Investigation of Single Luminophore, Polymer-Ceramic Pressure Sensitive Paint for High Speed Wind Tunnel Testing

Jamison N. Murphree* and Phil A. Kreth †
University of Tennessee Space Institute, Tullahoma, TN, 37388

The following paper details the characterization of an experimental pressure sensitive paint (PSP) formulation derived from previous literature. The initial characterization focuses on creating calibration curves for the PSP at room temperature using a vacuum chamber. The results were compared to Porous, Fast-Response PSP manufactured by Innovative Scientific Solutions, Inc. (ISSI) as a control case. It was found that the experimental formulation had good agreement to the ISSI calibration curves overall. The maximum normalized errors between the experimental calibration curve and the ISSI curves were 5.4% for the 20 °C case and 14% for the 25 °C case. Both of these maximum normalized errors occurred near pressure ratios of one, i.e. the ambient condition. For the low pressure ratio region, the experimental paint exhibited excellent agreement. Future efforts will include expanding the calibration curves to include a range of operating temperatures and testing the paint in a dynamic environment. These efforts will continue to further the University of Tennessee Space Institute's goal of gaining a better understanding of the mechanisms and sensitivities of PSP for effective use in high speed aerodynamic experiments.

I. Nomenclature

A_n	=	calibration coefficients for PSP
I_{REF}	=	"wind-off" intensity at constant pressure P_{REF}
P_{REF}	=	"wind-off" reference pressure measurement

II. Introduction

Hypersonic vehicles are subject to intense mechanical loading throughout their flight profiles. As a result, it is of extreme importance to identify critical locations of increased mechanical loading on an aircraft to ensure mission success. One method to determine areas of intense pressures is Pressure Sensitive Paint (PSP). PSP has been utilized as a non-intrusive optical diagnostic technique in wind tunnel measurements since the early 1990s [1]. This application can be incredibly useful in aerodynamic testing to obtain full-field pressure data when pressure transducers are not feasible. For example, some model geometries may not be able to accommodate pressure transducers, or in some cases, the amount of pressure transducers required to obtain a full-field pressure measurement would be cost-prohibitive or impractical. The major advantage of PSP is that it can be used to measure pressure over large regions or on curved surfaces without requiring large numbers of instrumentation throughout the model.

In general, PSP works by exciting luminescent particles within the paint using an ultra-violet light of appropriate wavelength. When exposed to the UV light, the luminescent particles embedded in the paint fluoresce. The intensity of the fluorescence is dependent on the local partial pressure of oxygen. A higher partial pressure of oxygen results in more oxygen quenching and a lower intensity fluorescence by the luminophore. The luminescent intensity can be measured using a high-speed camera and translated to pressure values. The end result is a global representation of the pressure field on the painted area of interest. When coupled with pressure transducers as anchor points, PSP can provide quantitative pressure values at each pixel of the acquired images [2].

As the speed regimes of interest in the aerodynamics commmunity have increased, PSP has become a frequently used diagnostic in high-speed Ludwieg Tubes and blowdown facilities. These facilities have short run times and rapid dynamics; thus, for PSP to be effective in these environments, it must have a sufficiently fast response time. The required

*Graduate Research Assistant, Mechanical, Aerospace, and Biomedical Engineering Dept., and AIAA Student Member
†Assistant Professor, Mechanical, Aerospace, and Biomedical Engineering Dept., 411 B. H. Goethert Parkway, and AIAA Member

response time depends on the type of facility and also varies within facilities of the same type with different design parameters. For example, in the Mach 4 Ludwieg Tube at the University of Tennessee Space Institute (UTSI), the steady-state run time is approximately 120 milliseconds [3]. In this case, the PSP must be able to respond on the order of milliseconds to obtain usable steady-state data. This project seeks to characterize a PSP previously described by Pandey and Gregory [4] and compare it to the industry standard ISSI Fast-Response PSP with the goal of gaining a better understanding of the mechanisms and response times of different PSP formulations and how they may be effectively used in the facilities at UTSI.

III. Technique

The paint mixed in this experiment consists of a polymer-ceramic base coat and a luminescent top coat. The base coat is comprised of deionized water, ceramic dispersant (Dow Chemical, Duramax™D-3005), titanium dioxide (Chemours, Ti-Pure™R-900), and acrylic polymer emulsion (Dow Chemical, Duramax™B-1000). The top coat is comprised of a luminophore (Fisher Scientific, Platinum(II) tetra (pentafluorophenyl) porphyrin (PtTFPP)) suspended in methanol.

