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Using Temperature Sensitive Paint Technology

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ABSTRACT

New facilities and test techniques afford research aerodynamicists many opportunities to investigate complex aerodynamic phenomena. For example, NASA Langley Research Center's National Transonic Facility (NTF) can hold Mach number, Reynolds number, dynamic pressure, stagnation temperature and stagnation pressure constant during testing. This is important because the wing twist associated with model construction may mask important Reynolds number effects associated with the flight vehicle. Beyond this, the NTF's ability to vary Reynolds number allows for important research into the study of boundary layer transition. The capabilities of facilities such as the NTF coupled with test techniques such as temperature sensitive paint yield data that can be applied not only to vehicle design but also to validation of computational methods.

Development of Luminescent Paint Technology for acquiring pressure and temperature measurements began in the mid-1980's. While pressure sensitive luminescent paints (PSP) were being developed to acquire data for aerodynamic performance and loads, temperature sensitive luminescent paints (TSP) have been used for a much broader range of applications. For example, TSP has been used to acquire surface temperature data to determine the heating due to rotating parts in various types of mechanical systems. It has been used to determine the heating pattern(s) on circuit boards. And, it has been used in boundary layer analysis and applied to the validation of full-scale flight performance predictions.

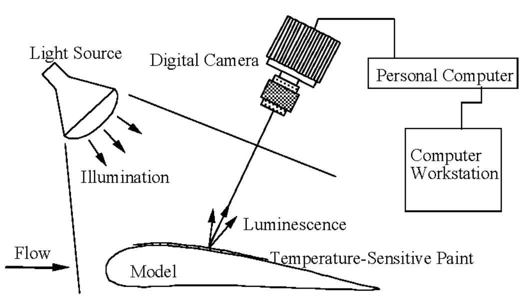


Figure 1 Schematic of a "Typical" Intensity Based Temperature Sensitive Paint System

That is, data acquired on the same model can be used to develop trends from off design to full scale flight Reynolds number, e.g. to show the progression of boundary layer transition. Figure 1 depicts a "typical" intensity based temperature sensitive paint system. A discussion of issues related to successfully setting-up TSP tests and using TSP systems for boundary layer studies is included in this paper, as well as results from a variety of TSP tests. TSP images included in this paper are all grey-scale so that similar to pictures from sublimating chemical tests areas of laminar flow appear "lighter," or white, and areas of turbulent flow appear "darker."

INTRODUCTION

Although PSP and TSP systems are very similar in broad strokes, the luminescent paints themselves differ fundamentally in the physical processes by which they operate. Pressure sensitive paint has traditionally been an oxygen sensor, and operates by a process called oxygen quenching. That is, oxygen, in contact with and diffusing throughout the pressure sensitive paint, quenches its luminescent emission creating an intensity distribution that can be calibrated to quantitatively represent pressure measurement. Temperature sensitive paint operates by means of thermal de-excitation. That is, the chromophores present in TSP are sensitive to changes in temperature. As the temperature increases, the emission from these chromophores typically decreases due to their increased usage of thermal pathways to de-excitation. There is no requirement for any diffusion for TSP to operate. Therefore, TSP's can be "worked," e.g. sanded or polished, much more than PSP's.

This paper will focus on using TSP for aerodynamic applications, particularly boundary layer analysis. TSP has successfully been used to determine regions of laminar and turbulent flow over a wide range of Reynolds numbers at low, transonic and supersonic speeds. For example, data acquired using a high-speed natural laminar flow (HSNLF) airfoil model at Mach = 0.3 and 0.7 will be presented. This data clearly shows laminar flow over a chord Reynolds number range from 2.6×10^6 to 7.9×10^6 at Mach = 0.3 and from 5.3×10^6 to 10.5×10^6 at Mach = 0.7. During these tests no laminar flow was detected at chord Reynolds numbers greater than about 15.0×10^6. A comparison of these results to results from hot film measurements will be briefly discussed in the NASA LaRC's 0.3-Meter Transonic Cryogenic Tunnel – Results section below.

Data from tests using a 2.2% High Speed Research (HSR) model at Mach = 0.3 and 0.9 in NASA Langley Research Center's National Transonic Facility (NTF) will also be presented. These TSP results are compared to results using sublimating chemicals. Temperature sensitive paint data acquired in these tests covered a chord Reynolds number range from 8.5 x 10^6 to 90.0 x 10^6 at Mach = 0.3 and from 10.0 x 10^6 to 80.0 x 10^6 at Mach = 0.9. Both free and fixed transition data was acquired on baseline (leading-edge flaps = 0.0 degrees, trailing-edge flaps = 0.0 degrees), transonic (outboard leading-edge flaps = 10.0 degrees, outboard trailing-edge flaps = 3.0 degrees) and high-lift (leading-edge flaps = 30.0 degrees, trailing-edge flaps = 10.0 degrees) configurations. This paper focuses on the baseline configuration. Acquisition of this data required the test facility to vary the temperature of the flow while maintaining a constant Reynolds number. A discussion of issues related to setting-up and running these TSP tests will be included in this paper.

CHALLENGES – A REVIEW OF FUNDAMENTAL PRINCIPLES

Boundary Layer Theory

The use of temperature sensitive paint in boundary layer studies primarily requires the exploitation of the difference in heat transfer between laminar and turbulent boundary layers. However, before discussing specific issues related to heat transfer it will be helpful to briefly review some aspects of boundary layer theory. Ultimately an understanding of three types of boundary layers: the velocity boundary layer; the thermal boundary layer; and, the concentration boundary layer will be required for a thorough understanding of the various aspects of TSP usage included in this paper. The reader is directed to references such as Schlichting's ***Boundary-Layer Theory*** and Kuethe and Chow's ***Foundations of Aerodynamics*** as required.[4, 1]

Using temperature sensitive paint as part of an experimental boundary layer study focuses on differentiation between laminar and turbulent boundary layers, and on boundary layer transition. In essence, because turbulent boundary layers are characterized by increased heat, and mass, transfer relative to laminar boundary layers surface temperatures vary correspondingly. This allows researchers to visually discriminate between the two boundary layer states. In addition, because boundary layer transition occurs over a finite spatial distance researchers can examine aspects of transition at various test conditions. In addition, TSP's response to changes in temperature is relatively fast allowing examination of the receptivity of a boundary layer to instabilities.

Key to this work is the representation of laminar velocity boundary layers, using equations for conservation of mass, momentum and energy for a flow in the presence of a solid surface, and in which the Reynolds number plays a key role. The details of various flows may differ, but if the critical Reynolds number is exceeded for a particular flow it can become unstable. That is, exceeding the critical Reynolds number is an indication that an environment exists in which disturbances, or instabilities, can grow and transition to a turbulent boundary layer may follow. This depends on whether instabilities are amplified or attenuated, which in the absence of other factor(s) such as flow control, depends on the Reynolds number, i.e. the ratio of the inertia to viscous forces. For more information on flow instabilities and transition the reader is referred to "Recent Insights into Instability and Transition to Turbulence in Open-flow systems."[2] Tests and data in this report include a variety of test conditions representing a broad range of Reynolds numbers and models, i.e. simpler two-dimensional models as well as complex three-dimensional models.

Heat Transfer

To use temperature sensitive paint as part of an experimental boundary layer study a basic understanding of heat transfer is required. This is to ensure that only the intended results from convection heat transfer are used in the analysis of images acquired using temperature sensitive paint. For example, it is important to realize that conduction heat transfer can give the erroneous appearance of movement of boundary layer transition. Therefore, although radiation heat transfer can generally be neglected, both conduction and convection heat transfer play major roles. "Application of Temperature Sensitive Paint for Detection of Boundary Layer Transition" by T.G. Popernack, Jr., et al, included results of the proof-of-concept temperature sensitive paint tests at NASA Langley Research Center's 0.3-Meter Transonic

Cryogenic Tunnel and compared these results to computational solutions obtained using an explicit time marching/forward difference technique to solve the energy equation.[3] This comparison is illustrated in Figures 2 and 3 below.

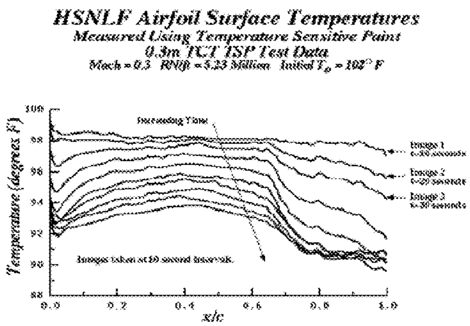


Figure 2 Measured Surface Temperatures

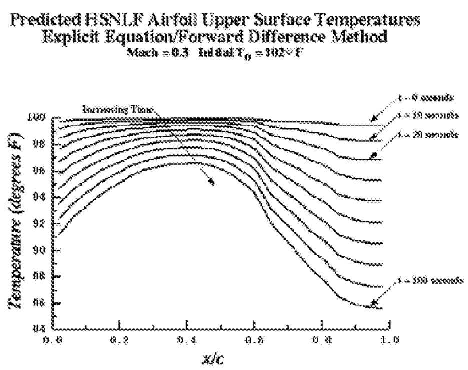


Figure 3 Computed Surface Temperatures

As part of the risk reduction process in implementing TSP as a new test technique, several paints and models were tested at the 0.3-M TCT. Based on Reynolds number it was anticipated that the boundary layer would transition from laminar to turbulent during most of the test runs. It was believed that exceptions could occur at very low and very high Reynolds numbers where the boundary layer might have been entirely laminar or entirely turbulent respectively. So, to verify TSP performance trip dots were applied to the models used in these tests. During the NTF tests, in cases where the boundary layer was intentionally tripped, small gaps were left in the trip allowing regions of laminar flow to remain observable so that researchers could visually verify trip performance.

