Lecture 10: Pressure Sensitive Paint (PSP) & Temperature Sensitive Paint (TSP) - Part 01

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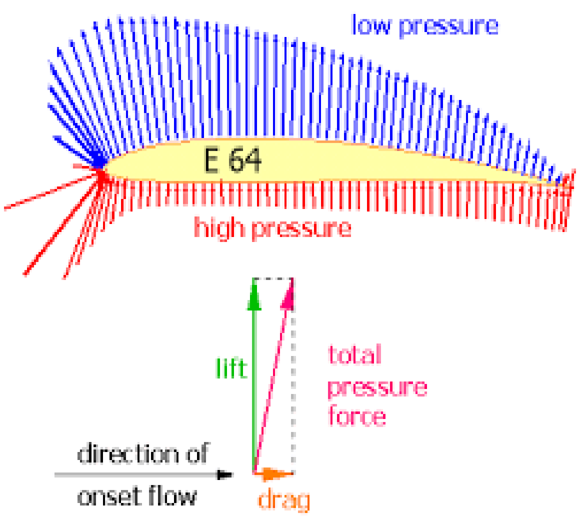
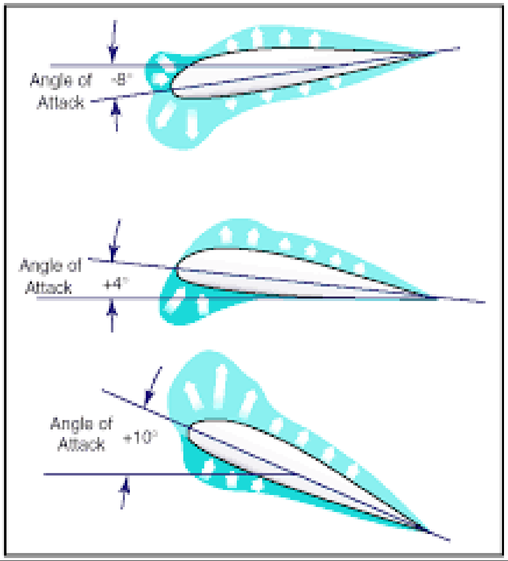
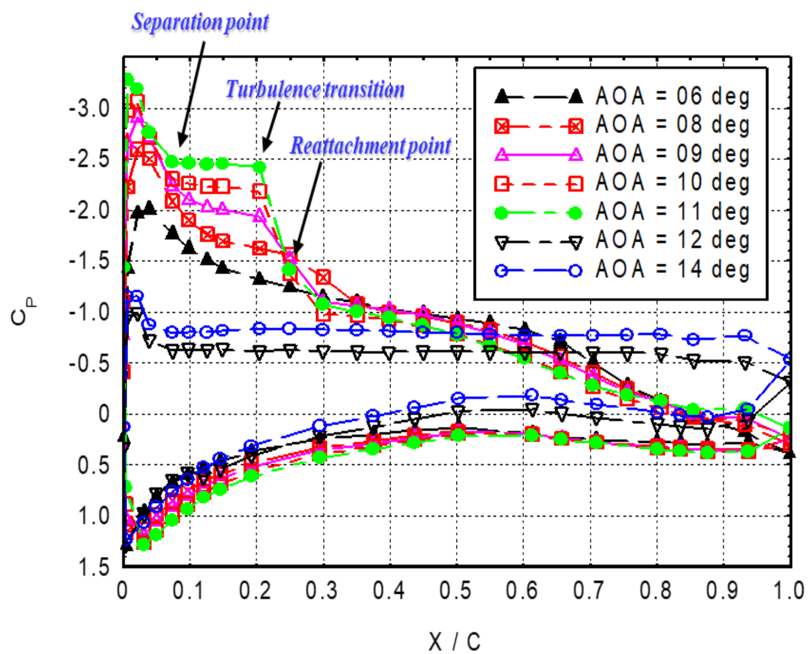
❑ Introduction