The base coat is applied with a spray gun and allowed to dry for approximately four hours. The top coat is applied with a spray gun once the base coat has dried. The top coat dries very quickly as the methanol evaporates, leaving the luminophore applied on the surface of the model. Now, the luminophore can be excited by UV light. An illustration of this concept can be seen in Fig. 1.

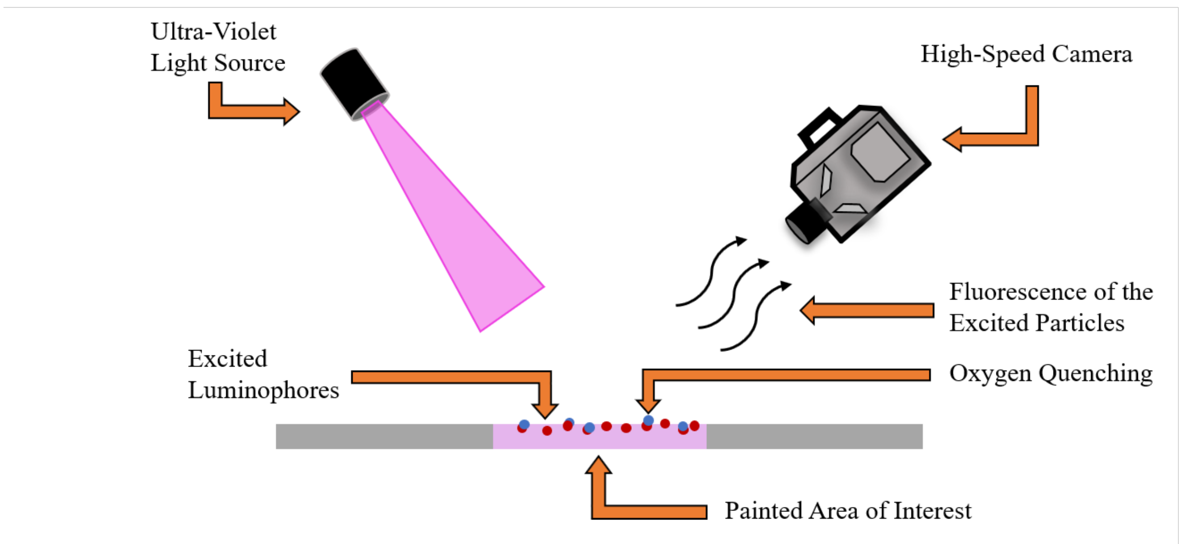

Fig. 1 Schematic of the mechanisms of PSP, including oxygen quenching of the luminophores.

The blue particles shown in Fig 1. represent the oxygen molecules present in the air over the painted area of interest. When an oxygen molecule interacts with an excited luminophore, it prevents the fluorescent light emission and relaxes the luminophore back to its base state. This process is known as oxygen quenching. When the oxygen in the air quenches the luminescent intensities of some of the luminophores on the painted surface, it results in lower overall intensities measured by the camera sensors. Therefore, higher pressures result in increased oxygen quenching and lower luminescent intensities. As pressure decreases, the luminescent intensities are higher. This inversely proportional relationship is described in a modified version of the Stern-Volmer relationship [5].

$$\frac{I_{\mathrm{REF}}}{I} = \sum_{n=0}^{N} A_n(T)\left(\frac{P}{P_{\mathrm{REF}}}\right)^n \tag{1}$$

The reference condition denoted by the subscript "REF" corresponds to the respective intensity and pressure values at a static condition, also known as the "wind-off" condition. When the calibration coefficients, A_n, are known, it becomes trivial to convert a measured intensity value to a pressure value. For commercially available PSP, these constants are typically provided by the manufacturer. For PSP where these constants are not readily known, a calibration curve must be constructed. This can be done by stepping through a series of known pressures and measured intensity values. The intensity ratios can then be plotted against the pressure ratios and have a curve fit applied to them. The coefficients of the n^{th} order curve fit correspond to the A_n coefficients. It is important to note that these coefficients are temperature dependent. As noted by Liu *et al*, the effects of non-uniformities of illumination, paint thickness, and luminophore concentration are eliminated by taking the ratio I/I_{REF} [5].

