

# Investigation of Boundary-Layer Transition on Smooth Hemispherical Bodies

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The main goal of this project was to determine if known correlations can be used to predict the occurrence and location of boundary-layer transition on “smooth” hemispherical surfaces with very small roughness heights ( $\leq 25 \mu\text{in}$ ). A number of empirical correlations were evaluated against experimental data, however, no universal correlation was found that could acceptably describe the observed transition events during the flight tests analyzed. Only a sparse set of data was available for deriving and assessing the various correlations; correlations derived from a larger set of data may be better suited for predicting transition. The correlations examined implement many of the parameters traditionally used (such as geometry, surface roughness, edge Mach number, boundary-layer momentum thickness, and Reynolds number), but are based on an incomplete understanding of the relevant physics. Because these correlations do not account for the physical processes driving transition, they cannot be used to accurately predict the occurrence or location of transition from laminar to turbulent flow. In addition, two of the flight tests considered showed periods of higher heating inconsistent with predictions based on laminar theory that were not investigated by the original authors. Transition during these periods appears to be forced by transitory events related to the operation of the sounding rockets, such as motor burn-out transients and other unidentified mechanisms. In order to be able to better predict transition, it will be necessary to obtain a clear understanding of the physical processes that cause transition.

## I. Introduction

TRANSITION of boundary-layer flow from laminar to turbulent has a very large impact on the aeroheating experienced by air vehicles. For example, completely turbulent flow produces aeroheating that is 3–8 times greater than that produced by laminar flow. However, contrary to what might be expected, a fully-turbulent boundary-layer is not the worst possible scenario. When a boundary-layer transitions from laminar to turbulent, the resulting aeroheating at the transition point can be significantly greater than if the boundary-layer were completely turbulent. In order to obtain accurate results from aeroheating analyses, it is essential to be able to predict when and where boundary-layer transition occurs.

Unfortunately, predicting boundary-layer transition is a very difficult problem that researchers have been struggling to solve for decades.<sup>1,2</sup> The largest difficulty in predicting boundary-layer transition is that much remains unknown concerning the physical mechanisms that drive the transition from laminar to turbulent flow. Several fundamental “modes” of physical phenomena are believed to be responsible for causing boundary-layer transition—none, however, are very well understood,<sup>2,3</sup> and even less is known about possible interactions between modes. Additionally, virtually all wind tunnels have a higher level of disturbances present in the free-stream flow than for free-flight environments.<sup>1,4</sup> As a result, it is believed that transition will occur sooner on a wind tunnel test model than it would on a vehicle in free-flight.

The traditional method of predicting boundary-layer transition is through the use of empirical correlations that attempt to link boundary-layer transition to certain geometry, flow, and boundary-layer properties (such

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# Report Documentation Page

Form Approved  
OMB No. 0704-0188

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1. REPORT DATE <b>17 NOV 2010</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2010 to 00-00-2010</b>	
4. TITLE AND SUBTITLE <b>Investigation of Boundary-Layer Transition on Smooth Hemispherical Bodies</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Naval Air Warfare Center, Weapons Division, China Lake, CA, 93555</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM202978. Presented at the AIAA Missile Sciences Conference Held in Monterey, California on November 16-18, 2010. Sponsored by the Office of the Under Secretary of Defense, Acquisition Resources and Analysis Security Management.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>59</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

as surface roughness or curvature, edge Mach number, boundary-layer momentum thickness Reynolds number, etc.).<sup>1,2</sup> Many correlations for predicting boundary-layer transition have been created over the decades, but these correlations are only applicable to a limited range of vehicle geometries and flight conditions. No “general” boundary-layer transition correlation has been discovered that can be applied universally. As a result, it can be difficult to determine how to handle boundary-layer transition when performing aeroheating analyses. If the range of applicability for a transition correlation is not fully understood, the correlation could incorrectly be applied to problems for which it is not well suited. Such an analysis could easily lead to non-conservative results with potential negative consequences for system performance.

## II. Objectives

The objective of this project was to determine appropriate boundary-layer transition correlations that are applicable to the aerothermal analyses of “smooth” hemispherical surfaces with very small roughness heights ( $\leq 25 \mu\text{in}$ ). One goal of this project was to determine if known correlations can be used to describe and predict boundary-layer transition on these surfaces of interest. It was desired to identify at least one correlation that could be effectively used to predict boundary-layer transition on “smooth”, blunt bodies (such as sphere-cone or sphere-cylinder geometries). Only flight test data was used for this effort, in an attempt to eliminate the influence of wind tunnel noise on the correlations.

## III. Literature Survey

A literature survey was conducted as the first step in this project. This literature survey had several goals. First, it was necessary to identify correlations and parameters that can be used to predict the occurrence and position of boundary-layer transition. Second, it was desired to obtain experimental data that could be used to assess the accuracy and applicability of these correlations. The different phases of the literature survey are discussed in more detail in the sections below.

### III.A. Boundary-Layer Transition Correlations

A review of the literature was undertaken to identify candidate correlations that could be used to predict boundary-layer transition. Particular attention was given to correlations that would take into account the effects of roughness on boundary-layer transition. A review conducted by Schneider<sup>2</sup> identified a number of correlations that have historically been used to predict boundary-layer transition. These correlations are discussed in the sections below.

From this paper it was also possible to identify a list of variables that seemed relevant to the boundary-layer transition phenomena that could be included in new correlations.

#### III.A.1. Momentum Thickness Reynolds Number Correlations

A commonly used variable for boundary-layer transition correlations is the momentum thickness Reynolds number,  $Re_\theta$ , which is computed from the boundary-layer edge flow properties and the momentum thickness of the laminar boundary-layer at the point of transition:

$$Re_\theta = \frac{\rho_e U_e \theta}{\mu_e} \quad (1)$$

A commonly-used correlation involving the momentum thickness Reynolds number is:

$$Re_\theta \quad \text{vs.} \quad M_e \quad (2)$$

However, this correlation does not consider the influence of surface roughness on transition. In order to take into account the surface roughness, it was decided to evaluate the correlation:

$$Re_\theta \quad \text{vs.} \quad \frac{k}{\theta} \quad (3)$$

which compares the momentum thickness Reynolds number to the surface roughness normalized by the boundary-layer momentum thickness. It was decided to also compare  $Re_\theta$  to the surface roughness normalized

by the boundary-layer thickness (the edge of the boundary-layer was defined to be the point where the velocity was equal to 99.5% of the freestream value):

$$Re_{\theta} \quad \text{vs.} \quad \frac{k}{\delta} \quad (4)$$

and to the surface roughness without any normalization:

$$Re_{\theta} \quad \text{vs.} \quad k \quad (5)$$

One additional correlation presented by Schneider<sup>2</sup> that considers the momentum thickness Reynolds number, the edge Mach number, and the surface roughness is that used on space shuttle studies:

$$\frac{Re_{\theta}}{M_e} \quad \text{vs.} \quad \frac{k}{\delta} \quad (6)$$

This correlation compares a Mach-normalized momentum thickness Reynolds number to the surface roughness normalized by the boundary-layer thickness. It was decided to also compare  $Re_{\theta}/M_e$  to the surface roughness without any normalization:

$$\frac{Re_{\theta}}{M_e} \quad \text{vs.} \quad k \quad (7)$$

A final correlation that was considered based on the momentum thickness was:

$$Re_{\theta} \quad \text{vs.} \quad Re_{\infty} \quad (8)$$

The purpose of this correlation was to determine what influence the free stream flow properties had on the transition momentum thickness Reynolds number. Note that this correlation did not take into account surface roughness effects.

### III.A.2. Roughness Reynolds Number Correlation

The roughness Reynolds number,  $Re_k$ , is a commonly used correlation variable for determining the effects of surface roughness on transition.<sup>2</sup> The roughness Reynolds number is computed based upon flow properties within the boundary-layer at the roughness element height:

$$Re_k = \frac{\rho_k U_k k}{\mu_k} \quad (9)$$

The roughness Reynolds number can be a useful parameter for determining if a given surface roughness will have a significant impact on boundary-layer transition. The literature suggests that surface roughnesses producing an  $Re_k \leq 10$ –25 are unlikely to greatly influence transition, though in some cases an  $Re_k$  as low as one can still be sufficient to cause transition.<sup>2</sup> However, for the three models and test flights considered as part of this effort, the roughness Reynolds number was computed to always be less than one. Thus, it was decided to not pursue a roughness Reynolds number correlation for this effort.

### III.A.3. Correlations Selected for Assessment

For this effort it was decided to pursue the correlations given by Eq. (2), Eq. (3), and Eq. (4) and assess the accuracy of these correlations for predicting transition on smooth, hemispherical surfaces. It was also decided to investigate a new correlation:

$$Re_{\theta} \quad \text{vs.} \quad \phi \quad (10)$$

that took into account both the momentum thickness Reynolds number at transition and the position of the transition point on the sphere (measured in degrees from the stagnation point).

## III.B. Experimental Data

Schneider<sup>1</sup> has conducted a review of flight test experiments pertaining to boundary-layer transition. This review paper summarizes a large number of test efforts, and identifies references that contain data suitable for further analysis. Based on Schneider's survey, it was possible to identify three sources of experimental boundary-layer transition data for smooth, blunt bodies that could be used for assessing the effectiveness of different correlations in predicting boundary-layer transition. A summary of each of these three references is given in the following sections.

### III.B.1. Buglia Sphere-Cone

Buglia<sup>7</sup> presents boundary-layer transition results for a test flight of a sphere-cone model with a cone half-angle of  $14.5^\circ$ , a base diameter of 17.56 inches, a nose radius of 6.498 inches, and a surface roughness of 2-5  $\mu\text{in}$ , as measured by an interferometer. A schematic of the test item is presented in figure 1. The flight test spanned a range of Mach numbers from 2.13 to 3.14; the unit Reynolds number varied between  $13.1 \times 10^6$  and  $16.5 \times 10^6$ . It was assumed that the model angle of attack throughout the test was  $0^\circ$ . The sounding rocket propelling the test item had an M6 “Honest John” first stage motor, with an M5 “Nike” upper stage.

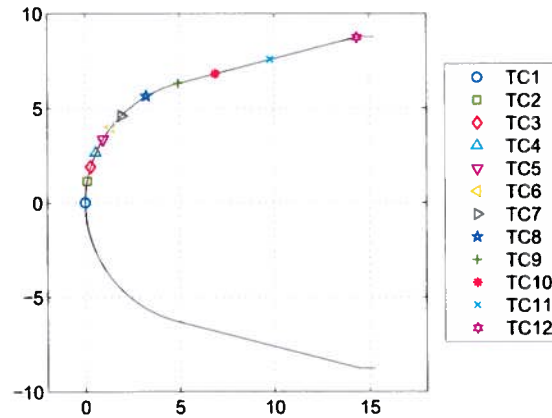


Figure 1. Schematic of the sphere-cone nose cone test item utilized during the Buglia test flight, with thermocouple positions indicated; dimensions are in inches.

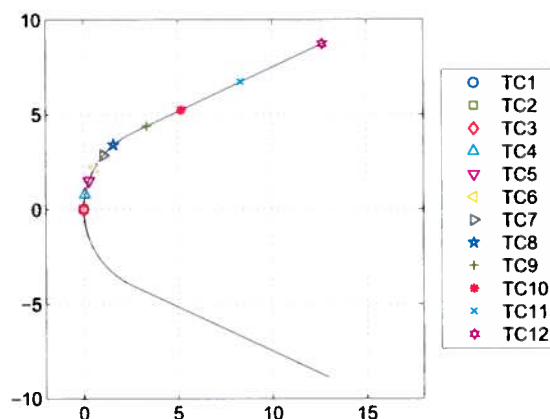
Only the last second of data was analyzed in the original report. From reviewing the wall temperature histories, it appears that the flow was laminar for much of the early part of the flight. However, it seems that at about four seconds into the flight some mechanism (proposed by the present authors to be vibrations from the first-stage rocket motor at burn-out) caused the boundary-layer to trip to turbulent at the sphere-cone junction. At about five seconds into the flight it appears that laminar flow was restored over the model. A more complete analysis of the first seven seconds of flight test data was made as part of this effort and is described in Section IV.A.

Formal analysis of the flight test data (as presented in the original report) began at seven seconds into the flight. At that moment transition was detected on the cone portion of the model; transition then quickly moved forward to a point on the sphere  $38^\circ$  from the stagnation point. It was assumed that the transition position coincided with the position of the furthest aft thermocouple that recorded a Stanton number consistent with that predicted by laminar boundary-layer theory. Thermocouples located further aft of this selected transition point recorded Stanton numbers more comparable to that predicted by turbulent boundary-layer theory. However, it is likely that transition actually occurred between thermocouples.

The flight profile and thermocouple responses from launch through eight seconds of flight time were presented in the original paper. No data was available after eight seconds of flight time. Analysis of the boundary layer was made by Buglia at the flight times 7.0, 7.2, 7.4, 7.6, 7.8, and 8.0 seconds, which corresponded to a free stream Mach number of 2.32, 2.47, 2.63, 2.8, 2.97, and 3.14, respectively.

### III.B.2. Chauvin and Speegle Sphere-Cone

Chauvin and Speegle<sup>8</sup> present flight test data for boundary-layer transition on a blunt cone with a cone half-angle of  $25^\circ$ , a base diameter of 17.75 inches, a nose radius of 4.44 inches, and a surface roughness of approximately 25  $\mu\text{in}$ , as measured by a profilometer. A schematic of the test item can be seen in figure 2. The Mach number during the test varied from 2.5 to 4.7, and the unit Reynolds number varied between  $12.25 \times 10^6$  and  $21.7 \times 10^6$ . It was assumed that the model angle of attack throughout the test was  $0^\circ$ . This report also presents data for a similar, sharp-nosed cone; the data for the sharp-nosed cone was not used during this study. The Chauvin test flight employed the same sounding rocket setup as was used for the Buglia test flight.



**Figure 2.** Schematic of the sphere-cone nose cone test item utilized during the Chauvin test flight, with thermocouple positions indicated; dimensions are in inches.

Only the last two seconds of data were analyzed in the original report. Throughout this period boundary-layer transition was fixed at a point on the sphere  $22^\circ$  from the stagnation point. Transition location was determined based on Stanton number calculations in the same manner as in the Buglia experiment, as discussed in Section III.B.1. The wall temperature histories suggest that the flow was laminar for much of the early part of the flight. However, at about three seconds into the flight it seems that something caused the boundary-layer to become turbulent on part of the conical afterbody. By about four and a half seconds into the flight the transition point had shifted forward onto the spherical portion of the test item. At about five and a half seconds into the flight it appears that laminar flow was restored over the model. A more complete analysis of the earlier portion of the flight test was made as part of this effort and is described in Section IV.B.

The original paper included data describing the flight profile and the thermocouple responses from launch through about nine seconds of flight time. Chauvin and Speegle conducted analyses of the boundary-layer from measurements at five free stream Mach numbers: 2.5, 3.0, 3.5, 4.0, and 4.7, which were taken at flight times of 7.2, 7.75, 8.25, 8.7, and 9.28 seconds, respectively.

### III.B.3. Garland and Chauvin Sphere-Cylinder

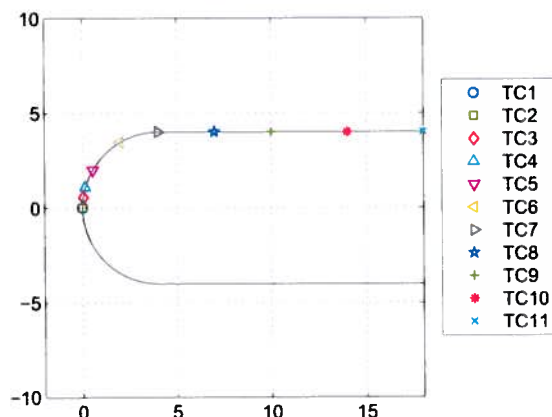
Garland and Chauvin<sup>7</sup> present flight test data for a sphere-cylinder model with a diameter of 8 inches. The RMS surface roughness on the nose section of the model was  $25 \mu\text{in}$ , and the aft section had a roughness of  $60 \mu\text{in}$ , as measured by a profilometer. A schematic of the test item can be seen in figure 3. The flight test spanned a range of Mach numbers from 2.0 to 3.88, and a unit Reynolds number range from  $4.0 \times 10^6$  to  $18.9 \times 10^6$ . It was assumed that the angle of attack of the model remained  $0^\circ$  throughout the flight. This test used a two-stage rocket for model propulsion; the first stage was an M5 “Nike” and the second stage was an ABL “Deacon”.

Transition position was determined from Stanton number calculations in the same manner as discussed in Section III.B.1. Transition occurred at a point on the sphere  $15^\circ$  from the stagnation point early in the flight, and then moved aft. After about five seconds of flight time transition moved off of the sphere and onto the cylinder, becoming fixed at trip cause by a junction between two cylindrical segments of the model.

The thermocouple responses and the flight profile data from launch through 29 seconds of flight time were provided by Garland and Chauvin. The original report contained analyses of the boundary-layer for several instances during the flight. Nine of these analyses were found to be particularly relevant to this effort, and corresponded to four different Mach numbers: 2.0 ( $t = 2.75$  and  $27.25$  seconds), 2.5 ( $t = 3.2$  and  $5.45$  seconds), 2.8 ( $t = 3.45$ ,  $4.62$ , and  $17.05$  seconds), and 3.08 ( $t = 3.8$  and  $17.3$  seconds).