- Pressure measurements are the primary measurements made in most practical aerodynamic testing or basic fluid mechanics experiments.
- Surface pressure measurements are used for:
  - Identifying specific flow phenomena (boundary layer separation, shock wave impingement, etc.) that are not easily measured by “standard pressure tap” measurements.
  - Validation of computational codes
  - Loads calculations by integration of the surface pressures



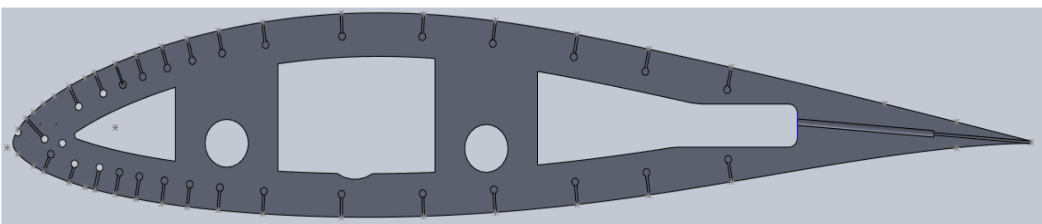


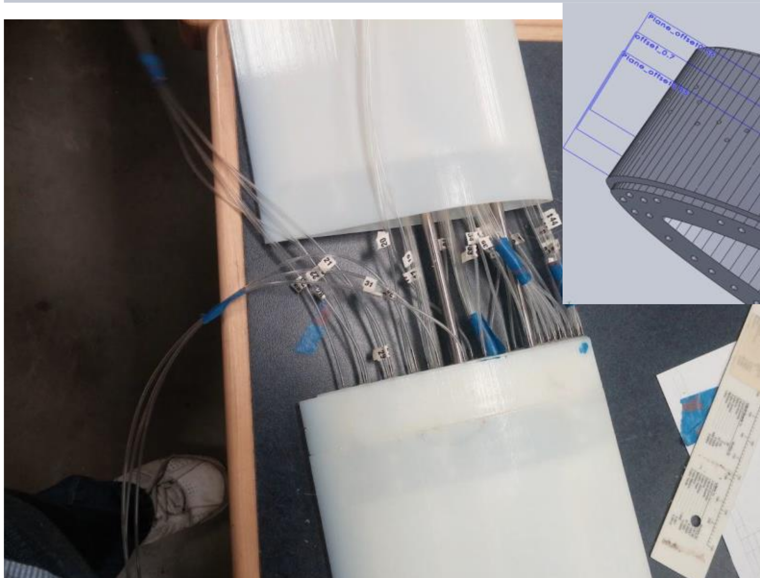


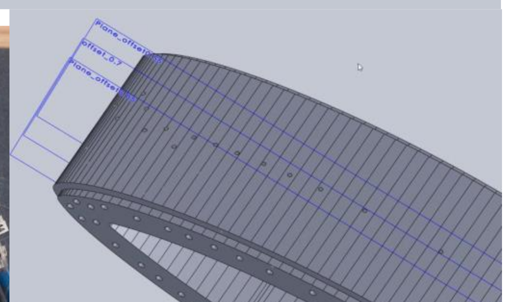
Introduction

- **Conventional pressure measurements: Transducers or taps**
  - *Discrete pre-determined locations*
  - *Very high accuracy (< 0.05% FS)*
  - *Well understood with long testing background*
  - *High data rate with scanned systems (1000+)*
  - *Limitations to where they can be installed*
  - *Potential effect on the flow field – intrusive measurements*
  - *Expensive installation costs*

DSA3217 (Shown)







