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AUTOMATED THERMAL MAPPING TECHNIQUES USING CHROMATIC IMAGE ANALYSIS

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SUMMARY

Techniques for quantitative thermal mapping and automated data reduction are introduced using a chromatic image analysis system (CIAS). Such optical thermal mapping techniques have proven valuable in measuring surface temperature distributions and corresponding surface heat transfer on aerothermodynamic test models in hypersonic wind tunnels. Measurements are made on complex vehicle configurations in a timely manner and at minimal expense. The CIAS was first developed for quantitative thermal mapping applications using two-color thermographic phosphors (TCTP) but has been found useful in interpreting phase-change paint (PCP) and liquid crystal (LQC) data as well. The system utilizes separate wavelength filtered images to analyze surface spectral intensity data. Techniques are investigated using 3/4-inch video tape recording and image processing at the NASA Langley Research Center Image Processing Laboratory. In each of three thermal mapping techniques investigated (TCTP, PCP, and LQC) enhanced measurement capabilities are realized using the CIAS. A portable digital acquisition/processing system for real-time wind-tunnel data analysis is also currently under development.

INTRODUCTION

A recent program for hypersonic wind-tunnel testing techniques was established at Langley to develop surface heat transfer measurement capabilities. Highly accurate measurements with fine spatial resolution are needed for calibration of computational fluid dynamics (CFD) codes, but low instrumentation costs are required to operate in an increasingly expensive and sometimes destructive testing environment.

Optical techniques are viable candidates for providing global surface temperature data and reducing model instrumentation costs. Recent advances in electronic imaging and image processing have made the tools available for model surface gages that use advanced optical systems where wires are not required. This reduces instrumentation

TWO-COLOR THERMOGRAPHIC PHOSPHORS (TCTPs)

The TCTP technique is based on the ratio of blue to green emission, 450 nm and 520 nm wavelengths, respectively, from an UV (365 nm) excited phosphor coating. System details and early demonstration studies were reported in reference 2. Emission wavelengths are compatible with color filters found in standard video cameras. Figure 1 is a diagram representing the spectral sensitivity of a typical three-tube camera with a shortwave cut-off filter to block UV reflections. Camera optical filtering (either three-tube video or three-chip charge coupled device (CCD)) is necessary to prevent signal coupling or cross-talk as with single-chip color cameras. In Figure 2 a data acquisition/computer analysis system is shown for wind-tunnel applications. Figure 3 shows the relative spectral emission of ZnS:Cu phosphor at 80°F (27°C) excited by 365 nm UV radiation with separate inlays showing blue and green transmission through limited bandpass interference filters. Each wavelength filter transmits over a 40-nm bandwidth, blue centered at 450 nm and green at 540 nm. In figure 4, the ratios of filtered intensity measurements with temperature are shown for both ZnS:Cu and a lower temperature sensitivity phosphor, ZnS:Cu:Ni. These calibration curves are based on experiments using a flat-response radiometer and surface thermocouples from 75°F to 320°F (24°C to 160°C). Both phosphors have peak emissions at 450 nm and 520 nm wavelengths.

The advantage in using a chromatic analysis technique is that it does not require absolute intensity measurements. A system is calibrated using the thermal response of a ratio of measurements. A given calibration is unique, but constant, for a given phosphor and measurement system used. The measured ratio is independent of the incident ultraviolet energy, since it is based on relative emission probabilities of the phosphor, and not overall intensity.

The TCTP technique has been demonstrated using a Saticon-tube camera and separate video recording of red, green, and blue camera outputs. Data is recorded on 3/4-inch video tape and processed at

PHASE-CHANGE PAINTS (PCPs)

Phase change paints consist of materials having calibrated melting points suspended in an inert volatile liquid. The coatings are sprayed or painted onto models to produce a dull finish, opaque film. The colors of these coatings vary from white, bright blue, green, to pink. Upon heating to the phase-change temperature, the film melts and becomes a glossy transparent liquid. Jones and Hunt (3) tested these coatings over the expected range of pressure and heating rates and found the measured temperatures in agreement with values provided by the manufacturer. Such coatings offer visual information on the time evolution for a particular isotherm and thus provide valuable temperature-time data when used on aerothermodynamic wind-tunnel test models.

