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ABSTRACT

The current pressure sensitive paint (PSP) technique assumes a linear relationship (Stern-Volmer Equation) between intensity ratio (I_o/I) and pressure ratio (P/P_o) over a wide range of pressures (vacuum to ambient or higher). Although this may be valid for some PSPs, in most PSPs the relationship is nonlinear, particularly at low pressures (<0.2 psia when the oxygen level is low). This non-linearity can be attributed to variations in the oxygen quenching (de-activation) rates (which otherwise is assumed constant) at these pressures. Other studies suggest that some paints also have non-linear calibrations at high pressures; because of heterogeneous (non-uniform) oxygen diffusion and quenching. Moreover, pressure sensitive paints require correction for the output intensity due to light intensity variation, paint coating variation, model dynamics, wind-off reference pressure variation, and temperature sensitivity. Therefore to minimize the measurement uncertainties due to these causes, an in-situ intensity correction method was developed.

A non-oxygen quenched paint (which provides a constant intensity at all pressures, called non-pressure sensitive paint, NPSP) was used for the reference intensity (I_{NPSP}) with respect to which all the PSP intensities (I) were measured. The results of this study show that in order to fully reap the benefits of this technique, a totally oxygen impermeable NPSP must be available.

NOMENCLATURE

$A\ \&\ B$	Stern-Volmer Coefficients
I	Emission intensity at oxygen pressure P
I_0	Emission intensity at zero oxygen partial pressure
I_{NPSP}	Emission intensity of Non-PSP
I_{PSP}	Emission intensity of PSP
K	Stern-Volmer constant
K_f	Quenching rate of fluorescence
K_{ic}	Quenching rate of internal conversion
K_q	Quenching rate of oxygen
η	Paint efficiency
ϕ	Quantum Efficiency
P_1	Reference Pressure
P_2	Measured pressure

INTRODUCTION

PSP measurements provide a means for the recovery of global surface pressure distributions on aerodynamic test articles. A typical PSP (Figure 1) consists of a 25-40 μm thick reflective undercoat and a 25-40 μm thick coating of a luminophore dispersed in a binder layer. The binder is usually a polymeric material. The luminophore must be one for which its luminescence is quenched by oxygen. The principle of operation of pressure sensitive paints are well described in the literatures[1-5].

The intensity response of the paint, I, is related to incident intensity, i_o, paint efficiency, η, and luminescence quantum efficiency, ϕ, by
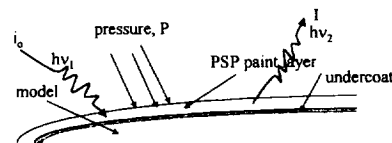
$$I = \iota_0 \eta \phi \qquad (1)$$

Figure 1. PSP schematic Responce

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The paint efficiency is a function of the reflectivity of the primer coat, the concentration of the luminophore in the binder and the permeability/diffusivity of oxygen in the binder. The luminescence efficiency basically is a measure of luminophore performance, which is governed by its activation and de-activation rates (Figure 2). The activation is caused by the absorption of photons by luminophores received directly from the light source as well as from the reflective undercoat layer, presuming the binder is inactive.
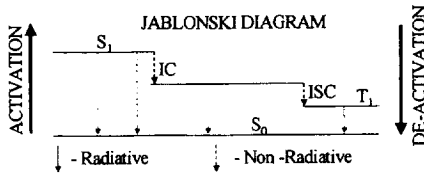

Figure 2. Photon activation and deactivation process

The de-activation, on the other hand, occurs by the non-radiative processes; such as, *internal conversion* (IC), *intersystem crossing* (ISC, which are temperature dependent) and oxygen quenching (which is pressure dependent), and by radiative processes like *fluorescence* and *phosphorescence*. In PSP applications, the emission intensity is correlated to the partial pressure of oxygen (proportional to oxygen concentration) by expressing the quantum efficiency in terms of de-activation rates as

$$I = \frac{i_0 \eta \kappa_f}{\kappa_f + \kappa_{ic} + \kappa_q(O_2)} \quad (2)$$

Where κ_f, κ_{ic} and κ_q are the quenching rates of fluorescence, internal conversion and oxygen, respectively. It is assumed that under equilibrium conditions the denominator in Equation 2 is equal to the photon (activation) energy absorbed by the luminophore.