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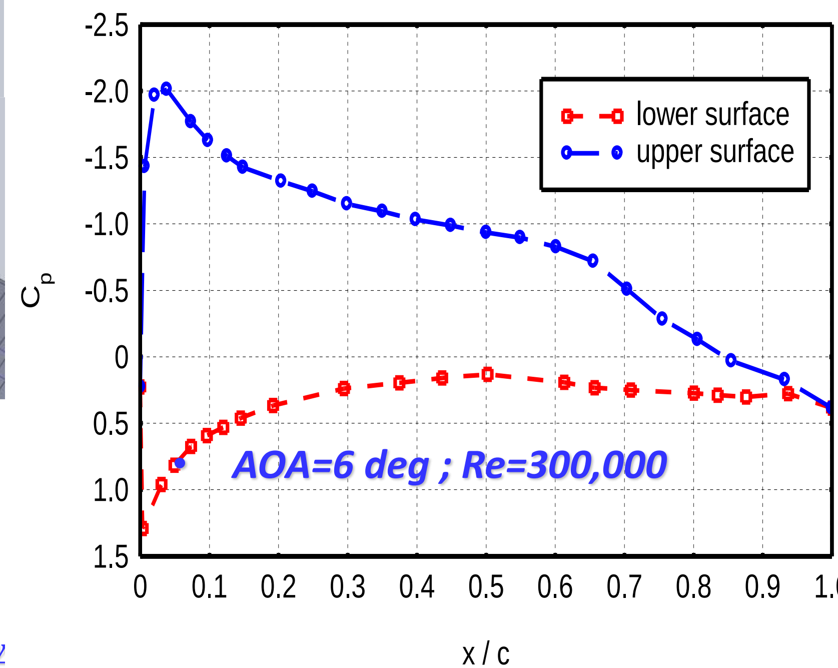
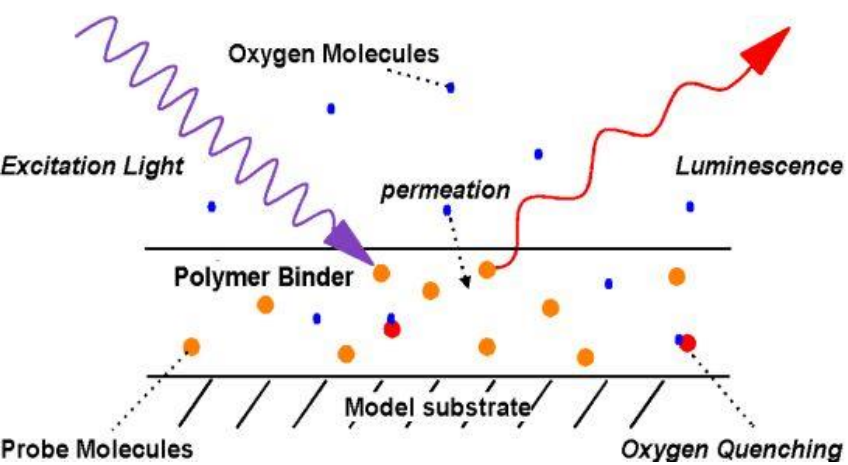
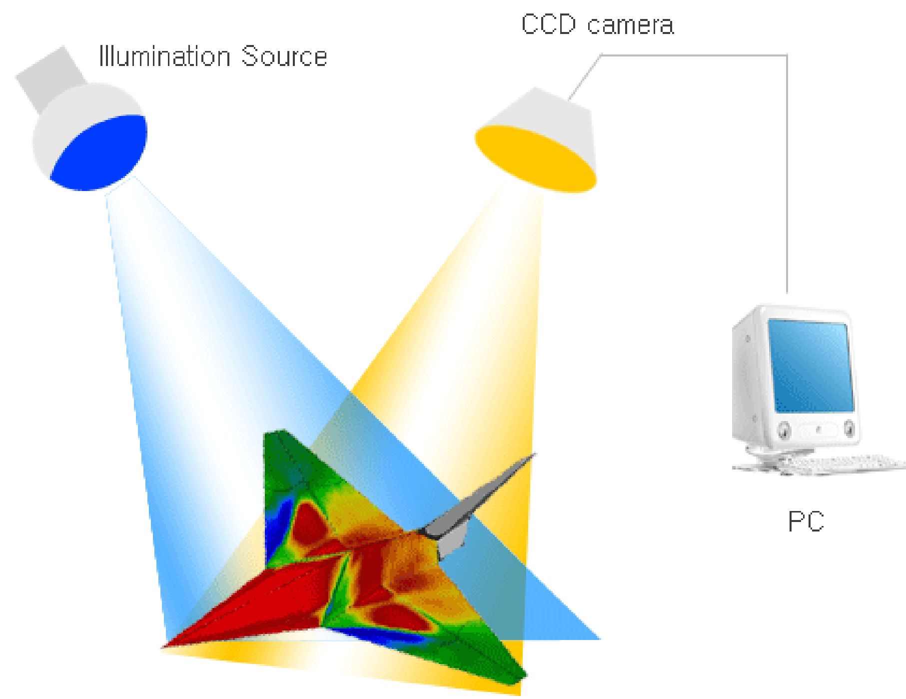


