# BOUNDARY LAYER TRANSITION DETECTION USING TEMPERATURE SENSITIVE PAINT IN THE ARA TRANSONIC WIND TUNNEL

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## Abstract

*A test campaign using the ARA Civil Reference Model in the ARA 2.74m x 2.44m Transonic Wind Tunnel (TWT) has been undertaken to investigate boundary layer transition detection using Temperature Sensitive Paint (TSP). The purpose of the test was to prove and further develop the processes and techniques for boundary layer transition detection with TSP within the ARA TWT.*

## 1 General Introduction

ARA typically uses the acenaphthene sublimation technique for boundary layer transition detection in its Transonic Wind Tunnel facility. However, recent advances in optical techniques and paints for the purpose of pressure and temperature measurements have opened up the possibilities for using the TSP paints for this purpose. The ARA Civil Reference Model has been used at ARA for over 20 years to check the tunnel flow quality and to trial and develop new equipment or test techniques. As such there is a large database of test data for this model to compare results against. The model itself is a simplistic representation of a civil transport aircraft in clean wing configuration (Figure 1), with pressure tappings on the upper surface of the port wing and lower surface of the starboard wing (total of 400 pressure taps). Results from this model have been consistent since it was first tested in 1998 and therefore any differences found when investigating new techniques can be confidently attributed to the technique in question.

Fig 1 The ARA civil reference model installed in the ARA TWT.

## 2 Background

Pressure and Temperature Sensitive paints have been available to researchers for many years, but it is only recently that they have started to gain a high reputation for commercial production wind tunnel testing. ARA became a leader in this productionisation of the Lifetime Pressure Sensitive Paint (PSP) technique when it joined forces with Innovative Scientific Solutions Inc (ISSI) of Dayton, Ohio, US, a leading developer of paints, plus associated hardware and software. Having developed a highly productive lifetime PSP system using the ISSI range of products to enable full 3D coverage of a model in the ARA TWT, it was the obvious next step to maximise the flexibility of this system by using it for boundary layer transition detection with TSP. The high quality, accuracy and cost effectiveness obtained from the Lifetime PSP system in the ARA TWT provided high levels of confidence in being able to achieve similar levels of quality and accuracy for the TSP system from ISSI.

# 3 Test Details

## 3.1 ARA Transonic Wind Tunnel (TWT) and Civil Reference Model Details

The ARA 2.74m x 2.44m (9ft x 8ft) Transonic Wind Tunnel (TWT) is a closed circuit, continuous running facility with an operating range from 0.2 to 1.4 Mach number at stagnation pressures from 0.8 to 1.2 atmospheres. The tunnel is driven by an 18.6MW AC motor, enhanced at high subsonic and supersonic Mach numbers by auxiliary suction using a 9.7MW compressor. The basic layout of the ARA TWT is shown in Figure 2.

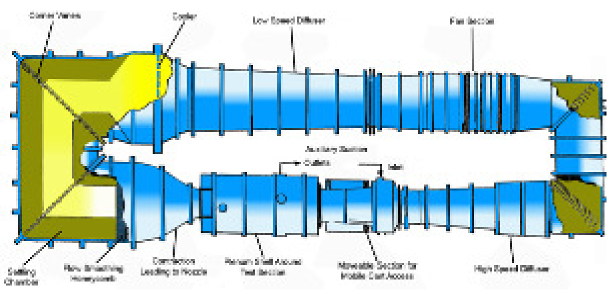


Fig. 2 Layout of the ARA TWT.

The axis of the tunnel is positioned 67.7m (222ft) above sea level. The main purpose of the ARA TWT is to provide a highly productive facility which is capable of handling both routine model testing and complex configurations. Models are prepared in secure work areas adjacent to the tunnel and mounted on a model support cart at the start of a test series. A network of rails and turntables permits a rapid changeover of model carts between test series [1].

The model used for these TSP development experiments was the ARA Civil Reference Model. The dimensions of the model as well as the moment reference point and balance centre are shown in Figure 3. The model was mounted on a 57.15mm (2.25”) diameter, 6 component internal strain gauge balance. Model incidence was measured by an onboard Sundstrand type QA1400 inclinometer.