Under the appropriate illumination and constant quenching rates of fluorescence and internal conversion, the intensity of the luminescence emission from the paint is inversely proportional to the oxygen concentration, and, hence, the air pressure on the surface. The luminescence of PSP may be expressed in terms of the well-known Stern Volmer relation given by

$$I_0/I = 1+KP \quad (3)$$

Where I_0 is the emission at zero oxygen level and I is the emission at any pressure P. K is equal to $\kappa_q/(\kappa_f + \kappa_{ic})$ which is assumed to be a constant. It is generally not practical to measure I_0 in the wind tunnel environment; since the tunnel would have to be pumped down to a vacuum. Instead of trying to achieve zero oxygen conditions the intensity of emission at "wind off", I_1, is used as the reference intensity, and the pressure at "wind off" is considered the reference pressure, P_1. In practice this is usually the local barometric pressure. In terms of the Stern-Volmer equation this takes the form of the ratio of the Stern-Volmer relation for two pressures.

$$wind\ off \quad I_0/I_1 = 1+KP_1 \quad (4)$$

$$wind\ on \quad I_0/I_2 = 1+KP_2 \quad (5)$$

$$I_1/I_2 = (1+KP_2) / (1+KP_1) \quad (6)$$

$$I_1/I_2 = \{1/(1+KP_1)\} + \{KP_2/(1+KP_1)\} \quad (7)$$

K and P_1 are constants, thus (7) may be expressed as:

$$I_1/I_2 = A + BP_2 \quad (8)$$

$$A = 1/(1+KP_1) \quad (9)$$

$$B = K/(1+KP_1) \quad (10)$$

Since luminescence intensity depends on illumination intensity, values for I are determined for each point on the wind tunnel model at each angle of attack. The values for A and B are then determined from a plot of I_1/I_2 vs. pressure, using pressure taps on the model for calibration. The accuracy of this type of calibration depends on maintaining constant and reproducible illumination at every model position. Since the light intensity at the surface of the model changes with the angle of attack, the reference intensity (I_1) at every model position must be measured. In order to correctly ratio these wind-off measurements to the wind-on measurements, spatial registration dots must be placed on the model. These enable the wind-off and wind-on images to be correctly aligned. The registration marks are usually round, black dots about 6 mm in diameter.

The objective of this study is to develop a paint and measurement system that would not require the "wind off" calibration and would correct for differences in illumination intensity over the model surface. Others have used dual luminophore PSPs to correct for light intensity variations and also temperature variations[5-8]. However, mixing different luminophores in the same

paint matrix nearly always produces spectral interference between the different luminophores. If the registration dots could be prepared from paint containing a luminophore that is not quenched by oxygen, the emission from the dots can also serve as a light intensity reference. The luminophore in the registration dots should be one that is excited by the same illumination used to excite the pressure-sensing luminophores in the PSP. Theoretically, the optimum system would have the same luminophore in the registration dots as in the paint but contained in a binder that is oxygen impermeable. This way the pixel intensity at the dot can be used as the light reference intensity. Having the same luminophore in the dot would eliminate the need for a filter wheel or filter shuttle on the camera in order to observe different wavelengths of light. The pixels representing the dot could be used for light referencing. However, practical binders have some oxygen permeability and even a small amount of quenching of the luminophore in the dot would cause serious errors. It is easier to find a luminophore, which is not quenched by oxygen than it is to find a totally impermeable polymer paint matrix. This would mean that the target dots would emit at a different wavelength of light than the PSP. Therefore, the reference luminophore should emit at a wavelength sufficiently different from that emitted by the pressure sensing luminophore to be resolved with different filters over the camera lens. Instead of taking the ratio of wind-off intensity to the wind-on intensity, the ratio of the intensity of emission from the nearest registration mark to the PSP emission intensity of interest would be used. Although this may not give a perfect correction for variations in light intensity, it should give a reasonably good correction.

