AIAA 2000-2649

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21st AIAA Aerodynamic Measurement Technology and Ground Testing Conference
19-22 June 2000 / Denver, CO

2000-2649

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Abstract

High-temperature luminescent coatings are being developed and applied for simultaneous pressure and temperature mapping in conventional-type hypersonic wind tunnels, providing global pressure as well as global aeroheating measurements. Together, with advanced model fabrication and analysis methods, these techniques will provide a more rapid and complete experimental aerodynamic and aerothermodynamic database for future aerospace vehicles. The current status in development of simultaneous pressure- and temperature-sensitive coatings and measurement techniques for hypersonic wind tunnels at Langley Research Center is described, and initial results from a feasibility study in the Langley 31-Inch Mach 10 Tunnel are presented.

Introduction

Significant advances have been made over the last decade in global measurement techniques for pressure, temperature and transient heat transfer measurements on wind tunnel models. These techniques revolutionize wind tunnel testing by providing high resolution surface measurements in very little time with low cost. Pressure- and temperature-sensitive paints have been developed for several applications in subsonic through supersonic conditions, including some low temperature hypersonic applications (Liu, et al., 1997). Two-color phosphor thermography techniques have been developed for higher temperature hypersonic wind tunnels for surface temperature and transient heat transfer measurements (Buck, 1988, 1991 and Merski, 1999).

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Use of a reference luminophor in two-color phosphor thermography provides a robust and quantitative system for temperature mapping. Coupled with rapid model fabrication techniques (Buck, 2000), phosphor thermography in hypersonic wind tunnels is presently providing orders of magnitude more aerothermal heating information than computational methods for a given period of time. This is particularly true for advanced aerospace vehicles having complex geometry such as X-33, X-34 and Hyper-X (e.g., vehicles having fins, control surfaces, inlets, nozzles, etc.) as opposed to more simple reentry capsules and aerobrakes.

In a recent, fast paced, vehicle design study (X-37 Pathfinder), more than 25 models of 10 different configurations and/or sets of control deflections were built and tested for aeroheating measurements with phosphor thermography in the Langley 20-Inch Mach 6 Air Tunnel, over a four-month period. The database resulting from these tests spanned a wide range of angles-of-attack and Reynolds numbers (corresponding to laminar, transitional, and turbulent boundary and shear layers) and encompassed the entire vehicle, including control surfaces such as body flaps, ruddervators and flaperons.

Use of powder coatings for the two-color phosphor thermography technique provides a means for uniform surface coverage with composite luminescent materials. Similar use of reference or multiple luminophores in pressure-sensitive paint (PSP) systems have been frustrated by solvent based paint formulations. With solvents the luminophores tend to pool, migrate, and/or separate on the surface before drying, making it difficult to apply a PSP mixture uniformly.

Current work focuses on a system for global simultaneous pressure and temperature measurements in hypersonic wind tunnels. The techniques developed use a high-temperature pressure- and temperature-sensitive coating (PTSC), consisting of a dry composite luminescent powder, which is electrostatically coated on a model or test sample, baked on and heat cured to maximum operating temperature for thermal stability. A digital color imager is then used for single exposure luminescence pressure and temperature measurements.

PTSC Development

It was previously shown (Buck, 1995) that an organic perylene compound, when adsorbed onto a ceramic substrate, exhibited useful characteristics at high temperatures to 150C for combined pressure and temperature measurements using a measure of relative brightness and color shift. PTSCs are being developed which combine adsorbed luminescent dyes with inorganic thermographic phosphors for a uniform powder coating with higher temperature operation and the ability for single exposure simultaneous pressure and temperature measurement using a three-color imaging system. This would facilitate angle-of-attack sweeps, in which the model is moved from its initial position, for aerodynamic studies with pressure and temperature, as well as video rate acquisition (15 frame per second for current digital imager) on a fixed angle-of-attack for temperature time history used in heat-transfer analysis.

The present objective in PTSC formulation is to increase shear stability as well as temperature stability and to balance emission colors for a single detector 10-bit digital color imager. Earlier formulations (presented at a PSP conference in 1998) were designed for a 3-detector analog-to-digital 8-bit imager which is currently used for two-color phosphor thermography. Earlier formulations also had a 15-percent relative-to-full-scale pressure sensitivity in brightness from 4 torr to atmosphere, which would translate to 38 counts of measurement resolution over a range of 760 torr for an 8-bit imaging system. One problem revealed from preliminary testing of that coating in a hypersonic wind tunnel was that the organic dye compound would flow from the nose and leading edges of the test model when those surfaces exceeded the maximum coating temperature (210C), fouling the coating downstream which would otherwise remain stable. The signal-to-noise ratio (S/N) was also too low for useful luminescent pressure measurements with the 8-bit analog-to-digital imager.

Hence, a new glass polymer was introduced in the powder formulation to immobilize the organic dye at higher temperatures and increase shear stability. Also, a new pressure-sensitive dye and phosphor mixture were used to match spectral sensitivity of a 10-bit color imager to increase S/N.

In preparing the PTSC, thermographic phosphors are combined with uncured glass polymer, baked at 400C for an hour, cooled and ground into a fine powder (around 35-micron particle size). The organic pressure-sensitive dye is adsorbed onto the composite powder and heated to 275C for one hour. The composite luminescent powder is then mixed with an additional uncured glass polymer powder that acts as a thermal-plastic/thermal-setting binder when coated. The final mix is electrostatically coated onto a test model or calibration surface and placed in a convection oven for adhesion and curing. The binder melts, adhering the powder coating to the surface at 125C. More than one coat may be applied and adhered to the surface at 125C before the final coating is thermally set and excess dye evaporated at 200C for 30 minutes.