During the test, Ballotini roughness bands were applied at 2 alternate chordwise positions on the starboard wing as detailed in Table 4. Two temperature sensors were installed onto the upper surface of the port wing to measure the temperature at the surface of the model. One temperature sensor was installed on top of the screen layer to take into account any thermal insulation provided by the paint, whilst the other temperature sensor was installed directly onto the clean metal surface (more details regarding the screen layer are provided in section 3.2 of this paper). The measurements from the temperature sensors were then used in the post processing of the TSP data.

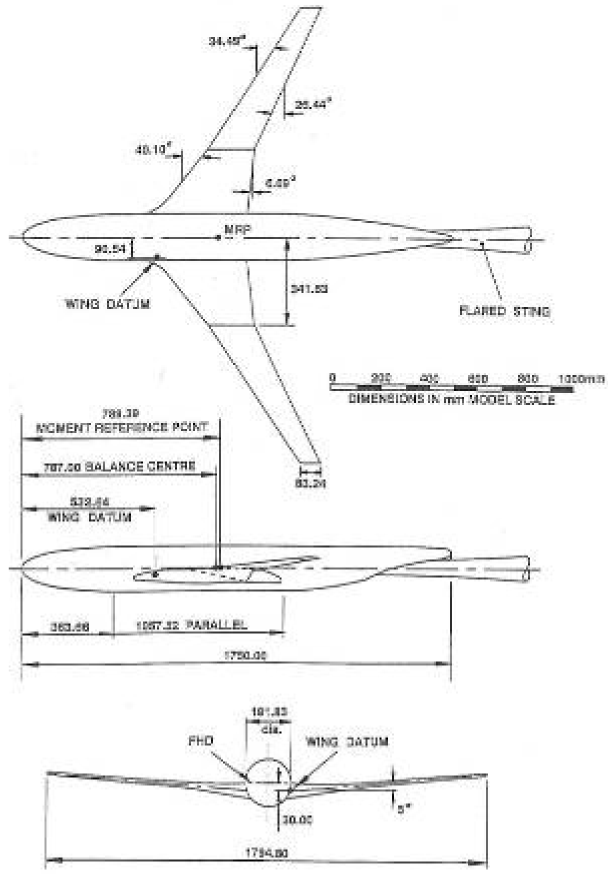



Fig 3 The ARA civil reference model.

Model reference dimensions used to non-dimensionalise the aerodynamic data obtained from the main balance are given below:

- Wing area 0.358986 $m^2$
- Wing span 1.794792 m
- Aspect Ratio 8.97327

- AMC( $c$ ) 0.243041 m
- Moment Reference Point 0.25$c$ located on the FHD

A fuselage base area of 0.0050265m$^2$ was used in the calculation of the base pressure correction.

| Configuration | Component | Band Width (mm) | Ballotini Diameter (mm) | Location of band aft of leading edge |
|---|---|---|---|---|
| 42050 | Wing upper surface (forward) | 1.3 | 0.106 to 0.125 | 0.05c at root<br>0.05c at $\eta_{NET}$ 0.325<br>0.05c at tip |
| | Wing lower surface (mid) | 1.3 | 0.106 to 0.125 | 0.20c at root, 0.15c at $\eta_{NET}$=0.325 and $\eta_{NET}$ =0.935 and 0.05c at tip |
| 42111 | Wing upper surface (mid) | 1.3 | 0.106 to 0.125 | 0.15c at root<br>0.15c at $\eta_{NET}$ 0.325<br>0.15c at $\eta_{NET}$ 0.325<br>0.05c at tip |
| | Wing lower surface (mid) | 1.3 | 0.106 to 0.125 | 0.20c at root, 0.15c at $\eta_{NET}$=0.325 and $\eta_{NET}$ =0.935 and 0.05c at tip |

Table 4 Details of wing roughness bands applied for the test.

## 3.2 ISSI Temperature Sensitive Paint System

The TSP system used for this test programme was from the ISSI range of TSP paints, which operate within the 400–500nm range. Illumination was provided using the ISSI LM4X water cooled lamp which emits UV light at 470nm with a power of 12w per lamp head. ARA has the capability to deploy up to 20 of these lamp heads within it's purpose built system. However, for the purposes of this test, only 3 lamp heads were used due to only the upper surface of the starboard wing being coated with TSP.

