta^3 + b_2\eta^6 + \dots]^2 .\end{aligned}$$

Then insertion of this value together with equation (13) into equation (14) gives,

$$R_{\delta_k}^2 = \frac{a_1^2 R_{x_k}}{\eta^3}\left[\eta^3 + \frac{a_1}{4} C_D \eta^6 + \dots\right].$$

Also substitution of equation (23) into equation (25) and the use of equation (27) gives,

$$\eta_w = \left(\frac{R_{x_k}^{\frac{1}{2}}}{R_{k_w}}\right)^{\frac{1}{2}} \eta^{\frac{3}{2}} \left[1 + b_1\eta^3 - b_1\left(\frac{R_{x_k}^{\frac{1}{2}}}{R_{k_w}}\right)^{\frac{3}{2}} \eta^{\frac{9}{2}} + b_2\eta^6 + \dots\right].$$

Substitution into equation (16) gives,

$$R_{\theta_T}^2 = \frac{a_1^2}{\eta^3}\frac{R_{k_w}^3}{R_{x_k}^{\frac{1}{2}}}\left[1 - 2b_1\eta^3 + 2\left(\frac{R_{x_k}^{\frac{1}{2}}}{R_{k_w}^{3}}\right)^{\frac{1}{2}}\left(b_1 + \frac{a_1}{8} C_D\right)\eta^{\frac{9}{2}} + (3b_1^2 - 2b_2)\eta^6 + \dots\right].$$

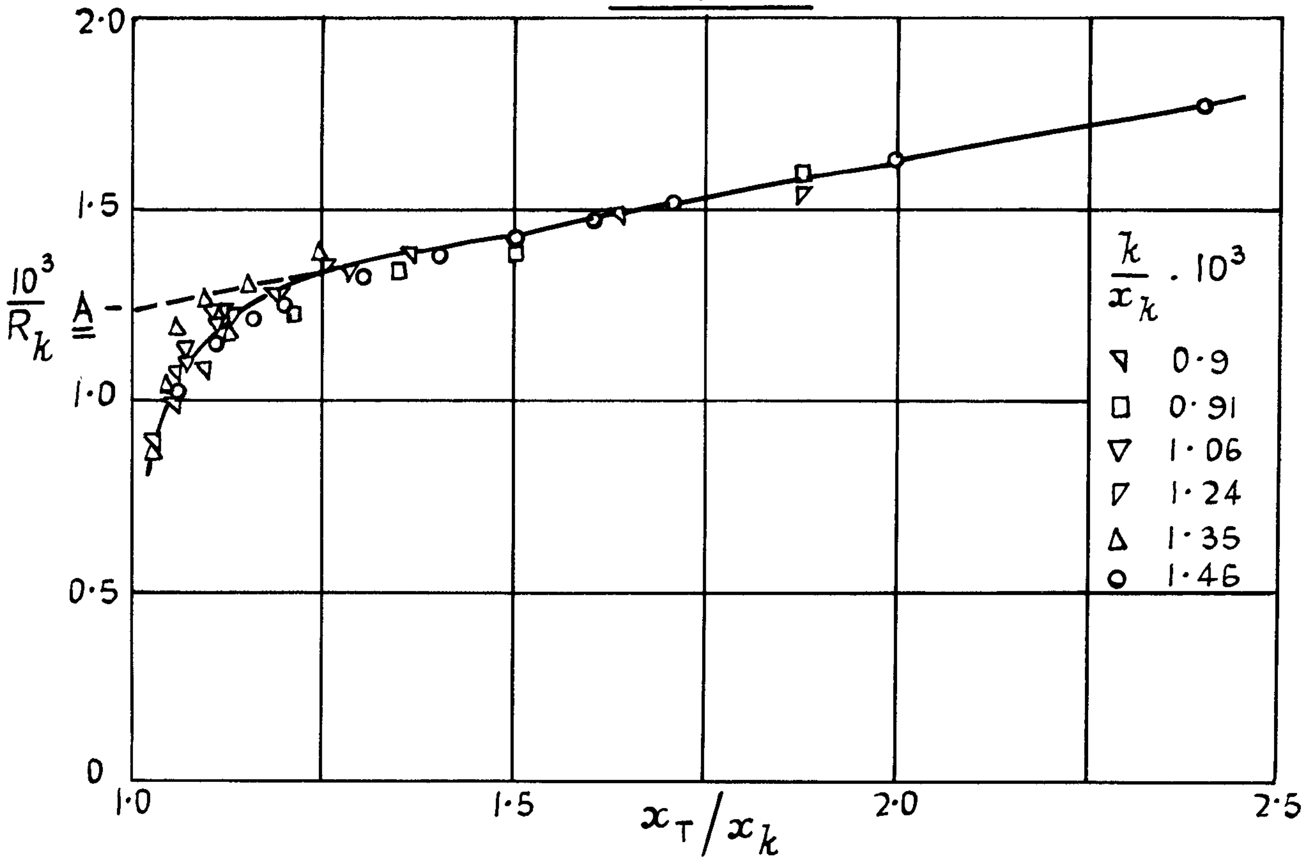
Writing $\eta' \equiv R_{k_w}/R_{x_k}^{\frac{1}{2}}$, we finally have from equation (24),

$$\frac{x_T}{x_k} - 1 = \left(\frac{\eta'}{\eta}\right)^3 - 1 + 2b_1\eta'^3\left\{\left(\frac{\eta'}{\eta}\right)^{\frac{3}{2}} - 1\right\} - \frac{a_1 C_D}{4}\eta'^3\left(\frac{\eta'}{\eta}\right)^{\frac{3}{2}}\left\{\left(\frac{\eta'}{\eta}\right)^{-\frac{9}{2}} - 1\right\} + \dots \qquad \dots(29)$$