In the past at Langley, wind-tunnel PCP data have been recorded on cinema film and manually reduced by projecting individual frames on paper and tracing melt lines with colored pencils. This technique is both labor intensive and subjective. Melt "lines" are more appropriately described as melt regions, within which isotherm identification is a matter of judgment. Such judgment affects comparisons between tests and with manufacturers' data.

Automated systems, using monochromatic image processing, have been developed in the past (4) in order to speed data processing and provide repeatable melt line recognition. Such systems, however, have proven inadequate for wind-tunnel applications. Several problems occur for wind-tunnel conditions. Melt line recognition is impaired when surface glare and shadowing are present. Upon melting, PCP becomes extremely glossy, and glare occurs around melt transition regions. The amount of glare is magnified by bright surface illumination. Monochromatic techniques also fail when uniform heating is present, such as on a ramp or extremely blunt configuration. In such cases, surface melt is also uniform and no discernable melt "line" exists. Finally, intense surface illumination presents a problem when the heating due to lamp radiation

For system demonstration, blue and red camera outputs were used. To balance signal levels, the blue video output was amplified 9 db or 2 times, similar to TCTP measurements. A coating of PCP was sprayed on a cast red epoxy plastic model of a generic lifting body. It was then tested in the Langley 31-Inch Mach 10 Tunnel. An image subtraction routine was used to generate the positive/negative computer images in figure 8 from the blue and red digitized images at sample times of 0.9 and 11.2 seconds in the tunnel. Successive positive/negative images in time can be subtracted from each other to produce an isotherm mapping with time, as shown in figure 9.

The paints used, 138^{O}F, 125^{O}F, and 109^{O}F temperature melt paints, were coated on a red model. The lamp color was a significant factor in providing adequate color contrast. With a red model, it was necessary to have a relatively blue light source, since the paint coatings were close to neutral (white). Otherwise, there was insufficient color contrast between the melted and unmelted regions. High intensity lamps were not required, since contrast is provided not by intensity, but wavelength distribution.

For each of the paint melt temperatures examined, melt line calibration on surface thermocouples indicated 3 to 7 degrees below manufacturer specifications. This is primarily due to the ability of the system to detect melt transition earlier than past (visual) techniques. This ability is desirable in wind-tunnel applications, in which the paint melts and begins to flow. Early melt line detection allows for temperature measurements before the paint begins to flow in regions of high shear, thereby altering heating values.

Second is the dependency on camera filters for the temperature sensitivity range. An overall 8°F (4.4°C) temperature sensitivity range is obtained using a ratio of blue to green intensity measurements. The manufacturer specifies a 5°F (2.8°C) sensitivity range, which was reportedly obtained using visual methods. The specified range is also from 55 to 60°F (12.8 to 15.6°C), and that measured using CIAS was 59 to 67°F (15 to 19.4°C) for the increasing temperature data. A reasonable explanation is that blue sensitivity of the chromatic system coincides with wavelength reflectance at higher temperatures. It is possible that another 4°F (2.2°C) of sensitivity towards lower temperatures is obtainable using red filtered output. Using all three camera filters, the useful measurement temperature range is possibly double the original specifications.

CONCLUDING REMARKS

A thermal imaging system using chromatic image analysis has been developed for surface temperature mapping on aerothermodynamic test models in hypersonic wind tunnels. Testing technique applications have included quantitative thermal mapping using wavelength distribution measurements of induced surface fluorescence of two-color thermographic phosphors, isotherm mapping using reflected wavelength transition measurements across a phase-change paint melt region, and spectrally filtered measurements of liquid crystal reflectance during a thermal cycle. Use of chromatic image analysis in each application has enhanced measurement capabilities over more conventional monochromatic image processing methods.