Experiments have been performed using the TSP paint with and without a screen layer applied to the surface of the model. Screen layer is a thin layer of insulating paint that can be applied before the TSP layer is applied. This screen layer helps to cover the differences in the materials the model might consist of and therefore reduce the impact of the thermal inconsistencies of those materials, thus improving the result from the TSP. However, it is vital that this additional layer is kept as thin as possible to remove the risk of compromising the wing profile.

Images are captured on a Scientific grade CMOS camera with a high resolution Nikon lens with an appropriate filter attached. In this case the cameras used were PCO-1600MOD cameras. 12 of these form the basis of the ARA Lifetime PSP system but again this test only required the use of 3 of those cameras to cover the upper surface of the starboard wing:

- Camera 1 – Covering the inboard of the Starboard wing upper surface
- Camera 2 – Covering the mid-section of the Starboard wing upper surface
- Camera 3 – Covering the outboard section of the Starboard wing upper surface

Acquisition was achieved using the ISSI Pro-Acquire software (V1.4) operating in the Master/Slave arrangement on each of the PC's dedicated to each camera. Signals between the software, cameras and lamps were synchronised using the Quantum Composer signal generator. Acquisition was triggered automatically via the ARA TWT Data Acquisition System, using a custom designed software module for the ISSI Pro-Acquire programme. Thereby synchronising TSP data acquisition with the data acquired from the pressure taps.

To ensure highly accurate data from the TSP system a series of inspected photogrammetric markers were applied to the model so that the acquired TSP data can be mapped onto a virtual 3D surface mesh of the model geometry.

Finally, the TSP paint was calibrated at a range of temperatures to provide a calibration file which enabled the intensities captured in the images from the cameras to be converted into temperatures during the post-processing.

## 3.3 TSP System Installation

The ARA TWT has a plenum area behind the porous walls within the working section of the tunnel. It is within this plenum area that the TSP acquisition cameras and lamps were installed. This can be a harsh and difficult environment for such sensitive electronic equipment. However, over many years, ARA has developed custom made mounting systems for cameras, light sources and associated hardware to enable secure operation of such devices. These mounts are designed to be flexible in application, enable views from multiple positions and both secure and vibration resistant. Access services to these systems for electricity, water and data transfer are via a bulkhead arrangement, usually utilising some form of signal boost or relay feature to cope with the relatively large cable lengths required, typically up to 50metres.

For this test all of the acquisition hardware was located in the roof part of this plenum area, looking down into the working section onto the upper surface of the model (Figure 5). Typical distance from camera to model is approximately 1 m, depending on model attitude.

Fig 5 TSP camera and lamp installation with the TWT plenum roof area.

Each camera has it's own dedicated PC which is used to control the camera settings and for the data acquisition, these are all located in the TWT control room, connected to each other on their own network. One of these camera control PC's is designated as the Master PC and is also connected to the ARA network for interaction with the TWT Data Acquisition System. The Quantum Composer is also located with these PC's and on the TSP acquisition network. The signals are then transmitted through to the cameras and lamps via BNC connections through the TWT bulkhead [2].

In addition to the TSP system and standard ARA tunnel data acquisition system, an Infra Red thermal imaging camera (FLIR P640) was installed with a view of the wing coated with the TSP. This was used purely for visual confirmation of transition position during the run. However, due to the low resolution of this particular camera it is not possible to obtain accurate positional information from these images. In addition this camera was not calibrated prior to the test and therefore temperature data was also only used for qualitative purposes. An example image from this camera can be seen in Figure 6.

