Roughness -Dominated Transition on Nosetips, Attachment Lines and Lifting-Entry Vehicles

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Extended Abstract

Modeling of roughness-dominated transition is a critical design issue for both ablating and non-ablating thermal protection systems (TPS). Ablating TPS, used for planetary-entry and earth-return missions, first experience recession under high-altitude, low-Reynolds-number conditions. Such laminar-flow ablation causes the formation of a surface microroughness pattern characteristic of the TPS material composition and fabrication process. For non-ablating TPS, such as the overlapping-tile, metallic heatshields proposed for future reusable launch vehicles, the surface roughness pattern is established apriori by the engineering design and assembly procedure.

In both cases, these distributed surface roughness patterns create disturbances within, and alter the mean velocity profile of, the laminar boundary layer flowing over the surface. As altitude decreases, Reynolds number increases, and flow field conditions capable of amplifying these roughness-induced perturbations are eventually achieved, i.e., transition onset occurs. Boundary layer transition to turbulence results in more severe heat-transfer rates. Ablating TPS experience increased recession rates, leading to potential burn-through, while non-ablating TPS experience accelerated temperature rise, leading to potential melting of key components.

Early experimental research on roughness-dominated transition, primarily due to isolated roughness elements, and the evolution of the critical roughness Reynolds number concept, are documented in References 1-7 and supporting references given therein. For isolated (single) roughness elements, breakdown to turbulence was generally first observed downstream of the element, but with small additional increases in freestream Reynolds number, the turbulent wedge would "flash forward" and become "attached" to the element. The trip was then defined as "effective." Such observations led to the terminology "critical roughness Reynolds number" for transition, the value of which depended on roughness element shape, type (2D or 3D) and flow field, e.g., incompressible/flat-plate. No universal value was discovered.

For 3D distributed roughness covering the entire test surface, the term "effective tripping" was replaced by critical roughness Reynolds number for the "onset" of turbulence . "Effective" and "onset" roughness Reynolds numbers for transition are

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based on the roughness element height and conditions in the laminar boundary layer at that height. An alternative approach is to base the critical Reynolds number on roughness element height and boundary layer edge conditions.

By the mid 1970's, cold-war concerns had generated extreme interest in transition physics on ablating nosetips of ballistic re-entry vehicles.[8,9] A substantial new data base for roughness-dominated transition on blunt bodies in hypersonic flow was generated in wind-tunnel environments.[10] At least five separate correlations were published claiming to correctly model the physics of transition onset and progression over the nosetip (see review of Reference 11). Ballistics-range experiments, using preablated nosetips of actual reentry materials, were subsequently conducted by Reda.[11] Analyses of this extensive "real-materials/real-environments" data base showed that only one transition correlation, based on the concept of a critical roughness Reynolds number for transition, could successfully describe both the wind-tunnel and ballistics-range data sets, thus validating the application of this concept to actual reentry conditions.

The content of this proposed paper is based on the author's review of these ballistics-range experiments and on the author's review and re-analyses of roughness-dominated transition data sets published since that time. In all of these more-recent cases, graphical or algebraic representations of the data were used to correlate the results. Based on present analyses, it will be shown that: (1) all of these more-recent data sets can be successfully correlated by the critical roughness Reynolds number approach; (2) similar flow fields, e.g., attachment lines on swept cylinders and attachment lines on windward surfaces of lifting-entry configurations, yield essentially the same value for the critical roughness Reynolds number; and (3) that the critical roughness Reynolds number for 3D distributed roughness elements can be an order of magnitude lower than the critical value for 3D isolated roughness elements. Results to substantiate these conclusions are summarized below.

Figure 1, taken from Reference 11, shows a schematic of the generalized correlation approach applied to the hypersonic wind-tunnel data base of Reference 10. Power-law relationships between the assumed disturbance parameter X (always based on the average surface roughness height) and the assumed transition parameter Y_{TR} (always based on the computed, smooth-wall laminar boundary layer) were sought. In log-log coordinates, a correlation fit with a -45 degree slope (n= -1) represented a unique situation where $Y_{TR} \cdot X = a =$ constant.