## IV. Flight Test Analysis

Aerothermal analyses were performed on the Buglia and Chauvin flight tests in order to obtain a better understanding of the origins of observed temperature rises in the thermocouple data that were not discussed



**Figure 3. Schematic of the sphere-cylinder nose cone test item utilized during the Garland test flight, with thermocouple positions indicated; dimensions are in inches.**

by the authors. The ATAC03 computer program, a combined aeroheating and thermal analysis code,<sup>8</sup> was used for these analyses. This code has been extensively validated against experimental data and has proved to be capable for reproducing experimental data for simple geometries, like those used in these two flight tests.

ATAC03 implements the method of steepest descent to trace the position of streamlines across the air vehicle geometry; the boundary-layer along these streamlines is computed using the Momentum/Energy Integral Technique (MEIT), described in more detail in the ATAC03 manual.<sup>8</sup> MEIT employs different shape factors to model laminar and turbulent boundary-layers. Properties for transitional boundary-layers are computed as a weighted average of the laminar and turbulent boundary-layer properties, with a transitional intermittency factor used as the weighting function. The transient, in-depth thermal response of the air vehicle wall is computed by implicitly solving a one-dimensional, finite-difference form of the conduction equation.

Inputs to the ATAC03 code included a geometrical description of the test article, the test article material properties and thickness, the flight profile (altitude and velocity as a function of time), and boundary-layer transition criteria. Outputs from the analysis were the backwall temperatures as a function of time at the location of each thermocouple, which could then be directly compared to the experimental thermocouple data.

For each flight test, a baseline analysis was performed using a laminar boundary-layer assumption. By comparing the predicted laminar thermal response to the measured thermal response from the flight tests, it was possible to identify periods of time and locations where the boundary-layer was turbulent. A subsequent analysis was performed whereby the time and position of transition was manually adjusted such that the predicted thermocouple temperatures closely matched the experimental measurements. In this manner it was possible to discover regions of turbulent flow that were not discussed by the original authors.

#### IV.A. Buglia

While Buglia only discussed the turbulent boundary-layer present during the last second of the test flight, an unexplained increase in the measured temperatures was apparent during the time frame of the first stage burn-out. The baseline analysis of this flight test (assuming a fully laminar boundary-layer) yielded temperatures that did not match the experimental thermocouple measurements during the period of time corresponding to the first stage motor burn-out, as can be seen in figure 4.

During the 4.0-5.0 second time frame, a rise in temperature can be observed (starting at thermocouple #9, and possibly as far forward as thermocouple #8) that does not agree with the predicted thermal response based on laminar theory. Additionally, during the 2.0-3.5 second time frame a smaller rise in temperature was observed for thermocouples #11 and #12 (located on the conical afterbody). Based on these observations, a time-dependent set of transition criteria were defined in order to investigate if transition at these times and locations could explain the observed thermal responses. (No attempt was made to reproduce the transition that occurs during the last second of the flight, since this had previously been analyzed by Buglia.) As can

be seen in figure 4, the resulting predicted thermal response agrees well with the measured thermocouple data, strongly suggesting that periods of turbulent flow were actually occurring earlier in the test flight.

Three periods of turbulent flow were identified, as depicted in figure 5; the boundary-layer appears to relaminarize between these periods of turbulent flow. During the first period (approximately 1.5-3.5 s) transition only occurred on the conical afterbody, while during the second period (approximately 4.0-5.0 s) transition occurred in vicinity of thermocouple #9 or thermocouple #8 (at or just forward of the sphere-cone junction). This second period of turbulence seems to coincide with the first stage motor burn-out transient, and it is speculated that vibrations caused by the burn-out transient could be inducing transition during this time frame. The third and final period of turbulence, during the last second of the flight, was analyzed in the original paper by Buglia; transition began on the conical afterbody, then shifted forward onto the spherical nose of the test item.

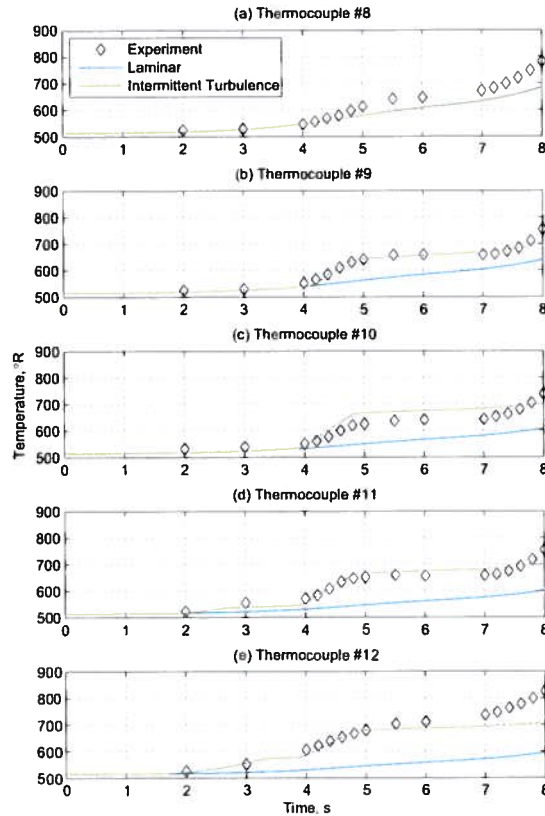


Figure 4. Comparison of experimental thermocouple temperature response to predicted values for laminar and intermittently turbulent boundary-layers for the Buglia flight test.

#### IV.B. Chauvin

Since periods of early transition were identified in the Buglia case, data from other flight tests were reviewed to see if other instances of transition occurring during the motor burn-out could be identified. Upon reviewing the Chauvin flight test report, an unexplained increase in the measured temperatures was also apparent earlier in the flight (during the time frame of the first stage burn-out) that had not been discussed.

Similar to the approach taken by Buglia, Chauvin also only discussed the turbulent boundary-layer present during the last few seconds of the test flight. It was therefore decided to conduct a more detailed analysis of the Chauvin flight test, in the same manner as was performed for the Buglia flight test (see Section IV.A). The predicted temperatures from the baseline analysis (assuming a fully laminar boundary-layer) of this flight test did not match the experimental thermocouple measurements during the period of the first stage motor burn-out, as can be seen in figure 6.

Starting at about 3.0 seconds into the flight, a rise in temperature can be observed for thermocouples #9

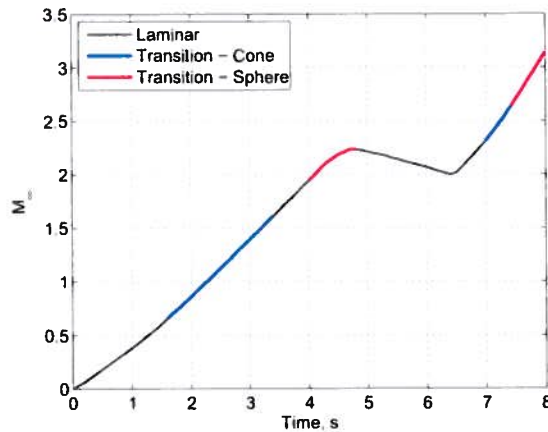


Figure 5. Mach number profile for the Buglia flight test, with instances of turbulent flow indicated.

– #12 (located on the conical afterbody) that does not agree with the predicted laminar thermal response. During the 4.5–5.5 s time frame, this observed rise in temperature had shifted forward onto the spherical nose of the test item (starting at thermocouple #7, and possibly as far forward as thermocouple #6).

As was done for the Buglia flight test, a time-dependent set of transition criteria were defined based on the observed temperature rises that were inconsistent with laminar theory. (As before, no attempt was made to reproduce the transition that occurs during the last two seconds of the flight, since this had previously been analyzed by Chauvin.) As can be seen in figure 6, the resulting predicted thermal response agrees well with the measured thermocouple data, strongly suggesting that a period of turbulent flow was actually occurring earlier in the test flight.

Two periods of turbulent flow were identified for the Chauvin flight test, as depicted in figure 7; the boundary-layer appears to relaminarize between these periods of turbulent flow. During the first period (approximately 3.0–5.5 s) transition began on the conical afterbody, then starting at about 4.4 seconds shifted forward onto the spherical nose of the test item. This early period of turbulence on the spherical nose seems to coincide with the first stage motor burn-out transient, and it is speculated that vibrations caused by the burn-out transient could be inducing transition during this time frame. The second period of turbulence at the end of the flight was analyzed in the original paper by Chauvin; during this time transition was fixed at a point on the sphere  $22^\circ$  from the stagnation point.

## V. Correlation Assessment

After the candidate boundary-layer transition correlations had been identified, it was necessary to evaluate them relative to the available sources of experimental data. This was accomplished by conducting new boundary-layer analyses of the flight test data in order to acquire all the necessary correlation parameters. It was then possible to plot the data at transition for the various correlations, which were then evaluated by comparisons to the computed boundary-layer parameters at different moments during the test flights.

### V.A. Methodology

Boundary-layer parameters and profiles were computed using the boundary-layer solver (also known as the Harris boundary-layer code).<sup>9</sup> Inputs required by the VGBLP boundary-layer solver included:

- Description of surface geometry
- Free stream flight conditions
- Wall temperature distribution
- Edge pressure distribution
- Print stations for boundary-layer output

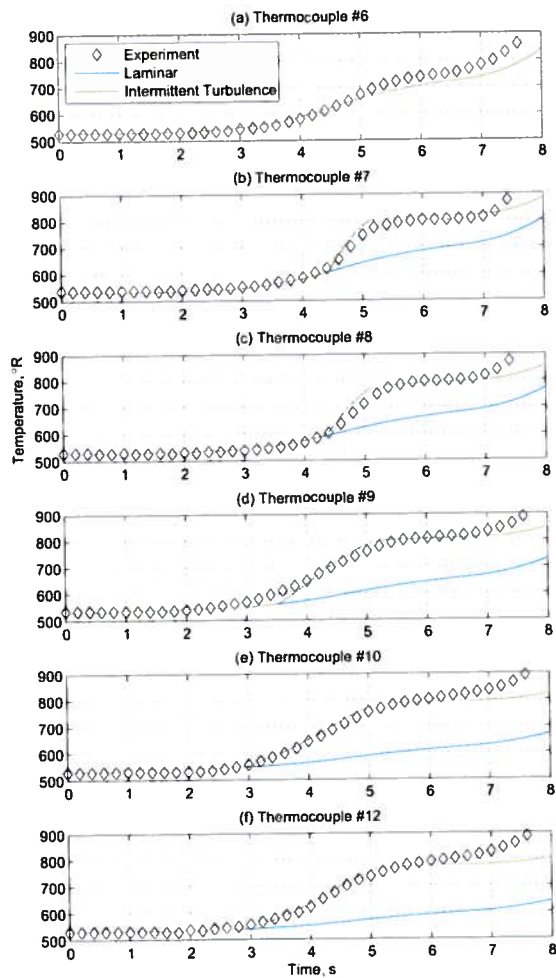


Figure 6. Comparison of experimental thermocouple temperature response to predicted values for laminar and intermittently turbulent boundary-layers for the Chauvin flight test.

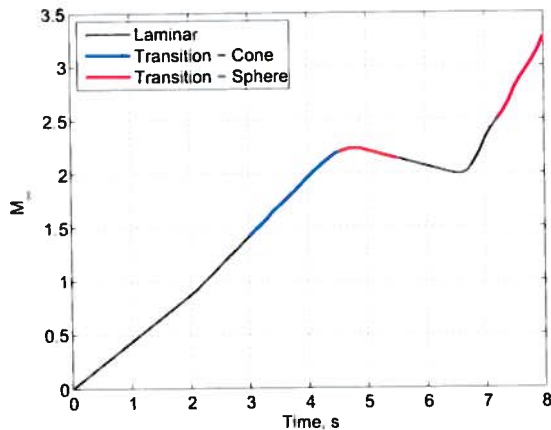


Figure 7. Mach number profile for the Chauvin flight test, with instances of turbulent flow indicated.

In each case, the surface geometry description ( $Z$ ,  $RMI$ ,  $S$  coordinates) and the free stream flow properties (total temperature, total pressure, Mach number) were extracted directly from the flight test reports, along with the wall temperature distribution. The edge pressure distribution ( $P_e$  as a function of  $S$ ) was obtained from an analysis performed with the ATAC03 computer program,<sup>8</sup> since this data was not available from the references. The ATAC03 code required as inputs a description of the geometry, the free stream flight conditions, and an average initial wall temperature. The print station coordinates were selected to match the thermocouple positions in the original tests.

From the VGBLP boundary-layer solver it was possible to obtain as outputs the following:

- Integrated boundary-layer parameters ( $\theta$ ,  $\delta$ ,  $\delta^*$ ,  $Re_\theta$ ,  $Re_s$ , etc.)
- Boundary-layer edge properties ( $M_e$ ,  $T_e$ )
- Boundary-layer property profiles ( $u$ ,  $T$ ,  $\rho$ ,  $\mu$  vs.  $y$ )

A post-processing tool was also employed that used the VGBLP code results and a given roughness height to compute the appropriate roughness Reynolds number. Once all the necessary boundary-layer parameters had been computed with the VGBLP code and its post-processor it was possible to plot up the desired transition correlations.

The VGBLP boundary-layer code was used to solve the governing axisymmetric boundary-layer equations using an implicit, finite-difference procedure. The boundary-layer profile was computed as a function of stream length through a space-marching technique. At each solution station, a mesh with 200 points in the wall-normal direction and a geometric progression constant of 1.0 was employed; solution stations were spaced 0.001 feet apart in the stream-wise direction. Up to ten solution iterations were permitted at each station. All calculations were made with the assumption of a fully-laminar, constant-entropy boundary-layer. Sutherland's law was used for computing viscosity. A discussion of the methods employed by the ATAC03 code can be found in Section IV.

## V.B. Results

After the boundary-layer calculations for the test flights had been completed, it was possible to plot the various boundary-layer transition correlations presented in Section III.A. Based on these correlation plots, it was possible to determine which correlations were useful for predicting boundary-layer transition on smooth, blunt bodies, and to identify those correlations that appear to not be applicable. Only the most promising correlations considered are discussed here.

### V.B.1. Momentum Thickness Reynolds Number vs. Edge Mach Number ( $Re_\theta$ vs. $M_e$ ) Correlation

A correlation for momentum thickness Reynolds number at transition as a function of edge Mach number ( $Re_\theta$  vs.  $M_e$ ) was obtained by plotting the transition point momentum thickness Reynolds number as a function of the corresponding edge Mach number. Only data from instances when transition occurred on the spherical nose of the test items was considered; the resulting plot can be seen as figure 8, where it can be observed that the data appear to follow a mostly linear trend. Because of this trend, a line was fitted to the data from the three different test flights considered in order to obtain the "Universal Fit" correlation. Lines were also individually fit to data from each of the three test flights to obtain the "Buglia Fit", "Chauvin Fit", and "Garland Fit" correlations.

The validity of these correlations for predicting transition was assessed by comparing the correlation curve fits to the computed boundary-layer data for the different test flights at instances when the boundary-layer on the sphere was turbulent, as well as when it was laminar. The comparison between the correlations and the computed boundary-layer for the Buglia test flight can be seen plotted in figure 9; subfigure (a) represents times when the sphere boundary-layer was laminar; subfigure (b) corresponds to times when transition occurred on the sphere (symbols indicate the observed transition point during the test flight). It can be seen that the "Universal Fit" correlation does not accurately describe transition in this case; it predicts that the boundary-layer ought to be turbulent starting near the stagnation region for all moments in time. The "Buglia Fit" correlation only slightly better describes transition. The "Buglia Fit" correlation correctly predicts a laminar boundary-layer for the instances when it was observed that the boundary-layer was, in fact, laminar. However, the "Buglia Fit" correlation predicts, for instances when the boundary-layer was turbulent, that the transition point should occur farther forward on the sphere than was actually

observed. Additionally, this correlation predicts that transition should not occur for one instance ( $t = 7.4$  s) when transition was observed to occur. Finally, the slope of these correlations is very similar to the slope of the data describing the computed boundary-layer. As such, any small uncertainty in the boundary-layer parameters will result in a much larger uncertainty in the location of the transition point.

A similar comparison was made for the Chauvin flight test, which can be seen in figure 10. As was the case for the Buglia flight test, the “Universal Fit” correlation does not accurately describe transition; in this case it predicts that the boundary-layer would remain laminar for all instances, even when the boundary-layer was observed to be turbulent. The “Chauvin Fit” correlation describes transition somewhat better, and correctly indicates when the boundary-layer should remain laminar (see subfigure (a)). However, since the slope of the correlation is nearly the same as the slope of the computed boundary-layer data (subfigure (b)) it is not possible to definitively predict the point at which transition would occur.

The same comparisons can be seen in figure 11 for the Garland test flight. In this case it appears that the “Universal Fit” and the “Garland Fit” correlations describe boundary-layer transition with about the same accuracy. Both correlations accurately predict when the boundary-layer should remain laminar, and both predict that transition will occur for most instances when transition was, in fact, observed. However, as was seen with the comparisons to the Buglia and Chauvin test flights, the slope of the correlation curve is similar to that of the computed boundary-layer parameter curve, which makes it difficult to definitively predict the transition location.