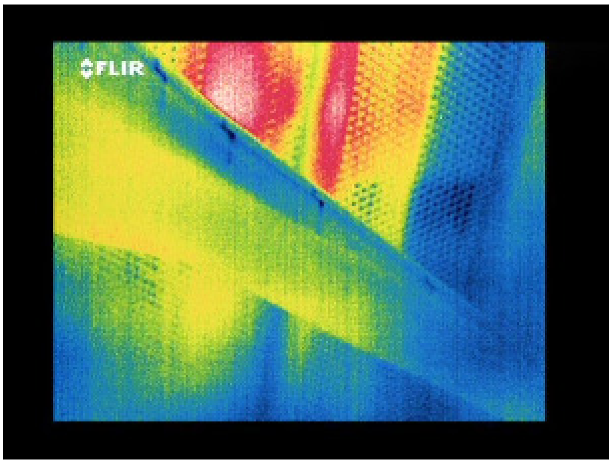



Fig 6 Example thermal image from FLIR P640 camera.

## 3.4 TSP Data Acquisition

The TSP section of this test consisted of a sequence of single data points recorded at a fixed $C_L$ of 0.4 for Mach numbers from 0.4 to 0.82. The overall forces, moments and pressures were measured simultaneously with the TSP data for diagnostic purposes only.

An Acenaphthene sublimation run was also undertaken on the port wing transition free, at the start of the test campaign to indicate the natural boundary layer transition position. The information of the natural transition position from this sublimation test was then used to verify the TSP results, Figure 7.

A rapid increase in the tunnel air temperature was generated before each TSP data point was acquired, this amplifies the effects of the boundary layer transition temperature change compared to the model surface temperature and therefore improves the TSP data.

Figure 7 Acenaphthene sublimation photograph showing natural boundary layer transition position.

## 3.5 TSP Data Processing

Images acquired by the TSP cameras are monochrome 16-bit tif image files. For processing into accurate temperature distributions they are taken into the ISSI Pro-Image software. Here the marker positions are identified, the tunnel conditions are applied, along with the camera and paint calibrations. The resultant post-processed file is ready for mapping onto the model mesh geometry prepared in advance. This mesh can be structured or unstructured with density chosen to suit individual areas of detail. The mesh is created from a combination of the original CAD geometry and a detailed assembled model inspection, during which the markers and pressure taps are also inspected and added to the geometry. The mesh is cut into sections relating to each camera view with a small area of overlap to allow for any model movement within the camera view.

The processed files are imported into the ISSI Pro-Field software along with the mesh file for that camera view. Within Pro-Field multiple processed and mesh files can be combined to give the full 3D view of the model if enough cameras have been used to facilitate this. Once the mesh and TSP data files have been accurately mapped the data analysis can be performed using a range of available tools within Pro-Field or exporting slices of data to other packages.

For the purposes of this paper the TSP data has been analysed by taking slices at the same locations as the pressure tap positions on the opposite wing. Visual comparisons with existing sublimation photographs from previous tests at these conditions were also performed.

# 4 Results

The test campaign covered a range of Mach numbers and conditions but for the purposes of this paper only the data taken at Mach 0.82 is presented. However, the results from the rest of the test campaign show comparable accuracy to those at M = 0.82.

When looking at the data from the cases with transition fixed a 0.05c and that at 0.15c it is clear that the 0.05c case is harder to interpret clearly. It was concluded that for the 0.05c case data has been affected in the following two ways; (i) the leading edge curvature was out of prime optical view thus preventing good TSP acquisition and (ii) the transition band proved less effective due to the strong favourable pressure gradient, especially near the wing root. Consequently, only results with transition fixed at 0.15c are presented here. Figure 8 and Figure 9 present sublimation results and pressure data, respectively, obtained in a previous test campaign with fixed transition at 0.15c. Figure 8 shows that transition is triggered by the band located at 0.15c. The transition line is visibly sharper in the region outboard of the crank position, but becomes less clear towards the wing root.

Fig 8 Sublimation photograph showing result of transition fixed at 0.15c.

difference between the corresponding camera views in Figure 10. In all view sections, the transition band located at 15% local chord is clearly visible. However, these initial results indicate that no flow transition can be identified in the TSP contour plot. Further investigation needs to be performed. Only the transonic shock leaves a faint footprint at approximately 30% local chord outboard of the wing crank. Furthermore, flow features cannot be detected near the wing root because of the wing's high thermal mass in this area and possible wing-body interactions.