Figure 2 shows a summary of the ballistics-range data set[11] for five different materials and three different nosetip radii exposed to quiescent, real-gas environments. This 3D, distributed-roughness data set was well represented by a critical roughness Reynolds number (based on conditions at the roughness height and the wall temperature) of 192. The value of this parameter for the 3D, distributed-roughness, wind-tunnel data set[10] was slightly lower (160), most probably due to additional disturbances imposed on the laminar boundary layer from nozzle-wall radiated noise.

Demetriades,[12] in his studies of the effects of distributed roughness on transition in a nozzle throat, found corroborating results to support the concept of a constant roughness Reynolds number for transition (~200) in the roughness-dominated regime. Bertin, Hayden and Goodrich[13] found essentially the same result (180) for 3D, distributed roughness patterns on the windward surface of a Shuttle Orbiter model at hypersonic Mach numbers. When cast in terms of boundary layer edge conditions (Figure 3), the ballistics-range data set[11] was well described by a critical roughness Reynolds number of 106.

The influence of isolated roughness elements on swept-cylinder, attachment-line boundary layer transition was studied by Poll[14,15] and Flynn and Jones.[16] Although these experiments were conducted in incompressible flows, results are relevant to attachment-line transition physics for lifting entry vehicles. While these authors acknowledged the roughness-Reynolds-number correlating approach, transition results were graphically presented in terms of Poll's disturbance parameter k/η (roughness height non-dimensionalized by a computed length scale dependent on the velocity gradient normal to the attachment line), and transition parameter $\overline{R}$ (a Reynolds number based on edge conditions and the same computed length scale). Plotting these data sets in log-log coordinates (Figures 4 and 5) showed the inverse dependence of the transition parameter on the disturbance parameter. The end result is that the computed length scale cancels out, yielding a constant critical roughness Reynolds number (based on roughness height and boundary layer edge conditions) of 800 for 2D isolated elements and 1000 for 3D isolated elements.

The influence of isolated roughness elements on boundary layer transition for hypersonic flows over lifting-entry configurations at high angles-of-attack was recently studied by Berry, et al[17,18] at NASA Langley. The critical-roughness-Reynolds-number correlating approach was not employed. Rather, an algebraic correlation was given between the postulated disturbance parameter k/δ (roughness height non-dimensionalized by laminar boundary layer thickness) and the postulated transition parameter Re_θ/M_e (edge Reynolds number, based on laminar boundary layer momentum thickness, divided by edge Mach number). The Shuttle Orbiter windward ceterline data[17] are shown re-plotted in log-log coordinates in Figure 6, while X-33 windward centerline data[18] and attachment-line data[18] are similarly re-plotted in Figures 7 and 8, respectively. Given the inverse dependence between the transition and disturbance parameters, coupled with the facts that M_e~2 for such high-angle-of-attack flow fields and (δ/θ) for laminar boundary layers is ~7.5, it can be directly shown that the critical roughness Reynolds number for transition, for 3D isolated roughness elements on this class of vehicles, is order 500 to 1000. Comparing the results of Figures 5 and 8 shows that critical roughness Reynolds numbers for 3D isolated elements are essentially the same (~1000) for incompressible and compressible attachment-line flows when based on boundary layer edge conditions. Further, comparing the results of Figures 3 and 7 shows that the critical roughness Reynolds number for transition due to 3D distributed roughness elements (~100) can be an order of magnitude lower than the corresponding value for 3D isolated roughness elements (~1000).

This latter observation is of more than scientific interest. The X-33 flight-test vehicle[19] was designed, and the single-stage-to-orbit reusable launch vehicle VentureStar[20] was defined, based on the isolated roughness element results of Figures 7 and 8. For both vehicles, the thermal protection system is comprised of overlapping, sharp-cornered, metallic panels yielding a periodic distributed array of "steps" with edges skewed to local flow directions (see Figure 1 of Reference 21). Hama[22,23] found that triangular plan-form, flow-aligned, roughness elements were most efficient at tripping both incompressible and compressible boundary layers to turbulence. To complicate matters further, these metallic panels "bow" or warp under re-entry heating.[21] The aerothermodynamic survivability of such metallic heat shield concepts remains to be proven.