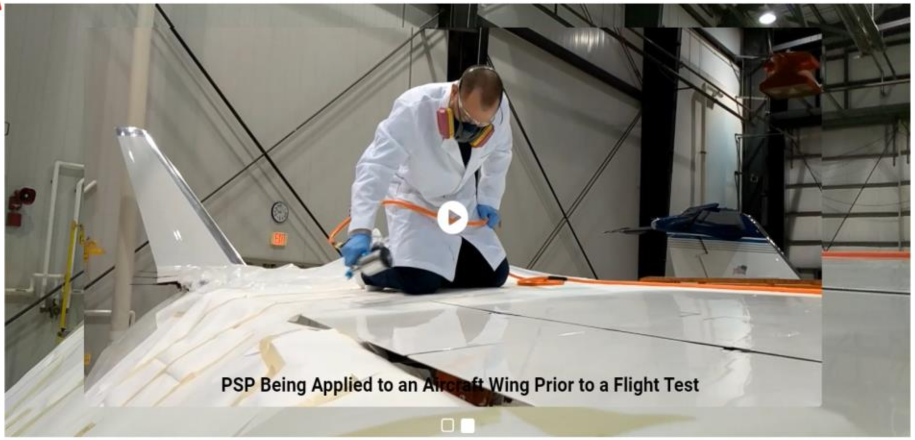
❑ Pressure Sensitive Paint (PSP)

- *Sprayed over entire exterior surface*
- *non-intrusive pressure measurements*
- *high spatial resolution with resolution limited only by detection system*
- *Limited to optical access applications*
- *Inexpensive application costs*
- *Relatively expensive initial costs to setup the system*
- *High-speed applications*
- *Newer method that is still being fully explored for low-speed applications.*