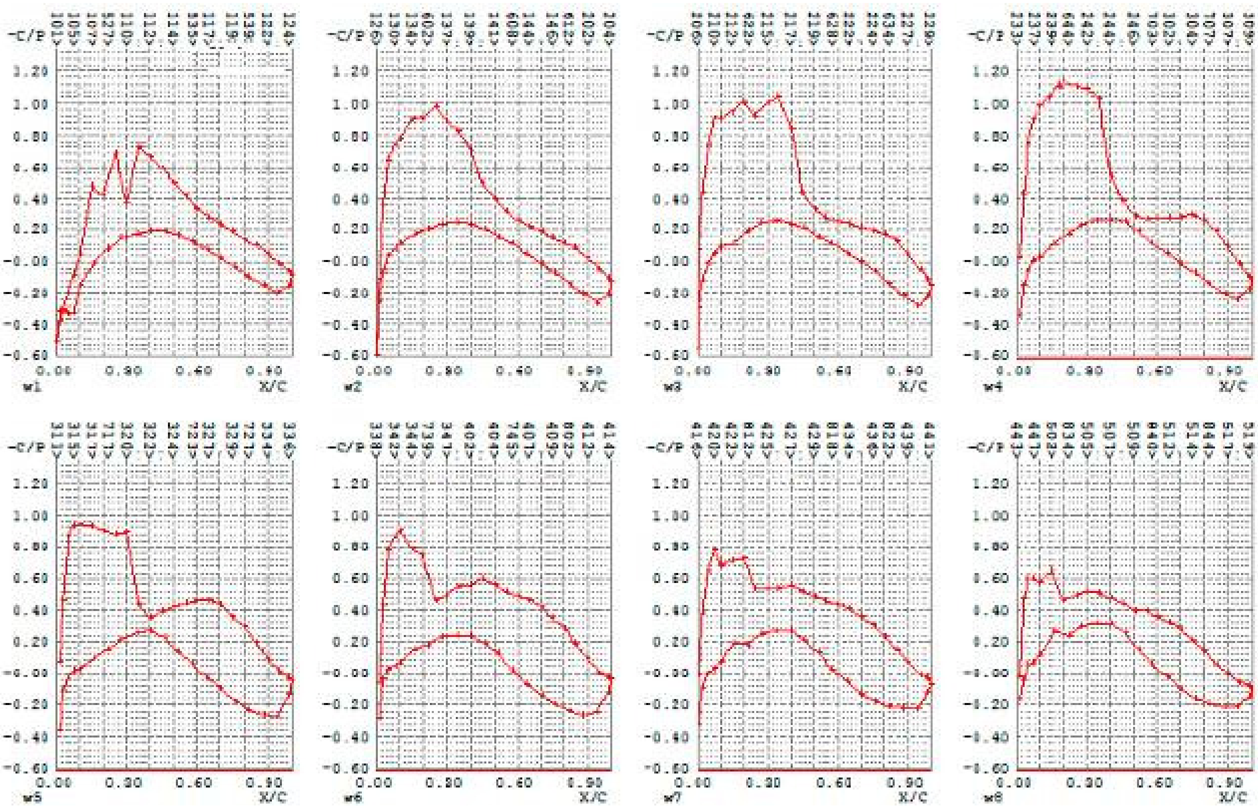


Fig 9 Pressure plots with fixed transition at 0.15c.

The associated pressure plots in Figure 9, taken at span-wise locations, reveal the existence of a relatively strong shock between 0.35c at station W3 and 0.20c at station W6 (see Figure 10 for pressure station locations).

A TSP contour plot taken at the end of the data acquisition window is presented in Figure 10. Here, red lines indicate the location of these pressure profiles on the upper wing surface shown in Figure 9. Note data from Camera 2 gave a significantly higher intensity reading than Cameras 1 and 3. This leads to a noticeable

The temperature profiles extracted from the TSP contour plot in Figure 10 confirms the observation above for data near the wing root, see slice at y=0.0188 in Figure 11(a). Note the slice positions are identical to the pressure stations given in Figure 9. For all other stations, the TSP response to the optical discontinuity caused by the transition band yields a spurious temperature oscillation, which is significantly larger than the expected temperature increase due to transition of approximately 0.5 K.