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Figure 1. **Generalized Correlation Approach**

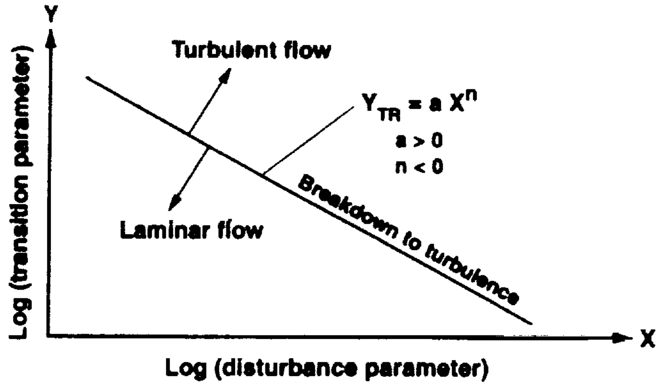

Figure 2. **NOSETIP TRANSITION**

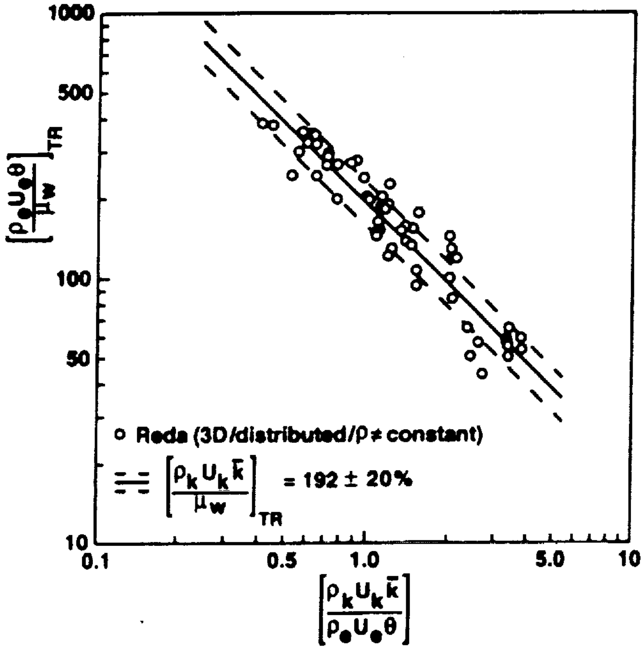

Figure 3. **NOSETIP TRANSITION**

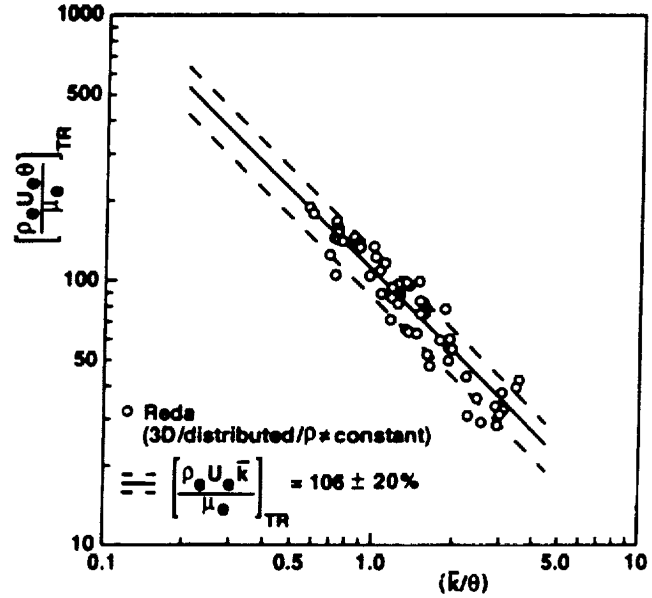

Figure 4. **SWEPT CYLINDERS ATTACHMENT LINE TRANSITION**