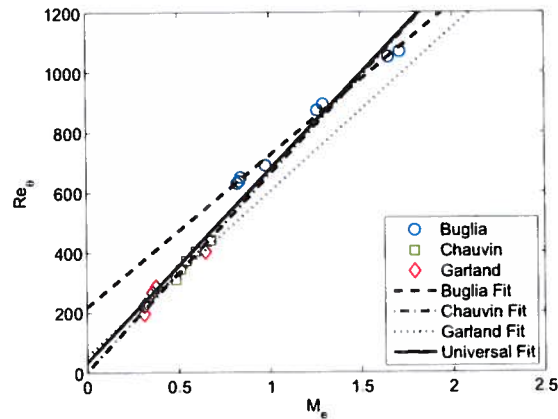
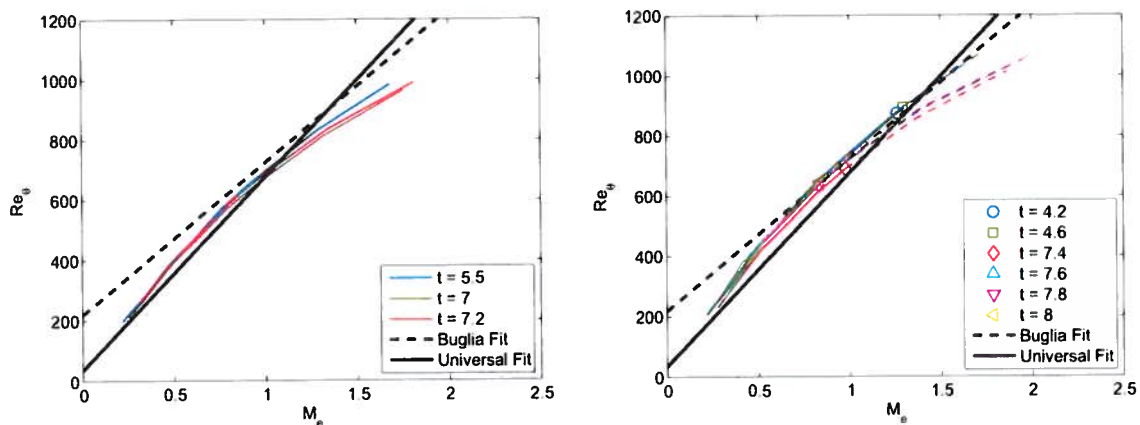
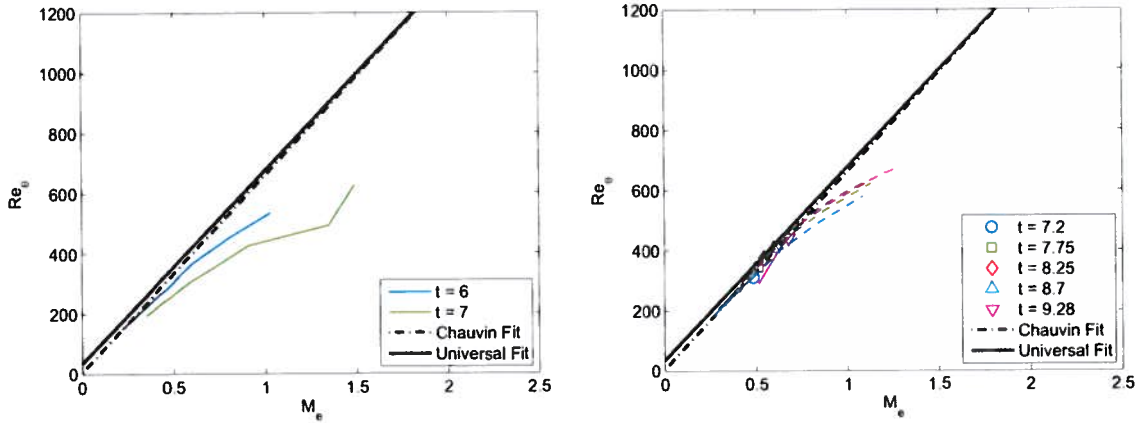


Figure 8. Momentum thickness Reynolds number vs. edge Mach number ( $Re_{\theta}$  vs.  $M_e$ ) correlation for transition on a sphere.



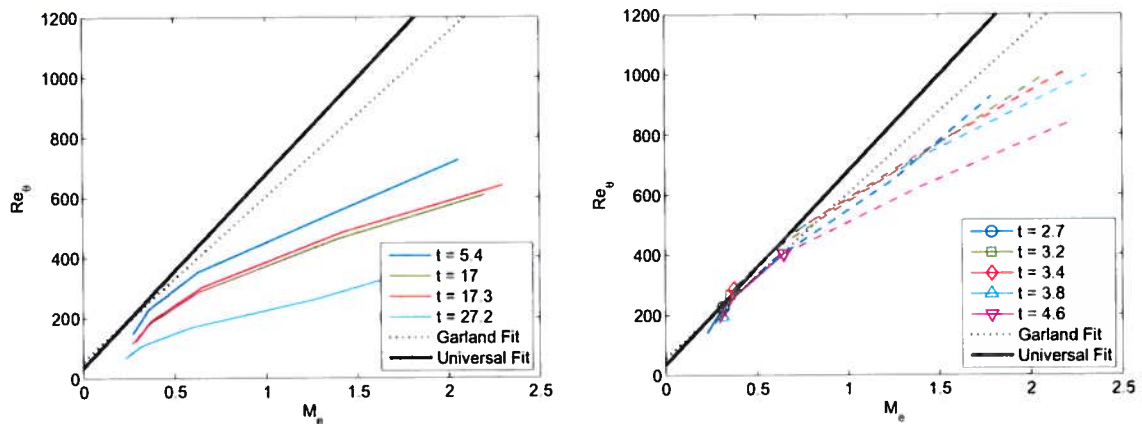
(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 9. Comparison of momentum thickness Reynolds number vs. edge Mach number ( $Re_{\theta}$  vs.  $M_e$ ) correlation to the computed boundary-layer for selected instances from the Buglia test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.



(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 10. Comparison of momentum thickness Reynolds number vs. edge Mach number ( $Re_\theta$  vs.  $M_e$ ) correlation to the computed boundary-layer for selected instances from the Chauvin test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.



(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 11. Comparison of momentum thickness Reynolds number vs. edge Mach number ( $Re_\theta$  vs.  $M_e$ ) correlation to the computed boundary-layer for selected instances from the Garland test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.

Based upon the limited data available, it seems evident that no “universal”  $Re_\theta$  vs.  $M_e$  correlation can be derived for predicting transition on a generic spherical surface, but it may be possible to derive specific correlations that are applicable to a particular test item. The sparseness of the data available could be a factor; a “universal” correlation derived from a much larger data set may be able predict transition more accurately. Since it was observed that the slopes of the correlation curves were very similar to the slope of the computed boundary-layer parameter curves, it is believed that this particular correlation simply describes the relationship between the momentum thickness Reynolds number and edge Mach number for a laminar boundary-layer on a sphere. In effect, this relationship simply correlates a boundary-layer to itself; it can, to a first order approximation, describe the relationship between momentum thickness Reynolds number and edge Mach number at any point on the boundary-layer (including transition), but it cannot accurately predict whether or not transition will occur at any given point on a sphere.

### *V.B.2. Momentum Thickness Reynolds Number vs. Position on Sphere ( $Re_\theta$ vs. $\phi$ ) Correlation*

Once it was observed that the  $Re_\theta$  vs.  $M_e$  correlation could not accurately predict transition, it was hypothesized that transition might be predicted by correlating the momentum thickness Reynolds number at transition to the position of the transition point on the sphere (measured in degrees from the stagnation point). Data from instances where transition occurred on the sphere can be seen plotted in figure 12. Because of the strong linear trend observed, a line was fitted to the data from the three different test flights considered in order to obtain the “Universal Fit” correlation.

The comparison between the  $Re_\theta$  vs.  $\phi$  correlation and the computed boundary-layer for the Buglia test flight can be seen plotted in figure 13; subfigure (a) represents times when the sphere boundary-layer was laminar; subfigure (b) corresponds to times when transition occurred on the sphere (symbols indicate the observed transition point during the test flight). It can be seen that the “Universal Fit” correlation does not accurately describe transition in this case. While it does seem to accurately predict the times when the boundary-layer ought to be laminar or turbulent, this correlation cannot be used to predict the position at which transition occurs for the Buglia test flight. In all cases where turbulence was observed, transition is predicted to start near the stagnation point of the sphere, instead of farther aft on the sphere as was actually observed during the test flight. It can also be observed that the slope of the correlation curve is virtually identical to the slope of the curves for the computed boundary-layer parameters.

A similar set of comparisons, except for the Chauvin flight test, can be seen plotted in figure 14. The “Universal Fit” correlation does agree with the two instances where a laminar boundary-layer was observed, but it also predicts that the boundary-layer should have been laminar for two instances during the test flight when the boundary-layer was observed to be turbulent. As was the case for the Buglia test flight, this correlation predicts that transition should start near the stagnation region, and the slope of the correlation curve is similar to the slope of the computed boundary-layer parameter curves.

The comparisons between this correlation and the Garland flight test can be seen in figure 15. The “Universal Fit” correlation agrees with the instances when the boundary-layer was observed to be laminar, but also predicts that the boundary-layer should remain laminar for most instances when a turbulent boundary-layer was observed.

Based upon these plots, it seems evident that the momentum thickness Reynolds number vs. position on sphere ( $Re_\theta$  vs.  $\phi$ ) correlation cannot be used for predicting transition. Since it was observed that the slope of the correlation curve was nearly equal to the slope of the computed boundary-layer parameter curves, it is believed that this particular correlation simply describes the relationship between the momentum thickness Reynolds number and the position on the sphere for a laminar boundary-layer. In effect, this relationship simply correlates a boundary-layer to itself; it cannot predict whether or not transition will occur at any given point on a sphere.

### *V.B.3. Momentum Thickness Reynolds Number vs. Roughness Height Normalized by Momentum Thickness ( $Re_\theta$ vs. $k/\theta$ ) Correlation*

In order to take into account the effect that surface roughness might have on transition, a third correlation, based on the momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_\theta$  vs.  $k/\theta$ ), was explored. Data from instances where transition occurred on the sphere can be seen plotted in figure 16. A line was fitted to the data from the three different test flights considered in order to

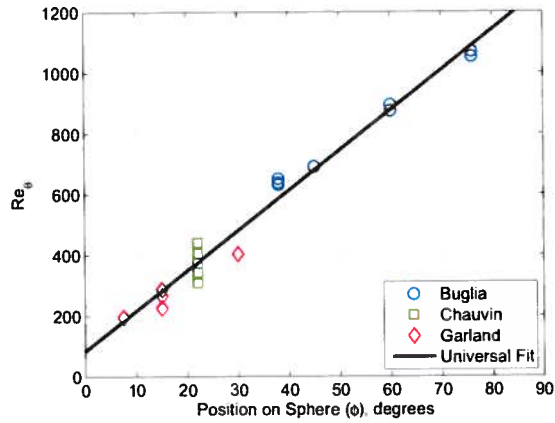
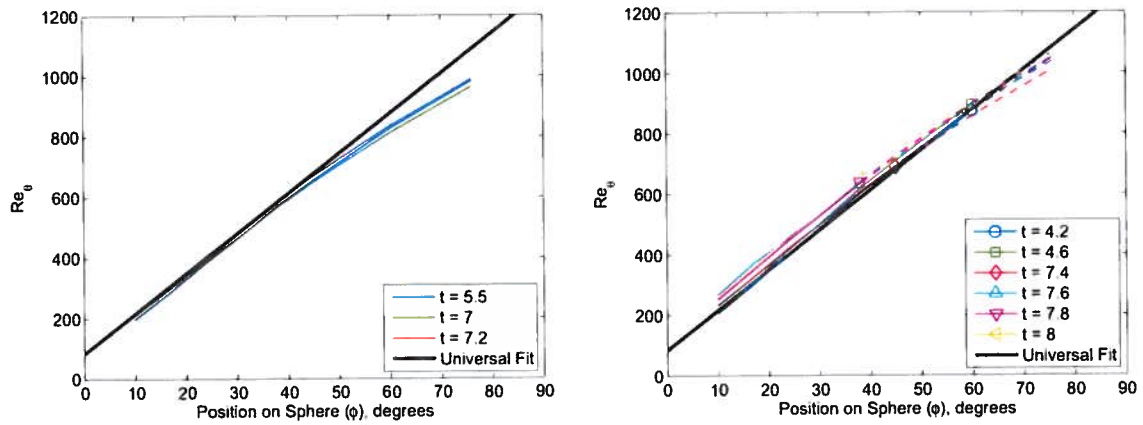
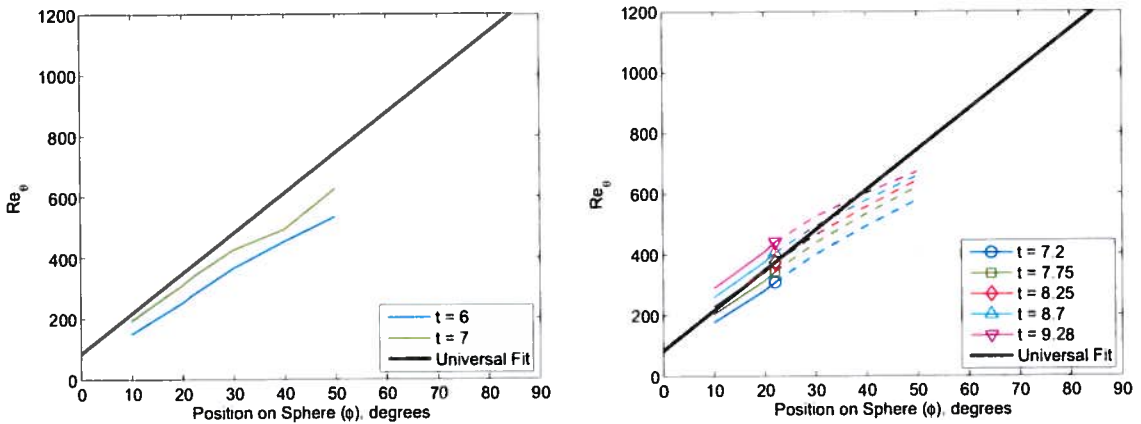


Figure 12. Momentum thickness Reynolds number vs. position on sphere ( $Re_{\theta}$  vs.  $\phi$ ) correlation for transition on a sphere.



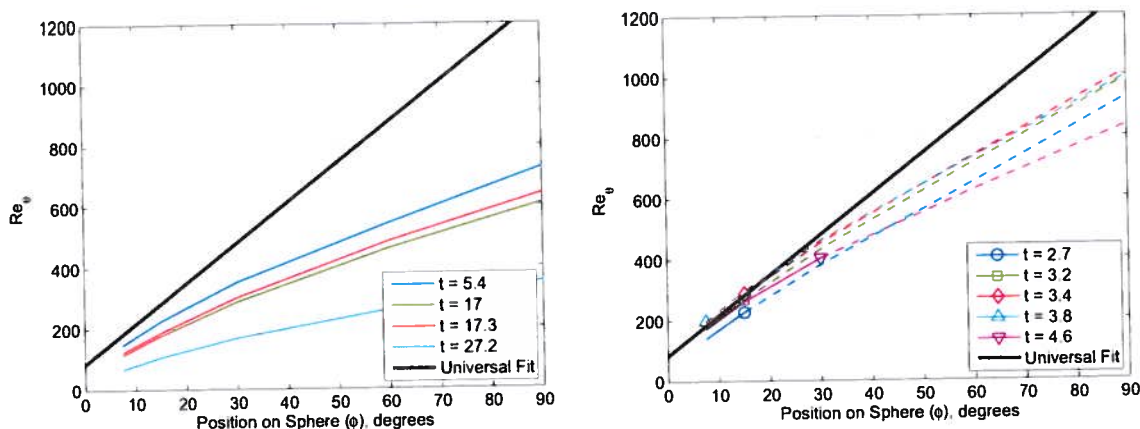
(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 13. Comparison of the momentum thickness Reynolds number vs. position on sphere ( $Re_{\theta}$  vs.  $\phi$ ) correlation to the computed boundary-layer for selected instances from the Buglia test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.



(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 14. Comparison of the momentum thickness Reynolds number vs. position on sphere ( $Re_{\theta}$  vs.  $\phi$ ) correlation to the computed boundary-layer for selected instances from the Chauvin test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.



(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 15. Comparison of the momentum thickness Reynolds number vs. position on sphere ( $Re_\theta$  vs.  $\phi$ ) correlation to the computed boundary-layer for selected instances from the Garland test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.

obtain the “Universal Fit” correlation, but the observed linear trend was weaker than that observed with the previous two correlations.

The comparison between the correlation and the computed boundary-layer for the Buglia test flight can be seen plotted in figure 17; subfigure (a) represents times when the sphere boundary-layer was laminar; subfigure (b) corresponds to times when transition occurred on the sphere (symbols indicate the observed transition point during the test flight). It can be seen that the “Universal Fit” correlation does not accurately describe transition in this case. While it does seem to predict the position of transition with reasonable accuracy for times during the test flight when the boundary-layer was observed to be turbulent, the correlation predicts that transition should occur at all times considered, including those instances when it was observed that the boundary-layer remained laminar.

Comparisons for the Chauvin flight test can be seen plotted in figure 18. The “Universal Fit” correlation predicts the location of transition with moderate accuracy for the instances when the boundary-layer was observed to be turbulent. However, as was also the case for the Buglia flight test, this correlation predicts that the boundary-layer ought to be turbulent during the two instances considered when it was observed to remain laminar.

The comparisons between the Garland flight test and this correlation can be seen in figure 19. As was the case for the Buglia and Chauvin flight tests, the “Universal Fit” correlation is reasonably accurate when predicting the location of transition during the instances when transition was observed to occur. For the Garland test flight this correlation also agrees quite well with most of the instances when a laminar boundary-layer was observed. However, the correlation did predict that the boundary-layer should be turbulent for one instance ( $t = 5.4$  s) when the boundary-layer was observed to be laminar.