Three-Color Imaging System

A Single-detector 10-bit digital color camera is used as an imager. Its 2/3-inch CCD is a 1300x1030 picture element (pixel) array with a 1:2:1 red-green-blue (R-G-B) distributed color filter pattern as shown in Figure 1. This results in an effective image resolution of 325x257 based on total number of R and B pixels. The spectral response for individually filtered pixels is shown as solid lines in Figure 2. The effective spectral response for the image is shown as dashed lines, factoring in the 1:2:1 R-G-B spatial aperture.

Pressure and Temperature Calibration

Figure 3 shows the color brightness temperature response at 4 torr vacuum and atmosphere for the new PTSC. Emission color brightness is based on a constant excitation of 365 nm at 200 μwatt/cm^2, using a bandpass filtered high-pressure mercury arc lamp (150-watt) and photometric camera calibration. Figure 4 shows actual camera output in 10-bit digital counts.

Thin metallic samples were coated with PTSC and placed in a vacuum oven for calibration. Figure 5 shows the pressure transducer and thermocouple temperature values for the PTSC calibration data. The vacuum oven was fitted with a one-inch thick silica glass window for excitation and viewing of the sample. The vacuum oven has a pressure range from 4 torr to atmosphere and temperature range from room temperature to 180C.

The ratio of red to blue emission R/B is found emperically from this data to be a function of temperature F1(T) with an added first order pressure term k1*P

$$c1*R/B = F1(T) + k1*P \qquad \ldots 1$$

$$k1 = 7.5 \times 10^{-5}\ \text{torr}^{-1}$$

where c1 is a coating constant. Figures 6(a) and (b) are plots of c1*R/B and F1{R,B,P} respectively

$$F1\{R,B,P\} = c1*R/B - k1*P = F1(T) \quad \ldots 2$$

where

from Equation 1. Figure 6(b) also shows a curve fit solution to temperature $F1^{(3)}(T)$ that is a spliced 3rd order polynomial.

Similarly, the ratio of green to blue G/B is found emperically to be a function of temperature F2(T) with an added first order pressure term k2*P

$$c2*G/B = F2(T) + k2*P \quad \ldots 3$$

$$k2 = 2.5 \times 10^{-5}\ \text{torr}^{-1}$$

where c2 is a coating constant. Figures 7(a) and (b) are plots of c2*G/B and F2{G,B,P} respectively

where

$$F2\{G,B,P\} = c2*G/B - k2*P = F2(T). \quad \ldots 4$$

from Equation 3. Figure 7(b) also shows a curve fit solution to temperature $F2^{(3)}(T)$ that is a spliced 3rd order polynomial.

Combining Equations 2 and 4 to eliminate pressure, and normalizing over the range of calibration (i.e. $0<F3<1$ for $20C<T<180C$) gives

$$F3\{R,G,B\} = (c2*G/B - k2/k1*c1*R/B)*1.492-1 = F3(T) \quad \ldots 5$$

which is a temperature function of color brightness independent of pressure. Temperature can be calculated explicitly from luminescence R, G, and B measurements using a polynomial curve fit of calibration temperature and function F3. Figures 8(a) and (b) show plots of temperature versus F3{R,G,B} with a curve fit solution for temperature $T^{(6)}(F3)$ that is a spliced 6th order polynomial.

These plots show that below a temperature of approximately 60C the temperature function fails to correlate the calibration data. This is not a result of using an over-simplified calibration model, or using a first order approximation to pressure sensitivity. It is a result of the linear dependency of G and B below 60C. This can be demonstrated in the similarity between the two brightness response curves shown in Figure 4. The two response curves may be overlapped with a single multiplicative constant.

Measured temperatures and pressures, Tm and Pm, can be calculated from luminescence brightness data using the following equations

$$Tm = T^{(6)}(F3) \quad \ldots 6$$

$$Pm = 1/k1*[c1*R/B - F1^{(3)}(Tm)] \quad \ldots 7$$

or

$$Pm = 1/k2*[c2*G/B - F2^{(3)}(Tm)] \quad \ldots 8$$

Figures 9(a) and (b) then show the comparison of calculated Tm and Pm with the thermocouple temperature and barocel pressure data, T and P. Pm is only calculated for Tm>60C, since the calibration would fail below that temperature and fill the plot. Uncertainty of the measured pressure data, shown approximately to be +/- 100 torr, is much larger than would be expected for measurement precision in a short duration wind tunnel measurement. The vacuum oven used has a low-power convective heating element which is slow and exposes the test sample to extreme temperatures for several hours. There is also no active cooling system. Movement of the sample and equipment and repeated removal and replacement of the window to increase cooling rates, may have had the effect of generating errors in the calibration data. An improved calibration system is currently being developed for more precise calibrations, faster temperature rise and decrease, and higher temperatures. The new glass polymer which was added to immobilize the organic pressure-sensitive luminophore and improve shear stability may also have decreased the pressure sensitivity from earlier formulations. The pressure sensitivity compared to full scale, shown in Figure 4 for B, is only 7 percent. In earlier formulations, the pressure sensitivity (then G was the most sensitive) was 15 percent relative to full scale. The net increase then in S/N for the present system is only a factor of 2, considering a 4 times increase in S/N with the conversion from 8-bit to 10-bit imager and half the sensitivity of the new PTSC formulation.