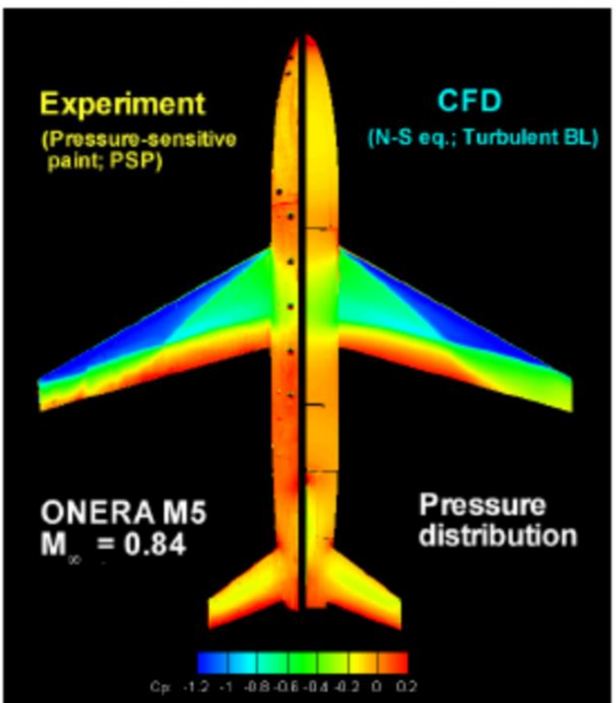




❑ Pressure Sensitive Paint (PSP) Tchnique



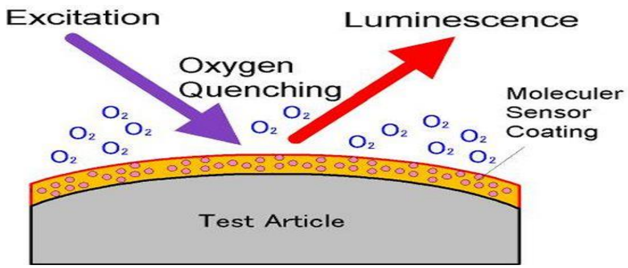
- https://innssi.com/psp/

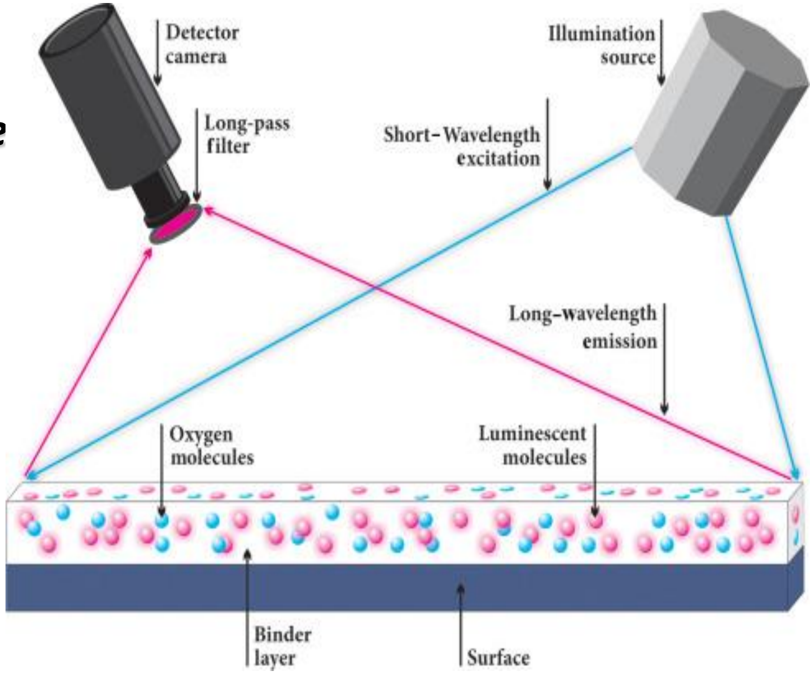


- *https://www.youtube.com/watch?v=cWKUZJroVN8*

❑ Basic Principles of Pressure Sensitive Paint (PSP)