Of the correlations described thus far, the momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_\theta$  vs.  $k/\theta$ ) correlation performed the best for predicting the location of transition when it occurred. However, as these comparisons have shown, it will not be possible to use this correlation to accurately predict whether or not transition will actually occur. However, the correlation assessment made here was based on a sparse set of data; it may be that a momentum thickness ( $Re_\theta$  vs.  $k/\theta$ ) correlation derived from a much larger set of data could predict transition more accurately.

#### V.B.4. Momentum Thickness Reynolds Number vs. Roughness Height Normalized by Boundary-Layer Thickness ( $Re_\theta$ vs. $k/\delta$ ) Correlation

A fourth correlation, based on the momentum thickness Reynolds number vs. roughness height normalized by boundary-layer thickness ( $Re_\theta$  vs.  $k/\delta$ ), was also explored. However, the results from this correlation were extremely similar to those of the momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_\theta$  vs.  $k/\theta$ ) correlation, and as such are not presented or discussed here.

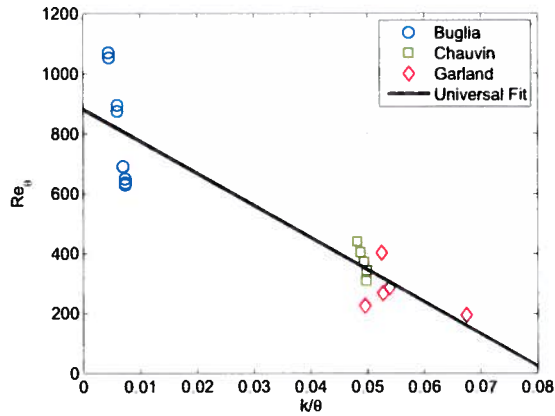
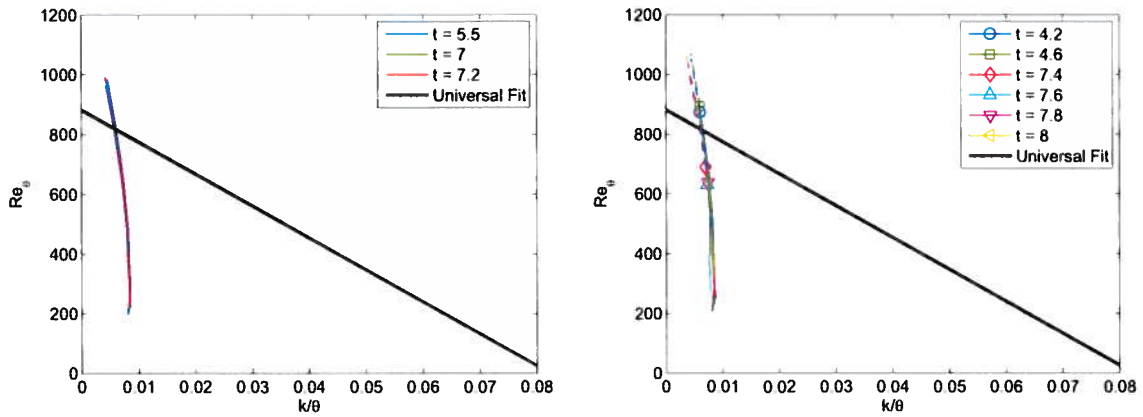
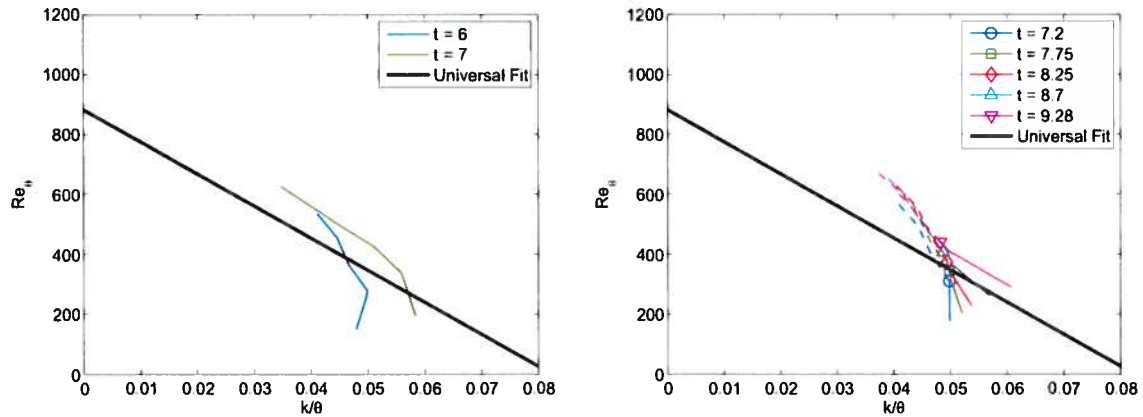


Figure 16. Momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_{\theta}$  vs.  $k/\theta$ ) correlation for transition on a sphere.



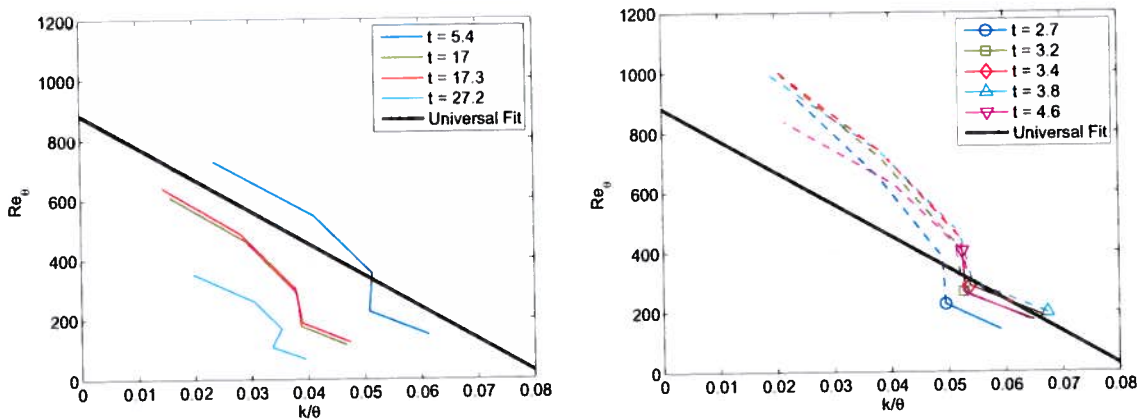
(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 17. Comparison of the momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_{\theta}$  vs.  $k/\theta$ ) correlation to the computed boundary-layer for selected instances from the Buglia test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.



(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

Figure 18. Comparison of the momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_{\theta}$  vs.  $k/\theta$ ) correlation to the computed boundary-layer for selected instances from the Chauvin test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.



(a) Laminar boundary-layer observed on sphere. (b) Turbulent boundary-layer observed on sphere.

**Figure 19.** Comparison of the momentum thickness Reynolds number vs. roughness height normalized by momentum thickness ( $Re_{\theta}$  vs.  $k/\theta$ ) correlation to the computed boundary-layer for selected instances from the Garland test flight. Solid and dashed colored lines correspond to the observed laminar and turbulent portions of the boundary-layer, respectively; symbols indicate the observed location of transition.

## VI. Conclusions

A number of empirical correlations were evaluated against experimental data, however, no universal correlation was found that could accurately describe the transition events observed during the analyzed flight tests. In several instances, the correlations predicted that transition would occur when the boundary-layer was, in fact, observed to remain completely laminar. In other instances, when the boundary-layer was observed to become turbulent, the correlations either predicted an incorrect location for the transition point, or they predicted that the boundary-layer would remain laminar. Several of the correlations explored appeared to just describe the relationship between various laminar boundary-layer parameters. While these correlations can describe the relationship between different boundary-layer parameters at transition, they cannot consistently and reliably predict the occurrence or location of the transition event.

The correlations examined implement many of the parameters traditionally used (such as geometry, surface roughness, edge Mach number, boundary-layer momentum thickness, and Reynolds number), but are based on an incomplete understanding of the physics causing transition. Because these correlations do not account for the physical processes driving transition, they cannot be used to accurately predict the occurrence or location of transition from laminar to turbulent flow. However, only a sparse set of data was available for deriving and assessing the various correlations. Correlations derived from a larger set of data may be better suited for predicting transition.

Two of the flight tests considered showed periods of higher heating inconsistent with predictions based on laminar theory that were not investigated by the original authors. Transition during these periods appears to be forced by transitory events related to the operation of the sounding rockets, such as motor burn-out transients, stage separation and other unidentified mechanisms.

In order to be able to better predict transition, it will be necessary to obtain a clear understanding of the physical processes that cause transition.

## Acknowledgments

This effort was made possible by Core Science and Technology discretionary funding provided by the Weapons and Energetics Department at the Naval Air Warfare Center — Weapons Division, China Lake, California. The authors would also like to thank Dr. Steven Schneider for willingly giving his time for insightful discussions on boundary-layer transition.

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- <sup>2</sup>Schneider, S. P., "Effects of Roughness on Hypersonic Boundary-Layer Transition," *Journal of Spacecraft and Rockets*, Vol. 45, No. 2, March-April 2008, pp. 193-209.
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- <sup>5</sup>Buglia, J. J., "Heat Transfer and Boundary-Layer Transition on a Highly Polished Hemisphere-Cone in Free Flight at Mach Numbers up to 3.14 and Reynolds Numbers up to  $24 \times 10^6$ ," NASA TN D-955, National Aeronautics and Space Administration, September 1961.
- <sup>6</sup>Chauvin, L. T. and Speegle, K. C., "Boundary-Layer-Transition and Heat-Transfer Measurements from Flight Tests of Blunt and Sharp  $50^\circ$  Cones at Mach Numbers from 1.7 to 4.7," NACA RM L57D04, National Advisory Committee for Aeronautics, 1957.
- <sup>7</sup>Garland, B. J. and Chauvin, L. T., "Measurements of Heat-Transfer and Boundary-Layer-Transition on an 8-Inch-Diameter Hemisphere-Cylinder in Free-Flight for a Mach Number Range of 2.00 to 3.88," NACA RM L57D04a, National Advisory Committee for Aeronautics, April 1957.
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Unclassified



**Naval Air Warfare Center Weapons Division**

# Investigation of Boundary-Layer Transition on Smooth Hemispherical Bodies

Presented by  
**Peter Cross**  
**Rick Burnes**  
Code 476100D  
November 17, 2010

**China Lake, California**

Unclassified



# Introduction & Background

- **Boundary-layer transition has large impact on aeroheating**
  - **Turbulent flow produces heating 3-8 times that of laminar flow**
  - **Aeroheating at transition can be significantly greater than that of a completely turbulent boundary-layer**
  - **Accurately predicting where transition occurs on a body is essential in order to obtain an accurate aeroheating prediction**
- **Predicting boundary-layer transition is a difficult task**
  - **Much remains unknown concerning the process of boundary-layer transition**
  - **Many correlations for predicting boundary-layer transition have been created over the decades, but...**
  - **These correlations are only applicable to a very limited range of vehicle geometries and flight conditions**
  - **Correlations are based on sparse data sets**
  - **Multiple fundamental “modes” of physical phenomena believed responsible for transition – none are very well understood**



# Objectives

- **Determine appropriate boundary-layer transition correlations applicable to smooth, blunt surfaces**
  - Sphere-cone or sphere-cylinder geometries
  - “Smooth” surface roughness ( $\leq 25 \mu\text{in}$ )
  - Low edge mach numbers ( $M_e < 2$ )
- **Identify at least one correlation that can be used to describe and predict boundary-layer transition on surfaces of interest**
- **Compare thermal analyses conducted with boundary-layer correlations to experimental data for validation purposes**
- **Consider only flight-test data to eliminate influence of wind tunnel noise**



# Transition Correlations

- **Literature was reviewed to identify candidate correlations for predicting boundary-layer transition**
  - **Particular attention given to correlations that could determine the effects of roughness on transition**
- **A list of variables that seemed relevant to the boundary-layer transition phenomena was identified**
  - **Could be used to develop new correlations**
- **Momentum Thickness Reynolds Number Correlations**
  - **$Re_\theta$  vs.  $M_e$**
  - **$Re_\theta$  vs.  $k/\theta$**
  - **$Re_\theta$  vs.  $k/\delta$**



# Transition Correlations

- **Roughness Reynolds Number Correlation**
  - Roughness Reynolds number ( $Re_k$ ) is computed based upon flow properties within the boundary-layer at the roughness element height
  - Surface roughnesses producing an  $Re_k < 10-25$  are unlikely to greatly influence transition
    - In some cases an  $Re_k$  as low as one can still be sufficient to cause transition
  - For the test flights considered as part of this effort, the roughness Reynolds number was computed to always be less than one
    - It was decided to not pursue a roughness Reynolds number correlation for this effort
- **Sphere Position Correlation**
  - It was decided to investigate a new correlation taking into account:
    - Momentum thickness Reynolds number at transition
    - Position of transition point on the sphere
  - $Re_\theta$  vs.  $\varphi$

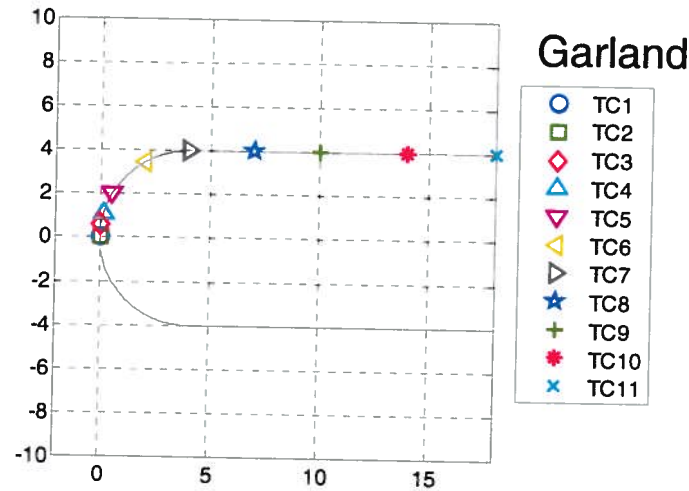
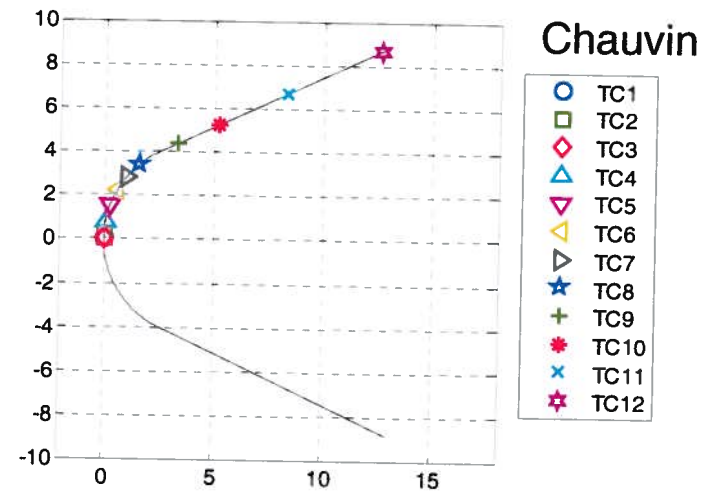
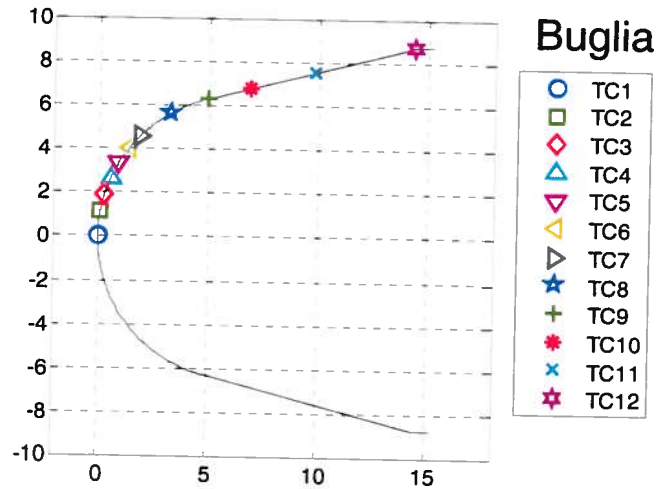


# Experimental Data Sources

- **“Heat Transfer and Boundary-Layer Transition on a Highly Polished Hemisphere-Cone in Free Flight at Mach Numbers up to 3.14 and Reynolds Numbers up to  $24 \times 10^6$ ”**
  - James J. Buglia; NASA TN D-955
- **“Boundary-Layer-Transition and Heat-Transfer Measurements from Flight Tests of Blunt and Sharp  $50^\circ$  Cones at Mach Numbers from 1.7 to 4.7”**
  - Leo T. Chauvin & Katherine C. Speegle; NACA RM L57D04
- **“Measurements of Heat Transfer and Boundary-Layer Transition on an 8-Inch-Diameter Hemisphere-Cylinder in Free Flight for a Mach Number Range of 2.00 to 3.88”**
  - Benjamine J. Garland & Leo T. Chauvin; NACA RM L57D04a, 1957



