A New Hypothesis for Transition on the Windward Face of the Space Shuttle

D.I.A. Poll*
Cranfield Institute of Technology, Cranfield, Bedford, England

This paper introduces the hypothesis that roughness induced transition of the attachment-line boundary layers is important for the flow over the windward face of the Space Shuttle. Attachment-line transition is described for the flow over a swept cylinder. The available knowledge is then used to model transition on a slender delta wing at large angles of incidence. This is compared with wind-tunnel data for roughness induced transition on the Space Shuttle. Agreement between the hypothesis and data is good and a simple transition onset criterion is proposed. This is completely general and can, in principle, be applied to vehicles of any shape. Finally, it is shown that the hypothesis provides an explanation for the instantaneous forward "flash" of the transition front that was observed on the Orbiter Columbia.

Nomenclature

A	= constant
b	= semispan of delta wing
d	= diameter of circular trip wire
k	= characteristic dimension of roughness element
L	= length of Space Shuttle model
M	= Mach number
Q	= resultant velocity $(U^2 + V^2)^{1/2}$
$\bar{R}$	= attachment-line similarity parameter
R_k	= roughness Reynolds number $(U_k \cdot k/\nu)$
r	= leading-edge radius
s	= trip (roughness)–detector separation measured along the attachment line
T	= temperature
U, V	= velocity components in the x and y directions, respectively
x,y,z	= orthogonal curvilinear coordinate system (Fig. 1)
α	= angle of incidence
γ	= ratio of specific heats
δ_1	= boundary-layer displacement thickness
η	= length scale for the attachment-line boundary layer
θ	= boundary-layer momentum thickness
Λ	= leading-edge sweep angle
μ	= dynamic viscosity
ν	= kinematic viscosity
ρ	= density

Subscripts

aw	= equivalent adiabatic wall condition
e	= at the edge of the boundary layer
k	= at a distance k from the wall
o	= stagnation value
r	= recovery value
w	= at the wall
$(\ )_*$	= evaluated at the reference temperature
∞	= in the undisturbed freestream

Introduction

THROUGHOUT the design, development, and construction of the Space Shuttle, careful consideration was given to the problem of boundary-layer transition on the windward face. When studies began in about 1970, it was recognized that the weight of the thermal protection system would be extremely sensitive to the location of boundary-layer transition. At that time, however, reliable transition prediction techniques were not available. Early attempts to provide the necessary information involved correlations of wind-tunnel data for a wide variety of configurations. Typical examples of these initial studies are provided by Kipp and Masek[1] and Hefner.[2] Unfortunately, it was found that the scatter in the data base was so large that it was impossible to determine a "best" transition criterion. The problem was also severely compounded by the observation that, when several plausible criteria were compared for the same vehicle following the same trajectory, the predicted transition locations showed very large differences. The uncertainty in the transition location was such that initial estimates for the TPS weight varied by as much as 25%.[3] In the absence of a reliable criterion, the TPS design was based upon smoothbody wind-tunnel data correlated in terms of the R_θ/Me parameter. This was expected to be conservative since wind-tunnel noise produces transition Reynolds numbers which are lower than those achieved in flight. However, during construction it was found that the smoothness requirements associated with this approach could not be achieved. To assess the implications of increased surface roughness a new series of wind-tunnel tests was conducted.[4] These represented the most comprehensive transition work performed for the Space Shuttle program and the results were used to provide the preflight assessment of the effect of surface roughness.

During the first five flights of the Orbiter Columbia, a massive amount of data was collected and much of this has been used to evaluate vehicle performance against preflight predictions.[5] In particular, analyses have been performed on the information gathered from an array of approximately 90 thermocouples mounted within the TPS tiles. By examining the temperature-time histories it has been possible to reconstruct the movement of the boundary-layer transition fronts during re-entry.[6,7] This analysis has provided a comprehensive picture of the transition behavior, which can be used to re-evaluate wind-tunnel results and, ultimately, improve the existing engineering prediction methods. Preliminary attempts at this task have already been published by Goodrich et al.[3,8] and by Harthun et al.[6] However, while some important new ideas have emerged from these studies, the windward-face transition process is not completely understood. Consequently, the criteria which have been proposed are strictly limited to the present orbiter geometry and to a narrow band of incidence, Mach number, Reynolds number, and wall-to-total temperature ratio.

The object of this paper is to introduce the hypothesis that attachment-line contamination is an important process for producing transition on the windward face of the Space

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*Senior Lecturer, Aerodynamics Division, College of Aeronautics. Member AIAA.

Shuttle. Attachment-line contamination has been studied for many years, mainly in the context of swept-back wings, and its principal characteristics are well known. It will be shown that many of the features of the Space Shuttle transition can be described using the new hypothesis and the currently accepted transition criterion can be reformulated in such a way that it applies to a wide variety of body shapes. It is anticipated that the results will have implications for the design of future generations of orbiter vehicles.