Mach 10 Wind Tunnel Test

Instrumentation and model requirements are generally determined by test facility. The range of total temperature, total pressure, and total pressure behind a normal shock ($P_{T,2}$) are given in Table 1 for Langley hypersonic wind tunnels. These and additional flow conditions and capabilities are given by Micol, 1998.

Candidate facilities for luminescence pressure mapping are limited to the 20-Inch Mach 6 Air and 31-Inch Mach 10 Air Tunnels at Langley, since pressure response is based on oxygen quenching and the other two hypersonic facilities at Langley operate with helium and a fluoromethane for the test gas. The Mach 10 tunnel has the most challenging flow conditions for PTSCs, as the heating values and surface temperatures are the higher of the two air facilities and the surface pressures lower. Both hypersonic facilities are short duration blow-down wind tunnels with model injection systems to protect the model from starting and ending shocks and for transient heating analysis.

A test of the recent PTSC formula and 10-bit color imager was made in the Mach 10 tunnel to look at coating survivability and range of application in that facility with a current vehicle configuration. The model tested was an 11-inch X-38 vehicle configuration. This model had been used previously for cavity heating studies behind deflected body flaps using a phosphor coated ceramic strip (Horvath, 2000). The X-38 vehicle is being developed as a docking vehicle for space station, with a primary mission of crew recovery and is being tested at NASA Langley for aerothermodynamic characteristics.

The test model was fabricated using a selective laser sintering rapid manufacturing process by DTM Corporation called RapidSteel®. It consists of a sintered stainless steel powder with an infiltrated brass metal matrix. The X-38 test model with PTSC is shown mounted on the 31-Inch Mach 10 Air Tunnel injection system in Figure 10. The PTSC was applied directly to the model without any intermediate material layer.

Figure 11 shows an image of measured temperature function F3{R,G,B} after 1 second in the flow. The total length of exposure for the model was 3 seconds; angle-of-attack, 35 degrees; freestream Reynolds number, $1x10^6$; and total pressure after a normal shock, 150 torr ($P_{T,2}$). A centerline profile for F3 is shown in Figure 12(a). Measurements were obtained on the nose for F3>1 exceeding the calibration range (Figure 8). Inspection of the model following the run and after subsequent runs showed very little degradation in the coating at the nose. Temperature calculated from F3 is shown in Figure 12(b). The figure to the right in 12(b) shows an expanded centerline at the nose. Where the temperature is above calibration, or F3>1, the measured temperature is set to zero. An image mask was generated and shown in Figure 13 to show the valid data calibration region in which 0.025<F3<1, corresponding to 55C<T<180C.

Several features shown in the derived temperature and pressure profiles (Figures 14, 15, 17 and 18) are expected, such as the flat temperature profile on the 20°-deflected body flap and corresponding increase in pressure. The large recompression region along the centerline (Figure 15) is not expected, but may be supported by flow visualization studies with optical schlieren in Mach 6 air (Horvath, 2000), which revealed an inflection in the bow shock over the windward surface. Presently, these preliminary results are qualitative and still being evaluated. An instrumented pressure and temperature hemisphere is being coated with PTSC for in-situ calibration measurements.

In the future, a reformulation of the PTSC powder will be necessary to remove the linear dependency of B and G at low temperatures, so that pressure and temperature measurements can be obtained in low heating areas such as the expansion region just before the split body flap (F3<0.025, T<55C) masked out in Figures 13 and 14. Measured temperature function on the nose in which F3>1 and a stable PTSC coating in that area indicates that the coating can be calibrated to temperatures much higher than 180C, which is the high temperature limit for the current calibration vacuum oven.

Summary

Pressure and temperature images were obtained simultaneously for the windward surface of an aerospace vehicle configuration in the 31-Inch Mach 10 Air Tunnel at NASA Langley Research Center. These preliminary results are at present qualitative. It is evident that the PTSC coating is stable throughout tests at the conditions of the Mach 10 tunnel for this configuration and substrate material and can be further adjusted and calibrated to provide quantitative pressure and temperature data for future hypersonic wind tunnel experiments. Coatings for simultaneous global pressure and temperature measurements are still being developed.

Acknowledgements

Paul Tucker of the Langley Aerothermodynamics Support Section is gratefully acknowledged for his contributions to this work, particularly for his help in the PTSC formula development and for coating and testing of samples.

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Table 1. - Flow Conditions for Hypersonic Wind Tunnels at Langley. (Micol, 1998)

Facility	Total Temp. (K)		Total Press. (atm)		P_{T2} (torr)	
	min.	max.	min.	max.	min.	max.
20-Inch M 6 Air Tunnel	482	516	1.9	32.3	49.4	727
31-Inch M 10 Air Tunnel	1000	1000	23.6	98.8	62.3	232
20-Inch M 6 CF4 Tunnel	624	648	5.9	131.6	8.6	164
22-Inch M 20 He Tunnel	293	293	20.4	225.1	63.8	390

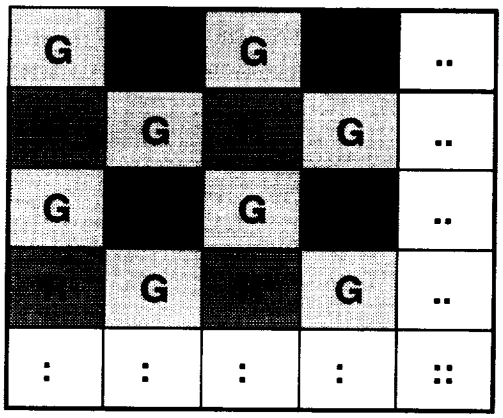

Figure 1. - Color filter pattern of single array digital color imager. (Sony ICX085AK Manual)