IV. Experimental Description

A. Facilities and Equipment

This paint was initially characterized on the benchtop using a vacuum chamber on UTSI's campus. The required light sources are high intensity, water cooled, UV LEDs manufactured by ISSI. The paint was imaged using a Photron FASTCAM Mini AX200 which has a maximum sensor pixel size of 1,024 x 1,024 at frame rates of up to 6kHz. Higher frame rates can be utilized with lower resolutions. The pressure controls on the vacuum chamber and the camera allowed for both the reference pressure and intensity values as well as the actual pressure and intensity values to be measured. These quantities stepped through several pressure values were sufficient to form a curve fit and determine the calibration coefficients.

For future dynamic testing of this experimental PSP, UTSI's Tennessee Aerothermodynamics Laboratory (TALon) possesses a Mach 4 Ludwieg Tube. It operates by pressurizing a long section of pipe called the driver tube until a Mylar® diaphragm bursts and allows the air to flow through a planar nozzle into the test section. Up to three diaphragms can be stacked to vary the Reynolds numbers ranging from 1-16 x 10^6 /ft (3.3-53 x 10^6 /m) . The Mach 4 facility has a 24"x 24" test section, 11" x 17" windows for optical access, and can sustain steady state Mach 4 flow for approximately 105-120 ms per run [3].

B. Procedure

The setup for this experiment was relatively straightforward. The paint was mixed and applied as described above using 5 mL of the base coat and 10 mL of the top coat. For this experiment, the painted model was a small test coupon of aluminum with a flat surface as shown in Fig. 2. The painted area of interest was then exposed to high-powered UV LEDs and imaged with a high-speed camera.

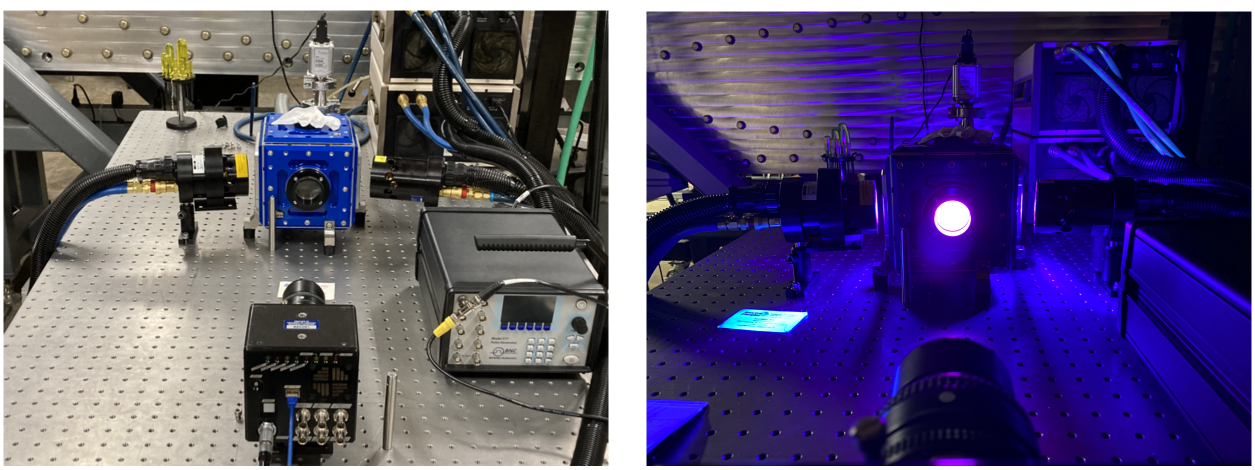

Fig. 2 (a) Experimental setup for the PSP vacuum chamber calibration and (b) UV illumination on the test article within the vacuum chamber.

The paint was imaged starting from ambient pressure (≈ 98.3 kPa) down to vacuum (≈ 1.33 Pa) in a random order to mitigate hysteresis errors. The distribution of the measured points were more densely populated at the lower pressure values. This was done to achieve greater resolution at lower pressures where the paint is typically going to be used for measurements. The camera was set to record at 20,000 Hz at 384 x 384 pixels and used a 575 nm longpass filter to block out the UV light from the LEDs. This allowed primarily the fluorescence from the paint itself to pass through to the camera sensors while reducing noise from shorter wavelengths. The controlled pressures in the vacuum chamber and the measured intensity values from the images were used to construct calibration curves. These results were then be compared to the commercially available Porous, Fast-Response PSP from Innovative Scientific Solutions, Inc. which was used as a control since it is well characterized.