The Attachment Line on a Long Swept Cylinder

In order to introduce the concepts of attachment-line flow and attachment-line transition it is best to begin by considering the flow past a long swept cylinder, as shown in Fig. 1. The attachment line is the line that divides the upper surface flow from the lower surface flow and it lies along A–A. If the cylinder was unswept, this would be the locus of two-dimensional stagnation points and it may be referred to as the "stagnation line." However, when the cylinder is swept, A–A ceases to be a locus of stagnation points since the flow has a spanwise velocity component, U_e. Consequently, the term "attachment line" is to be preferred. The existence of a velocity component at the attachment line also means that a conventional boundary layer is established along A–A. This may be laminar, transitional, or turbulent.

If there are no parameter variations in the spanwise direction x, dimensional analysis indicates that for steady, compressible flow the properties of the attachment-line boundary layer are completely specified by M_e, T_w/T_o, γ, Prandtl number, and Reynolds number $\bar{R}$. The Reynolds number must be based upon local edge conditions and a length scale.[9] The appropriate length scale for the attachment-line flow is

$$\eta = \left[\frac{\nu_e}{(\mathrm{d}V_e/\mathrm{d}y)_{y=0}}\right]^{1/2}$$

Consequently,

$$\bar{R} = \frac{U_e \eta}{\nu_e} = \left[\frac{U_e^2}{\nu_e(\mathrm{d}V_e/\mathrm{d}y)_{y=0}}\right]^{1/2} \qquad (1)$$

When a roughness element is placed across the attachment line to induce a transition, additional variables are introduced. If the roughness is a wire of circular cross section (axis lying in the y direction) then the appropriate variable is the diameter d. In addition, the flow properties will also depend upon the separation s between the trip and the point on the attachment line at which observations are made.

Transition in the attachment-line boundary layer on a swept cylinder has been studied extensively for low-speed flow (see Ref. 9). The results for two-dimensional trip wires are summarized in Fig. 2, which gives the variation of $\bar{R}$ with d/η and s/η for the onset of transition. The results exhibit several interesting features. First, there is a maximum tolerable roughness height ($d \approx 0.7\eta$) below which transition is determined by freestream disturbances. For roughness heights between 0.7 and 1.5η, the critical values of $\bar{R}$ are strongly dependent upon d. More important, however, is the fact that, as freestream speed is increased, for fixed values of sweep and roughness height, the bursts of turbulence are initially observed at the larger values of s and, as speed is further increased, the location for the first bursts of turbulence moves progressively closer to the trip. This behavior is consistent with that found on flat plates and cones.[10] However, when the roughness height exceeds 1.5η, a distinct change is observed. For values of d between 1.5 and 2.0η, we find that, at fixed $\bar{R}$, bursts of turbulence are observed at all values of s. This is because the bursts are being produced at the trip wire ($s=0$) and then convected along the attachment line indefinitely ($s \to \infty$). We note that this behavior has no counterpart in the flow over flat plates or cones. If the roughness height is increased beyond 2.0η, the results tend to an asymptotic limit in which the size of the disturbance no longer matters. It is clear from Fig. 2 that, as the freestream speed is increased, bursts of turbulence first appear at the trip location. However, at very low values of $\bar{R}$, the bursts decay rapidly as they are convected in the spanwise direction. Consequently, it is necessary to increase the freestream speed in order to drive the transition front to greater values of s. The need to increase speed ends abruptly as $\bar{R}$ reaches 245 since this is the Reynolds number above which bursts of turbulence are self-sustaining. This characteristic of unlimited propagation of turbulence from a very large trip as $\bar{R}$ exceeds 245 is the main distinguishing feature of the attachment-line contamination process.

At present, there is only a small amount of information available for contamination by three-dimensional roughness elements and all of this is for effectively incompressible flow. However, it has been demonstrated that for single conical[11] and spherical[12] elements located on an attachment line, transition begins simultaneously at all values of s when $\bar{R}$ exceeds 245—provided that the element characteristic dimension is larger than 2.2η. This is identical to the situation for large ($d > 2.0\eta$) trip wires described previously. The similarity is not totally unexpected, since the presence of flow divergence means that neither two-dimensional nor three-dimensional roughness elements can introduce a permanent momentum defect into the attachment-line flow. Only the disturbances can propagate along the span. For a trip wire whose diameter is less than 2.0η the criterion for a fully effective trip can be expressed in terms of a roughness Reynolds number R_k, i.e., for transition at the roughness element

$$R_k = \frac{U_k \cdot k}{\upsilon} = 550 \qquad (2)$$

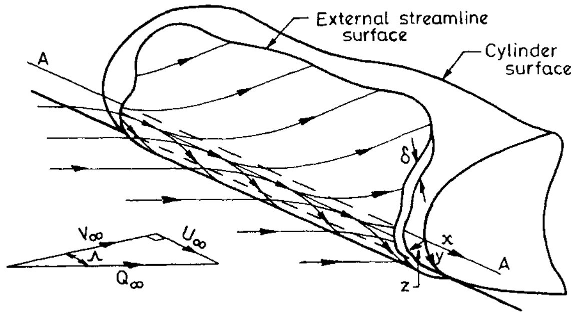

Fig. 1 Flow near the leading edge of a swept cylinder.