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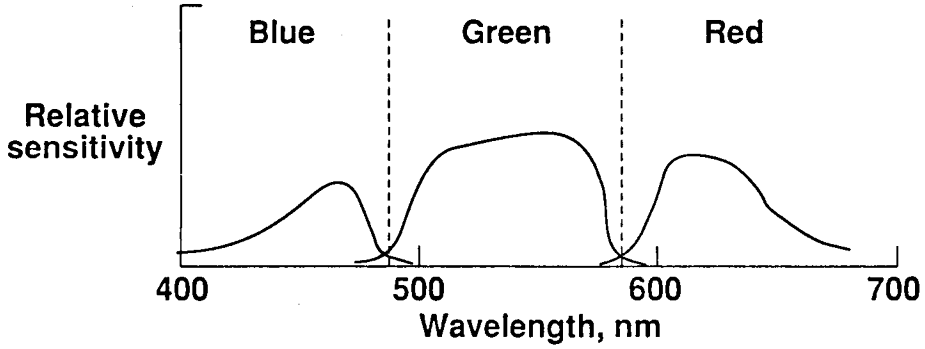

Figure 1. Spectral sensitivity of a typical three-tube color camera.

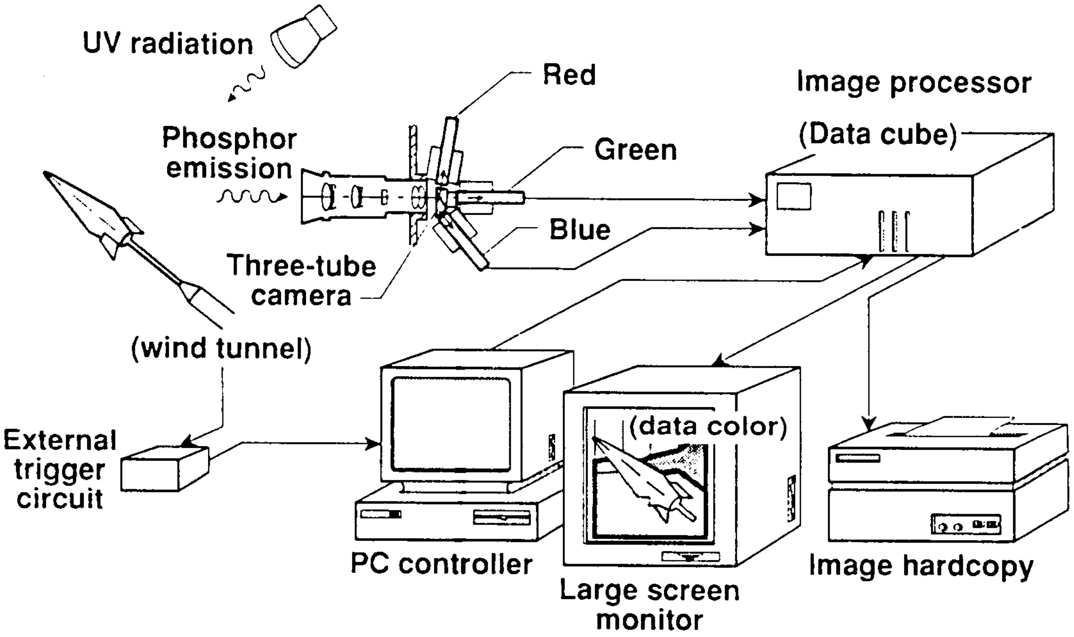

Figure 2. Chromatic image analysis system diagram.

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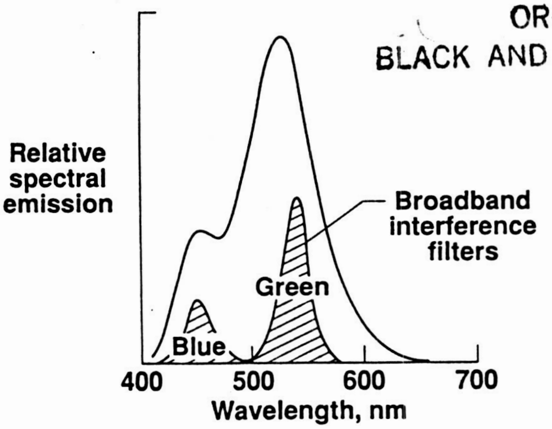

Figure 3. Relative spectral emission of ZnS:Cu phosphor at 80°F (27°C).

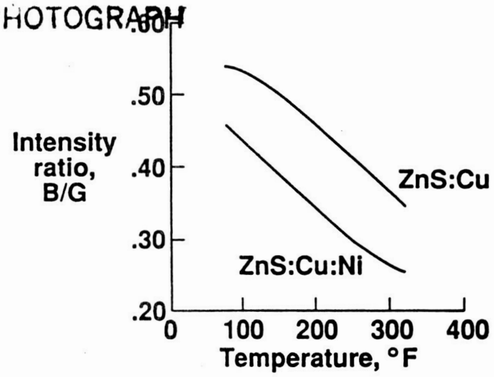

Figure 4. Phosphor temperature calibration, intensity ratio versus temperature.