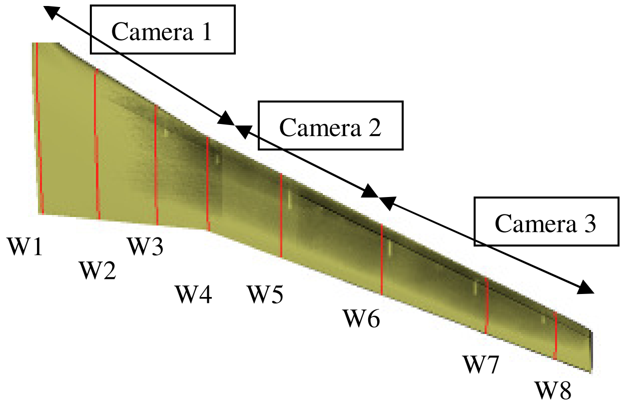
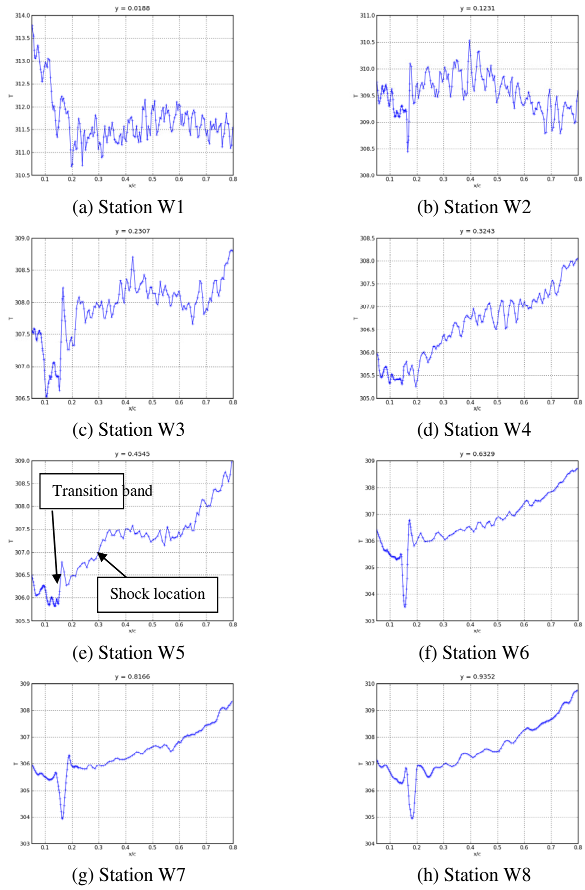



Fig 10 TSP contour plot with fixed transition at 0.15c.