ES

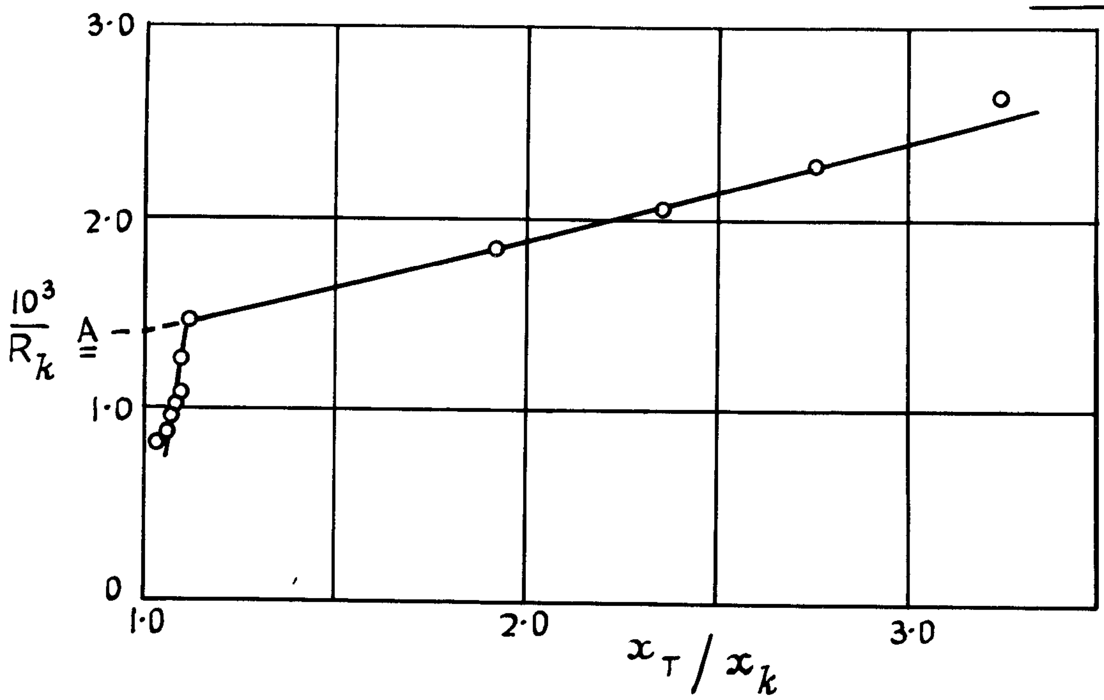
FIGS. 1 & 2.

FIG. 1.




Wire Reynolds number as a function of transition position for some of the results of Tani and Hama (Ref. 7)

FIG. 2.




Wire Reynolds number as a function of transition position for some of the results of Fage and Preston (Ref. 1)