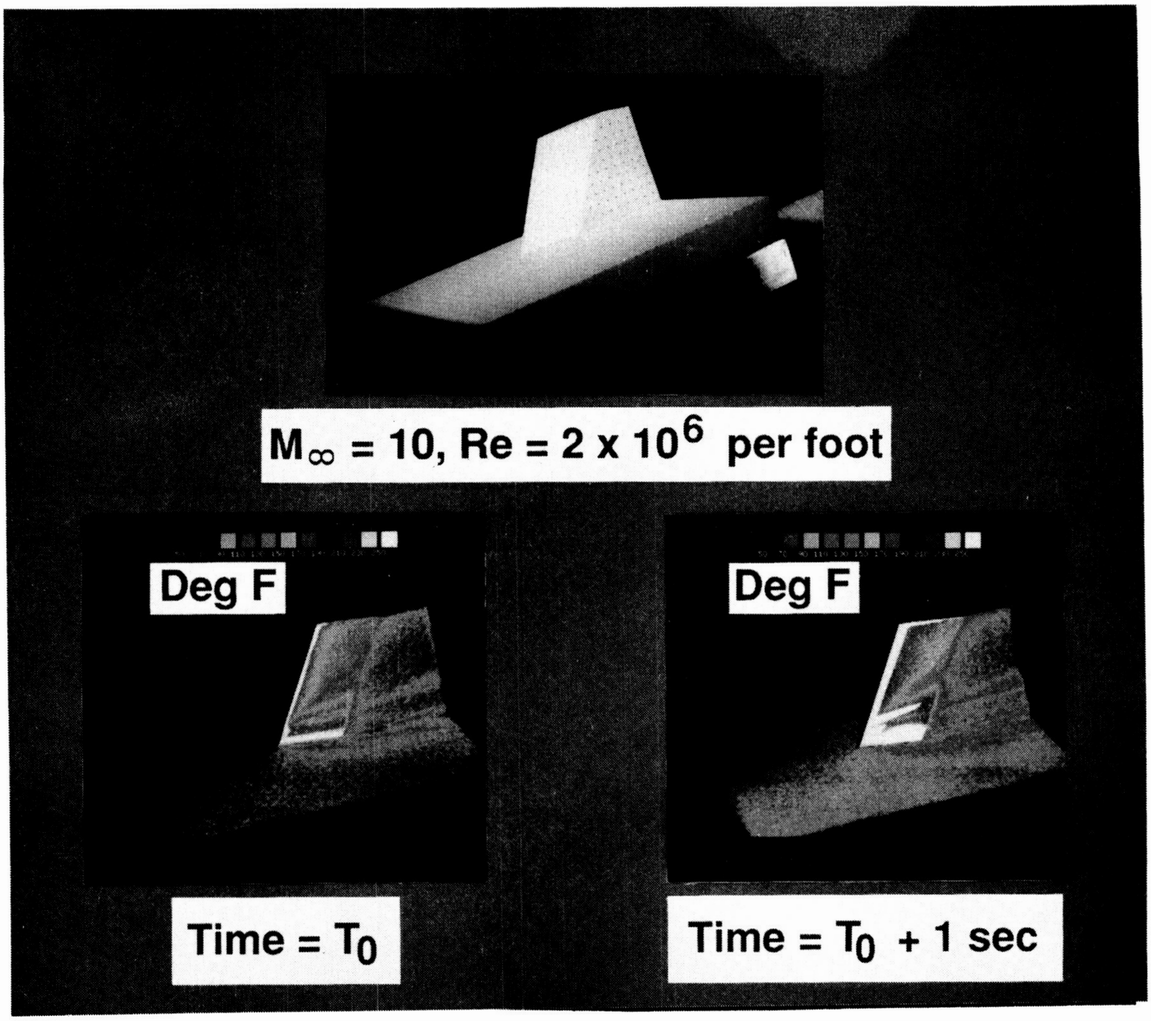

Figure 5. Hypersonic shock-shock interaction study using a phosphor coated ceramic wedge/strut configuration.