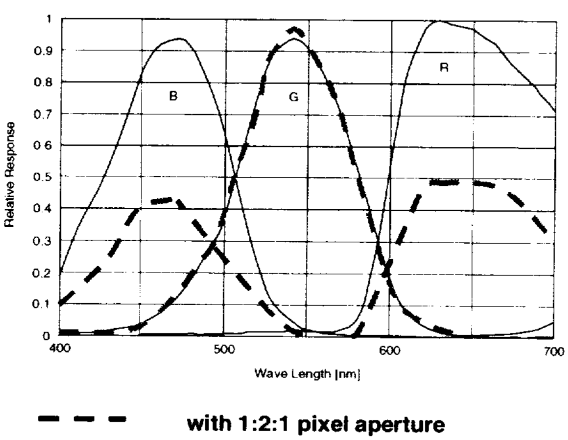

Figure 2. - Spectral Sensitivity Characteristics of Single CCD color imager. (Includes lens, excludes light source). (Sony ICX085AK Manual)

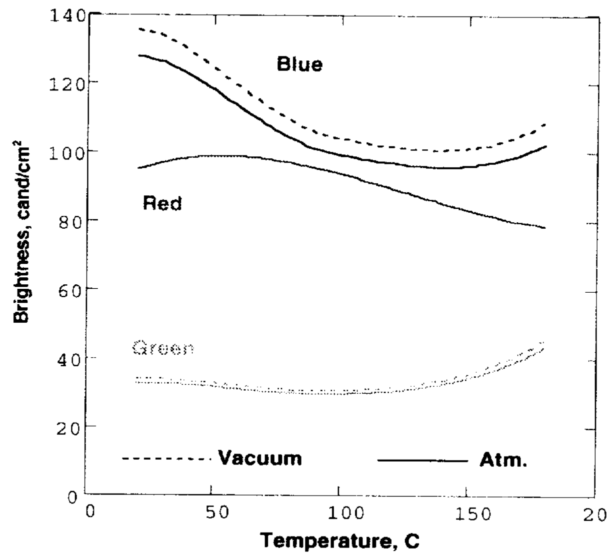

Figure 3. - PTSC three-color luminescence photometric pressure and temperature response.

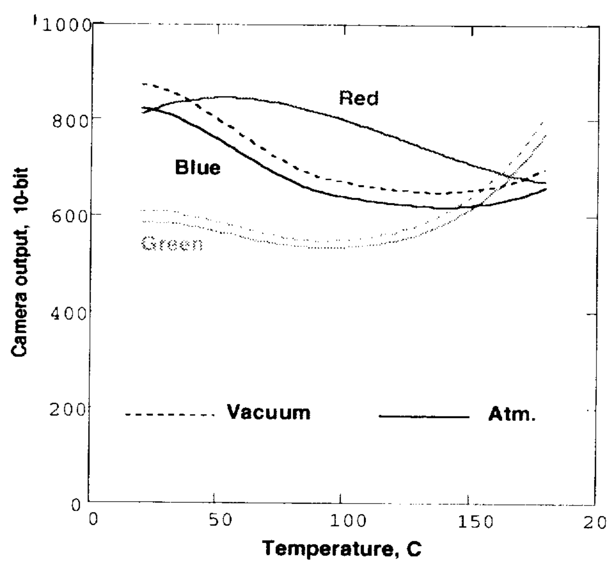

Figure 4. - PTSC three-color luminescence imager pressure and temperature response.

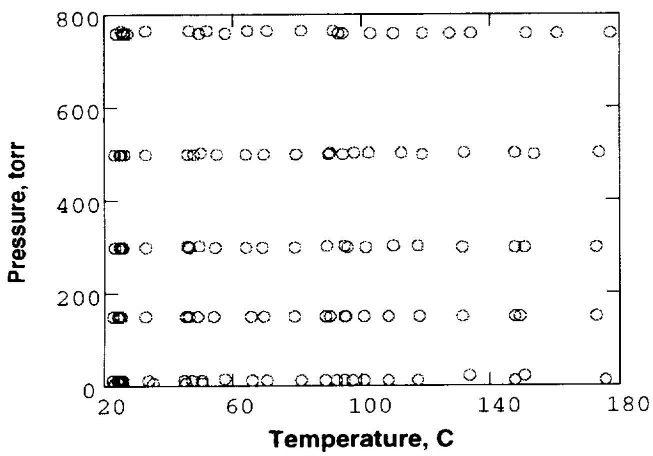

Figure 5. - Pressure transducer and thermocouple temperature measurements for calibration data.