If the temperature sensitivity of the luminophore in the registration dots and the temperature sensitivity of the PSP are known, the luminescence from the dots can be used to measure the temperature of the paint surface. This information could be used to make a correction for the effect of temperature on the PSP intensity.

The presented approach avoids the low reference intensity (and hence camera resolution) problems normally encountered in atmospheric pressure referencing. Furthermore, if the intensity variation due to temperature of the NPSP is made the same as the PSP, then the proposed referencing method can be also used for temperature sensitivity correction of the PSP. Also, the NPSP can be used as target markers for model deformation determination in wind tunnel testing.

Some tests were performed in the NASA Langley laboratory on a painted circular coupon in a test chamber to demonstrate this technique. The following section describes the experimental set up. Then, experiments with various PSP and NPSP combinations are explained. The results and discussions are presented in the following section, and finally some conclusions are given.

EXPERIMENTAL SET UP

The tests were conducted at one of the NASA-Langley Research laboratory. Figure 3 shows the experimental set up, which consists of an adjustable-vacuum chamber to vary the pressure range, a pressure transducer to measure pressure reading, two lamps for excitation, two 12 bit CCD digital cameras or two 16bit CCD cameras, two T-type thermocouple thermometers to monitor the specimens and test chamber temperature, and a data acquisition system for the specified cameras.

The test coupon size was 76 mm diameter. In the center of the coupon a 7 mm dia circle was painted with NPSP, and the remaining surface was painted with regular PSP paint (See Figure (4)). Several coupons were made with different NPSPs and PSPs to test the best performing paints over a given range of pressures and temperatures.
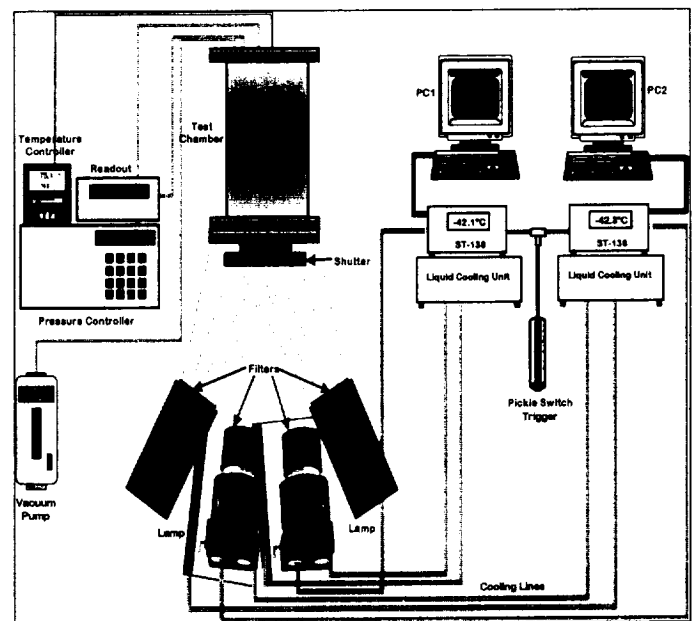

Figure3. Schematic of Experiment Set-up
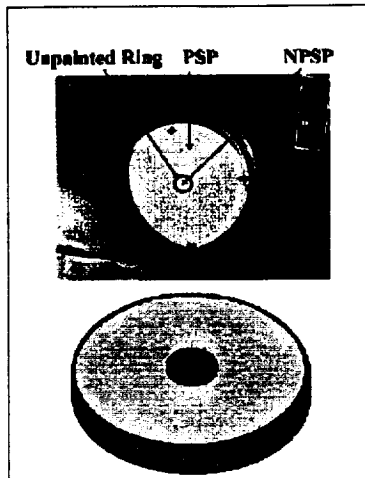
3
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Figure 4. Picture and Schematic of the test Specimen