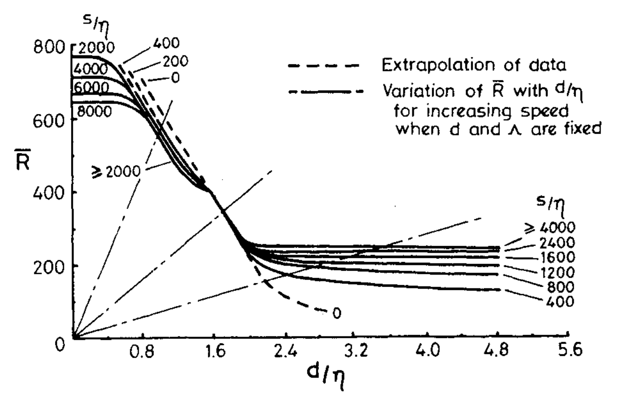

Fig. 2 Variation of $\bar{R}$ with d/η and s/η for transition onset at a swept-cylinder attachment line (incompressible flow).

provided that $\bar{R}>245$ (see Ref. 9). This is entirely consistent with Gregory's[11] results for small single conical elements ($k<2.2\eta$).

In the case of the long swept cylinder there is no pressure variation along the attachment line ($dp/dx=0$). It is therefore constructive to compare this behavior with that found in the incompressible, zero-pressure gradient, flat plate boundary layer. A convenient basis for comparison is to convert $\bar{R}$ into the more familiar displacement thickness Reynolds number R_{δ_1}. Appropriate relations are given in Ref. 9 where we obtain

$$R_{\delta_1}=1.026\bar{R} \tag{3}$$

Therefore, in the presence of a sufficiently large roughness element, transition begins in the attachment-line boundary layer as R_{δ_1} exceeds 250. This result contrasts sharply with the flat plate where self-sustaining turbulent spots cannot be generated until R_{δ_1} exceeds 400 (see Ref. 13). For small (spherical) roughness elements the effective tripping criterion for the flat plate flow can also be expressed in terms of a roughness Reynolds number. According to Klebanoff et al.[14] the relation is $R_k=577$ for $R_{\delta_1}>520$. With the exception of the limiting Reynolds number, this is almost identical to the attachment-line criterion given in Eq. (2).

The implication of this comparison is that, while small roughness elements appear to exhibit similar transition characteristics, large roughness elements do not. In particular, the Reynolds number for effective tripping with an element located on the attachment line may be much lower than that of an identical element located off the attachment line. This situation is sketched in Fig. 3. For the swept cylinder, the Reynolds number at which the elements off the attachment line become effective trips may be even higher than the two-dimensional flat plate values, due to the presence of strong favorable pressure gradients on the windward face.

For high speed flow conditions, transition in the presence of a gross ($d\rightarrow\infty$) disturbance has been examined by Poll.[15] It has been demonstrated that the data for transition onset correlate well if a modified attachment-line Reynolds number $\bar{R}_*$ is used. This has the form given in Eq. (1), except that the kinematic viscosity is evaluated at the turbulent reference temperature T_*. According to Poll,[16] this temperature is given by

$$T_*=T_e+0.10(T_w-T_e)+0.60(T_r-T_e)$$

Over a wide range of conditions, the criterion for the onset of transition is identical to the low-speed result,

$$\bar{R}_*=\left[\frac{U_e^2}{\nu_e(dV_e/dy)_{y=0}}\right]^{1/2}=245(\pm 35) \tag{4}$$

The available data do not exhibit any unit Reynolds number dependence. This is consistent with the behavior of flow over a cone at zero incidence in supersonic flow when transition is fixed by large, isolated roughness elements.[10,17]

Unfortunately, the "$\bar{R}_*=$const" criterion for transition onset does not readily lend itself to general physical interpretation. In order to overcome this problem the criterion has been used to compute the variation of the attachment-line momentum-thickness Reynolds number, R_θ, at transition onset as a function of the edge Mach number and the wall-to-recovery temperature ratio. The results are given in Fig. 4. This figure has two particularly interesting features. First, the Reynolds number for the onset of transition is raised by cooling the wall. Second, and most significantly, as the edge Mach number increases, R_θ appears to be tending towards a linear dependence upon M_e. Therefore, for values of M_e between 3 and 6, the "$\bar{R}_*=$const" criterion is equivalent to an "$R_\theta/M_e=$const" criterion. This latter form is instantly recognizable as the most popular criterion for transition on the windward face of the Space Shuttle.