Images acquired at the start of a test run had little or no variation in surface temperature because the model was in thermal equilibrium with the wind tunnel environment. During a test run tunnel total temperature was varied to evoke a measurable change in model surface temperature due to the differences in heat transfer. Because boundary layers are typically stabilized when the flow occurs over a relatively cooler surface,[4] the tunnel total temperature was both increased and decreased during the 0.3-M TCT tests to ascertain whether there was any measurable change in transition location. Within the precision of the measurement system used, no measurable effect on transition was observed regardless of whether tunnel total temperature was increased or decreased. Therefore, due to the much greater mechanical efficiency of decreasing tunnel total temperature that became the preferred process. This is discussed in more detail in the NASA LaRC's National Transonic Facility – Testing Challenges section below.

Performing a test wherein a model is "cooled" in an external flow represents a classic heat transfer problem in transient conduction. Approximating the test article as a plane wall we can model the heat transfer as

$$hA(T-T_{\infty})=\frac{kA}{L}(T_i-T)$$

where:
h = the convection heat transfer coefficient
A = area, m^2
T = surface temperature, K
T_{∞} = free stream temperature, K
T_i = internal temperature, K
k = thermal conductivity
L = characteristic length, m

Rearranging this equation yields the Biot number, hL/k, where; h is the convection heat transfer coefficient, L is the characteristic length, and k is the thermal conductivity of the test article material. A variety of methods by which a full analysis can be performed using this model, depending on whether the Biot number is less than, equal to, or greater than 1.0.[5] Note that it has been demonstrated that the desired condition to enhance temperature sensitive paint results occurs when the Biot Number equals 1.0.[6] However, where researchers performing tests based on these static sensitivity results were constrained to existing flow conditions, researchers using cryogenic test facilities can vary flow conditions to achieve the desired results, within the mechanical capabilities of the facility.

Roughness Effects

Researchers have long known that surface roughness effects boundary layer transition.[4] Semi-empirical methods for accounting for surface roughness in performance predictions have been developed, e.g. the charts for determining skin-friction coefficients developed at Douglas Aircraft Company in 1959.[7] The critical height of roughness elements has been studied extensively, particularly with respect to determining the required height for effective boundary layer trips, e.g. the use of grit for trips on wind tunnel models.[8] More recent studies of the phenomena have lead to concepts such as "receptivity." Today the effect of roughness elements continues to be the source of extensive study and discussion. Note that different researchers, who are often using the same criteria to determine the critical height of roughness elements, often vary their estimates by factors of several times to determine the final surface roughness requirements of models to be fabricated. That is, it is not uncommon to use two models that were designed by the same criteria at the same test conditions but that have a factor of four, or more, difference in surface roughness.

During TSP tests, one of the factors affecting the extent of laminar flow was clearly seen to be surface roughness. Although TSP can be worked to improve surface roughness, TSP itself is not a filler and can only partially correct for the surface roughness inherent on any given model. During initial tests at the 0.3-m TCT two trip dots were applied to the HSNLF model to visually determine the effectiveness of the TSP during testing. The altered boundary layer state due to these trip dots is clearly seen in the TSP images acquired, e.g. see Figure 4 below.

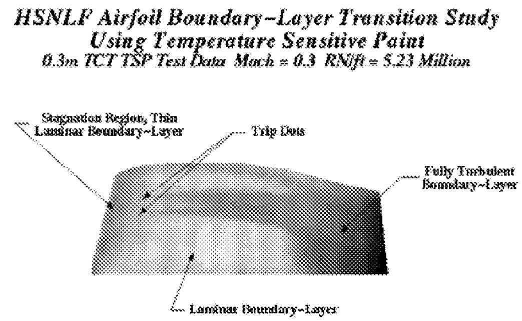
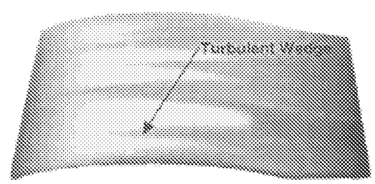


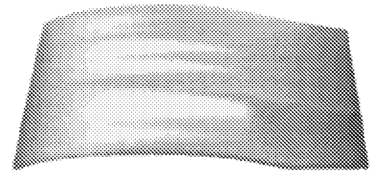
Figure 4 Temperature Sensitive Paint Image Illustrating the Use of Trip Dots to Verify TSP Performance

In addition, the effect of extensive surface roughness, even roughness elements at critical heights, is also clearly seen in the images. A sequence of images will be presented in Figures 5 through 7 that visually captures the changing boundary layer state downstream of a roughness element at the critical height.



Time Series Showing Disappearance of Turbulent Wedge, Mach = 0.30, Chord Reynolds Number = 5.6×10^6, Image 11.

Figure 5 TSP Image Showing a Turbulent Wedge



Time Series Showing Disappearance of Turbulent Wedge, Mach = 0.30, Chord Reynolds Number = 5.6×10^6, Image 12.

Figure 6 Intermediate TSP Image

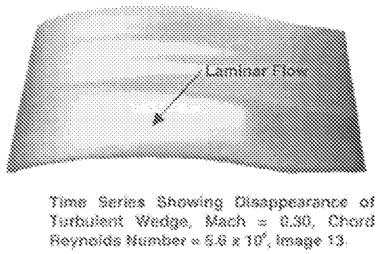


Figure 7 TSP Image Showing Laminar Flow Where a Turbulent Wedge had Previously Existed

Results from these tests illustrate TSP results for a simple airfoil model. Later tests with full models, including complex geometry such as leading edge sweep, wing camber and wing twist, have been completed and are also included in this paper.

TEMPERATURE SENSITIVE PAINT TESTS AND RESULTS

Tests in the NTF using the 2.2% Reference H model show that the percent laminar area at Mach = 0.3, chord Reynolds number = 8.5 x 10^6, was 44.5%, based on gross area. At Mach = 0.9, chord Reynolds number = 10.2 x 10^6, the percent laminar area was 37.9%. During these tests the percent laminar area based on either gross, or wimpress, area was reduced to about 10% at chord Reynolds numbers of about 30.0 x 10^6. Above about 30.0 x 10^6 chord Reynolds number the percent laminar area became impractical to calculate. Techniques used to determine the percent laminar area are discussed below, particularly with respect to the surface roughness effects present. Due to the presence of a trip ring on the forebody, flow over the fuselage was considered fully turbulent at all test conditions.

In addition, results from TSP tests have been applied to the validation of full-scale flight performance predictions. This analysis is based on a linear interpolation of data obtained from charts for a smooth, insulated flat plate. Then, the flat plate skin friction coefficient is scaled by the form factor, the wetted area and the reference area. Results from this analysis will be briefly presented for both Mach = 0.3 and Mach = 0.9. Beyond determining regions of laminar and turbulent flow, results from TSP tests can be used to determine where to fix transition for computational fluid dynamics (CFD) studies. The potential of this technique is briefly illustrated in Figure 8 below, using the 4.0% Arrow Wing High Speed Research model in a high-lift configuration. Furthermore, TSP has been successfully used for boundary layer analysis at high speeds. Tests were conducted in the McDonnell Douglas Corporation Polysonic Wind Tunnel at Mach numbers in excess of 2.0. This facility is a blow down wind tunnel. Details of successfully setting-up a TSP test for boundary layer analysis in such a facility will also be included in this paper.

Using Temperature Sensitive Paint for Boundary-layer Analysis – Comparison to Full-Scale Flight Predictions

The capability of directly determining the boundary layer state, i.e. laminar versus turbulent,

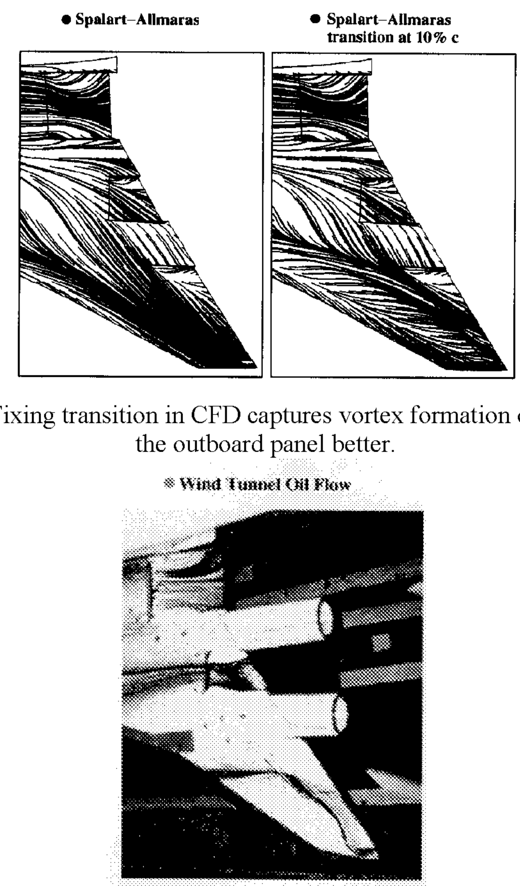


Figure 8 Effect of Fixing Transition in CFD Compared with Results from a Wind Tunnel Oil Flow Test

allows researchers to reconsider semi-empirical skin friction predictions. To determine the area of laminar boundary layer present two-dimensional temperature sensitive paint images are mapped to a three-dimensional grid. Because the extent of laminar flow is not symmetric for complex three-dimensional models, this grid is then split in two representing the upper and lower surface separately. These surfaces were further divided with planes determined by points at the edge of the laminar boundary layer nearest the side-of-body and nearest the trailing-edge. This is illustrated in Figure 9a. This technique disallows turbulent wedges issuing from areas of surface roughness such as exist for damaged paint. This may overstate the extent of laminar flow when larger transitional regions occur. The surface area representing this "laminar region" was then computed. Figure 9 below illustrates this process.