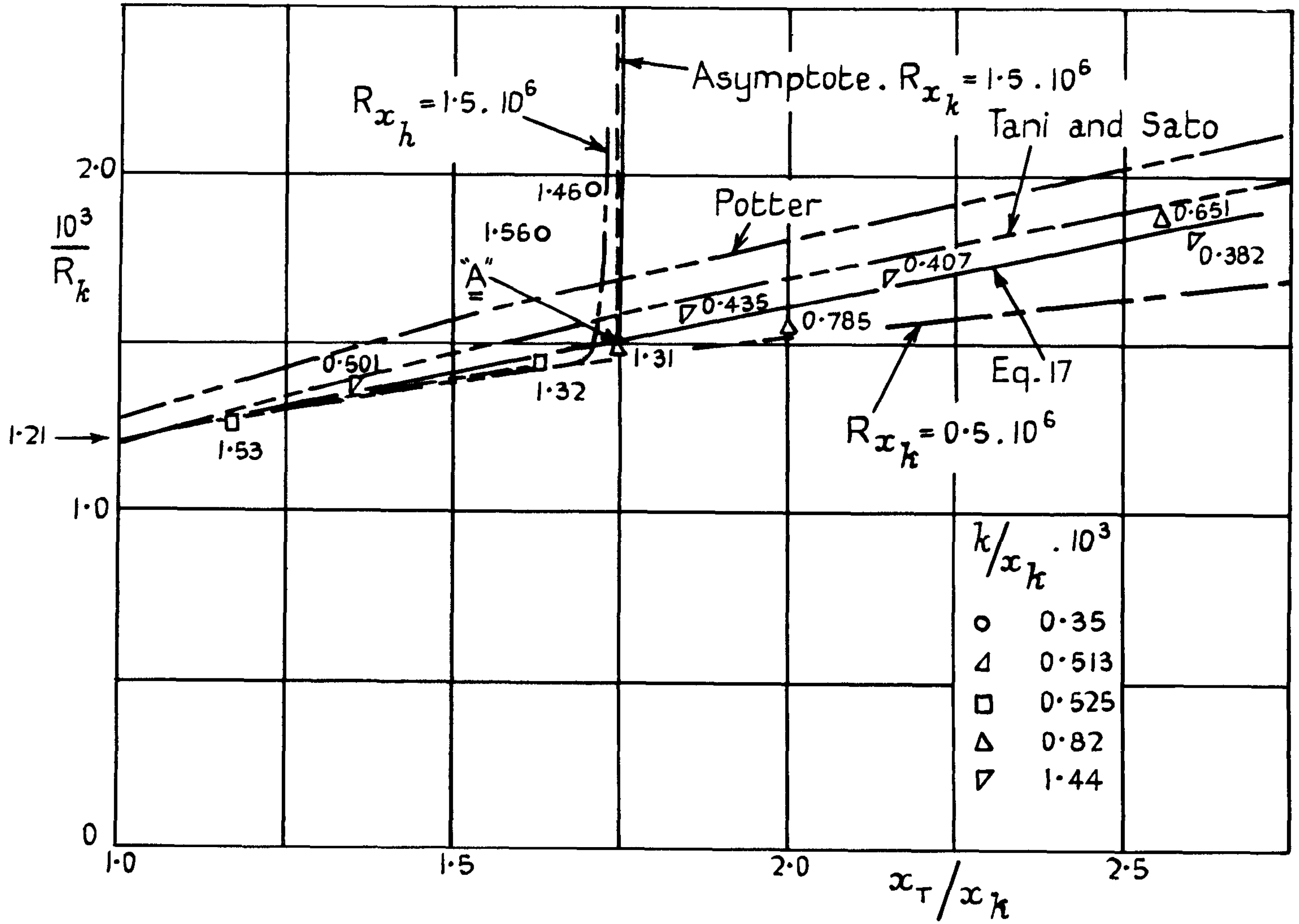
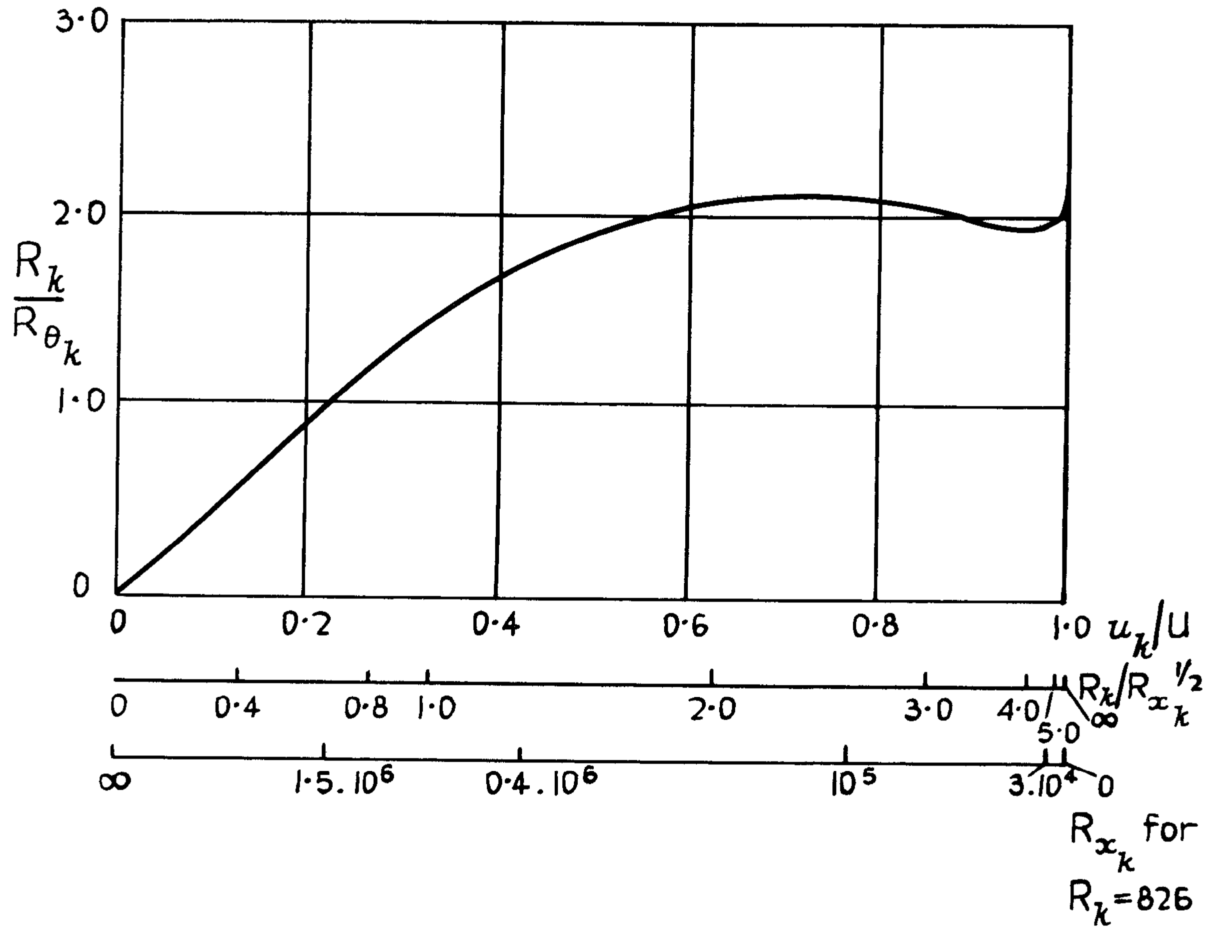