The Attachment Lines on a Delta Wing at Incidence

If the effects of attachment-line transition are to be investigated for a delta wing then it is necessary to know the location of the attachment lines for any given set of conditions. We begin by considering a slender delta wing with slightly rounded leading edges. At zero incidence the attachment lines lie along the leading edges (see Fig. 1). As incidence is increased, the character of the flow over the windward face will change and the attachment lines will move towards the plane of symmetry. At sufficiently large incidence, the two attachment lines will meet to form a single line of attachment, which is coincident with the windward symmetry plane. This progression of events has been described by Bertram et al.[18] whose results have been used to provide the schematic illustration given in Fig. 5. These sketches indicate that the attachment lines are straight and originate at the apex of the wing. We also note that the attachment lines mark the boundary between the flow that leaves the wing at the trailing edge and the flow that leaves at the leading edges.

An indication of the way in which the attachment lines move across the windward face may be obtained from the published results of the "thin-shock-layer" theory.[19] This provides a simple analytical description of the phenomenon. Experimental verification of the predictions has been provided by Richards.[20] The theory has been used to predict the attachment-line positions for a flat delta wing with a leading-edge sweep angle of 80 deg and the results are presented in Fig. 6. This figure shows that, at the higher Mach numbers, the attachment lines stay close to the leading edges while the angle of incidence is less than about 25 deg. However, beyond 25 deg, their location is very sensitive to incidence

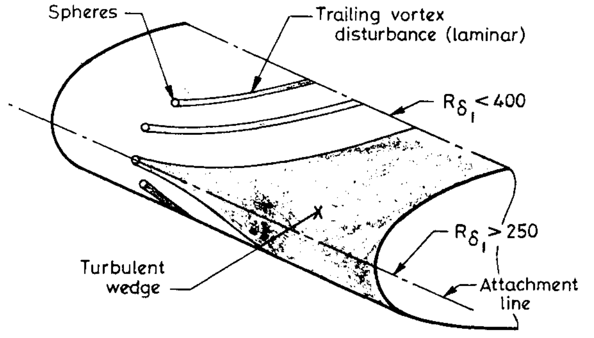

Fig. 3 Illustration of the likely effect of spherical trips for transition on a swept cylinder.

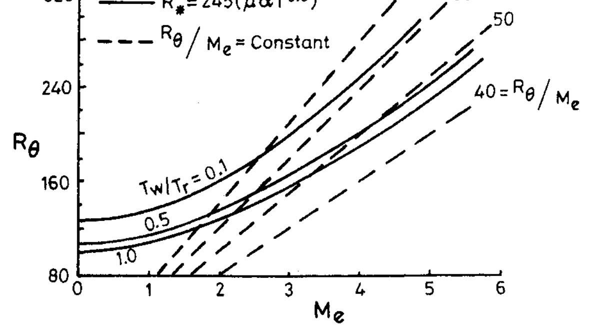

Fig. 4 Conditions for transition onset with a large trip on a swept-cylinder attachment line.

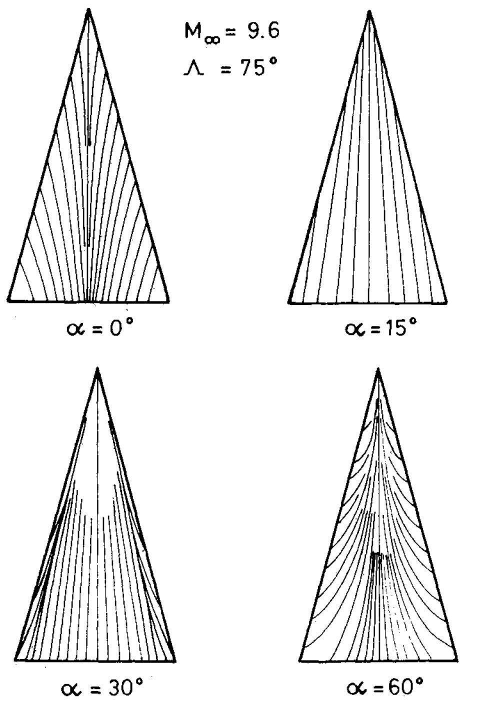

Fig. 5 Windward face flow patterns on a flat delta wing at incidence, after Bertram et al.[18]

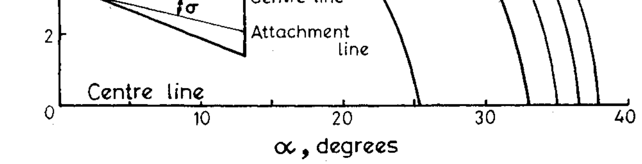

Fig. 6 Attachment-line location for a flat delta wing with 80-deg leading-edge sweep.

and they move very rapidly towards the windward centerline as incidence is increased. For angles of incidence above 38 deg, the attachment lines lie on the windward symmetry plane.