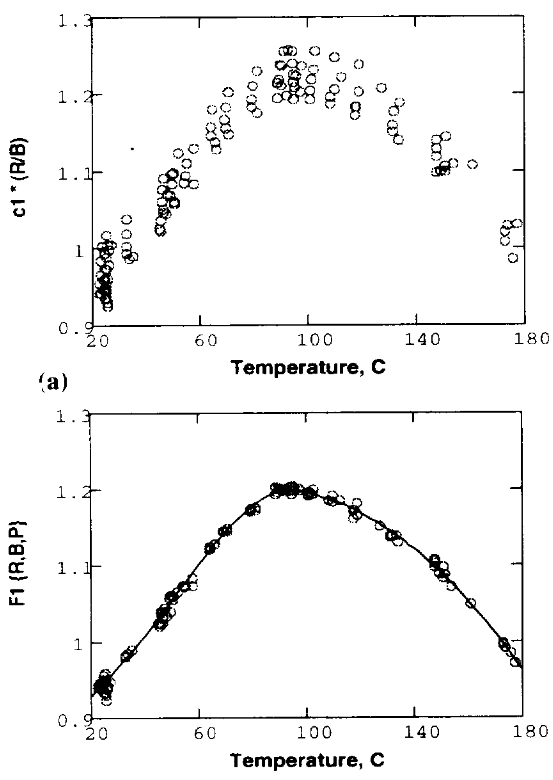

Figure 6. - (a) R/B color ratio and (b) F1 {R,B,P} minus pressure effects (F1=c1*R/B-k1*P).

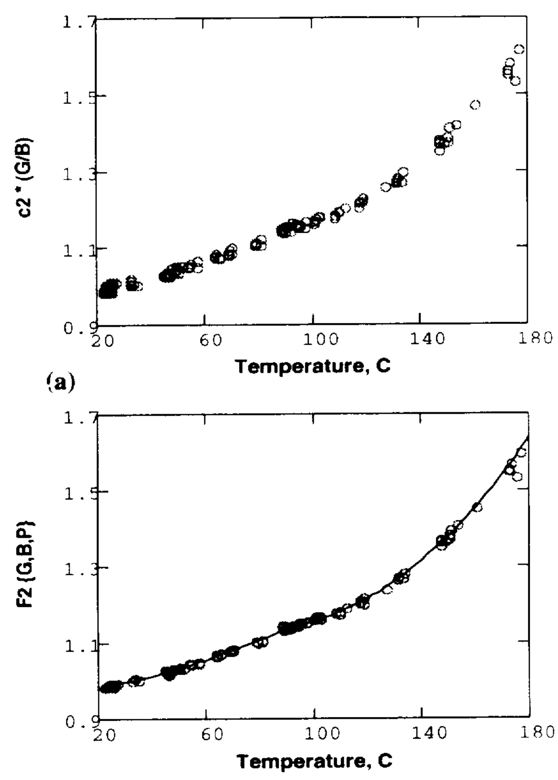

Figure 7. - (a) G/B color ratio and (b) F2 {G,B,P} minus pressure effects (F2=c2*G/B-k2*P).

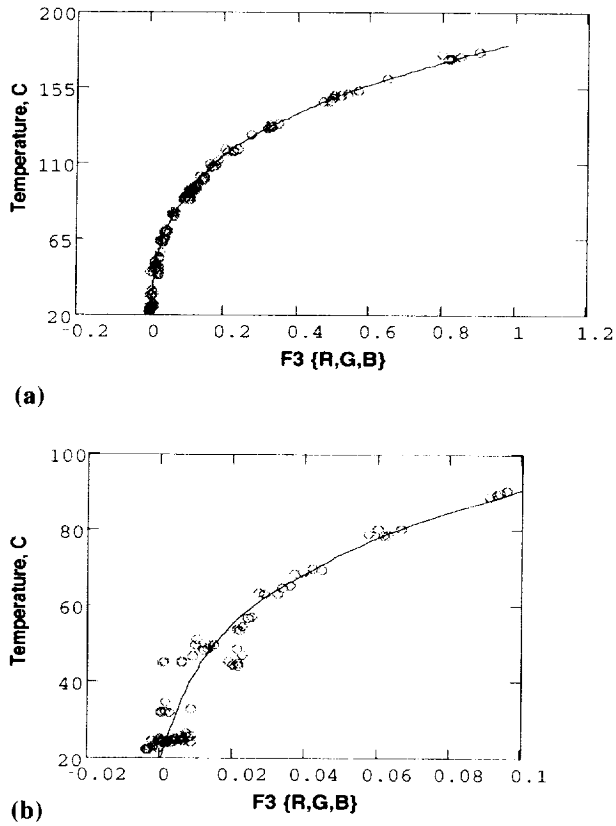

Figure 8. - (a) Independent temperature function F3{R,G,B} and (b) expanded at low temperatures.

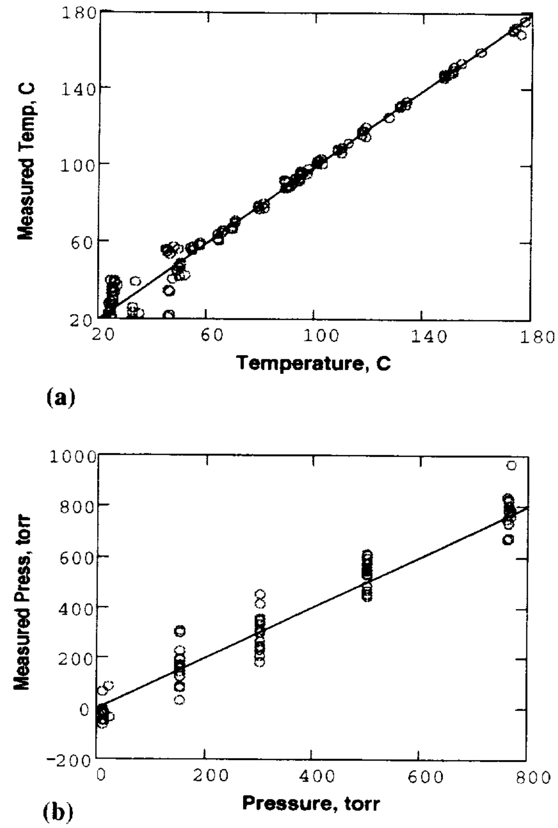

Figure 9. - Measured (a) temperatures and (b) pressures (for T>60C) from luminescence data.