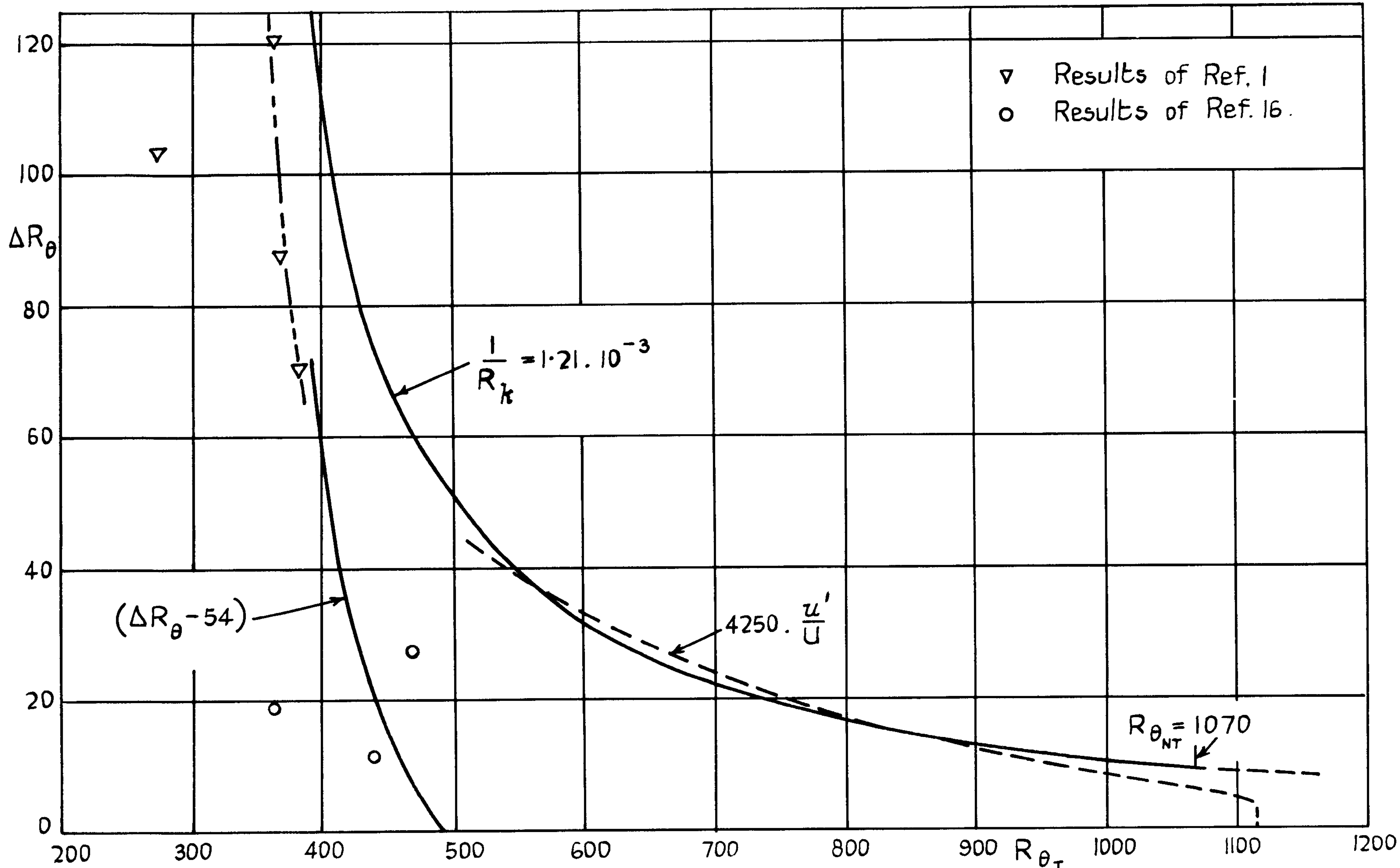

FIG. 3.

Wire Reynolds number as a function of transition position for the results of Tani, Iuchi and Yanamoto (Ref. 16). Low turbulent stream. Attached figures are values of $R_{x_k} . 10^{-6}$

Fig. 4.

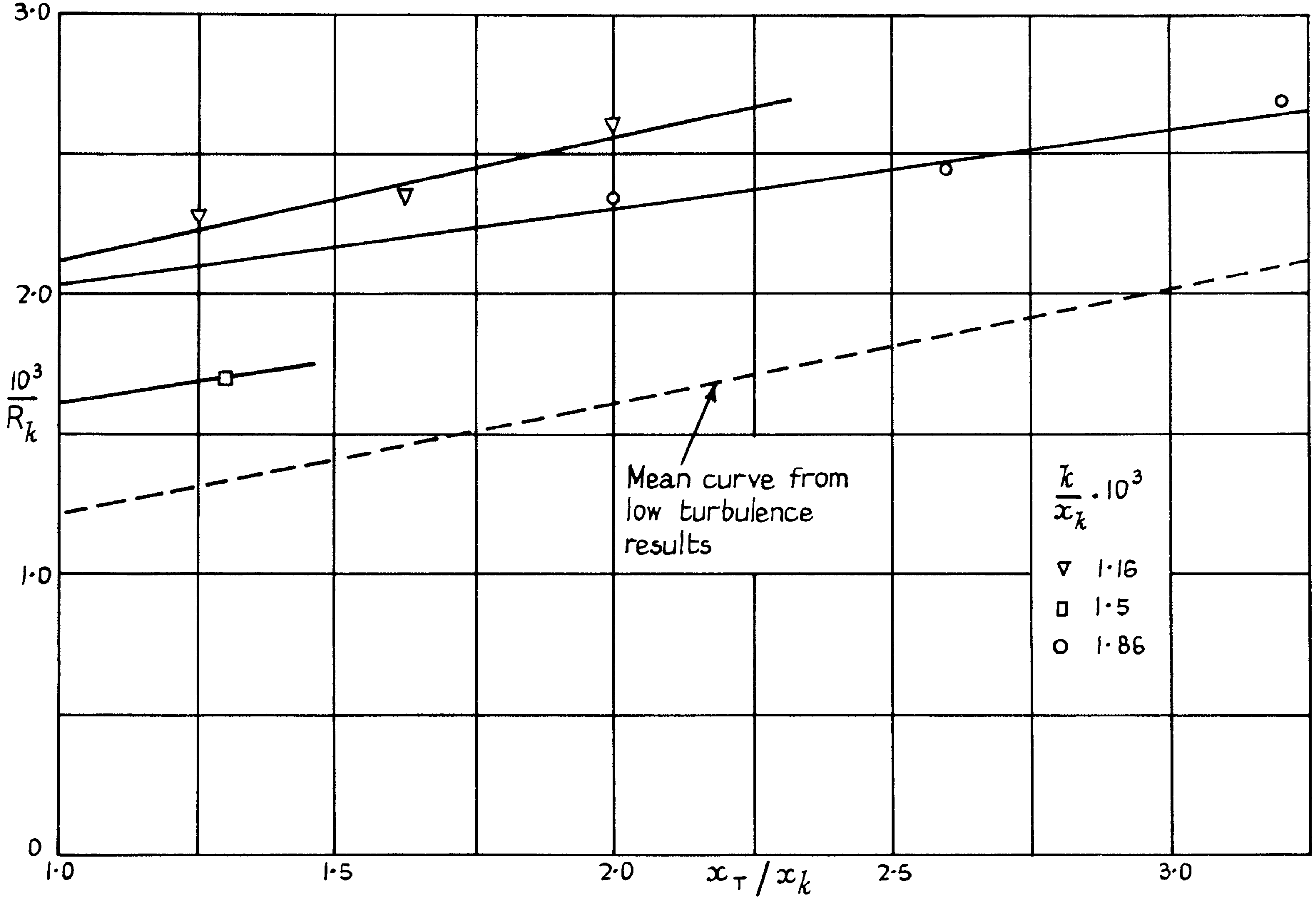



The boundary layer momentum thickness immediately downstream of the wire as a function of the wire size.




Increment to the momentum thickness added by the wire, as a function of the momentum thickness at transition.