The principal difference between the attachment-line flows on the swept cylinder and those on the delta wing is that, in the former case, the mean flow parameters—like δ_1—are independent of position while, in the latter case, they develop in the x direction. However, Poll and Paisley[21] have demonstrated that the existence of boundary-layer growth does not affect the transition behavior when large roughness is present. In particular, transition onset occurs at the trip wire, and at all downstream positions on the attachment line, when the value of $\bar{R}$ at the trip just exceeds 245. Therefore, if the postulation that large roughness elements located on an attachment line become effective trips at much lower Reynolds numbers than identical elements located elsewhere is correct, then, if the surface is rough, transition on the windward face of a delta wing will begin on the attachment lines. Evidence consistent with this view has already been

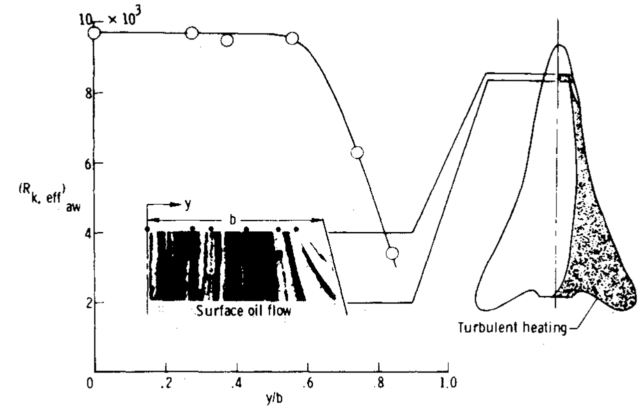

Fig. 7 Variation of trip effectiveness with spanwise position for an orbiter configuration, after Morrisette.[22]

provided by Morrisette,[22] who performed transition studies on a delta-wing orbiter model set at 20-deg incidence in a Mach 6 flow. Six three-dimensional roughness elements were distributed across the span at a fixed chordwise location (x = const) and the freestream unit Reynolds number was then increased until each element, in turn, produced a characteristic wedge of turbulence, i.e., became an "effective" trip. The Reynolds numbers R_k for transition at the elements were then plotted as a function of spanwise position. These results are reproduced in Fig. 7. The oil-flow indicates that the attachment line is located at about $0.78b$ and the data show that those roughness elements closest to the attachment line became effective trips at much lower Reynolds numbers than similar elements set nearer to the center line. Morrisette suggests, without evidence, that this effect may be due to local thinning of the boundary layer, or destabilization due to crossflow. However, the results are entirely consistent with the attachment-line contamination hypothesis. They also highlight an important effect which is particularly relevant to the central theme of this paper. This is that measurements taken on the centerline may provide an inadequate picture of the transition process if the centerline and the attachment lines are not coincident. The inset diagram in Fig. 7 shows that the roughness element closest to the attachment line produces a turbulent wedge which covers approximately one-third of the wing surface, while the flow on the windward centerline is laminar over the entire length of the model. Clearly, transition criteria based upon local boundary-layer parameters on the centerline would be of little value in this particular case.

Having identified the attachment line as a potentially important feature in the transition process on the delta wing, it is appropriate to examine the way in which the transition onset location varies in response to changes in the freestream conditions. To simplify the mathematical description of the flowfield, three restrictions are introduced: 1) the freestream Mach is always very large; 2) the incidence is such that the attachment lines are coincident with the windward centerline; and 3) the wall temperature is independent of position. If the inviscid flow is conical, the streamline at the edge of the attachment-line boundary layer is a characteristic of the external flow and hence, U_e and v_* do not depend upon the distance from the wing apex x. The crossflow velocity gradient $(\mathrm{d}V_e/\mathrm{d}y)_{y=0}$ does vary with x but, since the attachment line is on the wing centerline and the freestream Mach number is large, this may be approximated by the empirical relation proposed by Bertram et al.,[18] i.e.,

$$\left.\frac{\mathrm{d}V_e}{\mathrm{d}y}\right]_{y=0} \approx 0.224\left(0.745 + 1.57\frac{r}{b}\right)\cdot\frac{V_\infty}{b} = A\frac{V_\infty}{b}$$

If a single, three-dimensional roughness of height k is introduced at a station x, manipulation of Eq. (4) produces

$$\bar{R}_* = \left[\frac{U_e}{k(\mathrm{d}V_e/\mathrm{d}y)_{y=0}}\right]\cdot\frac{k}{\eta_*}$$

Now, since M_∞ and α are large,

$$U_e \simeq Q_\infty \cos\alpha$$

and

$$\left.\frac{\mathrm{d}V_e}{\mathrm{d}y}\right]_{y=0} \simeq A\cdot\frac{Q_\infty \sin\alpha \tan\Lambda}{x}$$

where Λ is the leading-edge sweep angle. Therefore

$$\bar{R}_* \simeq \left[\frac{x}{k}\cdot\frac{1}{A \tan\alpha \tan\Lambda}\right]\cdot\frac{k}{\eta_*} \tag{5}$$

It follows that, as the freestream unit Reynolds number is increased at fixed angle of incidence, the similarity parameter $\bar{R}_*$ increases linearly with k/η_*. The consequences of this for the transition onset may be inferred by superimposing this variation on the critical $\bar{R}$ plot given in Fig. 2. This is illustrated in Fig. 8. It is important to note that the principal features of Fig. 2 have been retained but $\bar{R}$ and η have been replaced by $\bar{R}_*$ and η_*. The substitution of $\bar{R}_*$ for $\bar{R}$ can only be justified in the case where gross contamination is present (see Ref. 15), while the use of η_* instead of η cannot be justified at all. Consequently, the values of $\bar{R}_*$ and η_*, which are associated with particular points on the curve, may not be accurate. However, it is expected that the essential physics of the process will be the same as in the incompressible case and, therefore, general qualitative conclusions may be drawn.