V. Results

In total, three runs were conducted on the experimental PSP. Sample images were taken at a total of ten different pressure values ranging from ambient to vacuum. Twenty images were taken at each sampling location. These images were then averaged together and cropped to reduce the size to a selected rectangular portion within the painted area of interest. An illustration of this can be seen in Fig. 3.

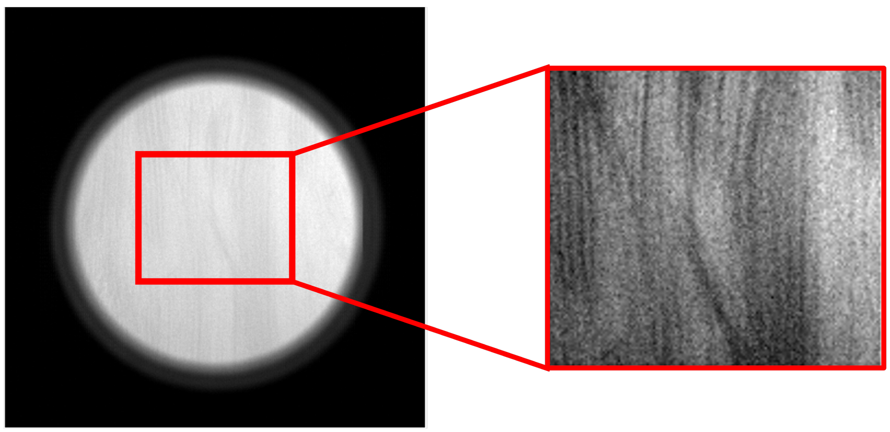

Fig. 3 (a) Sample mean image of data taken at ambient conditions and (b) the selected area of interest from the mean image used for the intensity ratio.

As seen in Fig. 3b, there were noticeable striations in the selected area of interest. These striations resulted from non-uniformities in the base coat of the paint and were clearly visible after the top coat was removed. The average intensity values of selected area within the mean images were calculated and associated with their respective pressure values for each run. The ambient condition for each run served as the reference conditions, i.e. the P_{REF} and I_{REF} from the modified Stern-Volmer equation. Each of the subsequent image sets from the run were normalized by the reference conditions and plotted together with a curve fit as shown in Fig. 4.

The experimental data from each of the runs showed similar trends as evidenced by the R^2 value and the low-order polynomial required to fit the data. The second-order fit was chosen to replicate the calibration process described by Liu *et al*. The ten pressure values were the same for each run but sampled in different orders for repeatability. There are some variations from run to run which may indicate photo degradation of the paint by repeated exposure to UV light, hysteresis error associated with the pressure transducer on the vacuum chamber, or generally random fluctuations in the data. The calibration curves of ISSI's Porous, Fast-Response PSP were plotted with the curve fit of the experimental data for comparison [6]. The results from this can be seen in Fig. 5.

Note that the values of P/P_{REF} terminate at one for the experimental data. This was because this experiment was not pressurized above the ambient reference condition. The experimental data showed good agreement with the ISSI curves at pressure ratio values of below one. The maximum normalized error between the experimental curve and the ISSI curve at 20°C was 5.4% and the maximum normalized error for the ISSI curve at 25°C was 14%. The maximum normalized errors both occurred at or near pressure ratios of one. These results suggest that accuracy of the experimental curve decreases slightly nearing pressure ratios of one. This could likely be resolved by sampling data at pressure ratios of greater than one to increase the accuracy of the curve fit over a greater range. A similar calibration experiment on a fast-response PSP was performed, although at a much larger scale, at the Arnold Engineering Development Complex (AEDC) in Tullahoma, Tennessee. This experiment yielded a slightly more linear calibration curve than the data presented in this paper but still showed good agreement in the low pressure ranges at the same temperatures. [7].