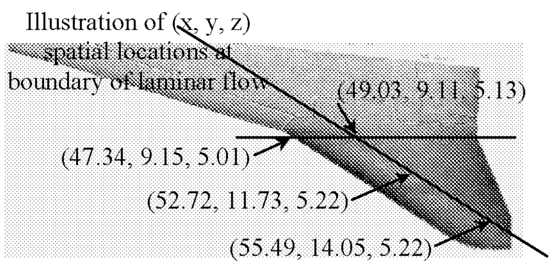


Figure 9a Cuts Taken With Respect to TSP Data to Determine the Spatial Extent of Laminar Flow

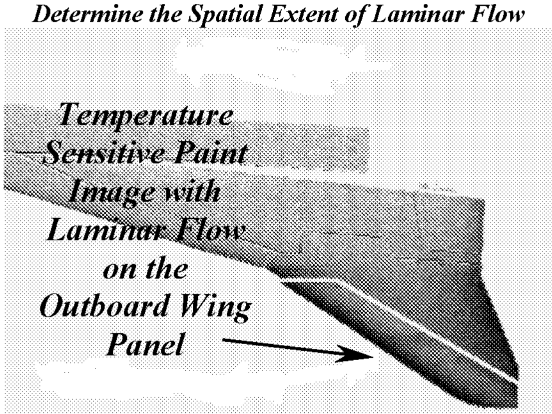


Figure 9b Cuts Taken With Respect to a Mapped TSP Image

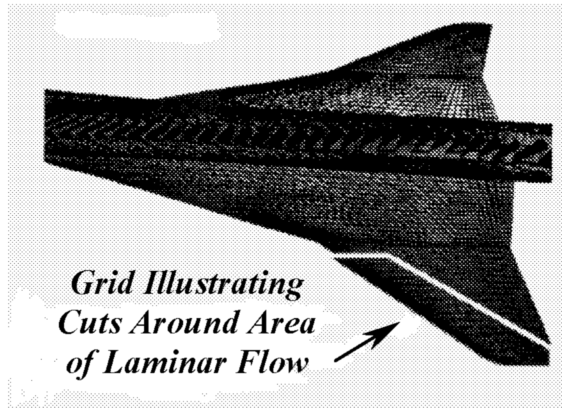


Figure 9c Cuts Taken With Respect to the Grid Generated by the Model's Geometry

Table 1 includes the computed "laminar region" for various test conditions using the 2.2% Reference H model. Because no lower surface data was obtained for the Mach 0.3, 34.0 x 10^6 Reynolds number condition, the upper surface laminar area was doubled to obtain the value shown in the table.

As illustrated in Figure 10, most of the laminar flow for this model occurs on the outboard panel. Since the flat plate skin-friction coefficient data was acquired at zero degrees angle of attack and the twist on the outboard panel of this model is about one and one

Mach	*Chord Reynolds Number ($x10^6$)*	*Laminar Area (in^2)*	*Percent Laminar Area Based on Gross Area*	*Percent Laminar Area Based on Wimpress Area*
0.3	8.5	109.9	44.5	39.6
	14.4	65.4	26.4	23.5
	21.6	54.6	22.1	19.7
	34.0	~32.8	13.3	11.8
0.9	10.2	93.8	37.9	33.7
	20.0	50.9	20.6	18.3
	30.0	35.3	14.3	12.7

Table 1 Percent Laminar Surface Area for the 2.2% Reference H Model Computed from Temperature Sensitive Paint Data Acquired in NASA LaRC's NTF

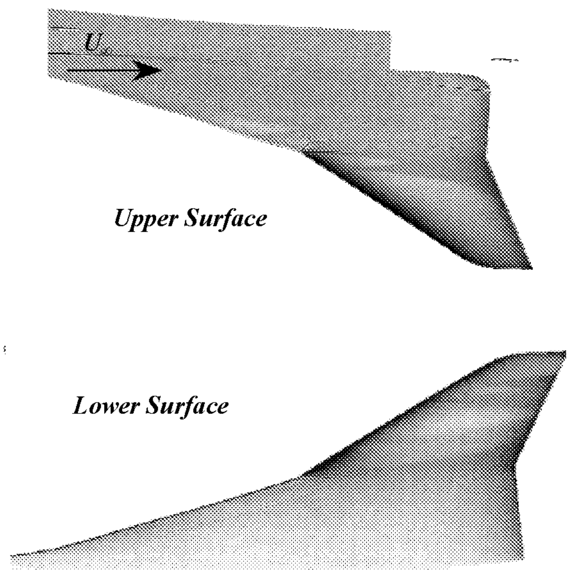


Figure 10 Illustration of Laminar Flow on the 2.2% Reference H Model at Mach = 0.30, Chord Reynolds Number = 8.5 x 10^6 in the "Warm" Nitrogen Mode at NASA LaRC's NTF.

-half degrees, values in this table were computed for data obtained at one degree angle of attack.

Figures 11 and 12 illustrate the superposition of semi-empirical skin friction predictions with previous force/moment and TSP test results. Because of the superior surface finish on the 2.2% Reference H model, 8 to 16 micro-inches, it can be considered a "smooth" surface and that assumption was built into the semi-empirical predictions. A comparable smooth surface as defined in Clutter's work was considered to be 20 to 80 micro-inches.[7] However, as the figures show for both 0.9 and 0.3 Mach numbers there is slightly less measured drag at lower Reynolds numbers. Also, TSP results would indicate even lower drag levels at lower Reynolds numbers. Correspondingly, there is less benefit from increasing Reynolds numbers than predicted. Using the Clutter Charts for a "rough" surface would further increase the calculated drag moving the predicted values even further from the measured values.

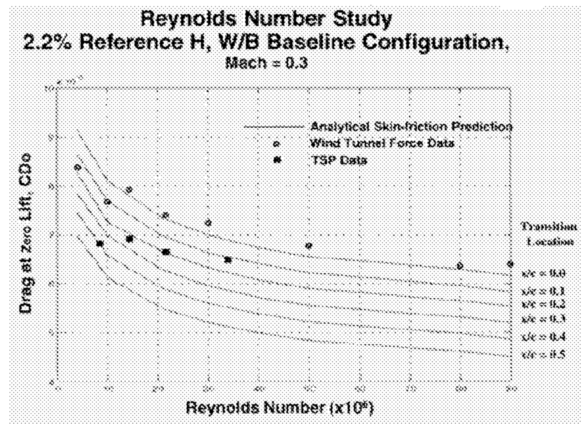


Figure 11 Comparison of Analytical/Semi-Empirical Skin Friction Predictions, Wind Tunnel Force Data and TSP Data at Mach = 0.30

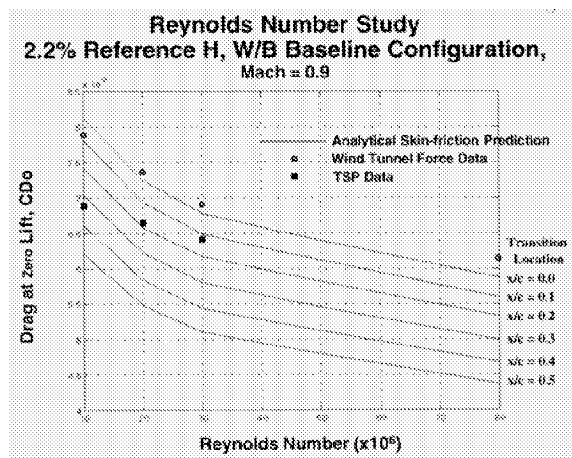


Figure 12 Comparison of Analytical/Semi-Empirical Skin Friction Predictions, Wind Tunnel Force Data and TSP Data at Mach = 0.90

This begs the question of exactly what a "smooth" surface is. In addition, it has been postulated that separation on the aft-body of the sting mounted model may be causing some of the increased drag measurements relative to the TSP results. Resolution of this issue should bring new insight into full-scale performance prediction methodologies for complex geometries.