# Comparison of Model Geometries



**Dimensions are in inches**



# Buglia Sphere-Cone

- **Test Item Geometry**
  - Sphere-cone model with a cone half-angle of  $14.5^\circ$
  - Base diameter of 17.56 inches
  - Nose radius of 6.498 inches
  - Surface roughness of 2-5  $\mu\text{in}$  (as measured by an interferometer)
- **Flight Profile**
  - The flight test spanned a range of Mach numbers from 2.13 to 3.14
  - Unit Reynolds number varied between  $13.1 \times 10^6$  and  $16.5 \times 10^6$
  - It was assumed that the model angle of attack throughout the test was  $0^\circ$
  - A two stage sounding rocket propelled the test item
    - First stage: M6 “Honest John”
    - Second stage: M5 “Nike”



# Buglia Sphere-Cone

- **Transition Behavior**
  - Only the last second of data was analyzed in the original report
  - The flow was laminar for much of the early part of the flight
  - Four seconds into the flight:
    - Something caused the boundary-layer to trip to turbulent at the sphere-cone junction
  - Five seconds into the flight:
    - Laminar flow was restored over the model
  - Seven seconds into the flight:
    - Transition began on the cone, then shifted forward onto the spherical nose
- **Data available**
  - Flight profile and thermocouple responses
    - From launch through eight seconds of flight time
    - No data was available after eight seconds of flight time
  - Analyses of the boundary-layer made by the original author
    - At the flight times 7.0, 7.2, 7.4, 7.6, 7.8, and 8.0 seconds (Mach 2.32, 2.47, 2.63, 2.8, 2.97, and 3.14, respectively)



# Chauvin and Speegle Sphere-Cone

- **Test Item Geometry**
  - Sphere-cone with a cone half-angle of  $25^\circ$
  - Base diameter of 17.75 inches
  - Nose radius of 4.44 inches
  - Surface roughness of approximately  $25 \mu\text{in}$  (as measured by a profilometer)
- **Flight Profile**
  - The Mach number during the test varied from 2.5 to 4.7
  - Unit Reynolds number varied between  $12.25 \times 10^6$  and  $21.7 \times 10^6$
  - It was assumed that the model angle of attack throughout the test was  $0^\circ$
  - A two stage sounding rocket propelled the test item
    - First stage: M6 “Honest John”
    - Second stage: M5 “Nike”
    - Same sounding rocket setup as was used for the Buglia test flight



# Chauvin and Speegle Sphere-Cone

- **Transition Behavior**
  - Only the last few seconds of data were analyzed in the original report
  - The flow was laminar for much of the early part of the flight
  - Three seconds into the flight:
    - Boundary-layer becomes turbulent on the conical afterbody
  - Four and a half seconds into the flight:
    - Transition shifted forward onto the spherical portion of the test item
  - Five and a half seconds into the flight:
    - Laminar flow was restored over the model
  - Seven seconds into the flight:
    - Boundary-layer transition was fixed at a point on the sphere  $22^\circ$  from the stagnation point
- **Data available**
  - Flight profile and the thermocouple responses
    - From launch through nine seconds of flight time
  - Analyses of the boundary-layer made by the original authors
    - At five free stream Mach numbers: 2.5, 3.0, 3.5, 4.0, and 4.7 (flight times of 7.2, 7.75, 8.25, 8.7, and 9.28 seconds, respectively)



# Garland and Chauvin Sphere-Cylinder

- **Test Item Geometry**
  - Sphere-cylinder model with a diameter of 8 inches
  - The RMS surface roughness on the nose section of the model was 25  $\mu\text{in}$
- **Flight Profile**
  - The flight test spanned a range of Mach numbers from 2.0 to 3.88
  - Unit Reynolds number ranged from  $4.0 \times 10^6$  to  $18.9 \times 10^6$
  - It was assumed that the angle of attack of the model remained  $0^\circ$  throughout the flight
  - A two stage sounding rocket propelled the test item
    - First stage: M5 “Nike”
    - Second stage: ABL “Deacon”



# Garland and Chauvin Sphere-Cylinder

- **Transition Behavior**
  - **Early in the flight:**
    - **Transition occurred at a point on the sphere  $15^\circ$  from the stagnation point early in the flight, before moving aft**
  - **Five seconds of flight time:**
    - **Transition moved off of the sphere and onto the cylinder**
    - **Became fixed at trip cause by a junction between two cylindrical segments of the model**
- **Data available**
  - **The thermocouple responses and the flight profile data**
    - **From launch through 29 seconds of flight time**
  - **Analyses of the boundary-layer made by the original authors for several instances during the flight**
    - **Nine of these analyses were found to be particularly relevant to this effort**
      - **Mach 2.0 (t = 2.75 and 27.25 seconds)**
      - **Mach 2.5 (t = 3.2 and 5.45 seconds),**
      - **Mach 2.8 (t = 3.45, 4.62, and 17.05 seconds)**
      - **Mach 3.08 (t = 3.8 and 17.3 seconds).**



# Flight Test Analysis Methodology

- **Aerothermal analyses were performed on the Buglia and Chauvin flight tests**
  - To understand observed temperature rises in the thermocouple data not discussed by the authors
- **The ATAC03 computer program was used for these analyses**
  - A combined aeroheating and thermal analysis code
  - Has been extensively validated against experimental data
  - Had proved to be capable for reproducing experimental data for simple geometries
- **Inputs:**
  - Geometrical description of the test article
  - Test article material properties and thickness
  - Flight profile (altitude and velocity as a function of time)
  - Boundary-layer transition criteria
- **Outputs:**
  - Backwall temperatures (as a function of time) at the location of each thermocouple
    - Could be directly compared to the experimental thermocouple data



# Flight Test Analysis Methodology

- **Baseline analysis**
  - Assumed a completely laminar boundary-layer
  - Compared predicted thermal response to experimental data
    - Could identify flight times & locations on test item where experimental data did not agree with prediction
      - Experimental thermal response greater than predicted thermal response with laminar boundary-layer
      - Boundary-layer believed to be transitional or turbulent
- **Subsequent analysis**
  - Transition behavior specified
    - Time and position of transition manually adjusted
    - Predicted thermocouple temperatures closely matched the experimental measurements
- These analyses revealed periods and regions of turbulent flow that were not discussed by the original authors

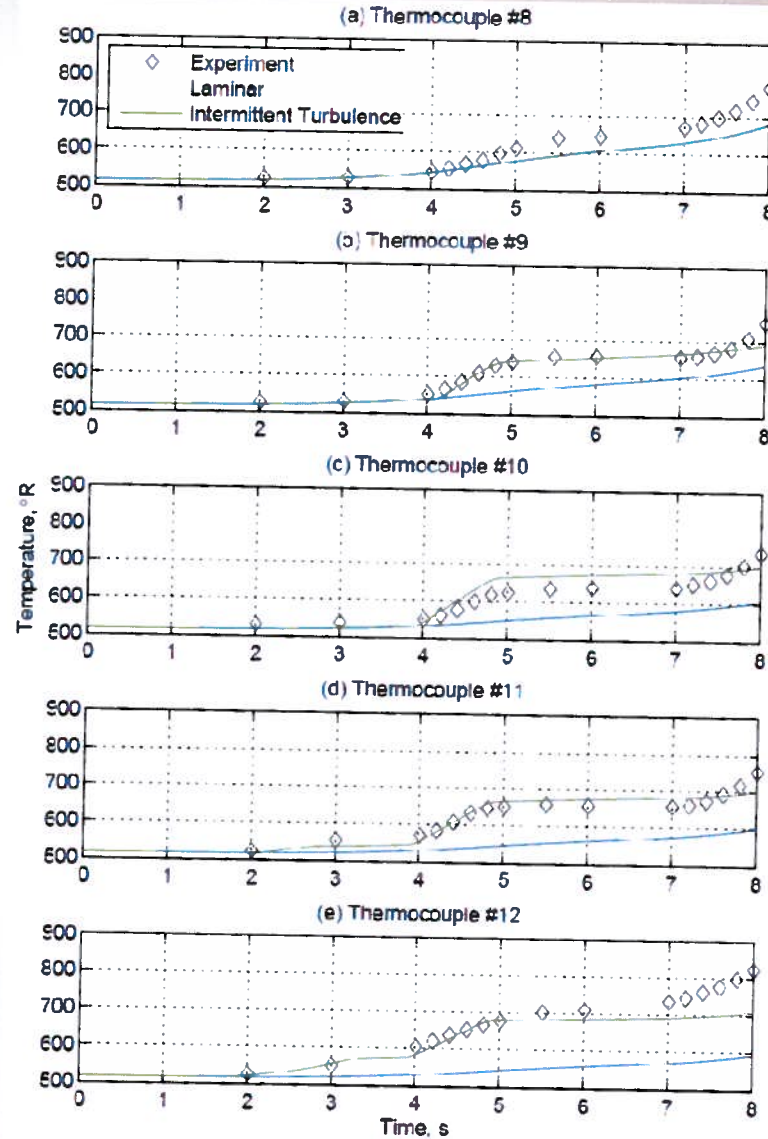
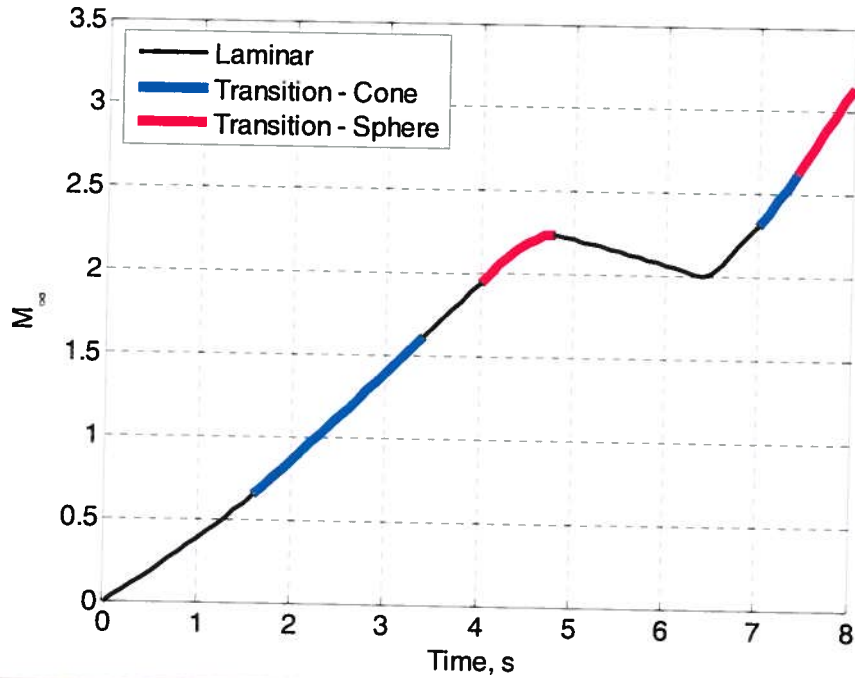


# Buglia Flight Test Analysis

- Buglia only discussed the turbulent boundary-layer present during the last second of the test flight
- An unexplained increase in the measured temperatures was apparent early in the flight
  - Corresponded to the time frame of the first stage burn-out
- Three periods of turbulent flow were identified
  - Boundary-layer appears to relaminarize between these periods
- First period (approximately 1.5 – 3.5s)
  - Transition only occurred on the conical afterbody
- Second period (approximately 4 – 5 s)
  - Transition occurred at or just forward of the sphere-cone junction
  - Seems to coincide with the first stage motor burn-out transient
    - It is speculated that vibrations caused by the burn-out transient could be inducing transition
- Third period (7 – 8 s)
  - Analyzed in the original paper by Buglia
  - Transition began on the conical afterbody, then shifted forward onto the spherical nose of the test item



# Buglia Flight Test Analysis



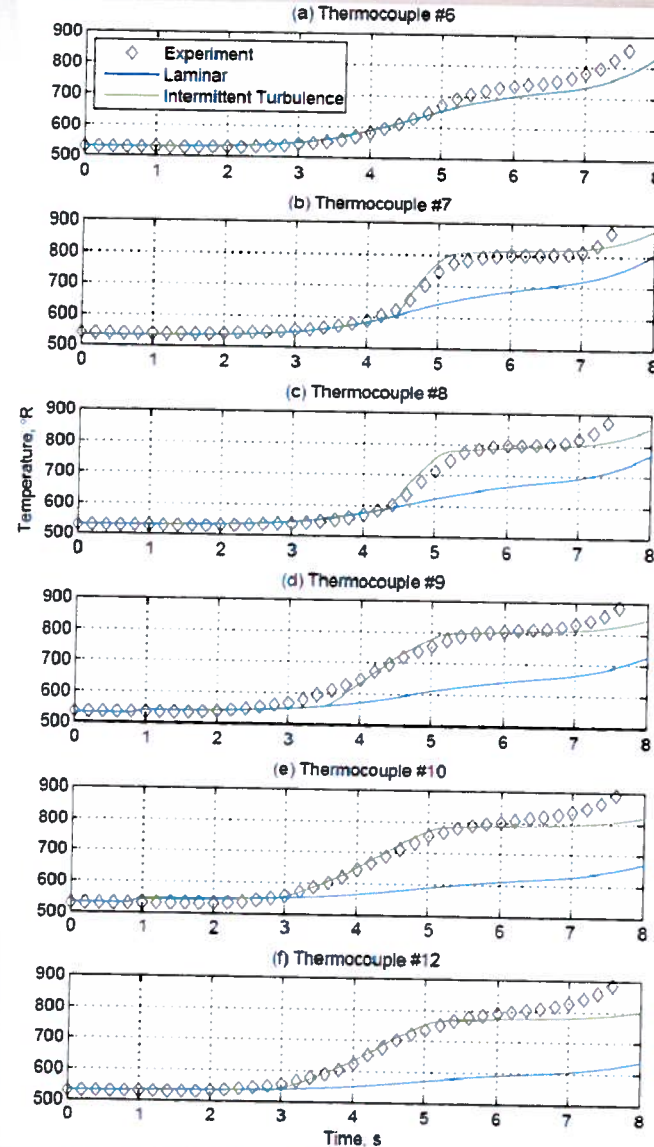
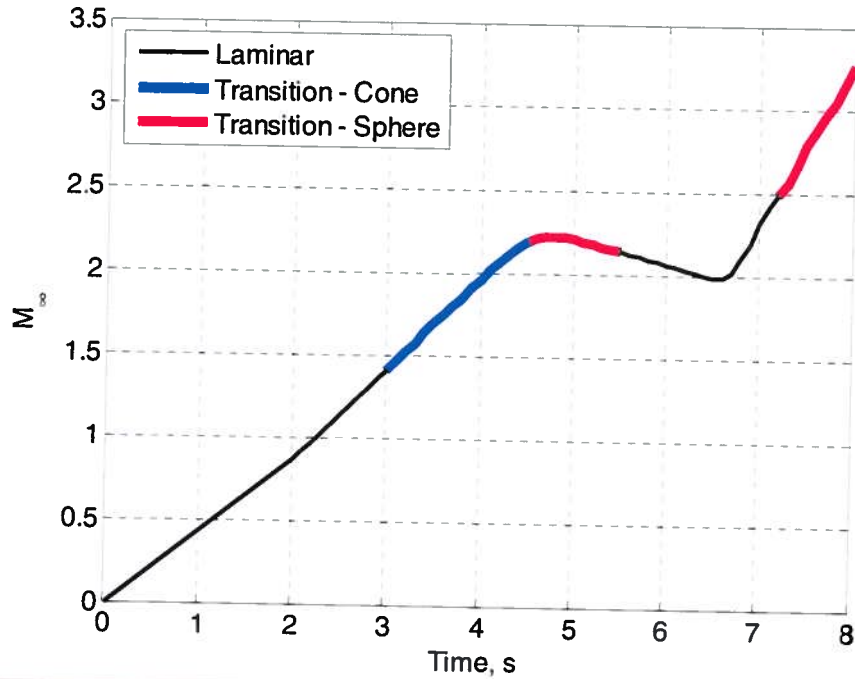


# Chauvin Flight Test Analysis

- Chauvin also only discussed the transitional boundary-layer present during the two seconds of the test flight
- An unexplained increase in the measured temperatures was apparent early in the flight
  - Corresponded to the time frame of the first stage burn-out
- Two periods of transitional flow were identified for the Chauvin flight test
  - Boundary-layer appears to relaminarize between these periods
- First period (approximately 3.0 – 5.5 s)
  - Transition began on the conical afterbody
  - Starting at about 4.4 seconds transition shifted forward onto the spherical nose
  - Seems to coincide with the first stage motor burn-out transient
    - It is speculated that vibrations caused by the burn-out transient could be inducing transition
- Second period (approximately 7 – 9 s)
  - Was analyzed in the original paper by Chauvin
  - Transition was fixed at a point on the sphere 22° from the stagnation point



# Chauvin Flight Test Analysis





# Correlation Analysis Methodology

- **Boundary-layer analyses of the flight tests were conducted**
  - Acquired the necessary correlation parameters
  - Employed the VGBLP boundary-layer solver
- **VGBLP boundary-layer solver inputs:**
  - **Surface geometry description, free stream flow properties, wall temperature distribution**
    - Were extracted directly from the flight test reports
  - **Edge pressure distribution**
    - Not provided in the flight test reports
    - Obtained from an analysis performed with ATAC03
  - **Print stations for boundary-layer output**
    - Selected to match the thermocouple positions in the original tests
- **Outputs:**
  - **Integrated boundary-layer parameters**
    - $\theta$ ,  $\delta$ ,  $\delta^*$ ,  $Re_\theta$ ,  $Re_s$ , etc.
  - **Boundary-layer edge properties**
    - $M_e$ ,  $T_e$
  - **Boundary-layer property profiles**
    - $u$ ,  $T$ ,  $\rho$ ,  $\mu$  vs.  $y$