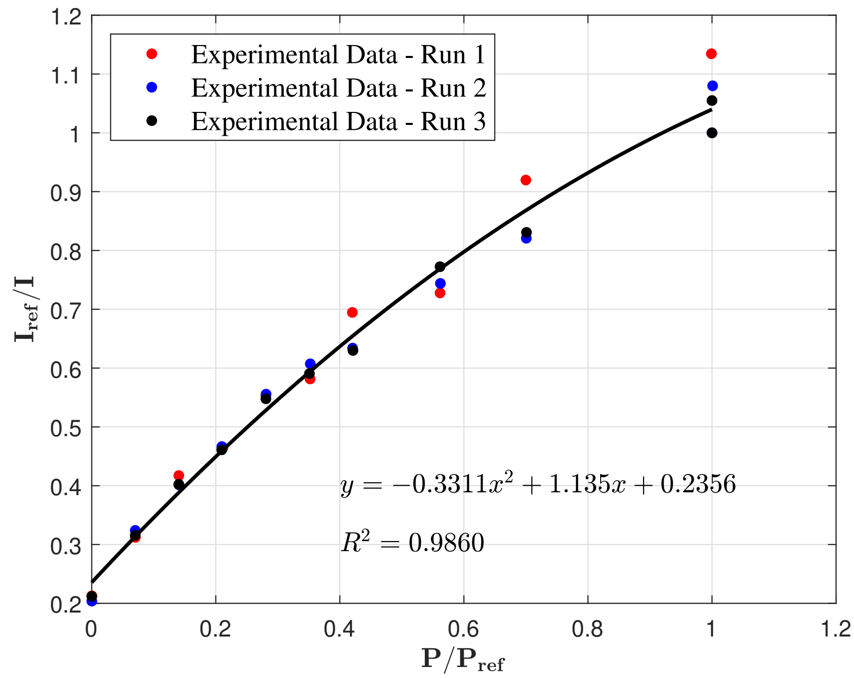

Fig. 4 Data points from each of the experimental runs were plotted together and curve fit with a second-order polynomial to form a static calibration curve.

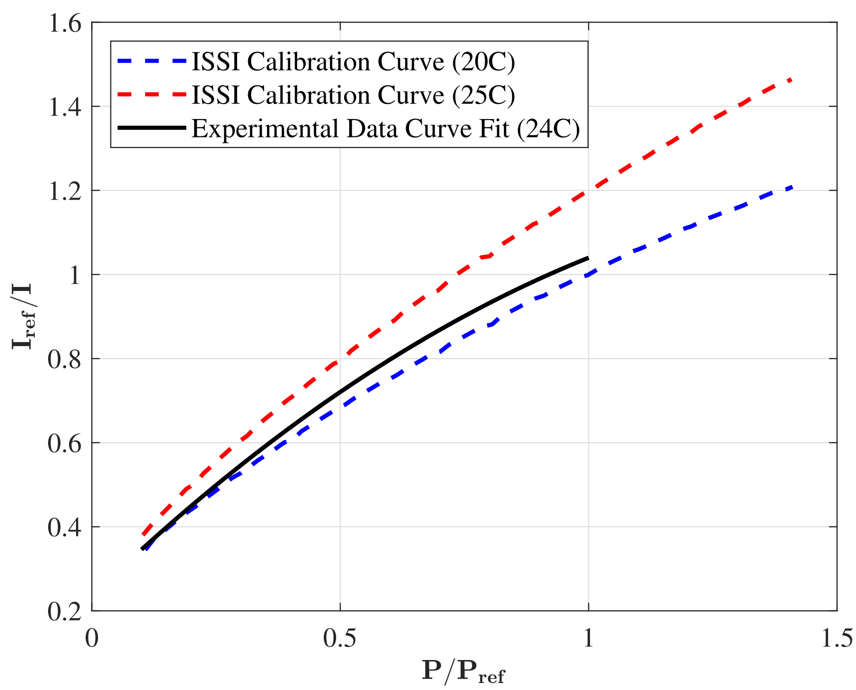

Fig. 5 The curve fit of the experimental data plotted with the ISSI calibration curves at similar temperatures showed good agreement, particularly for pressure ratio values below one.

Given these comparisons, it was reasonable to conclude that the experimental paint was behaving similarly to the ISSI PSP, especially at low-pressure regions where the paint was most likely to be used for measurements.

VI. Future Work

Currently, the vacuum chamber does not support heating or cooling of the test coupon. This set of calibration curves was produced at room temperature. Future work for this project will include adding the capability of sweeping the temperature as well as the pressure in the vacuum chamber. Once the paint has undergone a robust static calibration in the vacuum chamber, the paint will be dynamically tested to determine the frequency-response using an acoustic resonance tube similar to experiments by Pandey and Gregory [4]. In addition, the paint will be tested in UTSI's Mach 4 Ludwieg Tube. The Ludwieg Tube will allow for an *in situ* calibration to provide the most accurate results possible. The paint will be applied to a model that has been well characterized by commercial PSP in the Mach 4 facility, such as a hollow-cylinder flare.