Using Temperature Sensitive Paint for Boundary-layer Analysis in a Cryogenic Environment

NASA LaRC's 0.3-Meter Transonic Cryogenic Tunnel (0.3-M TCT)

Summary and Test Objectives

The 0.3-M TCT temperature sensitive paint tests were intended to answer several questions regarding the use of TSP as a test technique to perform boundary layer analysis in a cryogenic environment. In addition to acquiring data to answer specific questions, a number of temperature sensitive paint formulations were tested. Besides TSP, hot films on the SC(3)-0712 model were used to acquire data for boundary layer analysis. Data from the 0.3-M TCT tests, and the NTF tests, were used to determine the required temperature sensitivity of TSP for use in a cryogenic environment. The specific questions to be answered in the 0.3-M TCT tests included:

- Can we acquire TSP data of sufficient resolution to visually discriminate between laminar and turbulent boundary layer states under steady-state conditions?
- If not, what change in tunnel total temperature is required?
- What camera/data acquisition system resolution is required?
- What is the effect of increasing pressure?
- What Mach number effects are there?
- What is the short-term repeatability of the paint?
- How durable is the paint?
- What is the spatial resolution available?

These tests have been considered enormously successful. In addition to providing many answers to the specific questions above, a large body of data was acquired for comparison to various boundary layer stability codes. The most significant criticism of these tests was the lack of knowledge about the "N" factor in the 0.3-M TCT environment. While this is directly relevant to comparison of test results with stability code solutions, it is in no way a reflection on the operation of TSP as a test technique for use in boundary layer studies. A total of 155 test runs, each with multiple images acquired, were completed during the 0.3-M TCT tests at both "warm" and cryogenic conditions.

Facility, Hardware and Paint Specifications

One way to increase Reynolds number in a wind tunnel environment is to reduce temperature. Since 1971 personnel at NASA Langley Research Center have been investigating the implementation of cryogenic wind tunnel testing for this purpose. The 0.3-Meter Transonic Cryogenic Tunnel, as well as the U.S. National Transonic Facility, is the realization of that effort. The 0.3-m TCT test section has a 33-cm x 33-cm cross section at its entrance and is 142-cm long. The operating total temperature range of the facility is from about 78 K to 327 K, or about -319^{o} Fahrenheit to 130^{o} Fahrenheit, with total pressures ranging from about 17.5 to 88 pounds per square inch, absolute.

Two airfoil models were used during TSP tests in the 0.3-m TCT; a high speed natural laminar flow (HSNLF) airfoil model,[9] and a super-critical (SC(3)-0712) airfoil model.[10] The HSNLF model chord is 6.5 inches, the SC(3)-0712 model chord 6.0 inches. Both models were bolted directly to the 0.3-m TCT test section walls. Both models had unswept leading-edges and were made of stainless steel.

A basecoat was applied to the surface of the models to act as an insulator. The active TSP was applied over the basecoat. The total thickness of the basecoat and paint was measured to be between 0.003 and 0.005 inches. Since TSP is very hard and durable it was polished to minimize the presence of any isolated surface roughness elements. No surface roughness measurements were made after polishing.

Testing Challenges

Unfortunately, the TSP systems used simply did not have sufficient resolution to allow visual discrimination between the small surface temperature difference due to the variation in heat transfer between laminar and turbulent boundary layers under steady state conditions. So, in order to enhance the surface temperature differences, the facility was required to vary tunnel total temperature, while maintaining constant Reynolds and Mach numbers.

Because of the 0.3-M TCT's relatively small size with respect to the facility's mechanical systems this was easily accomplished. In fact, a number of runs were included in the test matrix to simulate varying rates of change in tunnel total temperature. For example, the quickest change in tunnel total temperature, called a "fast" temperature step, was very nearly a step change. A slower change in temperature set-up to simulate the environment in the larger NTF and that facility's capability to vary tunnel total temperature was called a "slow" temperature step. Interestingly, data acquired indicated that the "slow" step, or a temperature step equal to approximately 1° Fahrenheit every 10.0 seconds, produced higher quality TSP data for boundary layer analysis than the "fast" temperature step did.

Due to the limited optical access in the 0.3-M TCT only a 14-bit scientific grade CCD camera was used during testing to acquire TSP images. In fact, the camera viewed the model through a series of mirrors that were hard bolted to the test section and vibrated accordingly. In addition, the camera was bolted to a mounting system in an environmentally controlled canister that was also bolted to the test section. In the end, even though model dynamics were not an issue, there was still a lot of distortion of the images due to the overall vibration of the imaging set-up.

In addition, the limited optical access provided only enough space for three excitation lights. These had to be placed almost directly in the line of sight of the camera and constantly needed adjustment. There was also an issue of differences in radiant intensity from these lights between runs when they were operated in the cryogenic, or "cold," environment and when they were operated in a "warm" environment and air-cooled.

Basecoat and paint thicknesses in initial runs were based on previous work done using the static sensitivity model which suggested that the thicknesses should be as large as possible in order to achieve a Biot Number of 1.0. However, because of this thickness the paint cracked and came off the model during initial test runs at cryogenic conditions. Both basecoat and paint thicknesses were reduced and no further problems were incurred. The paint proved to be very robust in both the warm and the cryogenic environments.

Lastly, surface roughness proved to be a very interesting challenge in the 0.3-M TCT tests. Figure 13 shows traces from the hot films installed on the SC(3)-0712 model at 0.30 Mach number and Reynolds numbers from 2.6 x 10^6 through 7.8 x 10^6.

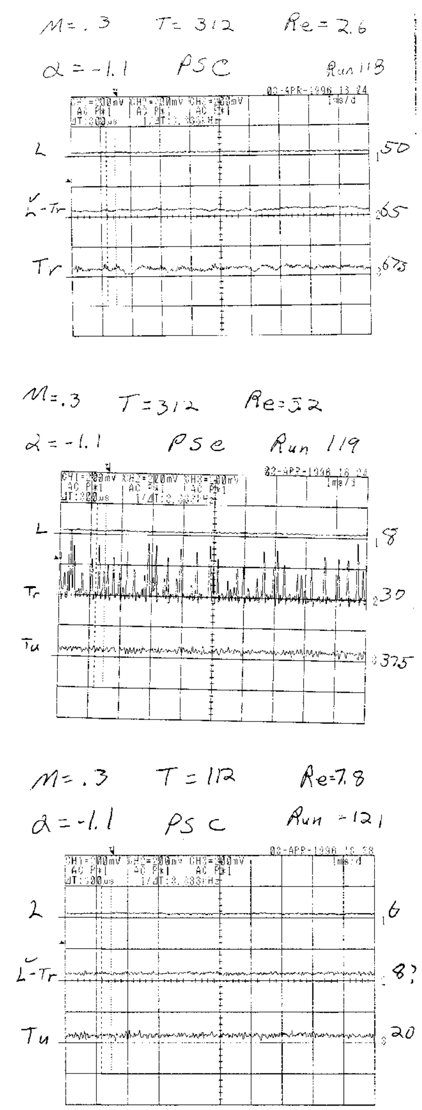


Figure 13 Hot Film Traces Illustrating the decreasing Extent of Laminar Flow with Increasing Reynolds Number at Mach = 0.30 in NASA LaRC's 0.3-Meter Transonic Cryogenic Tunnel

The images in Figures 14a through 14d illustrate a Reynolds number sweep using the SC(3)-0712 airfoil model using TSP, also at 0.30 Mach number but at a slightly reduced angle. The angle of attack was reduced to increase the extent of the laminar boundary layer on the upper (imaged) surface of the model.

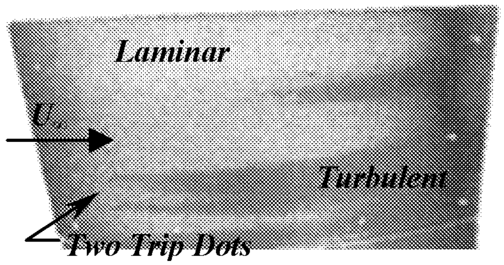


Figure 14a TSP Image of the SC(3)-0712 Airfoil Model at Mach = 0.30, Reynolds Number = 5.0 x 10^6, at -2^o angle of attack in NASA LaRC's 0.3-M TCT

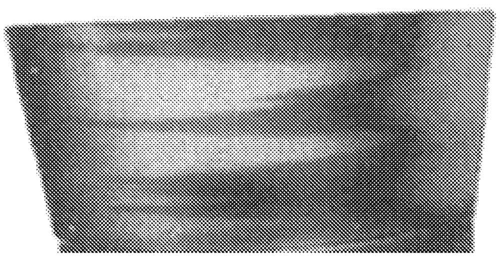


Figure 14b TSP Image, Reynolds Number = 7.5 x 10^6

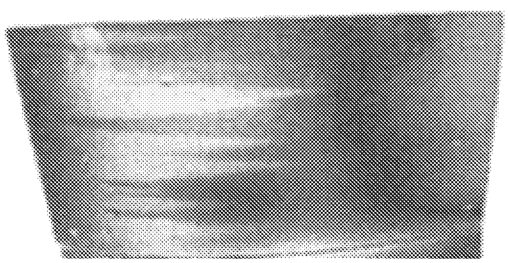


Figure 14c TSP Image, Reynolds Number = 10.0 x 10^6

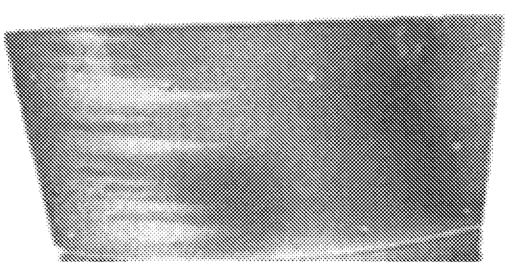


Figure 14d TSP Image, Reynolds Number =12.5 x 10^6

These TSP images clearly show the impact of surface roughness on the boundary layer with increasing Reynolds number. This illustrates why the effect of surface roughness makes it so difficult to accurately determine the global boundary layer state when point measurements are used. Only at one test point, 0.43 Mach number, 10.1 x 10^6 Reynolds number, did the hot films and TSP results correlate well. At other test points it was evident that the hot films often rendered misleading results due to their location in the turbulent wedges created by roughness elements. This result played a major role in determining the "best" data reduction method for TSP images.