# Correlation Analysis Methodology

- **Boundary-layer data used to derive correlations**
  - Data at point of transition plotted in order to observe trends
  - Curve fits applied to transition data
- **Correlation evaluation**
  - **Boundary-layer parameters computed for different moments during the test flights**
    - Instances when a completely laminar boundary-layer was observed
    - Instances when a turbulent boundary-layer was observed
  - **Compared correlation curve fits to computed boundary-layer parameters**
    - Do correlations predict laminar flow when laminar flow was observed?
    - Do correlations predict turbulent flow when turbulent flow was observed?
    - Do correlations predict transition at the same point on the test item that transition was observed?
- **Correlation evaluation plots**
  - Make it possible to determine which correlations can be useful for predicting boundary-layer transition on smooth, blunt bodies
  - Can also identify those correlations that appear to not be applicable

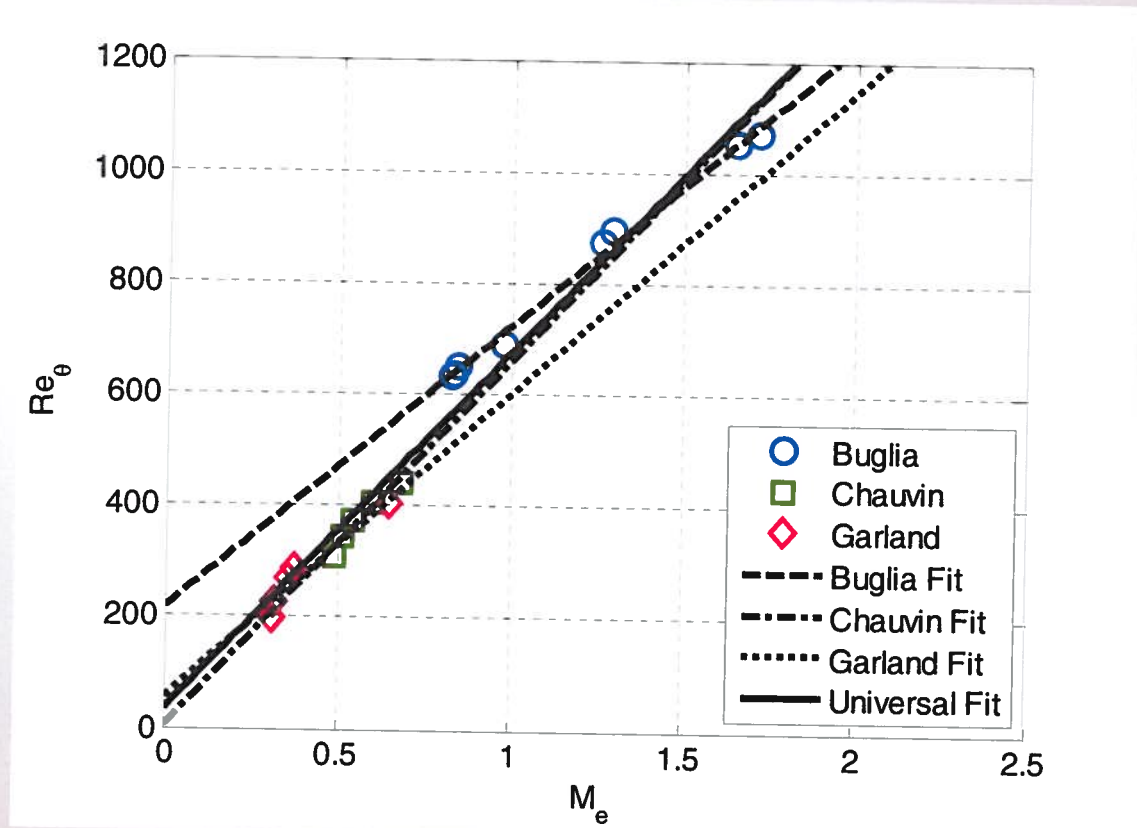


# $(Re_{\theta}$ vs. $M_e$ ) Correlation

- Only data from instances when transition occurred on the spherical nose of the test items was considered
- Data was observed to follow a mostly linear trend
  - “Universal Fit” correlation obtained by fitting a line to all of the data
  - Lines were also individually fit to data from each of the three test flights to obtain the “Buglia Fit”, “Chauvin Fit”, and “Garland Fit” correlations
- Observations
  - No “universal” correlation can be derived for predicting transition on a generic spherical surface
    - It may be possible to derive specific correlations that are applicable to a particular test item
  - The sparseness of the data available could be a factor
    - A “universal” correlation derived from a much larger data set may be able to predict transition more accurately
  - The slopes of the correlation curves were very similar to the slope of the computed boundary-layer parameter curves
    - This correlation simply describes the relationship between the momentum thickness Reynolds number and edge mach number for a laminar boundary-layer on a sphere
    - Correlation cannot be used to determine whether or not transition will occur at any given point on a sphere



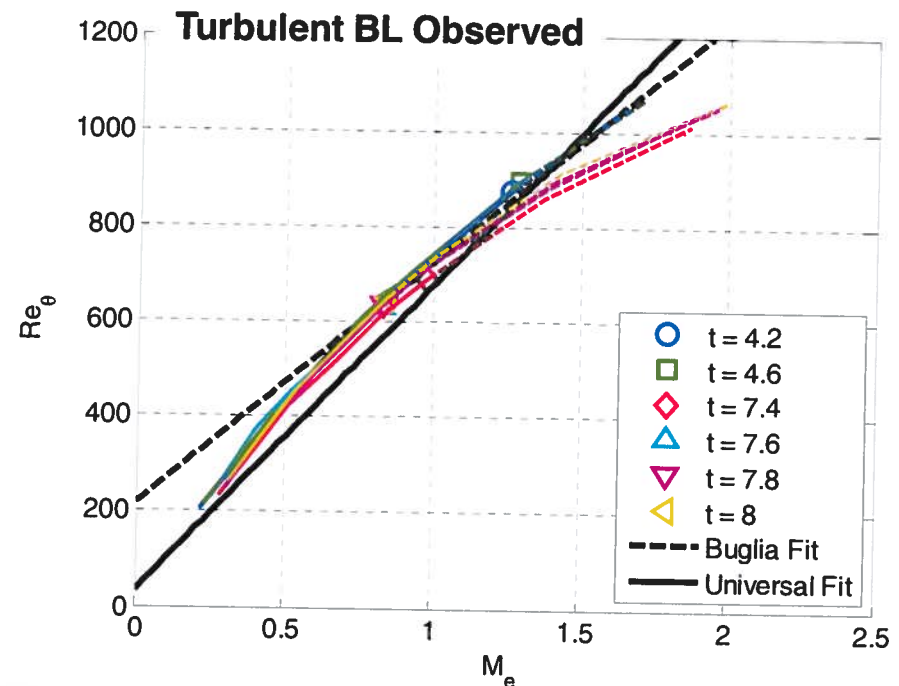
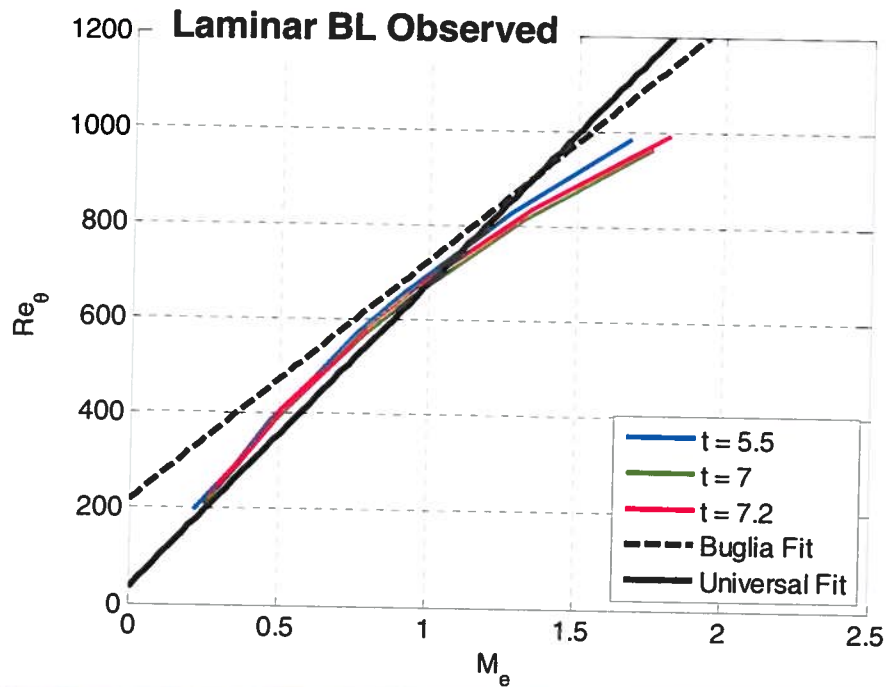
# ( $Re_\theta$ vs. $M_e$ ) Correlation





# $(Re_\theta$ vs. $M_e$ ) Correlation - Buglia

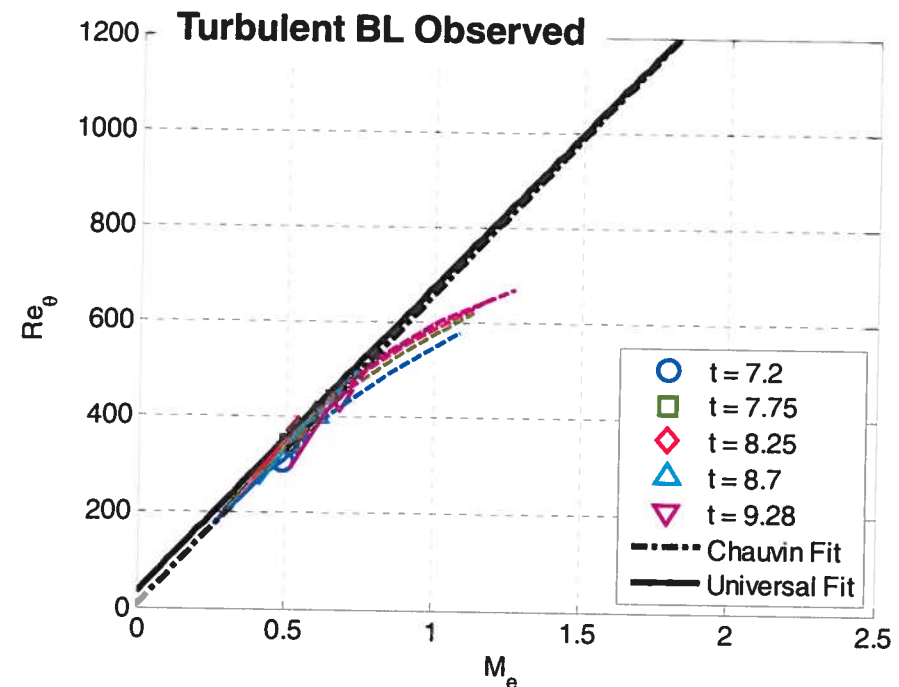
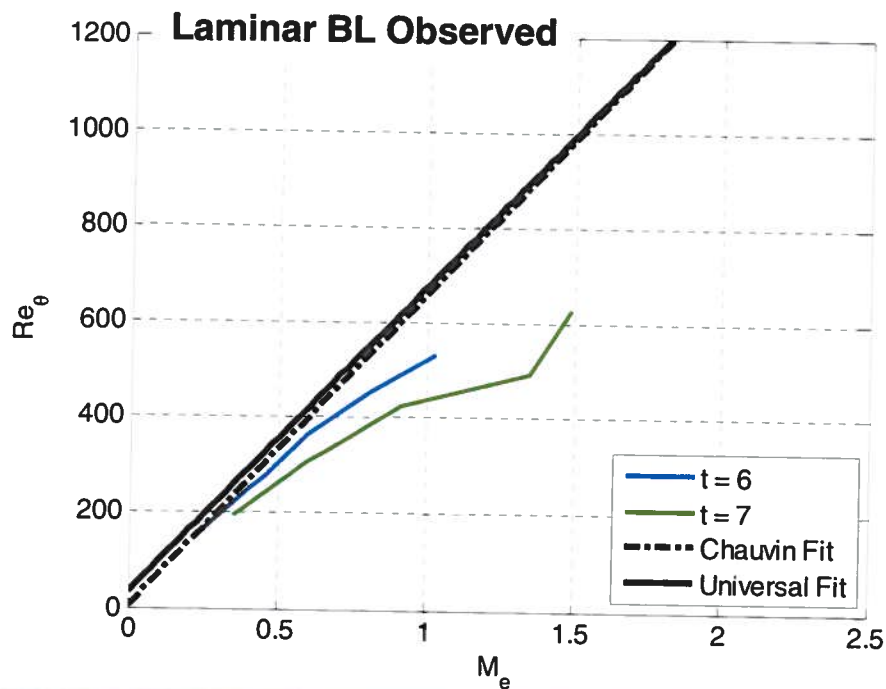
- “Universal Fit” correlation does not accurately describe transition
  - Predicts a turbulent boundary-layer starting near the stagnation point for all moments in time
- “Buglia Fit” correlation correctly predicts a laminar boundary-layer when the boundary-layer was observed to be laminar
- “Buglia Fit” correlation predicts, for instances with a turbulent boundary-layer, that transition should occur farther forward on the sphere than was actually observed





# ( $Re_\theta$ vs. $M_e$ ) Correlation - Chauvin

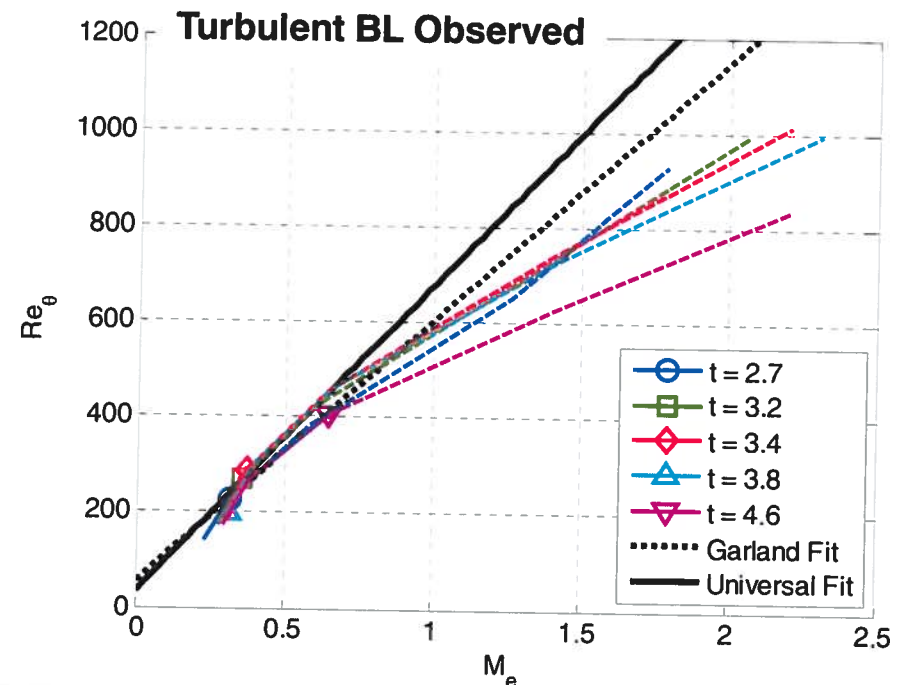
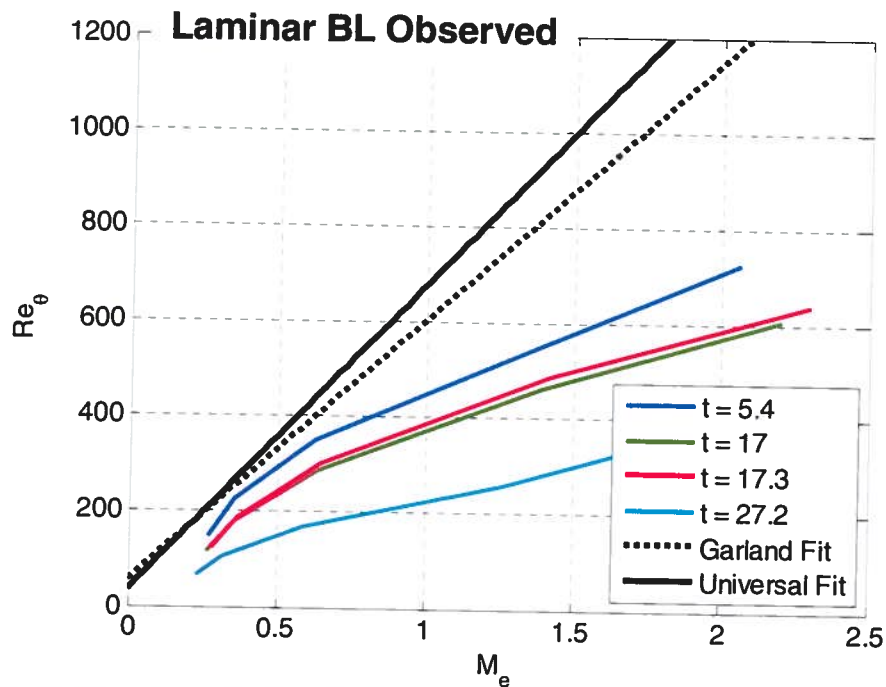
- “Universal Fit” correlation does not accurately describe transition
  - Predicts a laminar boundary-layer for all instances, even when a turbulent boundary-layer was observed
- “Chauvin Fit” correlation describes transition somewhat better
  - Correctly indicates when the boundary-layer should remain laminar
- Slopes of the correlations and computed boundary-layers are similar
  - It is not possible to definitively predict the point at which transition would occur