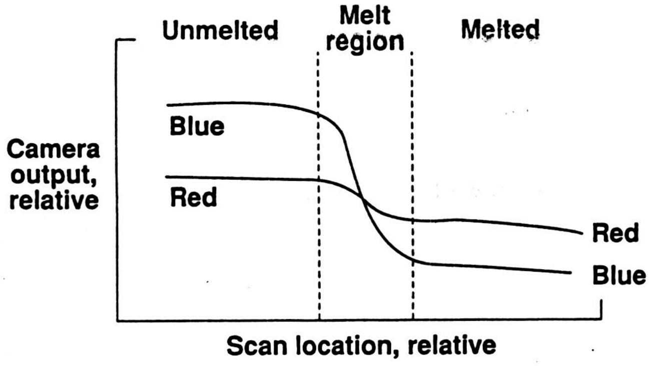

Figure 6. Relative camera output signals, high contrast (blue), and low contrast (red) across a PCP melt region.

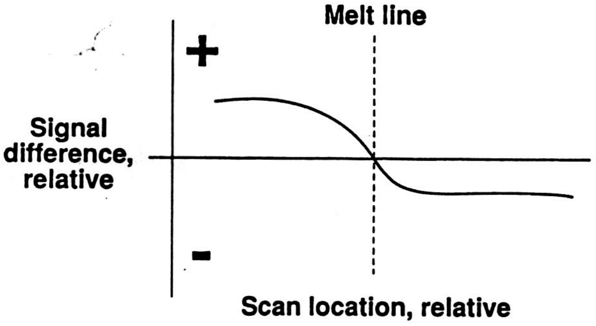

Figure 7. Calculated signal difference across a PCP melt region.