Data Acquisition and Reduction

The system used for illumination and to acquire images during these tests was completely analogous to the traditional paint system as shown in Figure 1. The camera used was a Photometrics CH250, 14-bit scientific grade CCD camera with 512 x 512 pixels. The sequence of events constituting a test run during 0.3-M TCT TSP testing included:

- Bring the model and tunnel structure to thermal equilibrium at the initial total temperature.
- Acquire reference images at this temperature.
- Turn the wind on, initiate a change in tunnel total temperature and acquire wind-on images as the temperature changes.

Ratioing the reference and wind-on images reveals the change in heat transfer associated with the various boundary layer states present. In general, a sequence of six to eight images were acquired as the tunnel total temperature was changed. Usually the third or fourth image in the sequence rendered the best data. This appears to be because convective heat transfer has not had time to alter the model's surface temperature in the first couple of images. And, the rate of temperature change is slowing down as the mechanical systems reach the end of the temperature step so that the model begins to reach a new thermal equilibrium by the time the last few images are acquired. Finally, mapping the ratioed two-dimensional image to a three-dimensional grid of the model geometry allows researchers to determine the spatial location, in Cartesian coordinates, of the flow phenomena present. For example, Figure 15 shows a mapped TSP image in which the spatial location of the onset of turbulent flow can be resolved to within one-eighth inch by determining the location of the associated increase in heat transfer.

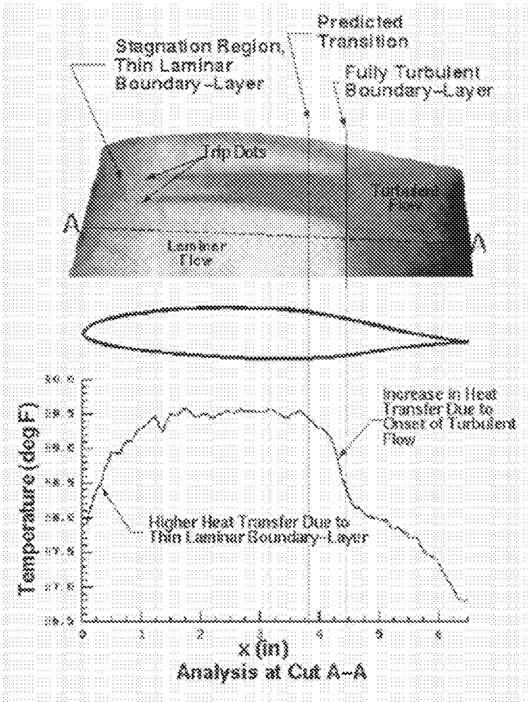


Figure 15 Mapped TSP Image and Corresponding Data Analysis

Applying lessons learned from the comparison of hot film and TSP results, cuts were taken in the TSP images across regions that did not appear to be affected by surface roughness. This allowed researchers to assess the boundary layer state in terms of the effects of transition mechanisms other than the effect of surface roughness. Using this data reduction methodology the measured "transition" location using TSP was compared to predicted transition locations using BRET, a Cebeci boundary layer method.[11] Of particular interest to this study is the unresolved question of exactly where the "transition" location occurs. For example, TSP images allow visual discrimination between areas of laminar and turbulent boundary layers. However, the apparently transitional region between these areas has a finite spatial extent, especially at low Reynolds numbers. This can be seen in Figure 15 as the approximately one-quarter inch distance across which heat transfer increases indicating the onset of fully turbulent flow. Also shown in this figure is the predicted transition location that occurs somewhat forward of the actual increase in heat transfer.

Results

As anticipated, the results of the 0.3-M TCT tests show the decreasing extent of laminar flow with increasing Reynolds number at both Mach 0.30 and 0.70. The smaller decrease at Mach 0.70, relative to Mach 0.30, has been postulated to be due to compressibility effects at the higher Mach number. As shown in Figure 16, when normalized TSP results were plotted with computed Delta Cp's for Mach 0.30, chord Reynolds number = 7.9×10^6, the variation in transition location as indicated by the TSP is consistent with the corresponding changes in pressure recovery.

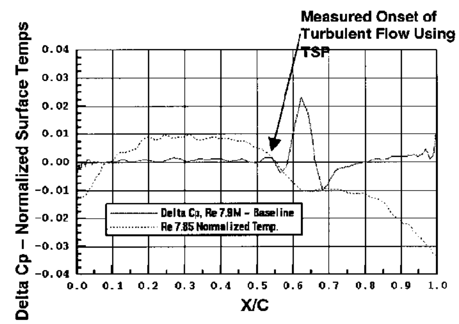


Figure 16 Comparison Illustrating the Design Pressure Gradient Effect on Boundary Layer Transition

Thus, the transition location at this condition is due to the pressure gradient present rather than Tollmein-Schlichting instabilities. Again, this test involved unswept two-dimensional models. Consequently the anticipated transition mechanisms were thought to be Tollmein-Schlichting instabilities and the effect of the pressure gradient over the model. For a more detailed discussion and comparison to boundary layer stability codes the reader is referred to "Application of Temperature Sensitive Paint Technology to Boundary Layer Analysis," M.P. Hamner, et al.[11]

The temperature sensitive paints used in these tests, i.e. both the 0.3-M TCT tests and the NTF tests, have been developed with increased operating range at the expense of temperature sensitivity. This is to minimize the "down time" of the facility during testing that would be required to repaint models as test conditions changed if the operating range was smaller. When used with current TSP systems, paints with a sensitivity of ~1.0% change in luminescent intensity per degree Fahrenheit yielded good results. Paints with a sensitivity of ~0.85% change in luminescent intensity per degree Fahrenheit did not yield consistent results.

NASA LaRC's National Transonic Facility

Summary and Test Objectives

Primary test objectives in the NTF were to obtain free and fixed transition data on three wing/body configurations: the high-lift configuration; the transonic configuration; and, the baseline configuration. Included in the test matrix was the acquisition of trip drag build-up data and fully turbulent performance data on all these configurations. As mentioned previously, this paper focuses on the baseline configuration. Secondary test objectives were TSP system development as required to facilitate the primary test objectives. This was to include initial system set-up, operation and specific aerodynamic issues such as an assessment of the intrusiveness of the technique. Then, a grit versus trip-dot study was to be performed, time permitting.

The NTF tests were scheduled for two shifts per day over an approximately 10 week period. The scheduled runs included Mach numbers of 0.30 and 0.90, with Reynolds numbers ranging from 8.5 x 10^6 to 90 x 10^6. Total pressure was varied from 20.0 to 99.4 pounds per square inch, absolute. Dynamic pressure was varied from 316 to 1800 pounds per square foot. Total temperature was varied from –250° to +120° Fahrenheit.

The WTC 1408-1 (HSCT) model installed is a 0.022 scale full-model representation of the Reference H configuration of the Boeing High Speed Civil Transport. This model is commonly called the 2.2% Reference H model. The model was built by Dynamic Engineering Incorporated under contract to NASA. This model is specifically designed and fabricated for testing at the high-pressure, cryogenic conditions in the NTF. Pertinent model geometry parameters include: a wing span of 34.23 inches; a wing reference area of 3.436 square feet; and, a mean aerodynamic chord of 22.71 inches. The model sting and stub sting previously fabricated for testing this model was also used during these tests.

An initial plan was developed for applying TSP to the 2.2% Reference H model during the paint phases of the tests. To avoid the complication of reflected excitation and TSP emission, a coating of the active TSP layer was to be applied only to the wing areas of the model. The model's wing was to be painted as a whole after being assembled in the respective configurations, e.g. the baseline, undeflected flaps configuration. Reference marks, or targets, applied along with the TSP, were considered a critical part of the ratioing and mapping process where the guideline for the spatial location of transition was initially set at ±1% of the local chord. In order to successfully process the images acquired the locations of the targets must be known to within 0.02 inches.[1] In addition, these targets had to be applied in the same location on each configuration tested. And, final quantitative results depend heavily on the accuracy of overlaying the images during the ratioing process. If the relative location of the images, i.e. the relative location of the reference marks, varied by even a pixel substantial differences in the final quantitative results were possible. Figure 17 shows a ratioed image including the reference marks. Approximate locations for the targets on the 2.2% scale Reference H model are shown in Figure 18. Note that the targets are located on the wing surface as opposed to flap surfaces where the specific (x,y) location would change with flap deflection. (x,y) locations remain the same for both upper and lower surfaces where z is measured vertically.