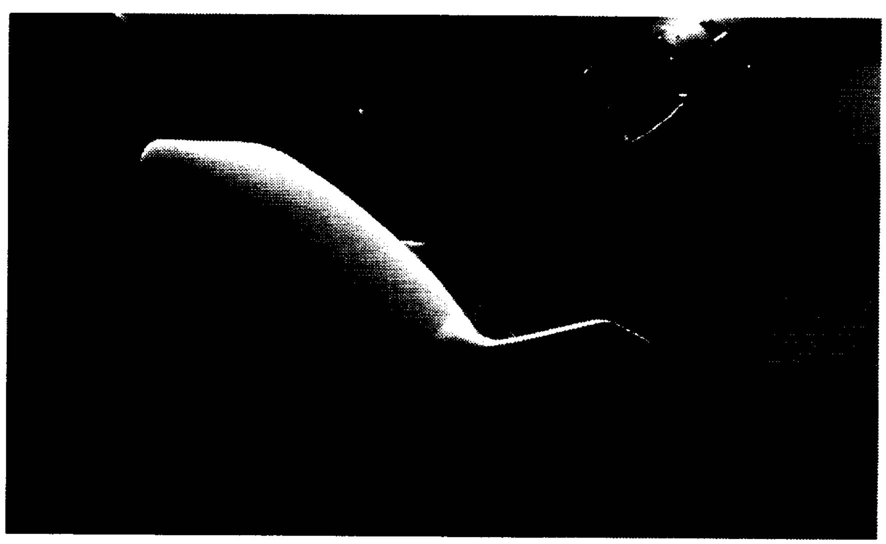

Figure 10. - PTSC coated Rapidsteel® model of X-38 Vehicle in Mach 10 Tunnel.

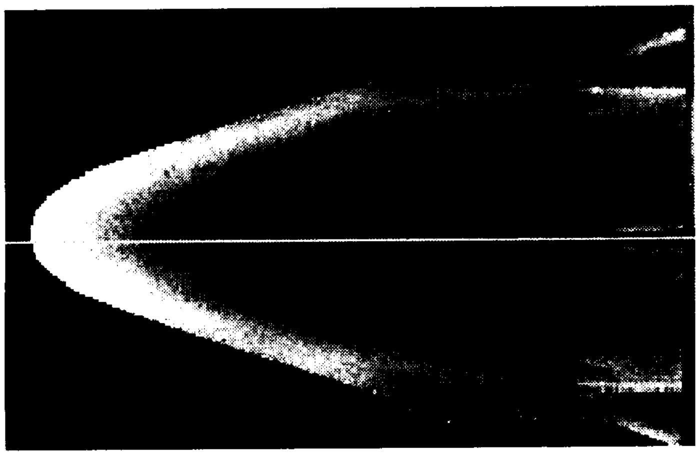

Figure 11. - F3{R,G,B} image of X-38 Vehicle in Mach 10 Tunnel at 1x10⁶ freestream length Reynolds number.