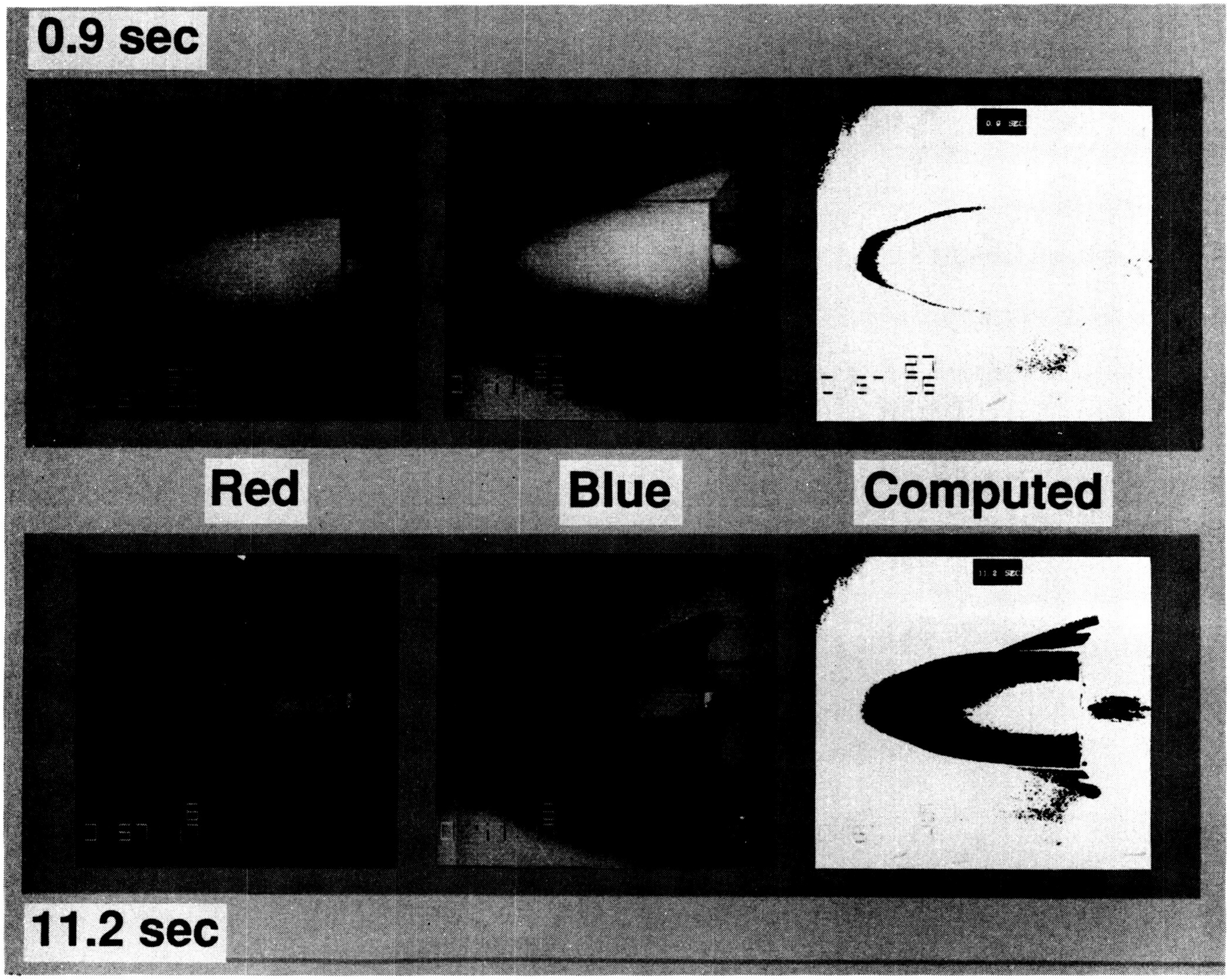

Figure 8. Paint melt line recognition using chromatic image analysis.

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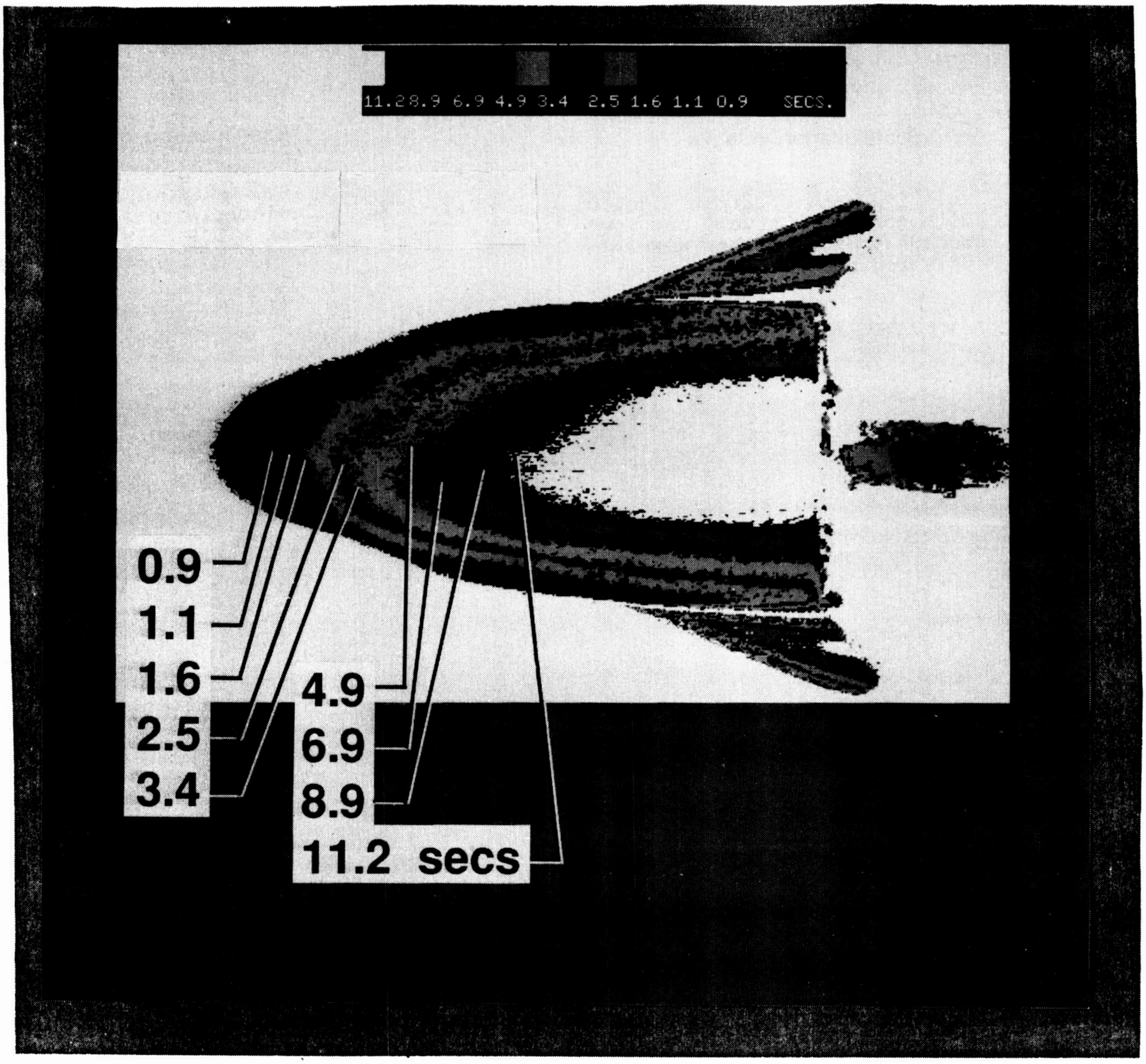