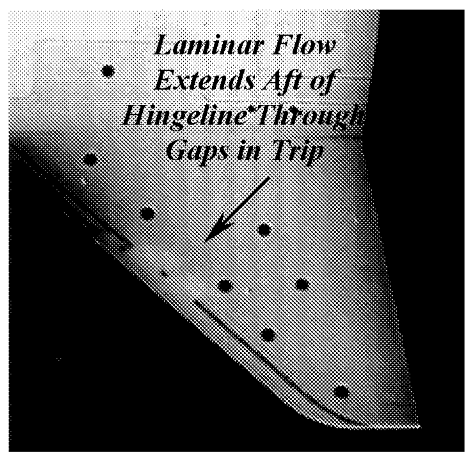


Figure 17 Ratioed TSP Image of the 2.2% Reference H Model in the Transonic Configuration Illustrating Reference Marks and Boundary Layer Trip with Gaps

[1] As determined at the Temperature Sensitive Paint System Check-out held July 1-2, 1996.

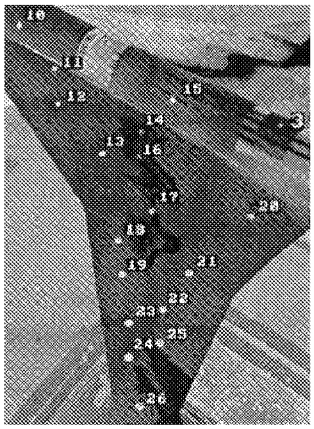


Figure 18 Illustration of Reference Marks for the Lower Surface of the 2.2% Reference H Model

Facility, Hardware and Paint Specifications

The NTF, shown below in Figure 19, is a fan driven, closed circuit, continuous flow, pressurized wind tunnel with an 8.2 ft by 8.2 ft test section that is 25 ft long. The facility is capable of high Reynolds number research, up to 120x10E-6 at Mach 1.0 (based on a reference chord length of 9.84 inches). The tunnel operating Mach number range is from 0.2 to 1.2, with a temperature range from +150° to -250° Fahrenheit, and a total pressure operating range from 15 to 130 psia.

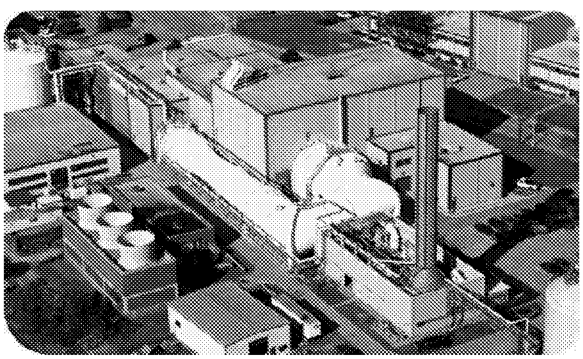


Figure 19 Aerial View of NASA Langley Research Center's National Transonic Facility

The NTF is used by the aircraft industry to accurately simulate the full scale, in-flight performance characteristics of large transport aircraft at transonic speeds through the use of cryogenic technology. Aircraft designs can be optimized when wind tunnel data are obtained at flight Reynolds number. The wind tunnel data so acquired are used to predict the performance of new aircraft to be sold to airlines. If the performance guarantees are missed, then the manufacturer may have to reimburse the airline for lack of performance.

Testing Challenges

One of the biggest testing challenges was maintaining the camera systems in the cryogenic environment, particularly the camera cables. Tests were required repeatedly both external and internal (at "warm" test conditions) to the NTF's pressure shell to trouble shoot camera operations.

A second big challenge was cracking of the TSP at model joints due to flexing during testing. The digital camera image in Figure 20 shows the results of this challenge.

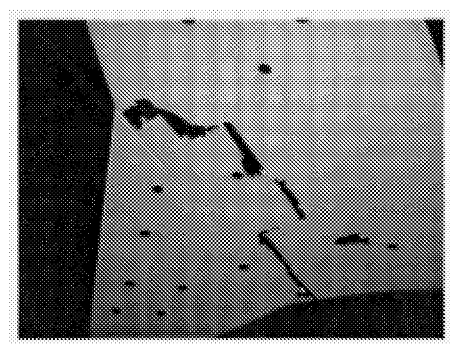


Figure 20 Digital Camera Image of Damage to TSP at the Model Part Line Between the Inboard and Outboard Wing Panels

By being the only wind tunnel in the United States that can match flight Reynolds number, the NTF is a vital tool for assuring predicted flight performance from scaled models matches actual flight vehicle performance. To eliminate this problem each model part was painted individually and then the model was assembled, rather than the original plan to paint the already assembled model.

Another big challenge was the spatial and temporal variation in radiant intensity from flash to flash of the flash lamps. This challenge was not specifically corrected during these tests because a sequence of images was acquired at each test point. In general the first image of the sequence was always omitted from the data reduction process. The remaining images show a maximum variation in radiant intensity of 0.6% over one sequence. This variation in incident intensity was not an issue in data reduction due to the much greater variation in surface temperature from the change in tunnel total temperature.

The last big challenge to discuss involves the mechanical operation of the facility itself. The total temperature in a cryogenic facility can be either increased or decreased. In order to decrease the tunnel total temperature, i.e. to make a "cold" temperature step, liquid nitrogen is injected into the tunnel circuit reducing temperature. Simply injecting liquid nitrogen, and hence reducing total temperature, is both easier and faster than the steps necessary to increase total temperature. However, as the nitrogen "boils off" pressure in the tunnel increases. In order to maintain other desired test parameters, e.g. a constant Reynolds number, some of the nitrogen gas must be evacuated. Thus the challenge is to simultaneously inject sufficient liquid nitrogen to make the required temperature change without altering other desired parameters or exceeding any mechanical limitations of the facility.

Data Acquisition and Reduction

A number of cameras were to be tested including a Photometrics CH250 14-bit scientific grade CCD camera, a Photometrics Sensys 12-bit scientific grade CCD camera, a Silicon Mountain Design 12-bit scientific grade CCD camera and the facilities 8-bit video cameras. Optical access, including a key for the various components at each portal, is shown in Figure 21. The approximate coverage from each camera is shown in Figure 22. Software was written to control camera operation including: synchronizing the camera trigger and flash lamps with facility data acquisition and dumping images from the cameras. The images from the three cameras were dumped to an NT server in three separate directories where they were held for distribution.

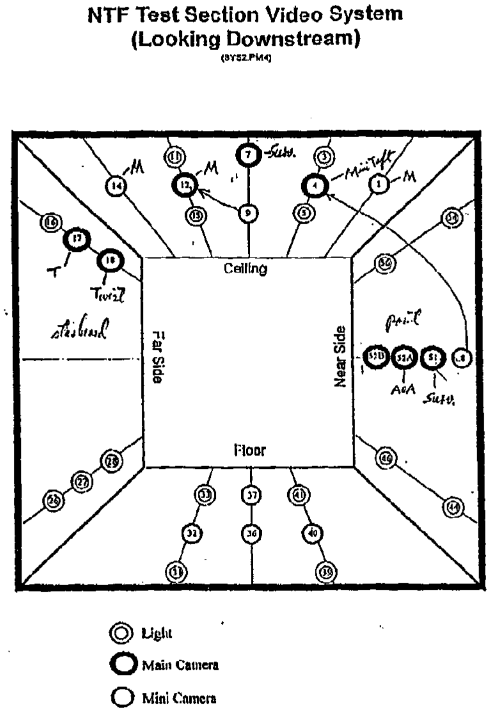


Figure 21 Optical Access and Corresponding Equipment in NASA LaRC's NTF

Three 4000 Watt-second flash lamps were used to excite the TSP. They were initially set to one quarter power to allow for the fastest possible recharging time. Model surveillance lights were filtered to prevent adding a bias to the image data acquired.

Once the tunnel was at condition, i.e. at the desired Mach number, Reynolds number, etc., two tunnel operators would simultaneously initiate a temperature step and data acquisition. It was anticipated that the timing of the "best" image acquisition would vary for each condition because the time required for the tunnel to change total temperature by 1° Fahrenheit varies for each condition. In addition, one of the limiting functions was the time required to dump images from the CCDs and append data from the video.dat file to the images.

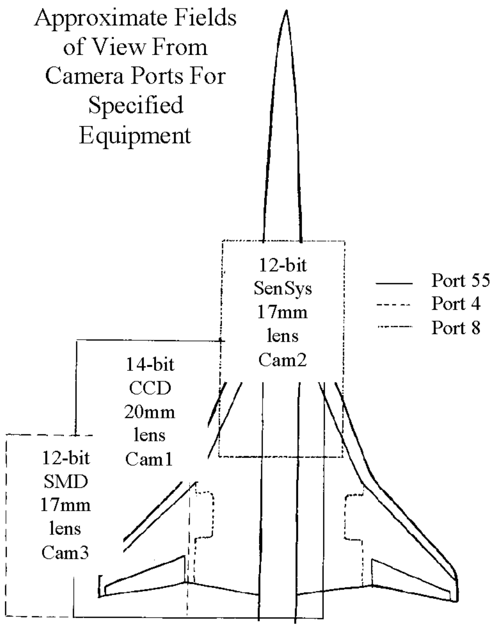


Figure 22 Approximate Field of View of Cameras Used During the TSP Tests at NASA LaRC's NTF

The video.dat file was created by the facility data acquisition system (DAS) and contained information such as date, time, test point, Mach number, chord Reynolds number, total temperature, total pressure and angle of attack. A number of software programs were written for the TSP system in the NTF including a subroutine pulling data from the video.dat file, creating a filename from that data and appending the data to the corresponding image. It was intended that there would be one file per image.