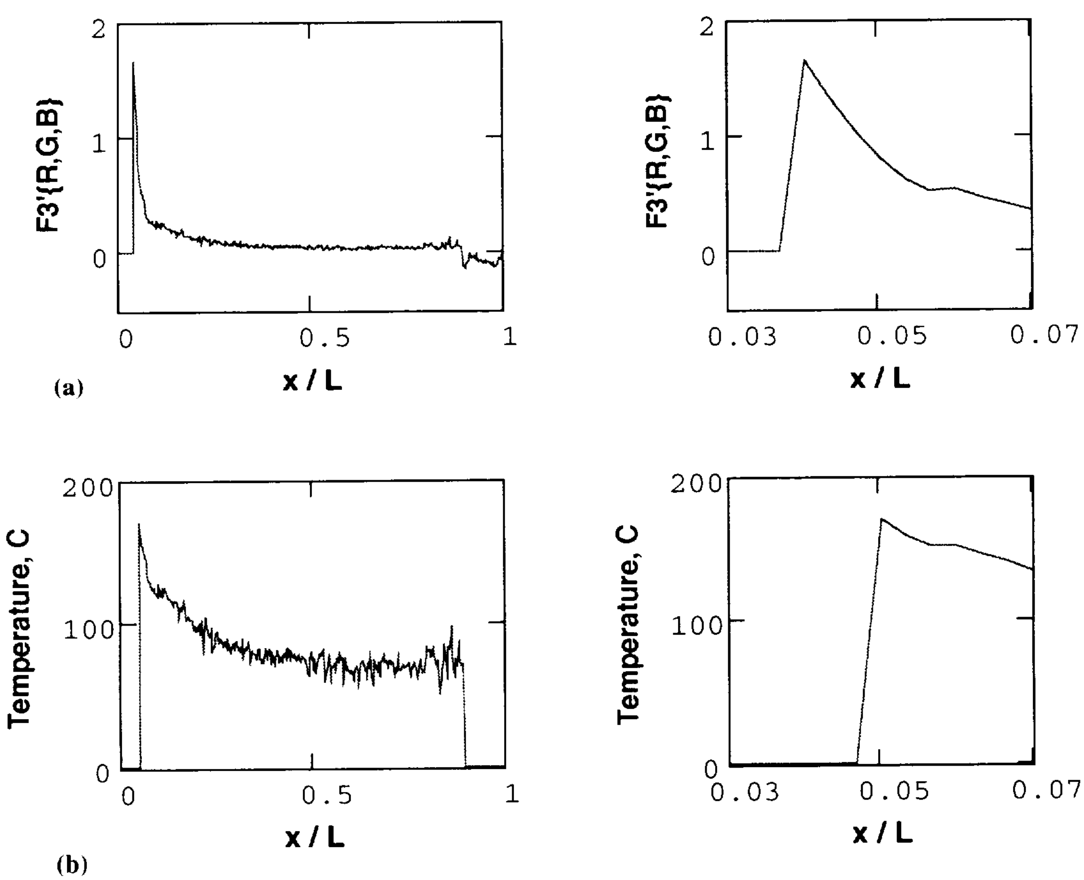

Figure 12. - Centerline profiles of (a) luminescence temperature function F3{R,G,B} (0 to 1 over calibration range) and (b) reduced temperature with expanded profiles at the nose to show temperature cutoff for F3>1.

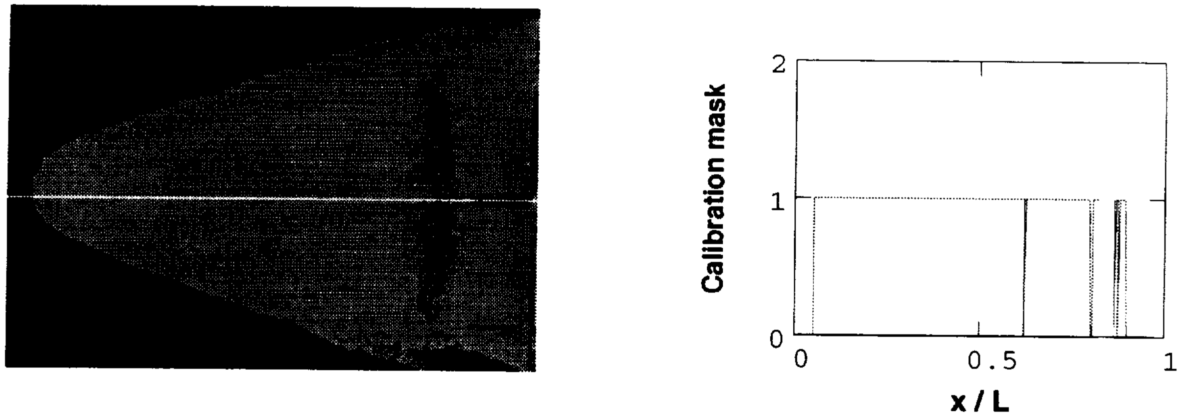

Figure 13. - Calibration mask (0.025<F3<1) image and centerline profile.

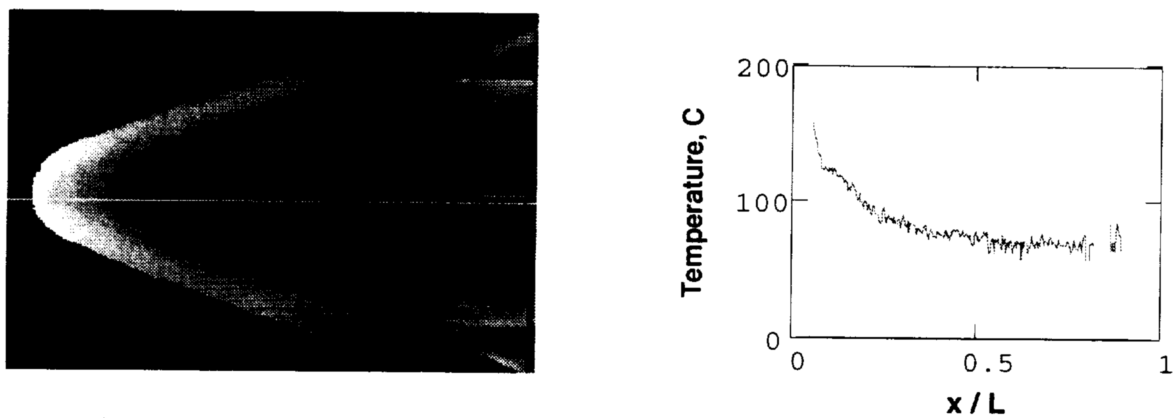

Figure 14. - Measured temperature image and centerline profile.