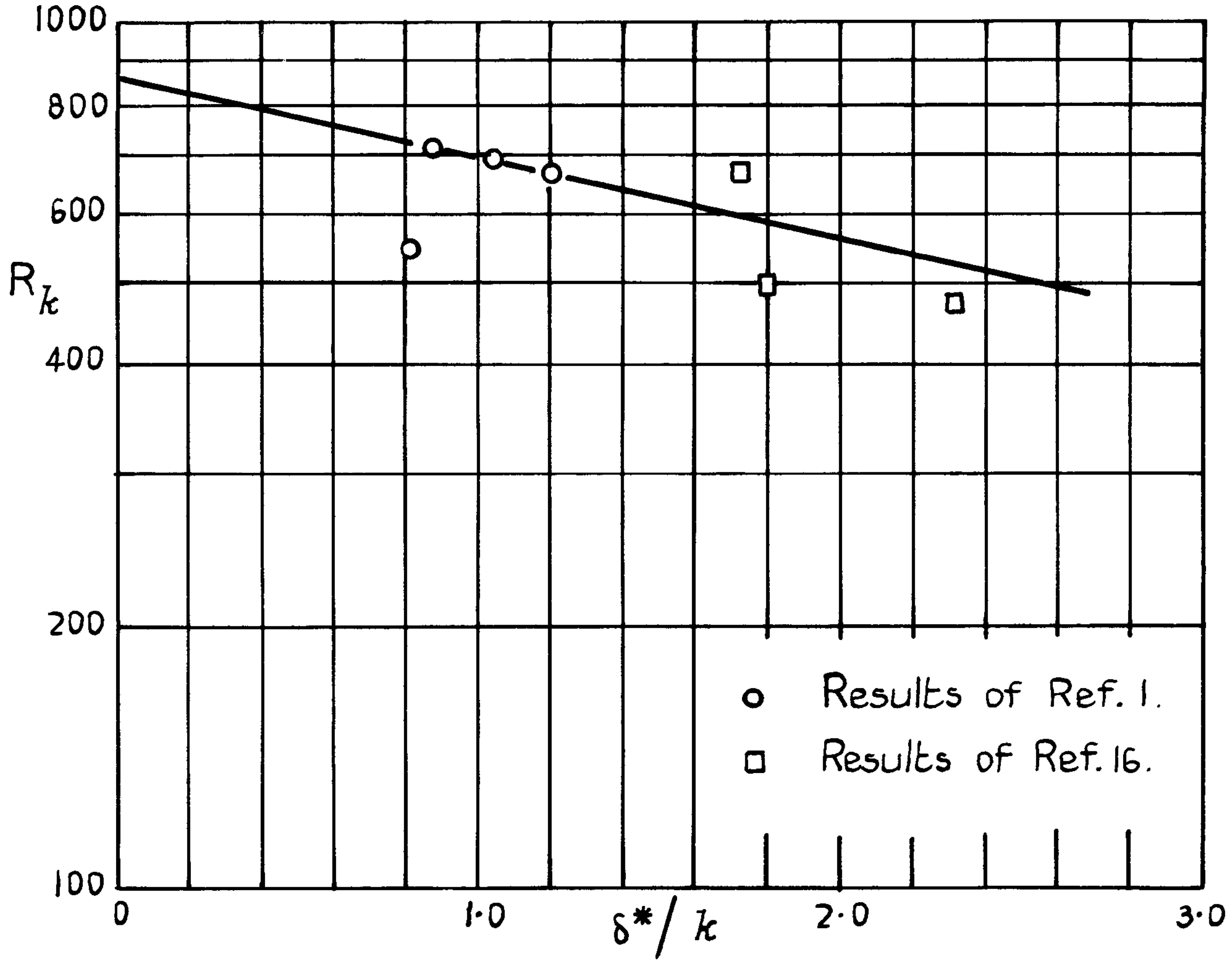
FIG. 5.




Wire Reynolds number as a function of transition position for the results of Tani, Iuchi, Yanamoto (Ref. 16). High turbulent stream.

FIG. 6.

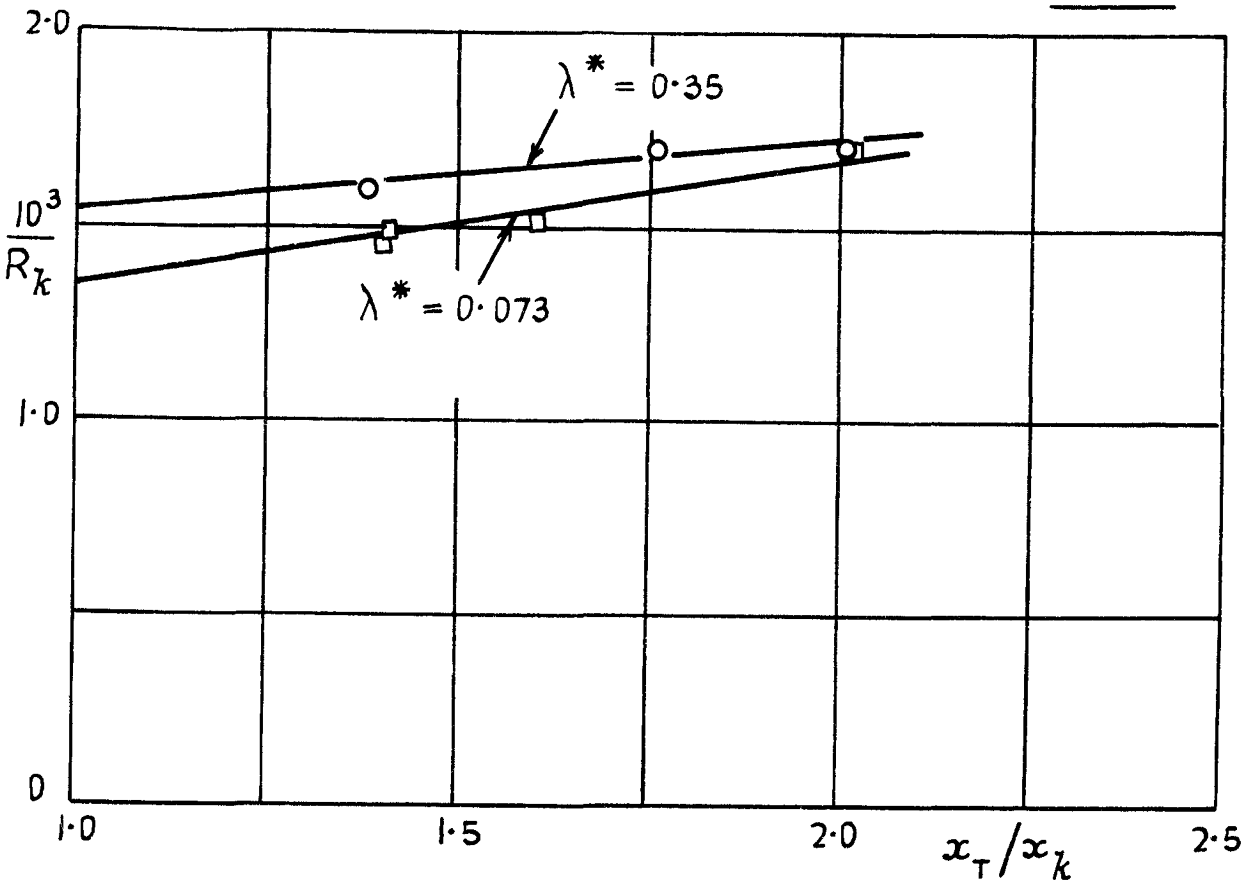
FIG. 7.