EXPERIMENTAL PROCEDURE

Several tests were performed on a painted circular coupon to demonstrate this technique and verify the theory. Six specimens of different PSPs and NPSPs, and camera combinations were tested. The pressure range was varied from 0.0-2.7 atmospheres, and the temperature range was varied from 15-35 °C. The following Table 1 shows the PSP and the NPSP paint and paint binder combinations tested.

Spec	PSP Lum.	PSP Binder	NPSP Lum.	NPSP Binder
1	PtPFPP	FEM-IBM♣	Ru-bypy	Clear Coat
2	PtPFPP	FEM-IBM	PtPFPP	Clear Coat
3	Ru-Bath	RTV-118	Ru-bath	Clear Coat
4	PtPFPP	FEM-IBM	PtPFPP	PMMA
5	PtPFPP	FEM-IBM	PtPFPP	Clear Coat
6	PtPFPP	FEM-IBM	Ru-bypy	Clear Coat

♣ 2,2,2-trifluoroethymethacrylate-co-isobutylmethacrylate

Table 1. Paint and Binder combinations that were tested

Figure 5 A and B show actual images of the test specimen at 0.035 and 14.7 psia, respectively. The PSP and NPSP in Figure 5A have their respectively maximum intensity levels at 0.035 psia. However, the PSP in Figure 5B is quenched and its intensity level is considerably reduced.
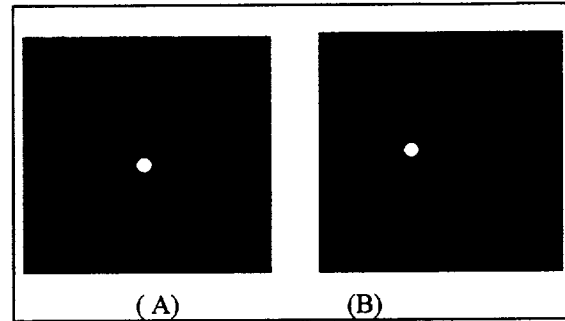

Figure5. A. Image of PSP and NPSP at 0.035 psia
B. Image of PSP and NPSP at 14.7 psia

RESULTS AND DISCUSSIONS

The results presented in the following Figures show how the PSP and NPSP intensities vary with respect to pressure, temperature, paint type and time.

Figure 6 shows the pressure response curves of the PSP and NPSP for the specimen 6 at 0.01 psia pressure (lowest pressure) and at 26 °C. The PSP intensity is found to decrease by a factor of 10 when the pressure is increased from 0.01 to 20 psia, while there is hardly any change in the NPSP intensity. Thus, the NPSP provides a constant intensity to which the PSP intensity can be referenced.
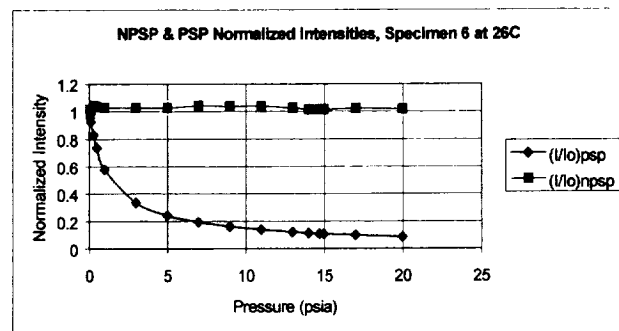

Figure 6. Plots of the normalized PSP and NPSP intensities.