Consider the line marked 1 in Fig. 8. As the freestream unit Reynolds number increases, $\bar{R}_*$ increases along 1. Eventually an intersection occurs with the transition curves. Since line 1 meets these transition curves above the point B, the transition front, which is initially far downstream of the roughness element, will move progressively towards the roughness as the unit Reynolds number is further increased. The situation is quite different for the line marked 2. Transition is, again, initially downstream of the roughness element. However, upon increasing the freestream unit Reynolds number, the intersections of 2 and the transition curves occur below B and, consequently, bursts of turbulence (transition onset) first occur at the roughness element, i.e., at $s=0$. Since $\bar{R}_*$ is greater than 245, and increases in the x direction, these bursts grow rapidly and are detectable at all downstream stations. Therefore, to an observer, the transition front will be seen to "flash forward," instantaneously, to the roughness element at the freestream unit Reynolds number corresponding to the intersection of the lines. The flash forward is a characteristic feature of attachment-line transition in the presence of a large roughness element. The "flash" can only occur if the variation of $\bar{R}_*$ with k/η_* is such that an intersection with the transition curves occur below B ($\bar{R}_* < 400$). This implies that the rate of change of $\bar{R}_*$ with k/η_* must be low—typically less than 250. It is apparent that such low rates of change occur for large roughness elements located close to the wing apex, i.e., low x/k (see Eq. 5). Similarly, large angles of incidence, large leading edge sweep angles, and large leading edge radii all reduce the gradient and tend to make the flash more likely.

Reconsideration of the Space Shuttle Wind-Tunnel Data

The most comprehensive wind-tunnel tests performed on the Space Shuttle are those reported by Bertin et al.[4] These were conducted in tunnels B and F at the Arnold Engineering Development Center. The model tested in tunnel B was used to investigate the effect of tile misalignment, while that in tunnel F had 80% of its windward face roughened by a grit-blasting technique. Roughness heights k on both models were similar and approximately 8×10^{-5} times the model length L. This corresponds to a height of 2.6 mm for the full size vehicle. Both models were tested at an incidence of 30 deg. For the tunnel B experiments the data were obtained at a freestream Mach number of 8, freestream body-length Reynolds numbers in the range 1.8×10^6 to 7.1×10^6, and wall temperatures between 0.114 T_0 and 0.435 T_0. Tunnel F data were given for a freestream Mach number of 11, freestream body-length Reynolds numbers from 3.99×10^6 to 17.62×10^6, and wall temperatures between 0.204 T_0 and 0.283 T_0. In both cases transition locations were inferred from heat transfer rate measurements made on the windward centerline. Bertin et al.[4] correlated the conditions necessary for transition at a given point on the centerline in terms of a ratio of rough to smoothbody values of R_θ/M_e and a roughness Reynolds number evaluated at a distance 0.1 L from the nose. While this approach is undoubtedly satisfactory for any particular configuration, there are several problems associated with it. First, the method provides no information about the distribution of turbulent flow off the centerline. Second, there is no guarantee that the correlations are independent of the angle of incidence. And third, the method cannot be used to estimate the transition location on a vehicle whose geometry differs significantly from that of the present orbiter. Clearly, these difficulties would be largely removed if the data from these tests could be shown to be consistent with the attachment-line contamination phenomenon.

The first step in the testing of the hypothesis was to obtain the location of the attachment lines on the windward face at an incidence of 30 deg and Mach numbers of 8 and 11. Close examination of photographs of oil flows suggests that, at 30-deg incidence, the attachment lines make an angle of approximately 8 deg with the windward centerline over the first 50% of the body length. This is consistent with the interpretation of others as indicated by Fig. 9b of Ref. 23. The apparent independence of attachment-line position with Mach number is consistent with the predictions of thin-shock-layer theory as indicated in Fig. 6. It was then necessary to estimate the shape of the turbulent wedge that would be set up by an isolated roughness element on the attachment line. This was done by assuming that, between the attachment line and the centerline, the streamlines at the edge of the boundary layer were straight and met at the nose. It was further assumed that the wedge would spread relative to these streamlines at a rate determined by the average local Mach number over this region. The spreading rate was taken from the data given by Fischer.[24] An example of the development of such a wedge is sketched in Fig. 9—note that, for clarity, the spreading angle has been exaggerated. If this gives a correct representation of the transition front, then, clearly, the critical conditions are those occurring at point A, on the attachment line, and not those at point B, on the centerline. Unfortunately, boundary-layer flowfield computations are not yet available for the complete windward face and, therefore, as a first approximation, the conditions at A were taken to be equal to those on the centerline at the same chordwise location, i.e., at A'. Using computed variations of momentum-thickness Reynolds number and local edge Mach number for the windward centerline, the values of R_θ and M_e on the attachment line were estimated for those data points which Bertin et al. had identified as being "roughness dominated," i.e., those points at which the roughness Reynolds number at location B was greater than 90. These transformed data are presented in Fig. 10, together with the gross roughness attachment-line contamination criterion.