Figure 9. Isotherm mapping with time on the windward surface of a generic lifting body. Phase-change 138°F paint used.

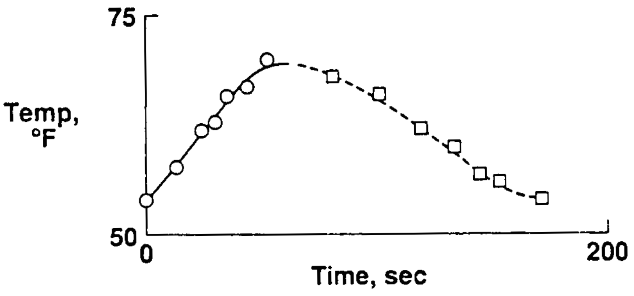

Figure 10. Surface thermocouple temperature-time history for LQC coated test sample.

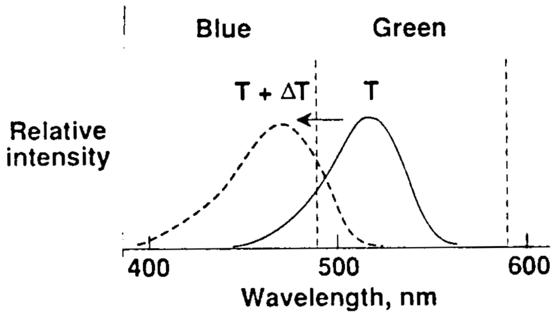

Figure 11. Typical LQC spectral reflectivity with change in temperature.

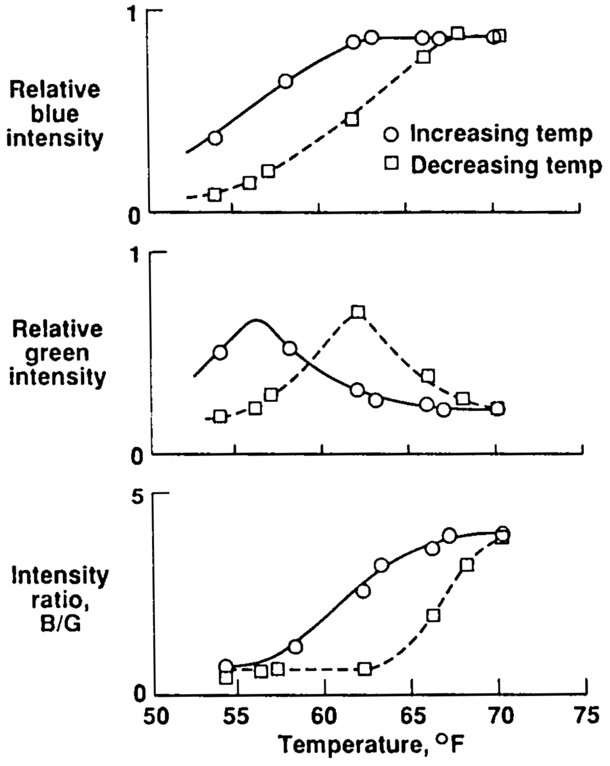

Figure 12. Measured blue and green LQC reflection intensities and intensity ratio versus temperature.