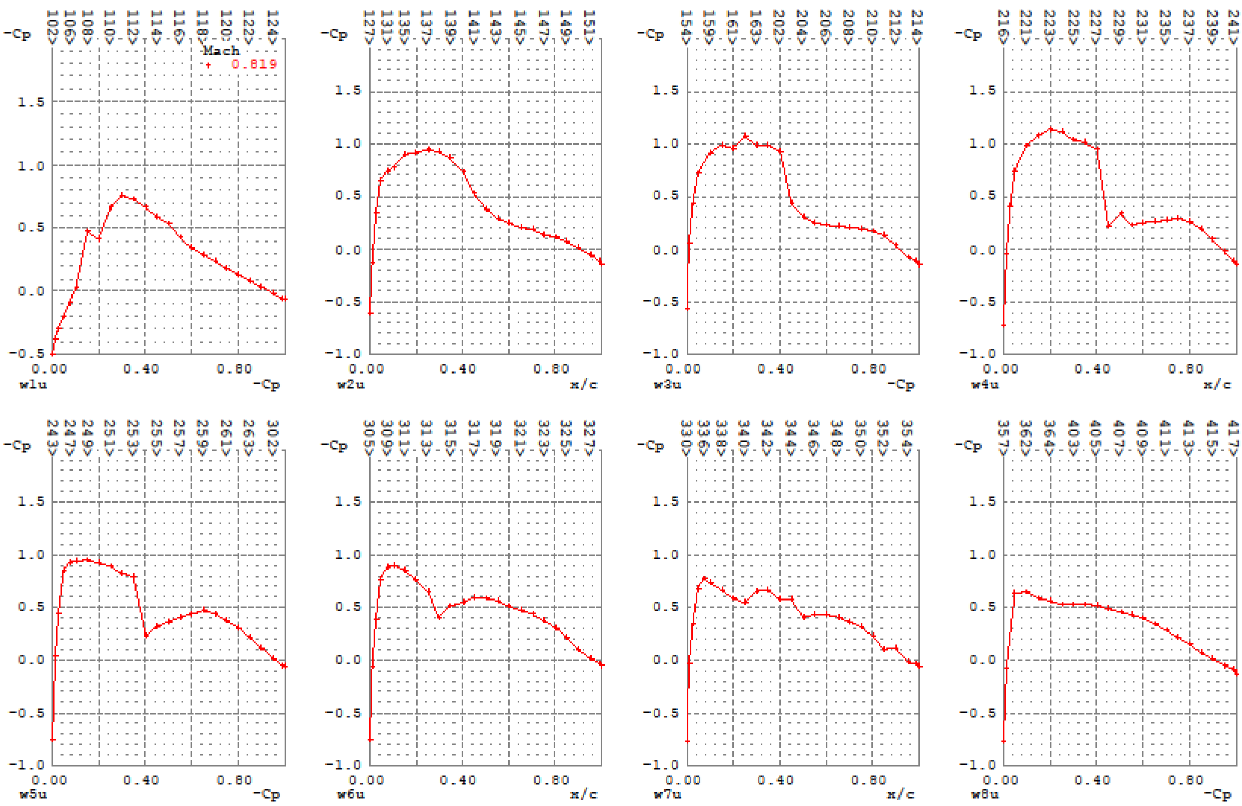
Nevertheless, for stations W5 to W8, transition can be determined speculatively across the transition band. Yet, the change in temperature due to the shock appears more clearly in the TSP results, especially with the intensity settings from Camera 2, see station W5 shown in Figure 11(e).

Fig 11 Slices of TSP data from results with fixed transition at 0.15c.




(a) Station W1 (b) Station W2 (c) Station W3 (d) Station W4 (e) Station W5 (f) Station W6 (g) Station W7 (h) Station W8

Figure 12 Pressure plots for natural transition tests.



A sublimation test was conducted at the beginning of the test programme on the upper surface of the port wing at a constant Mach number of 0.82, without a fixed transition band, Figure 7. During this test no temperature pulse was introduced and TSP data was taken on the upper surface of the starboard wing to check out the data acquisition and computing system. The temperature increased marginally during the sublimation test at a rate of approximately 0.4 K per minute (0.08 K per 20 seconds).

The sublimation results and associated pressure profiles at this flow condition are presented in Figure 7 and Figure 12, respectively. Near the wing root, no information is obtained from the sublimation test. However, early transition could be expected close to the leading edge due to cross-flow disturbances associated with the favourable pressure gradient. Around the mid-wing position, a distinct transition line is visible as it is triggered by the strong pressure gradient introduced by the transonic shock. Note the shock is located further down-stream compared to the test case with fixed transition at 15% chord. This picture of showing transition becomes less clear when considering regions near the wing tip. This is due to the gradual change in pressure gradient, where the transition at approximately 50% chord visible in Figure 7 can be associated with the greater change in the adverse pressure gradient shown in Figure 12.

Figure 13 shows the TSP data collected during the natural transition configuration, with the rapid thermal increase. As mentioned previously the high thermal mass near the wing root makes this area particularly difficult for obtaining good TSP data as can be clearly seen in Figure 13.