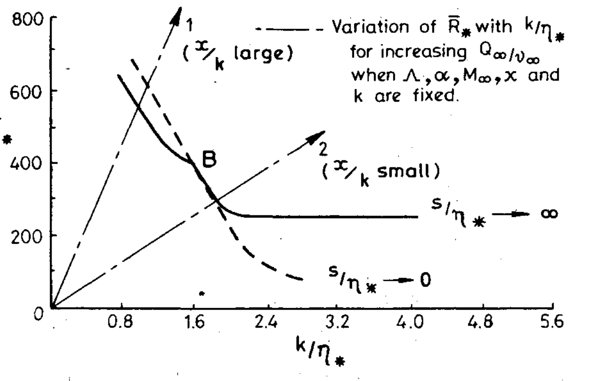

Fig. 8 Dependence of $\bar{R}_*$ upon k/η_* for an isolated trip on a delta-wing attachment line with changes in freestream unit Reynolds number at constant M_∞ and incidence.

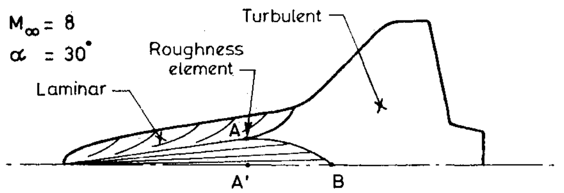

Fig. 9 Development of turbulence from an attachment-line trip on Space Shuttle (N.B. spreading angle exaggerated for clarity).

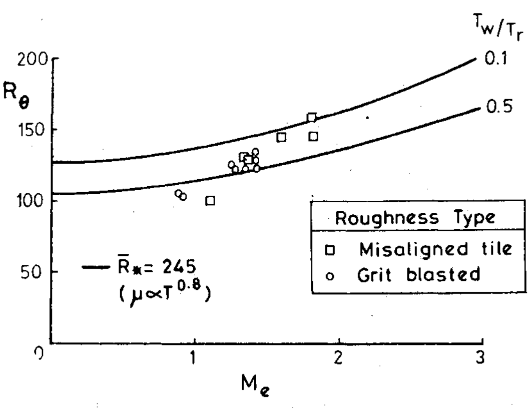

Fig. 10 Variation of local R_θ for transition at the attachment lines on Shuttle models with roughened windward faces.

In view of the difficulties associated with obtaining these revised data, the agreement with the attachment-line contamination criterion is remarkable. There is no discernable difference between the tile and the grit-blasted roughness, and the data scatter is as low, if not lower, than that obtained by Bertin et al. In addition, it is not possible to discriminate between Bertin's "critical" and "effective" trips. We conclude that the data are consistent with the hypothesis that, when large roughness elements are distributed over the windward face, transition begins on the attachment lines at the points where the similarity parameter $\bar{R}_*$ just reaches 245. This being the case, transition locations on other points on the windward face can be computed if the topography of the streamlines at the edge of the boundary layer is known.

Evaluation of Results from the Orbital Flight Test Program

Transition data from the first five flights of Columbia have already been extensively examined and analyzed in Refs. 3, 6, and 7. In Ref. 3 Goodrich et al. considered the movement of the transition front up the centerline of the windward face. The observations were then compared with predictions obtained by applying the criteria developed by Bertin et al.[4] It was found that during the early stages of re-entry, when smoothbody transition behavior was expected, the flow on the vehicle was, generally, laminar. An exception to this was STS-1, which has to be considered separately. The implication was that the disturbance levels present in the wind-tunnel tests were such that transition predictions were unduly pessimistic. However, the criteria were more successful in the latter stages of re-entry when the transition process was governed by disturbances from misaligned tiles. In particular, the transition front first appeared on the windward centerline as the Bertin critical roughness Reynolds number was exceeded. The transition onset location then proceeded to flash forward towards the nose in response to very small changes in the freestream conditions, or incidence. In some cases, e.g., STS-4, transition appeared to move from the trailing edge to the nose in one step; in other cases, e.g., STS-3, transition moved forward in several smaller steps. It was only when the transition front reached an x/L of 0.2 that there was substantial agreement between the observations and the predictions.