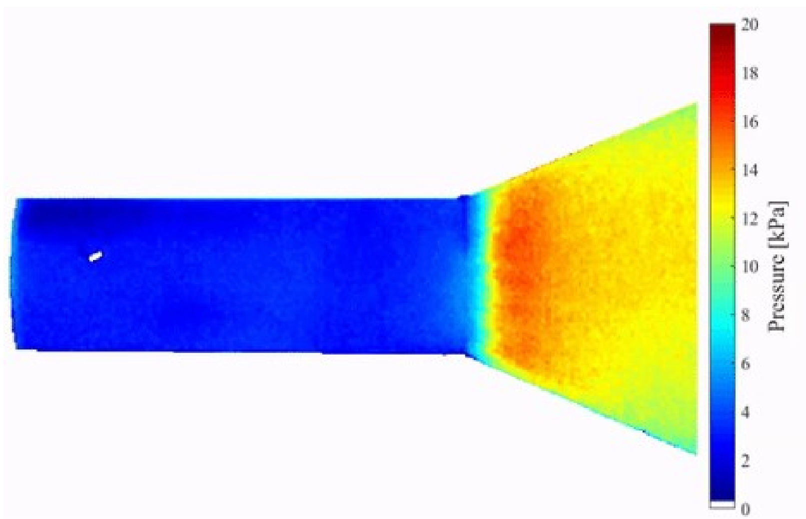

Fig. 6 PSP on a Hollow Cylinder Flare at Mach 4 from previous UTSI research sponsored by the Office of Naval Research.

Figure 6 shows an example of processed PSP data taken on a hollow-cylinder flare in the UTSI Mach 4 Ludwieg Tube. Similar results are expected from the dynamic testing that will be done using the experimental and control formulations. Results from the static bench top testing and the dynamic testing between the two formulations will be compared and contrasted to assess the viability of using the experimental formulation for conducting experiments in short duration impulse facilities and longer duration blowdown facilities.

VII. Conclusion

Pressure sensitive paint diagnostic techniques are a vast and rapidly growing field of study, especially within the high speed aerodynamics community. This research was focused on gaining a better understanding of the response characteristics of fast-response PSP formulations for use in facilities at UTSI. Results from the static calibration of the experimental formulation showed good agreement with the industry standard ISSI PSP. The promising results from this experiment warrant further exploration of the dynamic response characteristics of both formulations.

Acknowledgments

J. N. Murphree thanks Dr. John Schmisseur for his continued support and advisement, Dr. Phil Kreth for his advice on best practices for lab experiments, and Oriana Palumbo for her assistance with conducting these experiments.

References

[1] Kavandi, J., Callis, J., Gouterman, M., Khalil, G., Wright, D., Green, E., Burns, D., and McLachlan, B., "Luminescent Barometry in Wind Tunnels," *Review of Scientific Instruments*, Vol. 61, No. 11, 1990, pp. 3340–3347.

[2] McLachlan, B. G., and Bell, J. H., "Pressure-sensitive paint in aerodynamic testing," *Experimental thermal and fluid science*, Vol. 10, No. 4, 1995, pp. 470–485.

[3] Kreth, P. A., Gragston, M., Davenport, K., and Schmisseur, J. D., "Design and Characterization of the UTSI Mach 4 Ludwieg Tube," *AIAA Scitech 2021 Forum*, 2021, p. 0384.

[4] Pandey, A., and Gregory, J. W., "Frequency-Response Characteristics of Polymer/Ceramic Pressure-Sensitive Paint," *AIAA Journal*, Vol. 54, No. 1, 2016, p. 1. https://doi.org/10.2514/1.J054166.

[5] Liu, T., Campbell, B. T., Burns, S. P., Sullivan, J. P., et al., "Temperature-and Pressure-Sensitive Luminescent Paints in Aerodynamics," *Applied Mechanics Reviews*, Vol. 50, 1997, pp. 227–246.

[6] "Porous, Fast-Response Pressure Sensitive Paint Data Sheet," *ISSI Website*, 2022. URL https://innssi.com/wp-content/uploads/Pressure_Sensitive_Paint/Porous_Fast_PSP/Documentation/Porous-Fast-Response-PSP-FP-XXX-Data-Sheet.pdf.

[7] Sellers, M. E., Nelson, M. A., Burnside, N. J., and Roozeboom, N., "Evaluation of Unsteady Pressure Sensitive Paint Use for Space Launch Vehicle Buffet Determination," *55th AIAA Aerospace Sciences Meeting*, 2017, p. 1402.