Wire Reynolds number as a function of the third dimensionless group, $\delta^*/k$ for the results of Fage and Preston (Ref. 1) and the results of Tani, Iuchi and Yanamoto (Ref. 16).

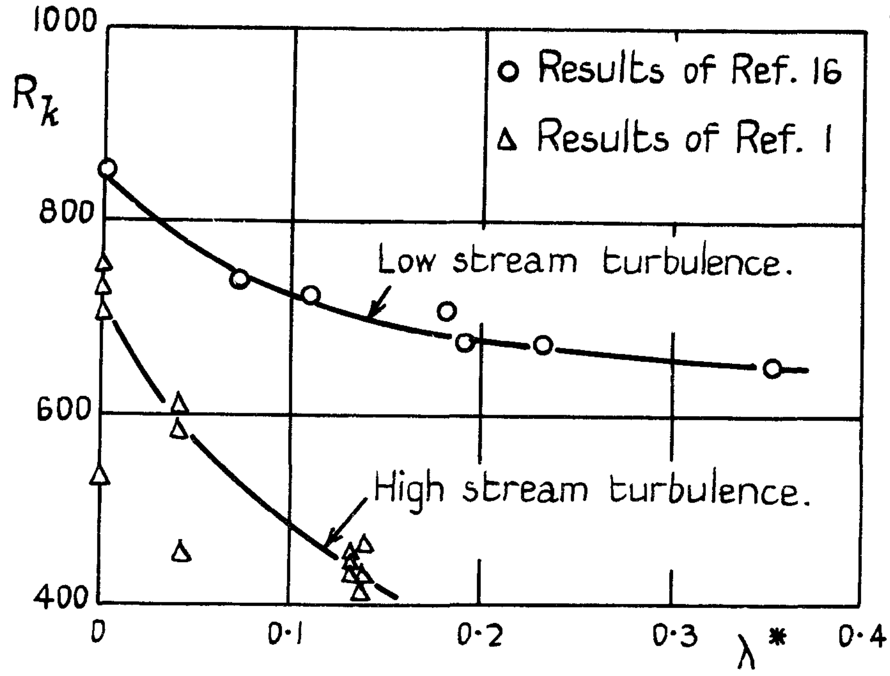
FIGS. 8 & 9.

FIG. 8.