Three image processing systems were used: a PC based system under development by NASA LaRC's ETTD; an SGI based system also under development at LaRC; and the "green boot" software developed by McDonnell Douglas running on an SGI platform. Additional software to bridge the different pieces of the TSP system that were used together was supplied by McDonnell Douglas. For example, a subroutine to split up image files and use the appended data to create the image database in green boot was written along with a subroutine for use with a McDonnell Douglas graphics package to facilitate use of existing High Speed Research CFD grids.

Results

In addition to test runs completed to fill out the matrix required for developing trends with Reynolds number, Mach number, etc., a number of runs were included in the test matrix to test the validity of TSP as a test technique for use in boundary layer studies. For example, Figure 23 shows the comparison of TSP results with results using sublimating chemicals.

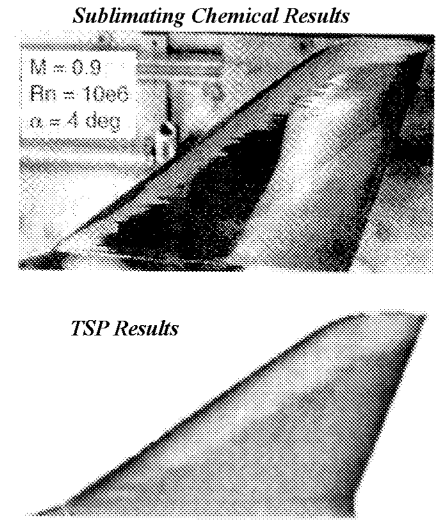


Figure 23 Comparison of Results Using TSP and Sublimating Chemicals – Lower Surface, Alpha = +4°, Mach = 0.90, Chord Reynolds Nr. = 10.2 x 10^6

This comparison can be made because of analogies that can be drawn between thermal and concentration boundary layers. That is, similar to the increase in heat transfer across a turbulent boundary layer there is an analogous increase in mass transfer across a turbulent boundary layer. However, because the amount of sublimating chemical remaining on the model is very dependent on run time, care should be exercised in drawing quantitative conclusions from this comparison.

In addition to validating TSP as a viable test technique for boundary layer studies, test runs were included to validate trip performance on the tripped configurations. As illustrated in Figure 17 above for the 2.2% Reference H in the transonic configuration, laminar flow extends slightly beyond the leading edge flap hingeline through gaps left in the trip thus verifying the trip's performance. The data shown was for the upper surface at 0.90 Mach, 10.3 x 10^6 Reynolds number, and +2 degrees angle of attack. However, data for the lower surface, also at 0.90 Mach and 10.3 x 10^6 Reynolds number but at +1 degree angle of attack or very nearly the zero lift condition presents a very different result. When the trip is applied using #150 grit, as sized by the Braslow criteria, there is a substantial amount of "ghosting" in the TSP image aft of the trip indicating that laminar flow is present aft of the trip. Thus, the trip is not really performing up to expectations. When the trip was applied using #120 grit from the outboard leading-edge break to the gap and #100 grit from the gap to the wing tip trip drag is minimized while still maintaining good trip performance. Unfortunately the pictures of these TSP images that are currently available are not of reproducible quality and so are not included in this paper.

Overall, more than 470 runs were completed and more than 6,600 images were acquired during these tests. The results at Mach number 0.30 and Reynolds numbers of 8.5, 14.4, 21.6 and 27.5 million for the baseline configuration are shown in Figures 24a through 24e. Similarly results at Mach number 0.90 and Reynolds numbers of 10.2, 20.0 and 30.0 million for the baseline configuration are shown in Figures 25a through 25c. Again, these results compared to semi-empirical predictions and force data acquired are shown in Figures 11 and 12.

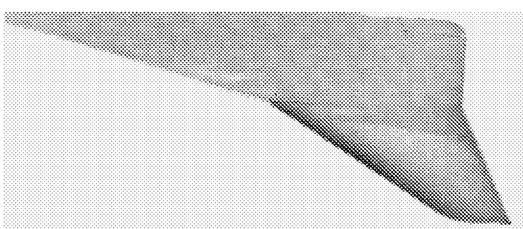


Figure 24a 2.2% Reference H Model at Mach = 0.3, Chord Reynolds Nr. = 8.5 x 10^6

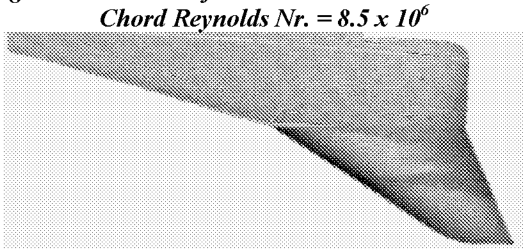


Figure 24b 2.2% Reference H Model at Mach = 0.3, Chord Reynolds Nr. = 10.0 x 10^6

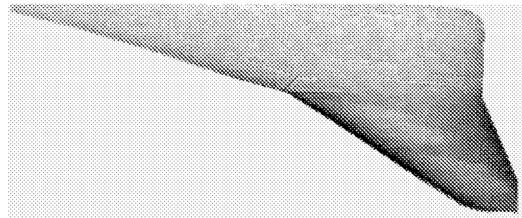


Figure 24c 2.2% Reference H Model at Mach = 0.3, Chord Reynolds Nr. = 14.4 x 10^6

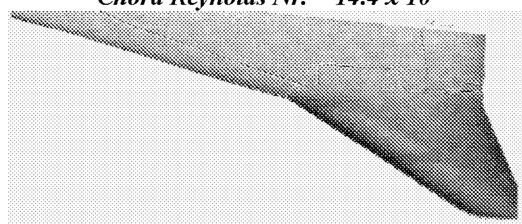


Figure 24d 2.2% Reference H Model at Mach = 0.3, Chord Reynolds Nr. = 21.6 x 10^6

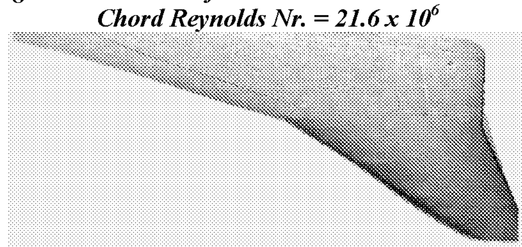


Figure 24e 2.2% Reference H Model at Mach = 0.3, Chord Reynolds Nr. = 27.5 x 10^6

Figure 25a 2.2% Reference H Model at Mach = 0.9, Chord Reynolds Nr. = 10.2 x 10^6

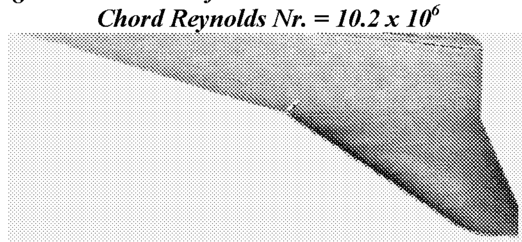


Figure 25b 2.2% Reference H Model at Mach = 0.9, Chord Reynolds Nr. = 20.0 x 10^6

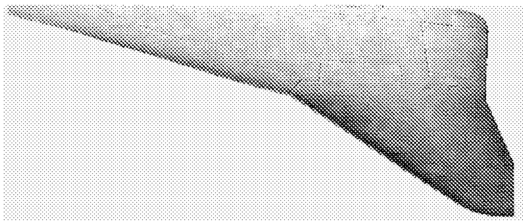


Figure 25c 2.2% Reference H Model at Mach = 0.9, Chord Reynolds Nr. = 30.0 x 10^6

Using Temperature Sensitive Paint for Boundary-layer Analysis in a Blow-down Facility

The McDonnell Douglas Polysonic Wind Tunnel

Summary and Test Objectives

Temperature sensitive paint has been used in the study of flow phenomena which create a variation in surface temperature, e.g. shocks, vortices, separation and boundary layer transition. The key to such studies is that the flow phenomena create sufficient changes in temperature to be detectable by current TSP systems. Some phenomena, for example shocks, create a large enough change in surface temperature to be readily detectable. Other phenomena, for example boundary layer transition, are currently detectable only by perturbing one or more test parameter. That is, test parameters such as tunnel total temperature or model temperature must be altered to enhance the variation in surface temperature created by the flow phenomena. Objectives for TSP testing in the McDonnell Douglas Polysonic Wind Tunnel included: application of the technique under various testing conditions; compatibility of the technique with other testing and analysis tools and intrusiveness of the technique.

The HSR M2.4-7A 0.1675 scale model of the McDonnell Douglas Arrow Wing, a model of a supersonic civil transport aircraft concept, was used for this testing at Mach 2.4 in the Polysonic Wind Tunnel (PSWT). The angle of attack range included in testing was from –1 degrees to +4 degrees. Reynolds numbers ranged from 4.5 x 10^6 to 9.0 x 10^6.

Facility, Hardware and Paint Specifications

The PSWT is a blow-down facility with an adjustable nozzle. This facility has the capability to heat the flow from ambient to 275° Fahrenheit prior to running. A schematic of the Polysonic is shown in Figure 26. Its operating characteristics, air production and storage are shown in Table 2.