A more comprehensive view of the movement of transition over the windward face of the Space Shuttle has been provided by Harthun et al.[6] and Hartung and Throckmorton.[7] These authors have reconstructed the movement of transition by analyzing the output from 90 thermocouples distributed over the port side of Columbia's lower surface. Both groups have reported the flashing forward of transition and both found that, in most cases, when transition moved close to the nose, the origin of the turbulent flow was not on the centerline. According to Harthun et al., a single, isolated, tile misalignment on the port nose landing gear door caused transition to flash forward on flights 1, 2, 3, and 5. This excrescence had a height of about 2 mm and lay on a straight ray originating at the nose and making an angle of 7.8 deg with the windward centerline. On these flights the flash occurred when the Mach number was about 8 and the incidence approximately 33 deg. As indicated in Fig. 9, the attachment lines at these conditions are estimated to lie at approximately 8 deg relative to the centerline. On STS-4 the roughness element that induced the transition flash was almost on the centerline. However, at the time of the flash, the vehicle was traveling at Mach 10 with an incidence of 40 deg. At this high angle, the attachment lines are coincident with the centerline.

The repeated observation of transition flashing forward under conditions at which the roughness element appears to lie on, or very close to, an attachment line is firm qualitative evidence in support of the attachment-line contamination hypothesis. However, it is also possible to provide a limited quantitative check. It has been noted that the identifiable excrescence on the landing gear door was about 2 mm high. This is some 20% smaller than the value modeled in the misaligned-tile, wind-tunnel tests.[4] Therefore, the roughness may not become effective as $\bar{R}_*$ reaches 245. In this case, we would expect that a simple "R_k = const," or similar, criterion would adequately describe the process. This expectation is borne out by Harthun et al.'s results. However, it is possible to take the analysis further. Using the available data, a flash condition was identified for each flight. These corresponded to times after passing the re-entry interface of 1252, 1263, 1193, 1030, and 1125 s, respectively, for STS-1 to 5. The origins of the turbulent flow, as given by Harthun et al., were assumed to be correct and the momentum-thickness Reynolds number and the local-edge Mach number were estimated for each point. The results are presented in Fig. 11, together with lines corresponding to $\bar{R}_*$ equal to 245 and 400. These values represent the limiting conditions for an attachment-line flash (see Fig. 8). The data lie within the limiting conditions for a flash and, therefore, are consistent with the attachment-line transition hypothesis. However, the results also suggest that the roughness elements encountered

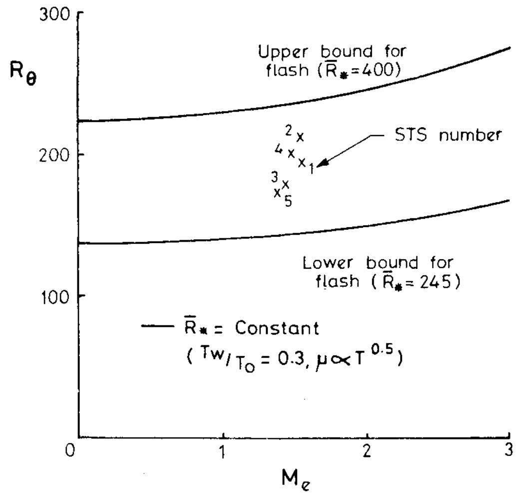

Fig. 11 Values of local attachment line R_θ for the forward flash of transition on the Columbia orbiter.

on the actual vehicle were not sufficiently large to produce the limiting attachment-line transition behavior, i.e., transition did not begin as the local value of $\bar{R}_*$ exceeded 245. Evidence in support of this last statement may be found from flight STS-1. In this case the starboard nose landing gear door was gouged during the flight. During re-entry this gouge, which was $200 \times 25 \times 25$ mm, promoted transition at a much earlier time ($\simeq 1000$ s) than the misaligned tile, which cased the flash at 1252 s. The gouge constituted a gross disturbance for the attachment line and, consequently, transition would be expected to occur earlier. Unfortunately, due to a system fault, the data necessary to confirm this result were lost.

Conclusions

The published wind-tunnel and flight data are consistent with the hypothesis that attachment-line contamination plays an important role in the process of boundary-layer transition on the windward face of the Space Shuttle. Existing knowledge of this phenomenon is incomplete—even in the case of low-speed flow over a swept cylinder. Nevertheless, a preliminary model has been produced for the delta wing. There are two principal features of attachment-line contamination which can be used to test the hypothesis. The first is that, in the limit of very large roughness elements, transition begins at the element as a fixed value of the local attachment-line Reynolds number is exceeded. It has been demonstrated that data from wind-tunnel tests on Space Shuttle models with grossly roughened surfaces exhibit this behavior. The second characteristic is the instantaneous forward flash of transition. This has been observed on all the flights of the Orbiter Columbia for which data are available.

Finally, it has been proposed that a roughness element located on an attachment line can become an effective trip at a much lower local Reynolds number than an identical element mounted elsewhere. This is a particularly important result. At present there is some experimental evidence which supports this view but it is not entirely conclusive. It is therefore suggested that further work should be performed to quantify the behavior of isolated excrescences, both on, and close to, the attachment lines formed on delta wings.

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