# ( $Re_\theta$ vs. $M_e$ ) Correlation - Garland

- “Universal Fit” and “Garland Fit” correlations describe boundary-layer transition with about the same accuracy
- Both correlations correctly predict when the boundary-layer should remain laminar
- Both predict that transition will occur for most instances when transition was observed
- Slopes of the correlations and computed boundary-layers are similar
  - Makes it difficult to definitively predict the transition location



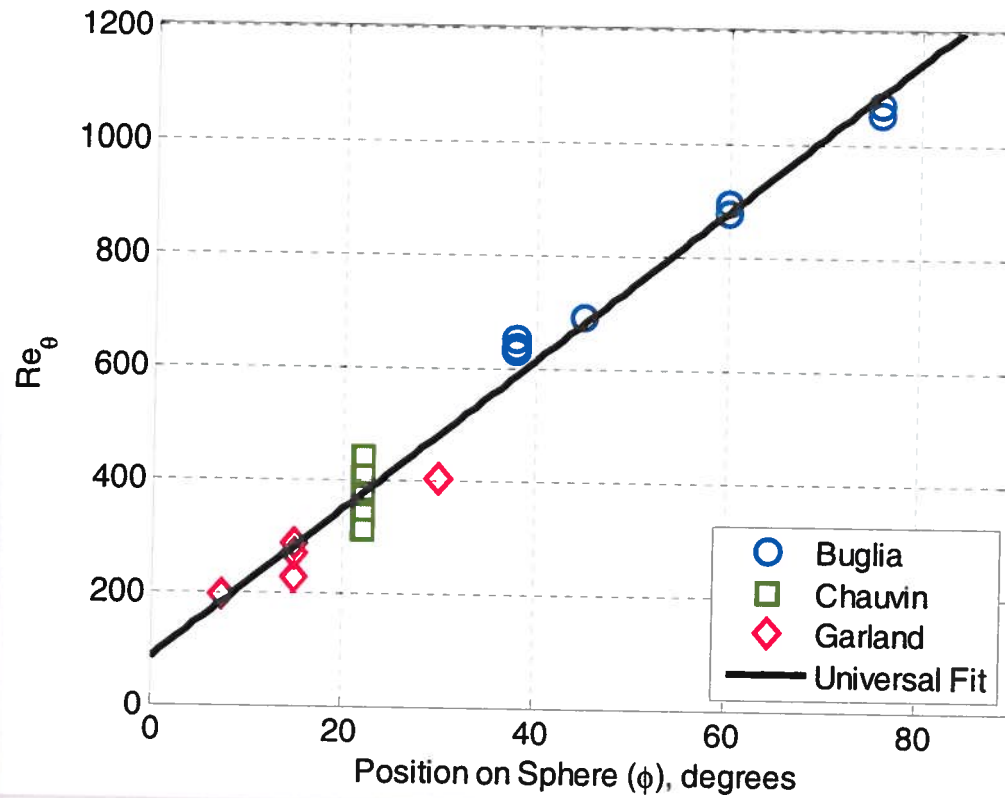


# $(Re_{\theta}$ vs. $\varphi$ ) Correlation

- It was hypothesized that transition might be predicted by correlating:
  - Momentum thickness Reynolds number at transition
  - Position on the sphere of the transition point
- A strong linear trend observed
  - “Universal Fit” correlation obtained by fitting a line to all of the data
- Observations
  - The momentum thickness Reynolds number vs. position on sphere ( $Re_{\theta}$  vs.  $\rho$ ) correlation cannot be used for predicting transition
  - The slope of the correlation curve was observed to be nearly equal to the slope of the computed boundary-layer parameter curves
    - This correlation describes the relationship between the momentum thickness Reynolds number and the position on a sphere for a laminar boundary-layer on a sphere
    - This relationship simply correlates a boundary-layer to itself
    - This correlation cannot accurately predict whether or not transition will occur at any given point on a sphere



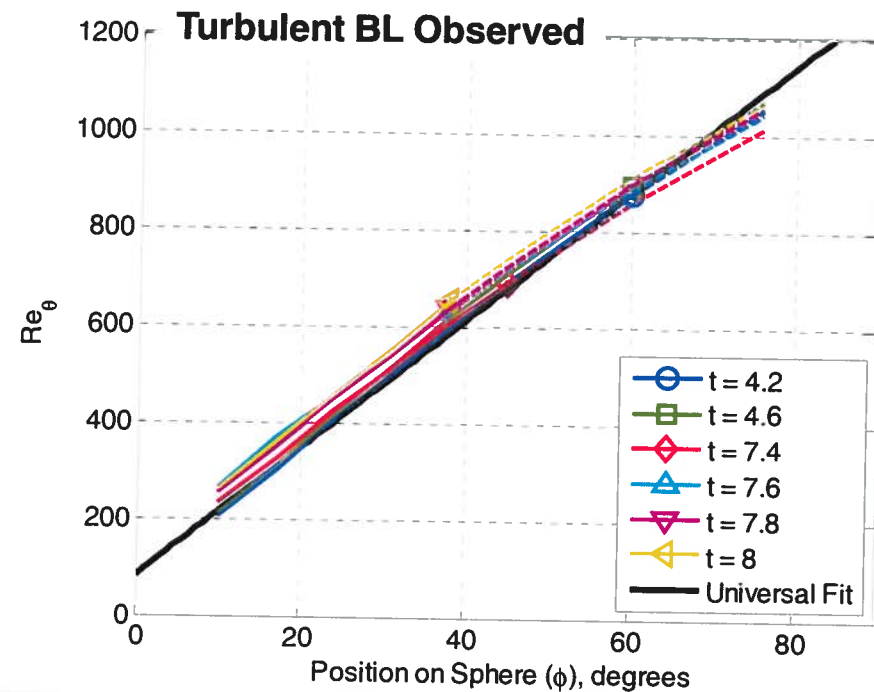
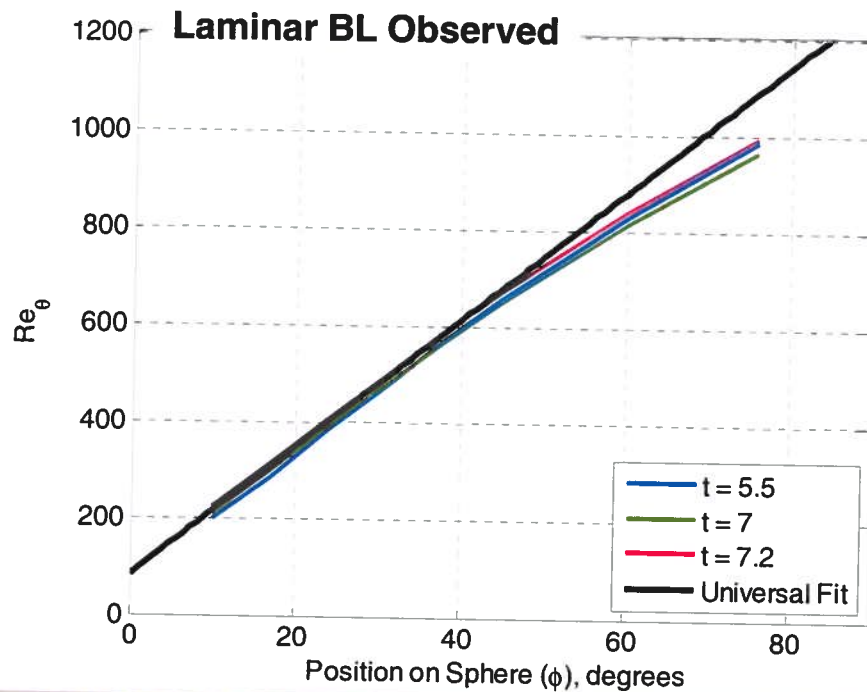
# ( $Re_\theta$ vs. $\phi$ ) Correlation





# ( $Re_\theta$ vs. $\phi$ ) Correlation - Buglia

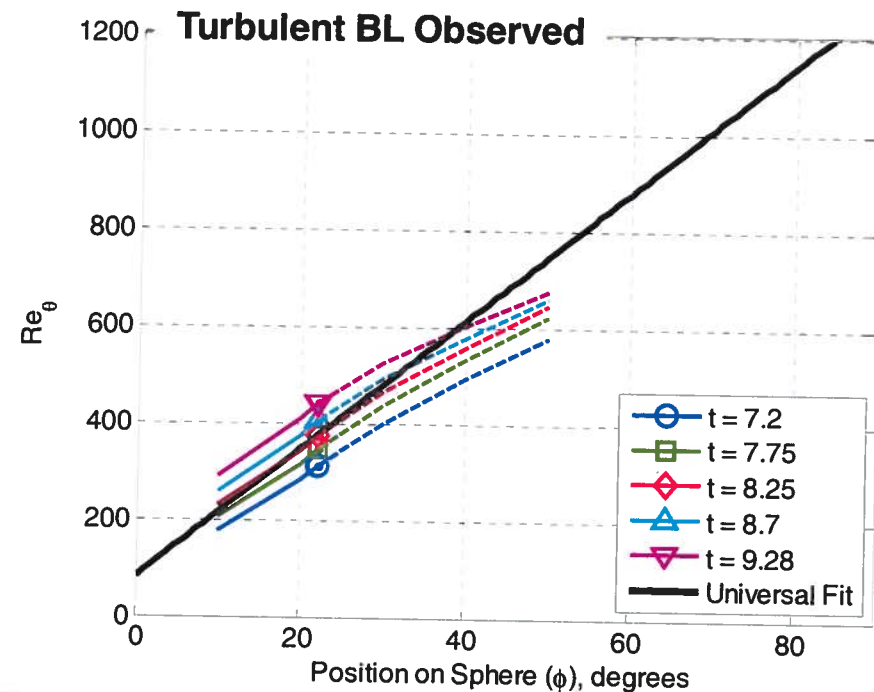
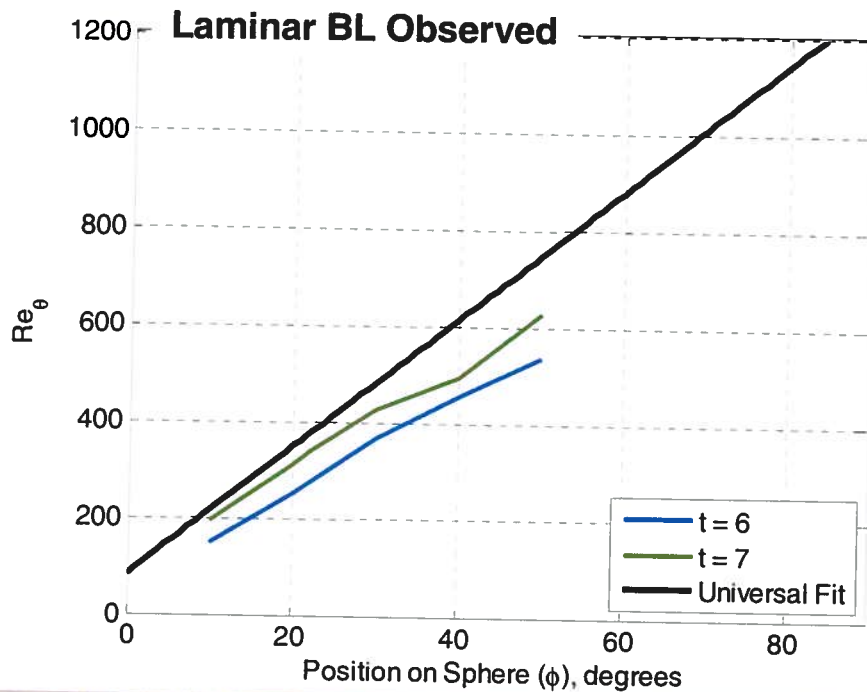
- Correlation can predict the times when the boundary-layer ought to be laminar or transitional
  - Correlation cannot be used to predict the position at which transition occurs
- Transition is predicted to start near the stagnation point of the sphere, instead of farther aft on the sphere as was actually observed
- The slope of the correlation curve is virtually identical to the slope of the curves for the predicted boundary-layer parameters





# $(Re_\theta$ vs. $\phi$ ) Correlation - Chauvin

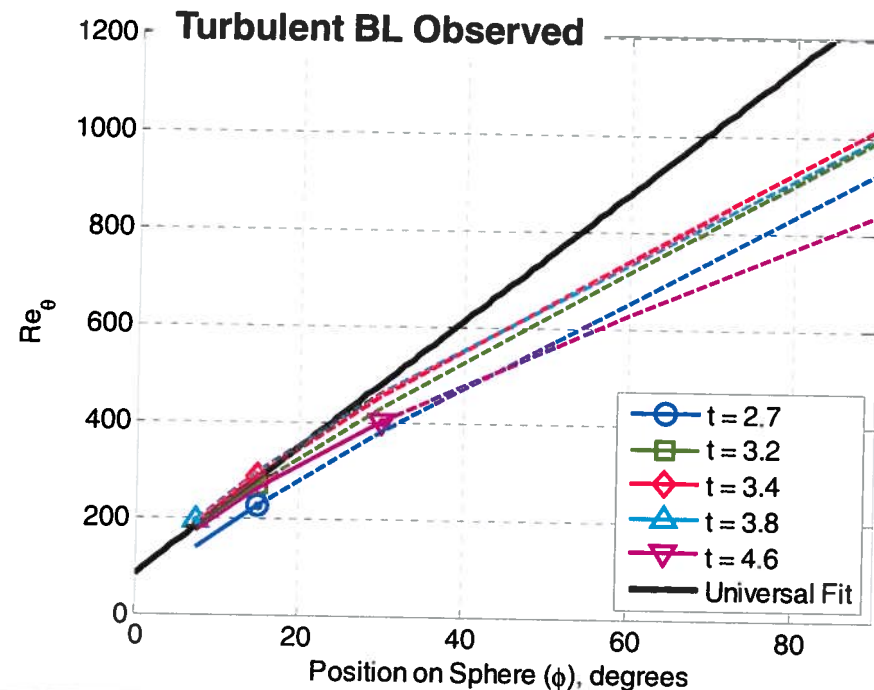
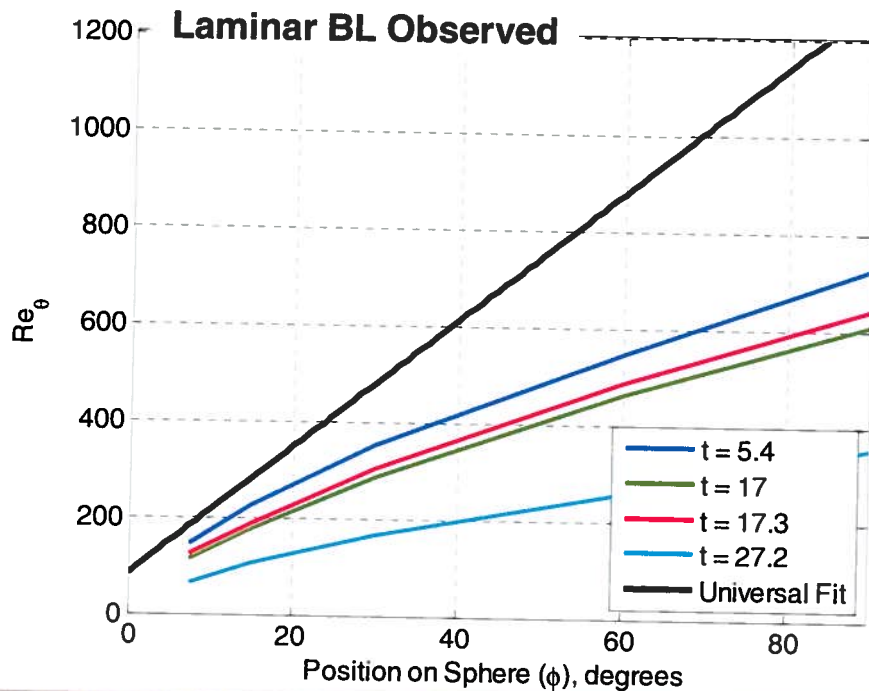
- “Universal Fit” correlation agrees with the two instances where a laminar boundary-layer was observed
- Correlation predicts that the boundary-layer should have been laminar for two instances when a turbulent boundary-layer was observed
- Correlation predicts that transition should start near the stagnation region
- Slope of the correlation curve is similar to the slope of the computed boundary-layer parameter curves





# ( $Re_\theta$ vs. $\phi$ ) Correlation - Garland

- “Universal Fit” correlation agrees with the instances when the boundary-layer was observed to be laminar
- Correlation predicts that the boundary-layer should remain laminar for several instances when a turbulent boundary-layer was observed