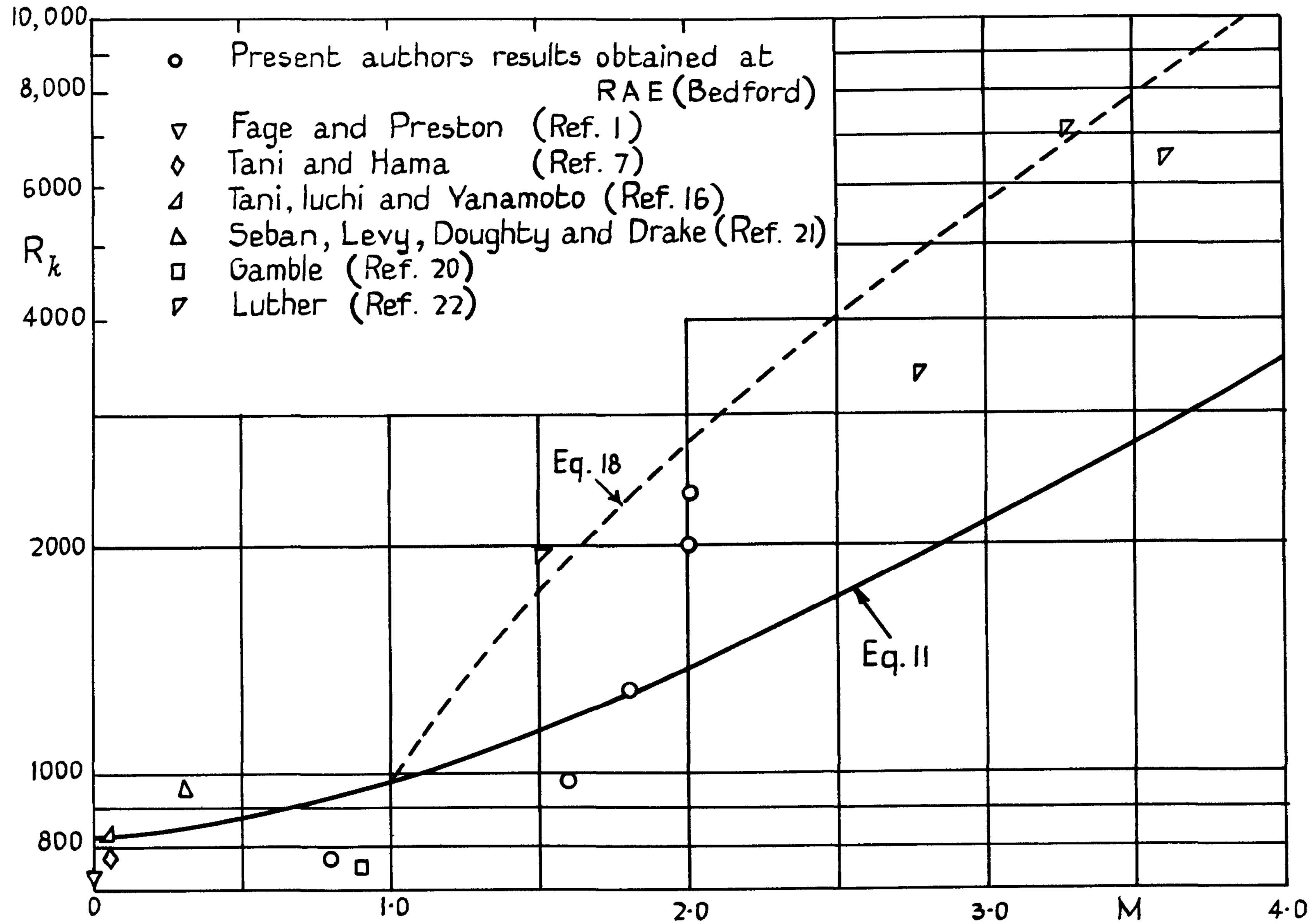



Wire Reynolds number as a function of transition position with streamwise pressure gradients at the wire. Some of the results of Tani, Iuchi and Yanamoto (Ref. 16) $\lambda^* \equiv \frac{\delta^{*2}}{\nu}\frac{dU}{dx}$

FIG. 9.



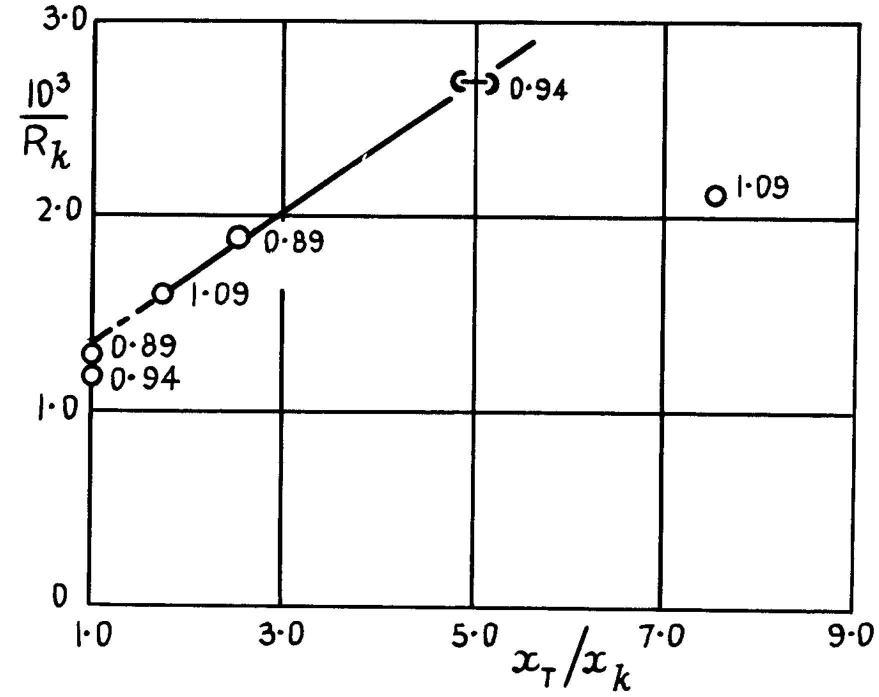

Wire Reynolds number for transition at the wire as a function of streamwise pressure gradient at the wire position.
$\lambda^* = \frac{\delta^{*2}}{\nu}\frac{dU}{dx}$




Wire Reynolds number for transition at the wire as a function of Mach number.