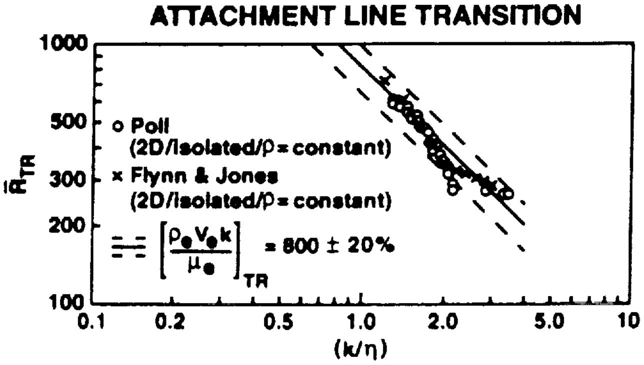

Figure 5. **SWEPT CYLINDERS ATTACHMENT LINE TRANSITION**

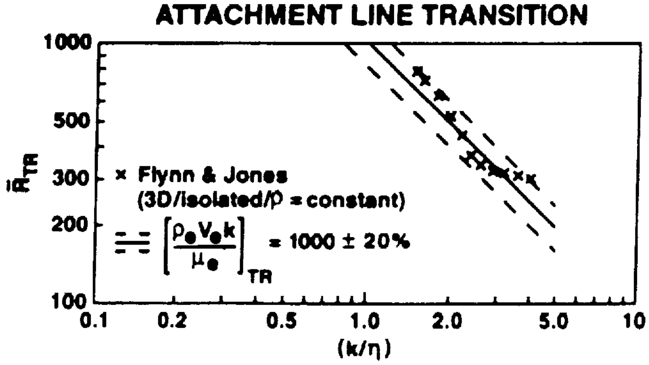

Figure 6. **SHUTTLE CENTERLINE TRANSITION**

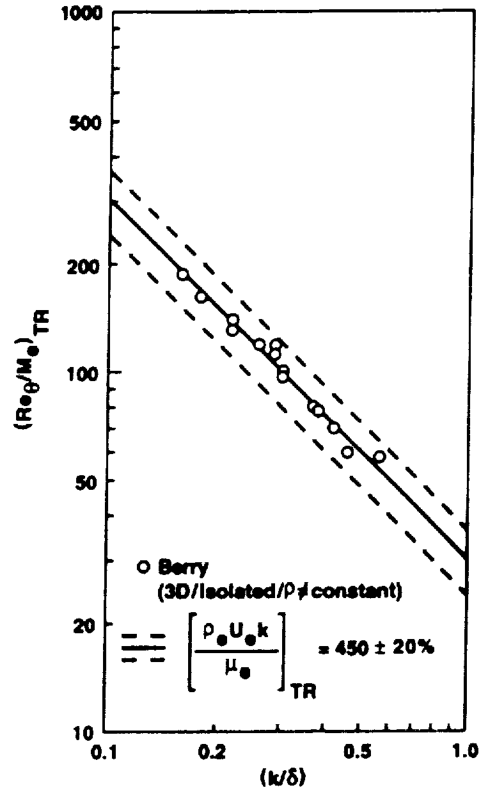

Figure 8. **X-33 ATTACHMENT LINE TRANSITION**

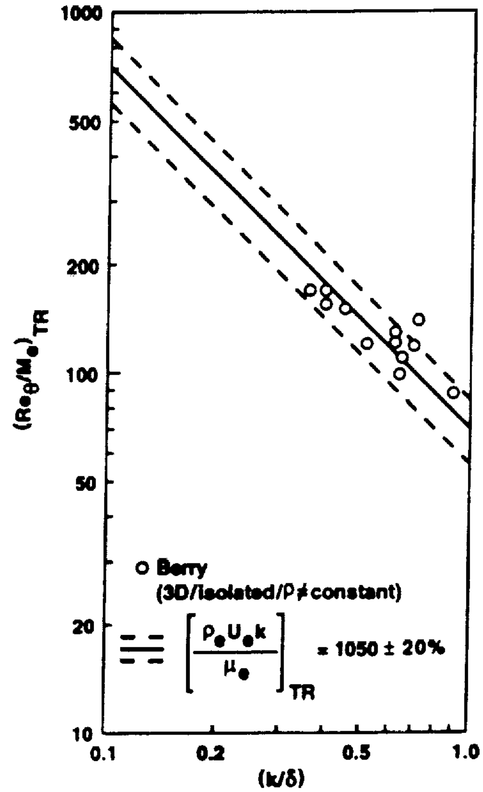

Figure 7. **X-33 CENTERLINE TRANSITION**