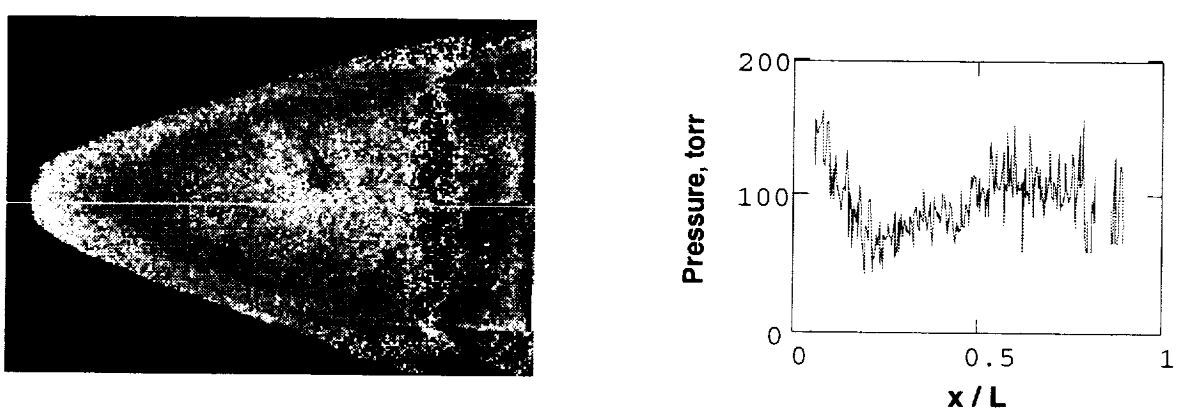

Figure 15. - Measured pressure image and centerline profile.

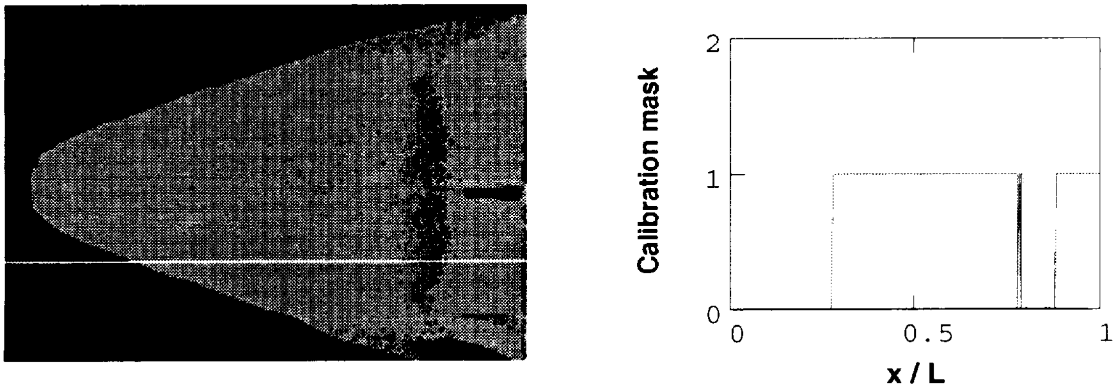

Figure 16. - Calibration mask (0.025<F3<1) image and profile along body flap.

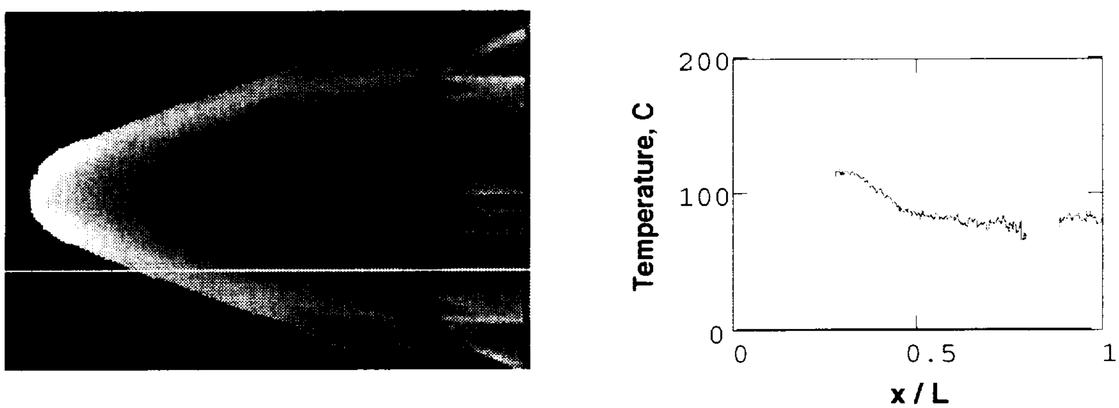

Figure 17. - Measured temperature image and profile along body flap.

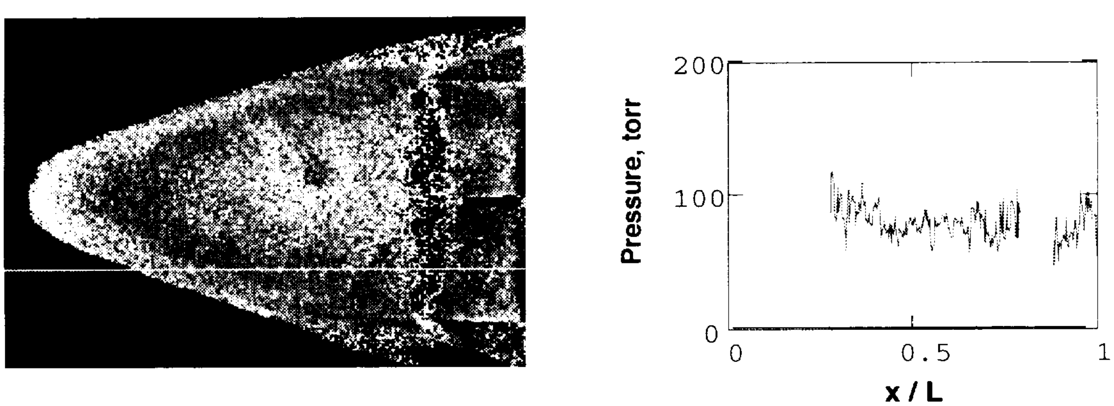

Figure 18. - Measured pressure image and profile along body flap.