Figure 7 is a plot of the ratio of the NPSP and the PSP normalized intensities, which can be used for calibrating a given PSP and NPSP combination. For the specimen 6 tests, one light source with a 390+-40 nm filter was used to excite both NPSP and PSP. A 16-bit Photometrics camera with a 650 +-10 nm filter was used for the PSP imaging and a 16-bit Photometric camera with a 580+-9 nm filter was used for the NPSP imaging. There was a 6.25 mm (0.25") wide darkened ring around the NPSP.
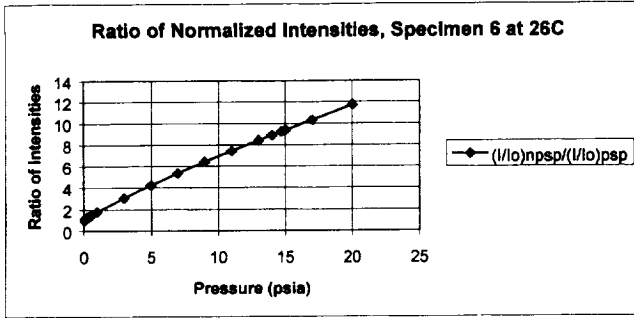
Ratio of Normalized Intensities, Specimen 6 at 26C

Figure 7. Ratio of PSP and NPSP normalized intensities versus pressure for specimen 6

Figures 8 shows the effect of temperature on the calibration curves for specimen 1. It should be noted that the plots in Figure 8 were based on using intensity reference at the temperature of the run. The changes in the shapes of the calibration curves show that the PSP binders were temperature sensitive. Intensity reference (I $_{ref}$) also changed with temperature, which shows that the luminophore was also sensitive to temperature. Thus, the use of the PSP and the NPSP does very little to correct for the effect of the temperature on the PSP calibration curves.
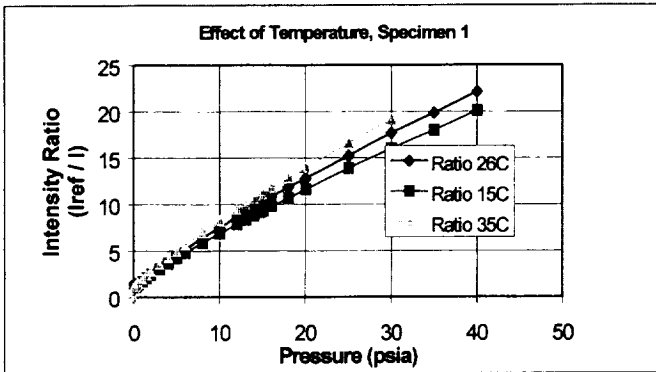
Effect of Temperature, Specimen 1

Figure 8. The Effect of temperature on the ratio of normalized PSP and NPSP intensities versus pressure for specimen 1

The intensity ratio variations show that the intensity ratio increased for increasing temperatures. For the specimen 1 tests, one light source with a 450 nm +-40 filter is used to excite both NPSP and PSP. However, a 12-bit Photometrics camera with a 650 +-10 nm filter is used for the PSP imaging and a 16-bit Photometric camera with a 580+-9 nm filter is used for the NPSP imaging. There was no darkened ring around the NPSP. Because of the spectral intensity

separation, no cross-talk between PSP and NPSP intensities is evident.

To better understand the effect of different binders and luminphore combinations, the calibration plots were developed for three different paint specimens, 1, 2 and 3 (see Table 1) as shown in Figure 9.
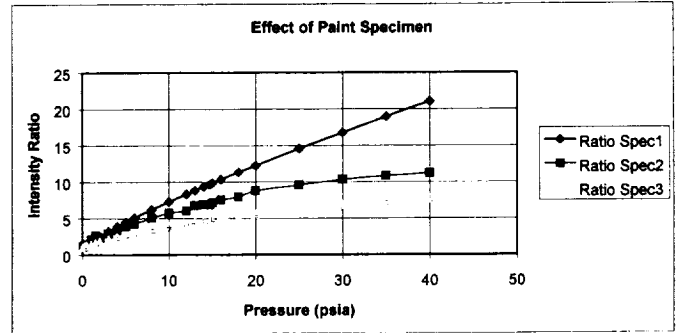
Effect of Paint Specimen