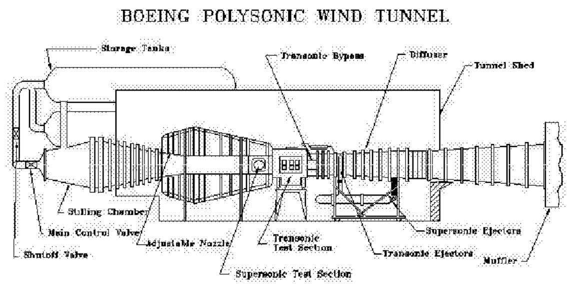


Figure 26 Schematic of the Boeing Polysonic Wind Tunnel in St. Louis, Missouri

PSWT Operating Characteristics

Mach Number Range	0.3 to 5.5
Reynolds Number Range	1 to 48 million/foot
Dynamic Pressure Range	100 to 7300 psf
Transonic Mach Control	+/- 0.005 Mach
Starting Load Protection	Ejectors
Run Time	29 seconds to 2 minutes
Blow Productivity	Up to 5 blows/hour
Run Productivity	Up to 8 sweeps/blow
Transonic Cart Install Time	1.5 hours

PSWT Air Production & Storage

Air Storage Volume	53,000 cuft @ 600 psi
Air Operating Temperature	Ambient to 275° F
Compressor Output	20 lbm/s @ 600 psi
Auxiliary Air	4150 psi
Auxiliary Air Temp	Ambient to 250° F

Table 2 Boeing Polysonic Wind Tunnel Operating Characteristics, Air Production and Storage

Testing Challenges

The biggest challenge to using TSP in a blow-down facility is establishing the appropriate test conditions. That is, sufficient heat must be added to the flow to prevent any detrimental effects from the supersonic expansion in the nozzle while still establishing the required temperature difference between the model surface (which is initially at the ambient temperature) and the flow for sufficient resolution in image acquisition. To determine the relevant temperatures the reader is referred to references such as Liepmann and Roshko's ***Elements of Gasdynamics***.[12] Note that to predict the surface temperature of the model, in addition to the classical calculations relevant to supersonic wind tunnels, calculations for the flow across the shock emanating from the nose of the model should be included, i.e. calculations for a conical oblique shock.

Data Acquisition, Reduction and Test Results

The McDonnell Douglas paint system was used to acquire and reduce TSP images in this test. It is a "traditional" intensity based system as is illustrated in Figure 1. Nine "free transition" test runs using TSP were completed. Figure 27 shows TSP data acquired at Mach 2.48, with a unit Reynolds number of 5.20 x 10^6, compared to the computed pressure distribution for this configuration at this condition.

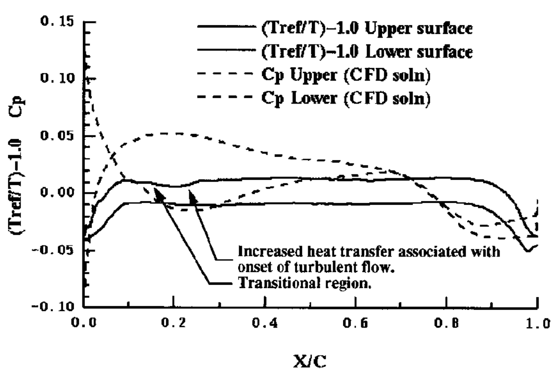


Figure 27 Comparison of Theoretical Pressure Distribution and Surface Temperature Measured Using Temperature Sensitive Paint:
CFD: Mach = 2.40, Alpha = -1.0°, T_{To} = 520 R, RN/ft = 5.20 x 10^6
TSP: Mach = 2.48, Alpha = -0.86°, T_{To} = 550 R, RN/ft = 5.36 x 10^6

Similar to the HSNLF model tested in the 0.3-M TCT tests, the pressure distribution for this design directly affects boundary layer transition. This was true for all test runs at Reynolds numbers of 5.2 x 10^6 or greater. Figures 28a and 28b, and 29a and 29b, illustrate the comparison of measured and calculated temperatures using quantitative temperature data from TSP images and computed temperature data from an explicit time marching/forward difference technique respectively.

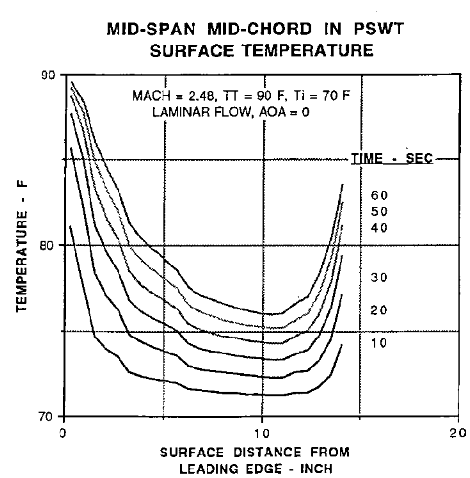


Figure 28a Computed Surface Temperatures

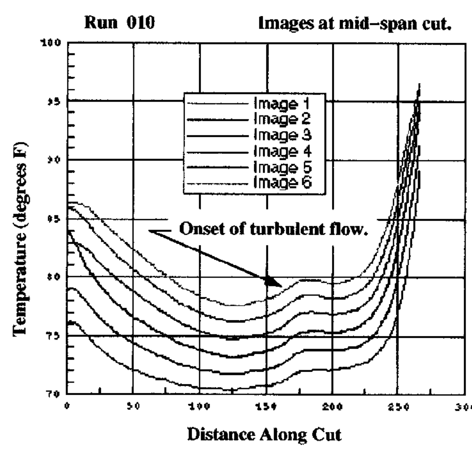


Figure 28b Measured Surface Temperatures Using TSP

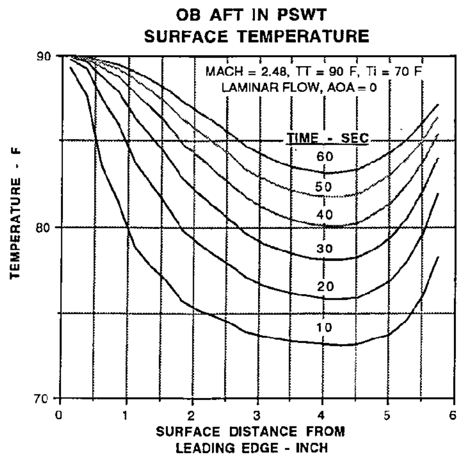


Figure 29a Computed Surface Temperatures

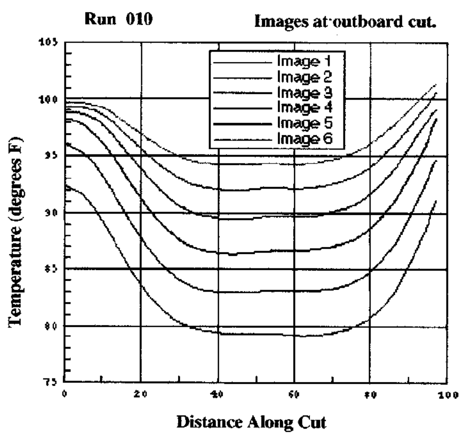


Figure 29b Measured Surface Temperatures Using TSP

SUMMARY

A number of tests have been conducted using temperature sensitive paint technology to perform boundary layer studies. This paper has focused specifically on those involving cryogenic environments or blow-down wind tunnels. Relevant facility, hardware and paint issues, and specifications have been included in this paper. Testing challenges, as well as lessons learned (or re-learned), have also been included. The results included demonstrate both the applicability of using TSP for boundary layers studies as well as the application of TSP under a variety of test conditions.

In general, researchers should carefully predict the spatial location of the critical Reynolds number based on the desired test conditions. Even if only an overly simplistic flat plate model is available. Then, if questions arise with respect to the extent of laminar flow, trip dots should be strategically used to verify the quality of the temperature sensitive paint data acquired. The converse, the potential for an entirely turbulent boundary layer, should also be kept in mind. Should that be a concern an additional test run, or test runs, at lower unit Reynolds numbers could be used to ascertain the quality of the data acquired.

Surface roughness should always be considered a challenge. As the images presented in this paper show, boundary layers over even the smoothest surface can still be subject to receptivity and/or bypass. However, even intentional roughness, such as trips, can yield unexpected test results such as those discussed with respect to validating boundary layer trip performance. Care should be taken to ensure that the surface is smooth enough to be representative of the desired test characteristics. Should surface roughness still be problematic, there are a number of basecoat materials that also act as fillers which can be worked, e.g. sanded or polished, more easily than reworking the metal surface of an existing model.

The biggest challenge to researchers using temperature sensitive paint technology for boundary layer studies will be to set-up their test(s) so that the temperature differences detected are sufficiently large to allow visual discrimination of the various boundary layer states present. Results from initial tests in the 0.3-M TCT have established a variety of criteria for use in setting-up TSP tests. One example of this was the determination that the naturally existing, steady-state surface temperature variation due to the change in heat transfer from a laminar to a turbulent boundary layer could not be detected with current TSP systems. Thus, to establish a successful test researchers must find a way to "enhance" the difference in temperature between the model and the flow over the model. For instance, a change in tunnel total temperature will result in an enhanced change in surface temperature in regions where a turbulent boundary layer exists relative to regions where a laminar boundary layer exists. This is true for at least the period during which the tunnel total temperature is changing. Once the tunnel total temperature has stabilized conductive heat transfer acts quickly to bring the model into thermal equilibrium.

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