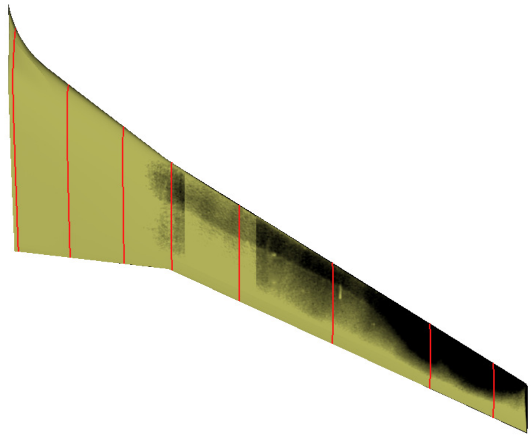
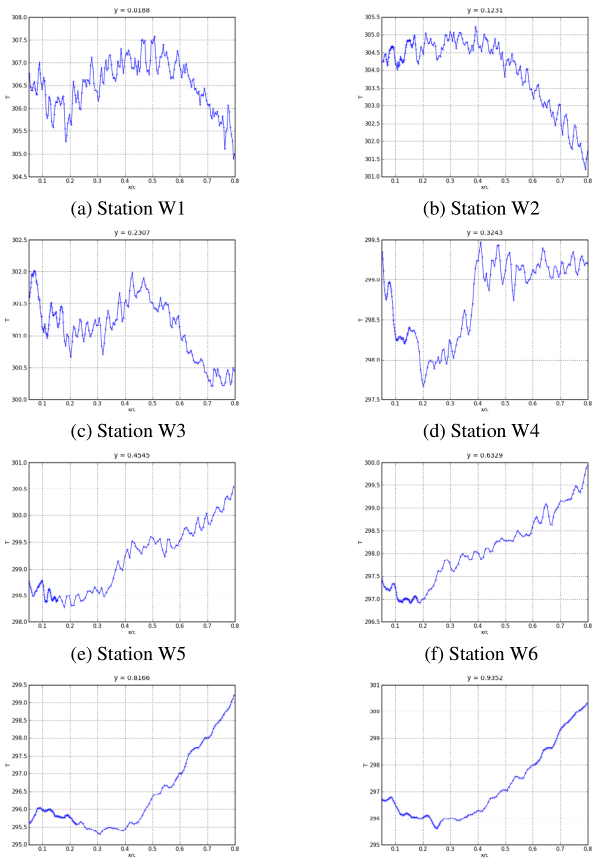


Figure 13 TSP data for natural transition configuration.



(a) Station W1 (b) Station W2

(c) Station W3 (d) Station W4

(e) Station W5 (f) Station W6

(g) Station W7 (h) Station W8

Figure 14 Slices of TSP data from the results of the test with natural transition.

The temperature increase due to transition can also be identified in the corresponding temperature profiles shown in Figure 14. A clear increment of 0.5 to 1 K is visible for the slices taken across the mid-wing, i.e. Station W4 to Station W6. For slices near the root and the tip of the wing, transition cannot be detected unambiguously, probably due to a combination of thermal mass of the wing structure, wing-body interactions and specific pressure distribution.

## 5 Conclusions

Analysis of the results from this test campaign has proven that successful detection of boundary layer transition is possible using TSP in the ARA TWT. These results also show that detection of the natural point of boundary layer transition is also possible using the methods described here.

However, the results also show that the internal structure of the model may affect the local thermal properties and consequently influence the TSP results in that local area.

The application of a screen layer to reduce these thermal effects has been shown to be effective in improving the TSP results. However, to minimize the risk of changing the wing profile it is necessary for this screen layer to be as thin as possible and therefore less effective in areas of large local structural thermal effects.

It was also noted that transition bands have a strong influence on the TSP data, resulting in spurious temperature oscillations one order of magnitude larger than the expected temperature increase from the change from laminar to turbulent flow.

Finally it was concluded that to maximise the quality of the TSP data it is important to optimise the settings of the acquisition cameras to give high intensity images. Wherever possible these intensity readings should be consistent across different cameras to ensure smooth data when multiple camera views are combined to give a total area result.

## References

[1] Vardaki E, Stokes N, Fonov S, Crafton J. Pressure sensitive paint measurements in the Aircraft Research Association transonic wind tunnel. *27th AIAA Aerodynamic Measurement Technology and Ground Testing Conference,* 28th June – 1st July 2010 Chicago, Ilinois, US, AAIAA 2010-4796.

[2] Vardaki E, Stokes N, Patel S, Gustafsson P. Pressure sensitive paint measurements on the Gripen model at the ARA transonic wind tunnel. *50th AIAA Aerospace Sciences Meeting,* 9th-12th January 2012, Nashville, Tennessee, US, AIAA 2012-1188.

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