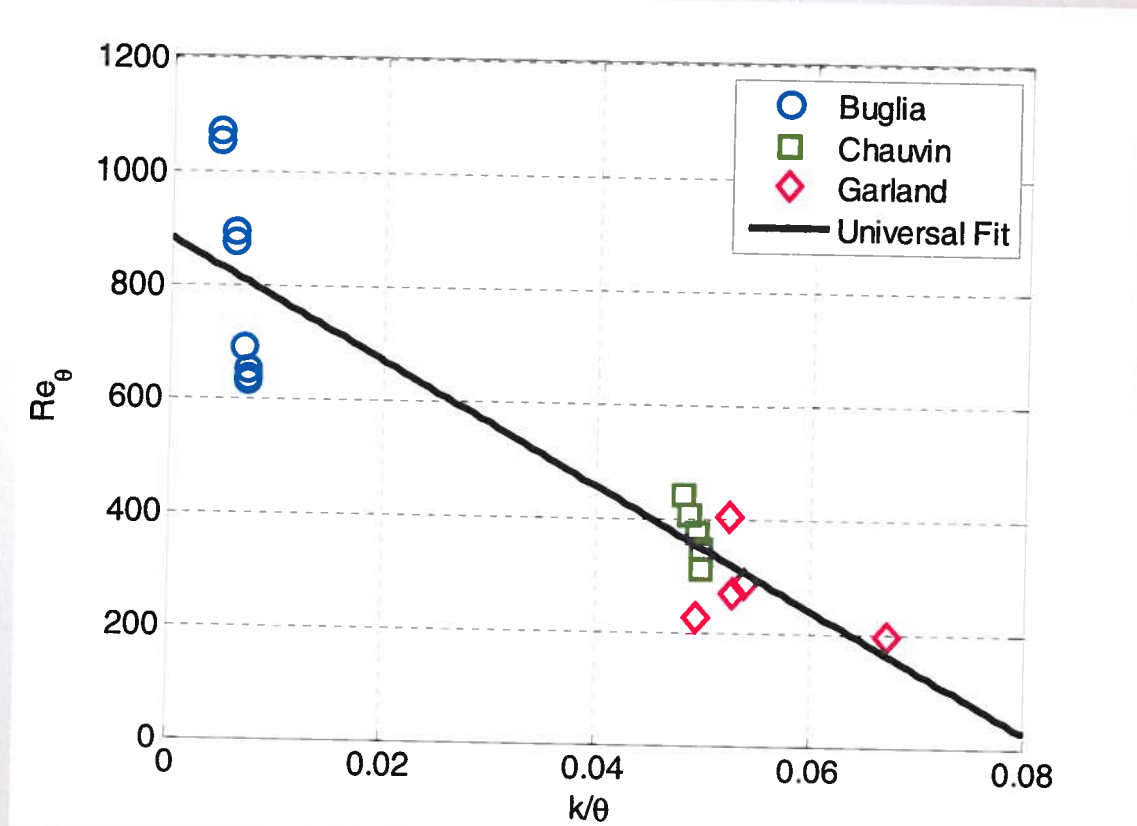


# $(Re_\theta$ vs. $k/\theta$ ) Correlation

- **A third correlation,  $(Re_\theta$  vs.  $k/\theta$ ), was explored**
  - Momentum thickness Reynolds number vs.
  - Roughness height normalized by momentum thickness
  - Takes into account the effect that surface roughness might have on transition
- **“Universal Fit” correlation obtained by fitting a line to all of the data**
  - Linear trend was weaker than that observed with the previous two correlations
- **Observations**
  - Performed the best for predicting the location of transition when it occurred
  - However, it will not be possible to use this correlation to predict whether or not transition will actually occur at any given point in time



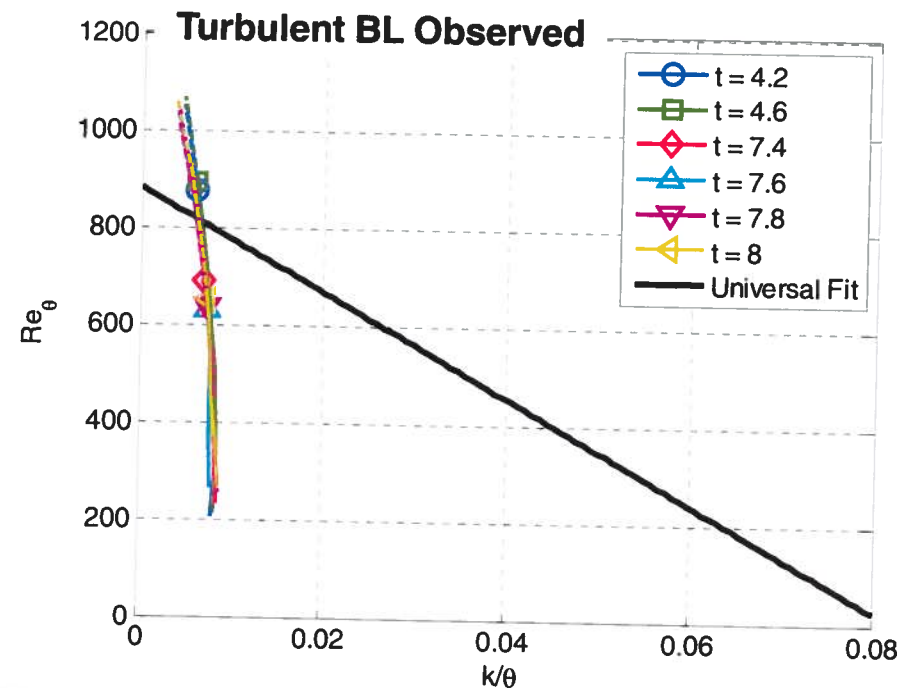
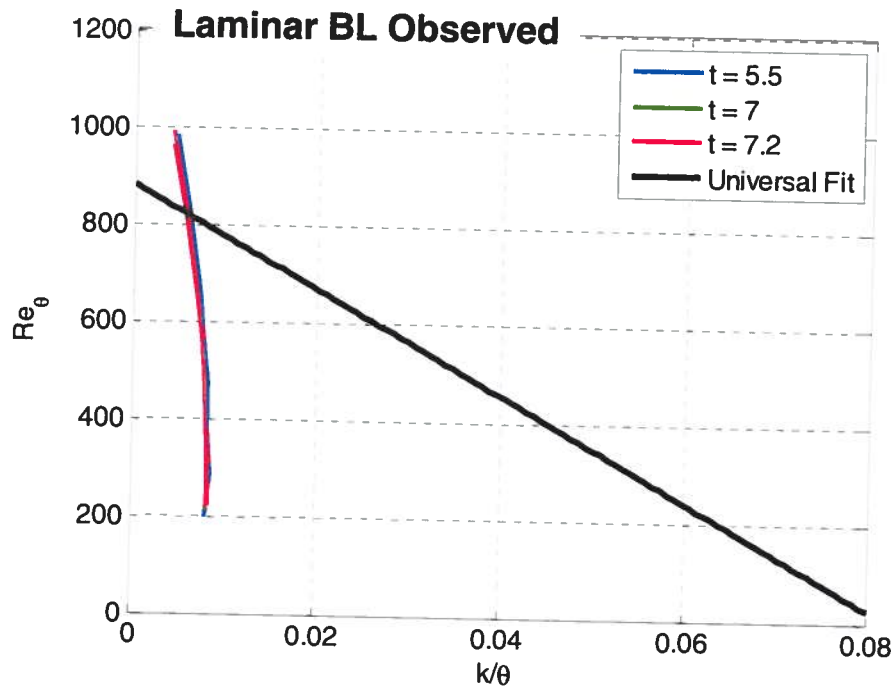
# ( $Re_\theta$ vs. $k/\theta$ ) Correlation





# $(Re_\theta$ vs. $k/\theta)$ Correlation - Buglia

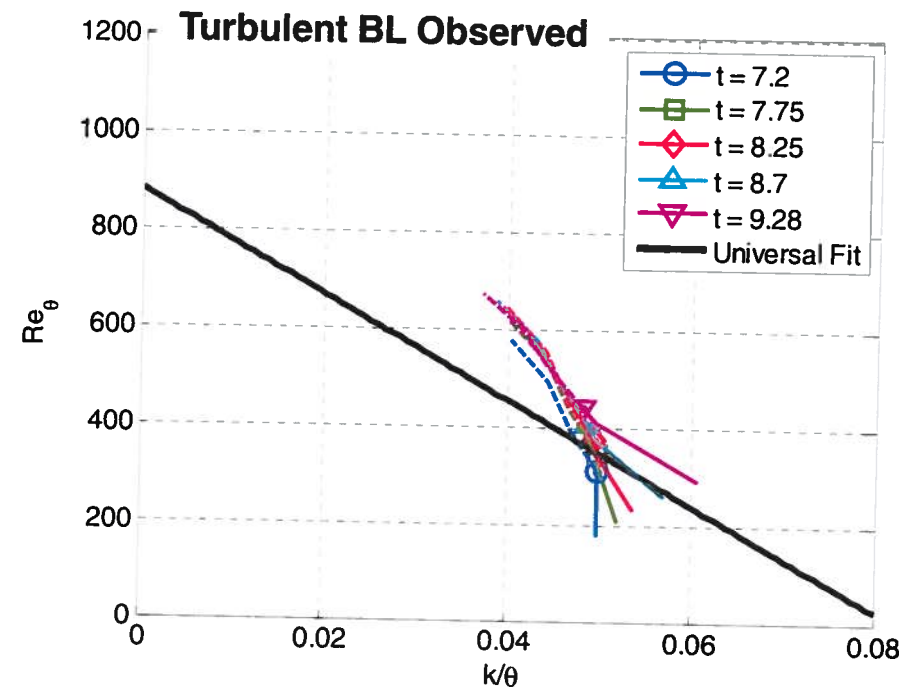
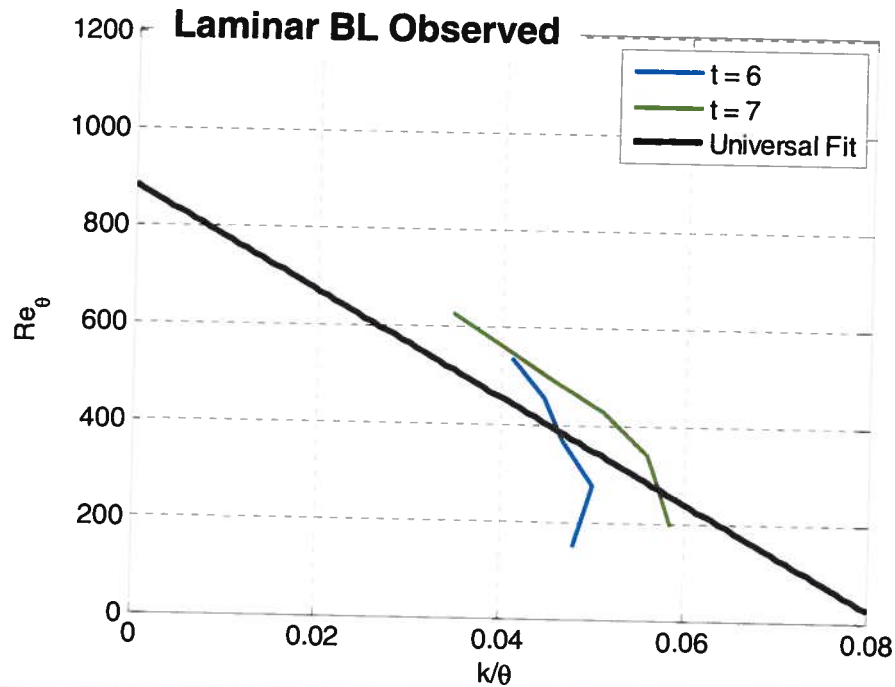
- “Universal Fit” correlation does not accurately describe transition in this case
- Predicts the position of transition with reasonable accuracy for instances when a turbulent boundary-layer was observed
- Predicts that transition should occur at all times considered
  - Including instances when a laminar boundary-layer was observed





# $(Re_\theta$ vs. $k/\theta$ ) Correlation - Chauvin

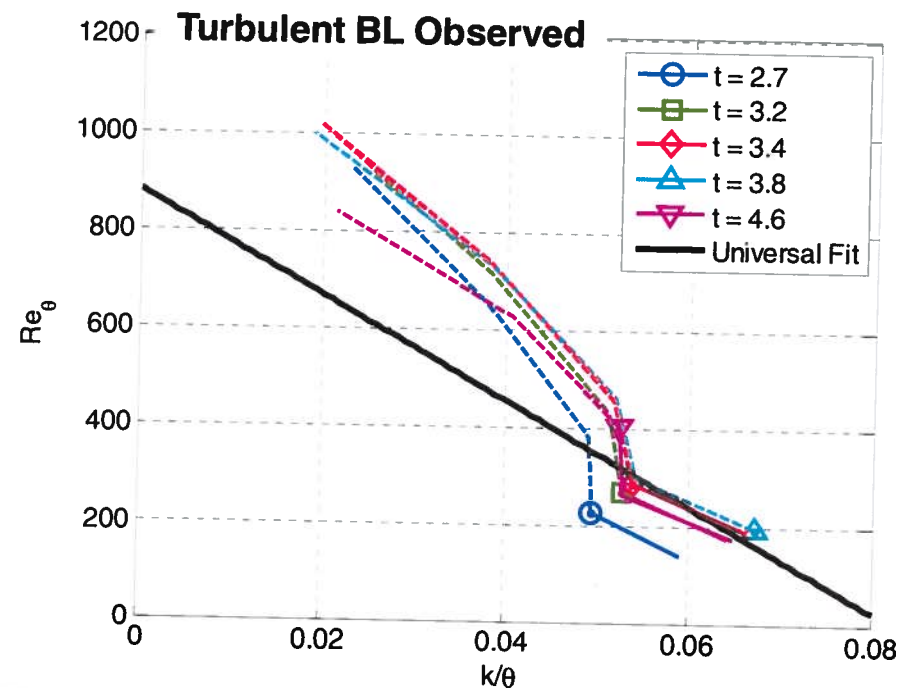
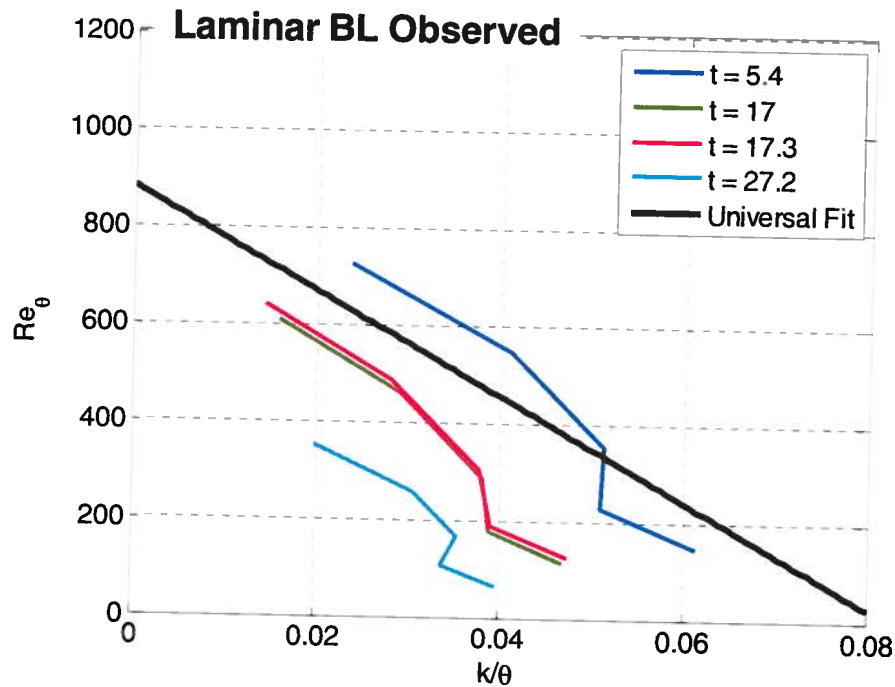
- “Universal Fit” correlation predicts the location of transition with moderate accuracy for instances when a turbulent boundary-layer was observed
- Predicts that the boundary-layer ought to be turbulent during the two instances when a laminar boundary-layer was observed





# ( $Re_\theta$ vs. $k/\theta$ ) Correlation - Garland

- “Universal Fit” correlation predicts the location of transition with reasonable accuracy for instances when transition was observed to occur
- Correlation also agrees quite well with most of the instances when a laminar boundary-layer was observed
- Correlation predicts that the boundary-layer should be turbulent for one instance ( $t = 5.4$  s) when a laminar boundary-layer was observed





# Conclusions

- **A number of empirical correlations were evaluated against experimental data**
- **No universal correlation was found that could consistently and reliably predict the occurrence or location of transition**
- **Several of the correlations explored appeared to just correlate a boundary-layer to itself**
  - **The correlations can describe the relationship between different boundary-layer parameters at transition**
  - **They cannot accurately predict if transition will occur or the location of the transition event**
- **Correlations examined implement many of the parameters traditionally used**
  - **Such as geometry, surface roughness, edge mach number, boundary-layer momentum thickness, and Reynolds number**
  - **Are based on an incomplete understanding of the physics causing transition**
  - **Because these correlations do not account for physical processes driving transition, they cannot be used to predict transition**



# Conclusions

- **Correlations were developed using sparse data sets**
  - **Correlations derived from a larger set of data may be able predict transition more accurately**
- **Two of the flight tests considered showed periods of higher heating inconsistent with predictions based on laminar theory**
  - **Periods of higher heating were not investigated by the original authors**
  - **Transition during these periods appears to be forced by transitory events related to the operation of the sounding rockets, such as motor burn-out transients, stage separation and other unidentified mechanisms**
- **In order to be able to better predict transition, it will be necessary to obtain a clear understanding of the physical processes that cause transition**



# Acknowledgments

- **This effort was made possible by Core Science and Technology discretionary funding provided by the Weapons and Energetics Department at the Naval Air Warfare Center – Weapons Division, China Lake, California**
- **Dr. Steven Schneider, of Purdue University, willingly gave his time for insightful discussions on boundary-layer transition**



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# Questions?