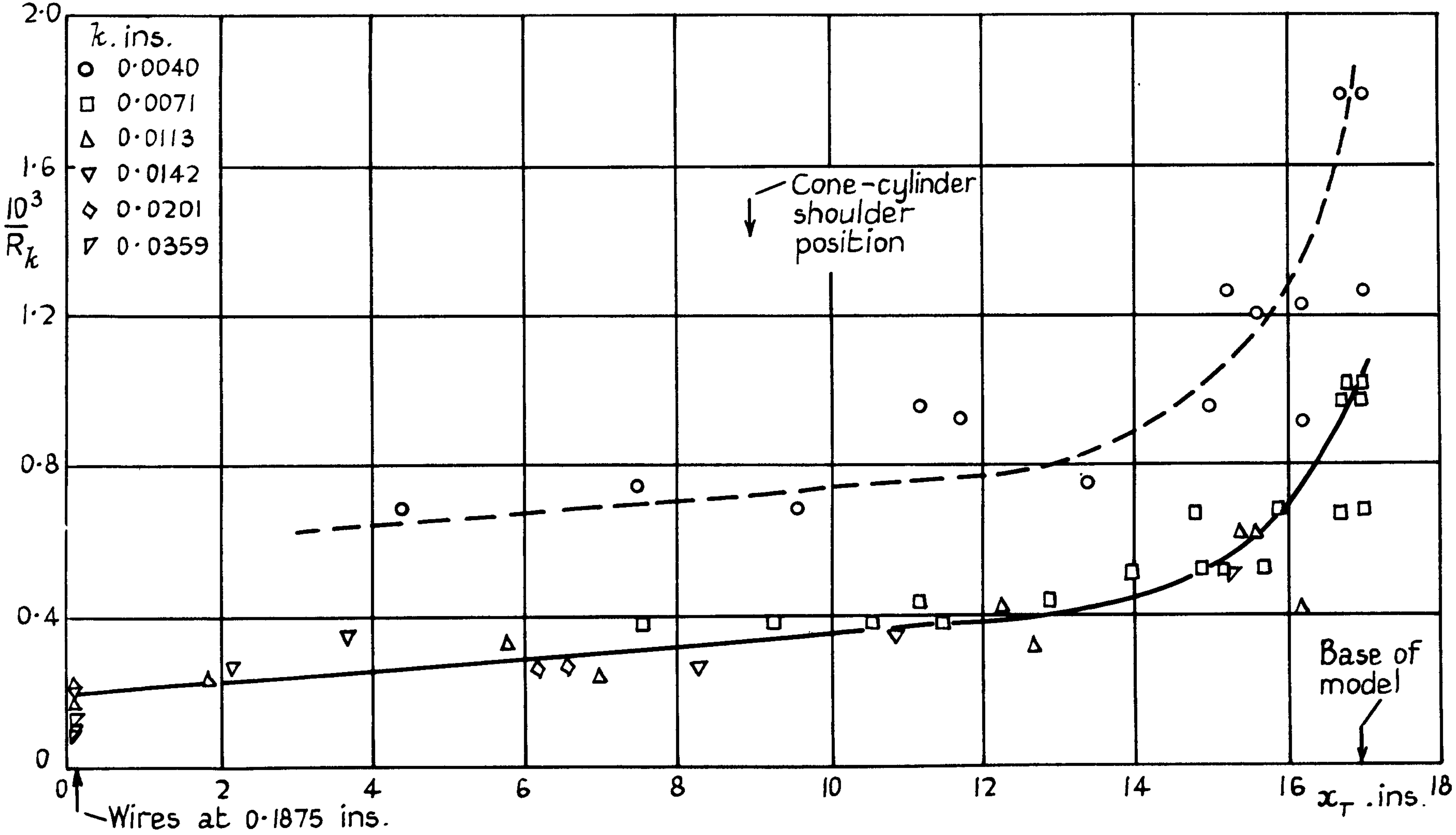
FIG. 10.

FIG. 11.



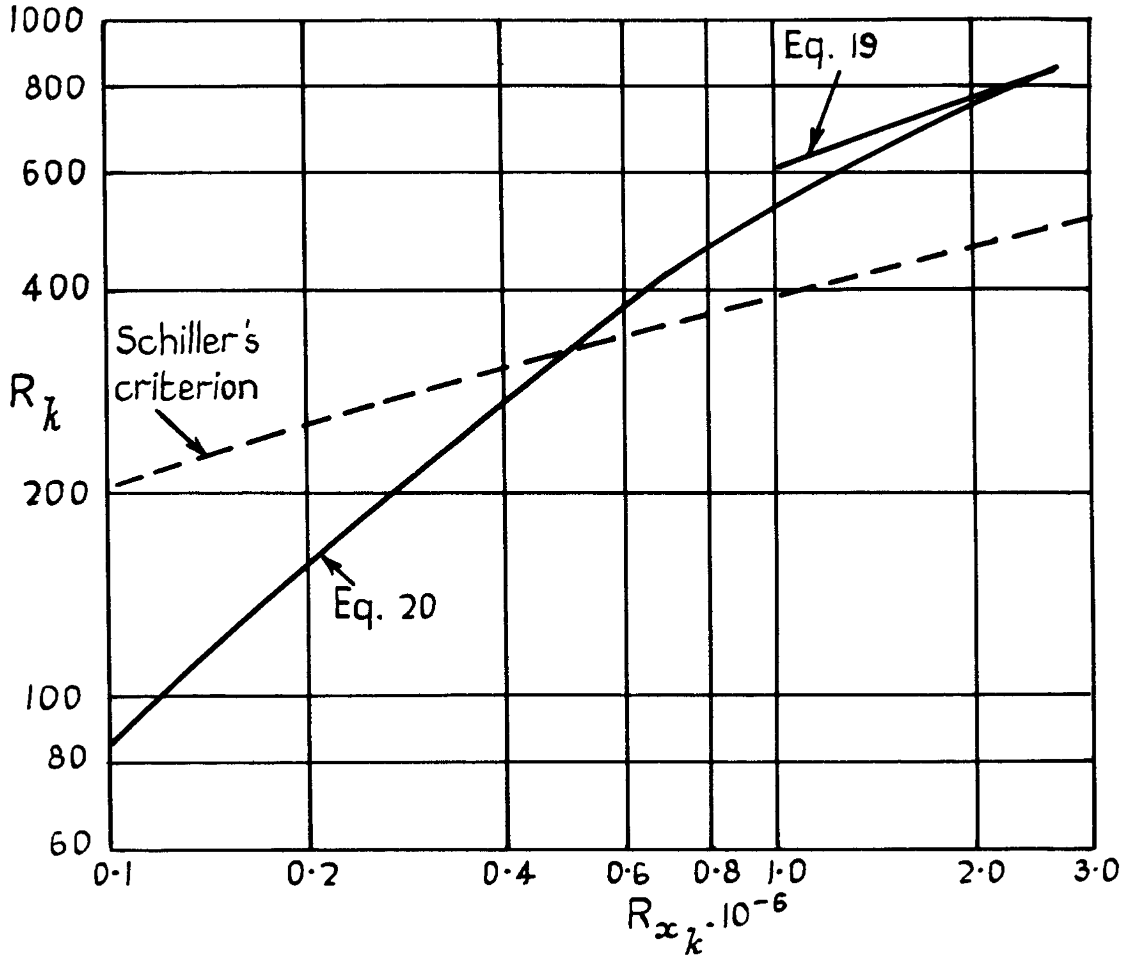

Wire Reynolds number as a function of transition position from the results of Gamble, (Ref. 20). Attached figures are values of local Mach number.

FIG. 12.




Wire Reynolds number as a function of transition position from some of the results of Luther (Ref. 22). $R_k$ based upon free stream conditions. Free stream Mach number 4·09.

FIG. 13.




Reynolds number for the largest wire permissible whilst transition is unaffected.

C.P. No. 462
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