Figure 9. Ratio of NPSP and PSP normalized intensities versus pressure for different paint specimens

If each specimen can be analyzed separately, one can notice the effect of each paint combination. For example, specimen 1 which had Ru-Bypy as the luminophores for the NPSP was not quenched at all. This gave a good light reference(See Figure 10A and 10B.)
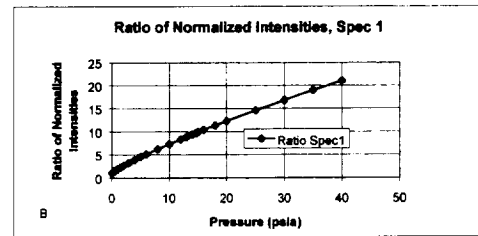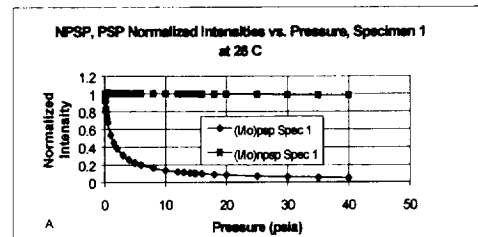
NPSP, PSP Normalized Intensities vs. Pressure, Specimen 1 at 26 C

Ratio of Normalized Intensities, Spec 1

Figure 10.A. Plots of the normalized PSP and NPSP Intensities, spec.1.
B. Ratio of PSP and NPSP normalized intensities versus pressure for spec.1.

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Specimens 2 and 3 use the same luminophore for PSP and NPSP, but with different binders. In this case, since the emission wavelength was the same for NPSP and PSP, significant spectral leakage of intensity occurred. The spectral leakage was minimized by placing a darkened ring around the NPSP. Specimen 2 has PtPFPP as NPSP luminophore, which give a larger signal, but was quenched by oxygen, and reference intensity ratio is decreased by an increase in the pressure (see figure11A). Notice that the Figure 11B is curved downward due to that effect.
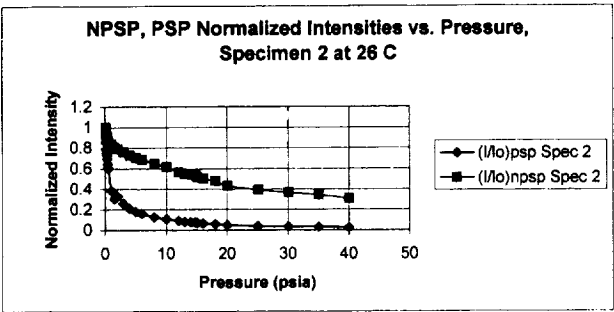

Figure 11A. . Plots of the normalized PSP and NPSP intensities, spec.2.
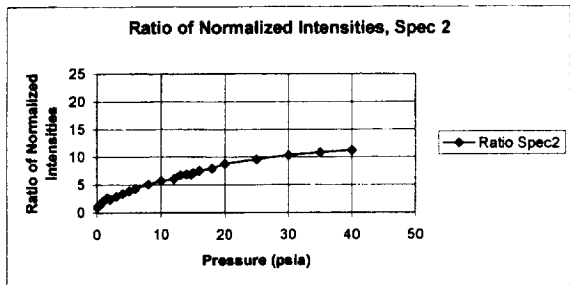

Figure 11B. Ratio of PSP and NPSP normalized intensities versus pressure for spec.2.

Specimen 3 (See Figure 12A and B), the NPSP intensity is decreasing with increase pressure because of its binder was not totally oxygen impermeable.
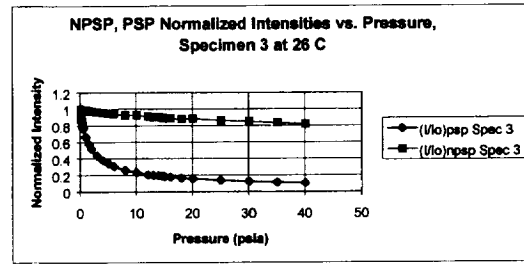

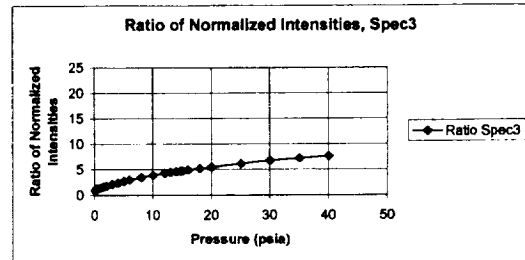Figure 12A . Plots of the normalized PSP and NPSP intensities, spec.3.

Figure12B. Ratio of PSP and NPSP normalized intensities versus pressure for spec.3

Moreover, in contrast for the specimen 1, the NPSP intensities for the specimens 2 and 3 were decreasing with increasing pressure because their binders were not totally oxygen impermeable. Figures 10B, 11B and 12B show that the calibration sensitivity is more linear for specimens 1 as compared to specimen 2 and 3.

Figure 13 shows the result of three repeated calibration of specimen 3 at 26 ° C. Replicates 1 and 2 were done without the darkened ring around NPSP, but replicate 3 was obtained with a 6.25 mm darkened ring. Each replicate took about 3 hours to complete. All 3 replicates were performed over a period of about 30 hours. For specimen 3, both PSP and NPSP had the same luminophores but different binders. The excitation source filter wavelength was 450 +- 40 nm and the emission filter wavelength was 580 +-9 nm. The NPSP intensity was found to decrease by 20 percent for 0.01 – 40 psia pressure change. Some oxygen permeability of the NPSP binder and some spectral leakage of intensity are believed to be the cause of this. The isolation of NPSP from PSP by the darkened ring is found to minimize the spectral leakage of intensity. In Figure 13, where the calibration plots are presented as the ratio of normalized intensities, there is no noticeable change in the paint performance between replicates 1 and 3.
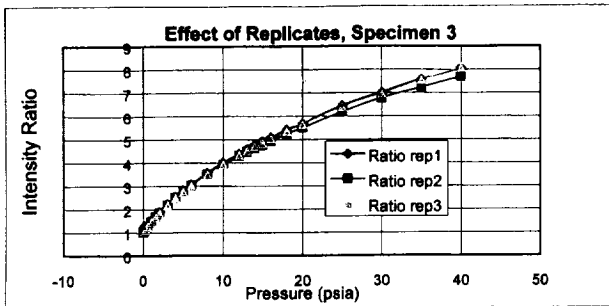
Effect of Replicates, Specimen 3

Intensity Ratio vs Pressure (psia)

— Ratio rep1
— Ratio rep2
— Ratio rep3

Figure 13. Effect of replicates on specimen 3 calibration at 26 degrees C

CONCLUSIONS

The following conclusions are drawn from the results of the tests performed on six specimens of different PSP and NPSP, and camera combinations in a pressure-vacuum chamber over a pressure range of 0.0-2.7 atmospheres, and temperature range of 15-35 °C.

(a) The technique works well when the PSP and NPSP have distinctly different spectral emissivity.

(b) The repeatability of the calibration relation is good and the temperature dependence of the calibration is small.

(c) The NPSP could be used as registration points in wind tunnel testing.

(d) When PSP and NPSP have the same luminescence probe molecules (in a different binder), spectral leakage/interference problems occur.

(e) None of the tested NPSP binders for the single-luminophore binary paint were completely impermeable to oxygen.

(f) This method does not provide a true globalize intensity correction, but only localized correction.

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