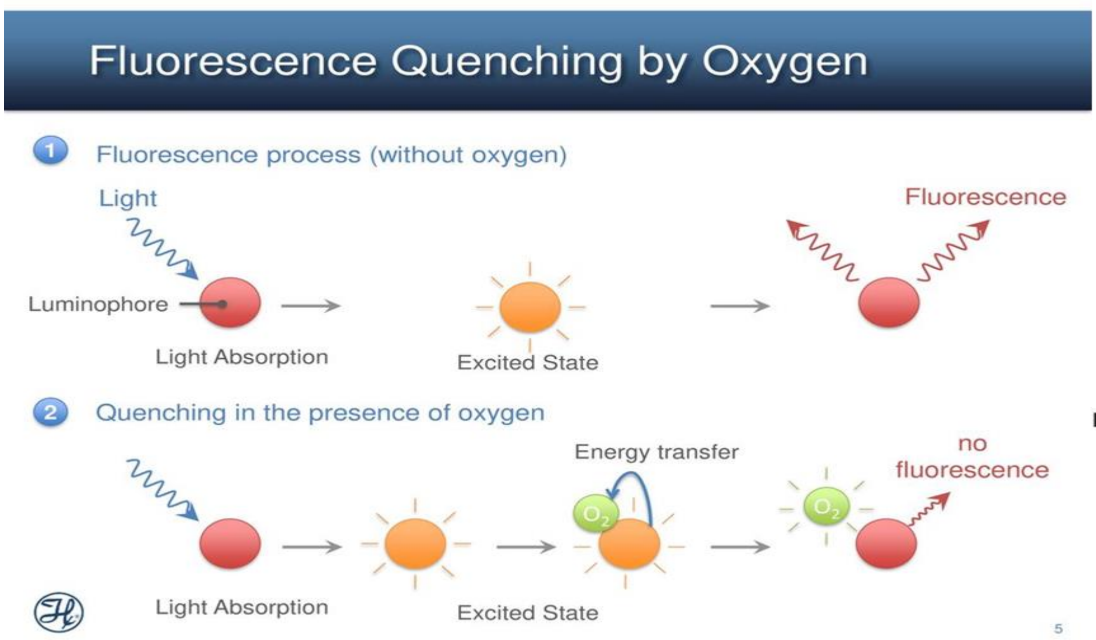
- ***Composition of Air: 78.08% N_2, 20.95% O_2, 0.93% Ar, 0.03% CO_2, 0.002% Ne, plus lesser amounts of Methane, Helium, Krypton, Hydrogen, Xenon.***
- ***The pressure of air can be determined if the particle pressure of oxygen (i.e., oxygen concentration) can be measured.***
- ***A typical pressure sensitive paint is comprised of two main parts: an oxygen sensitive fluorescent molecule and an oxygen permeable binder***

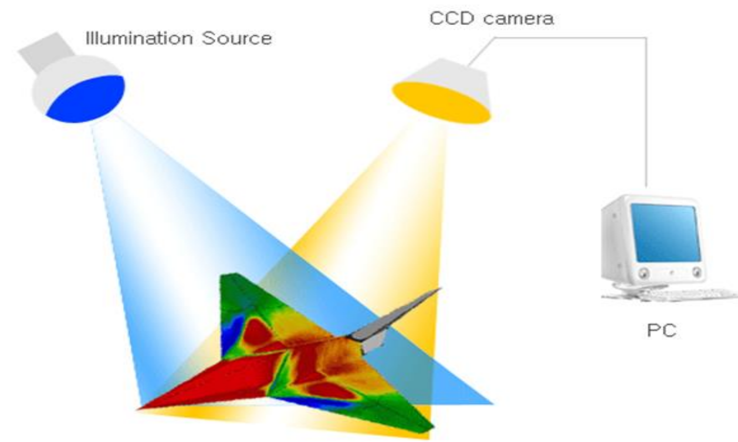


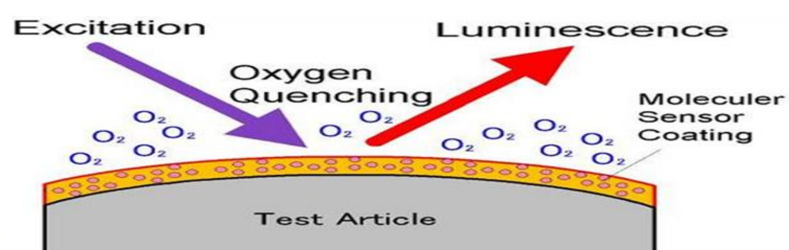


❑ Basic Principles of Pressure Sensitive Paint (PSP)

- ***The pressure sensitive paint method is based on the sensitivity of certain luminescent molecules to the presence of oxygen.***
  - ***When a luminescent molecule absorbs a photon, it is excited to an upper singlet energy state. The molecule then typically recovers to the ground state by the emission of a photon of a longer wavelength (i.e., fluorescence or phosphorescence).***
  - ***In some materials, oxygen can interact with the molecule so that the transition to the ground state is radiationless, this process is known as oxygen quenching.***
  - ***The rate at which these two processes compete is dependent on the partial pressure of oxygen present, with a higher oxygen pressure quenching the molecule more, thus giving off a lower intensity of light.***





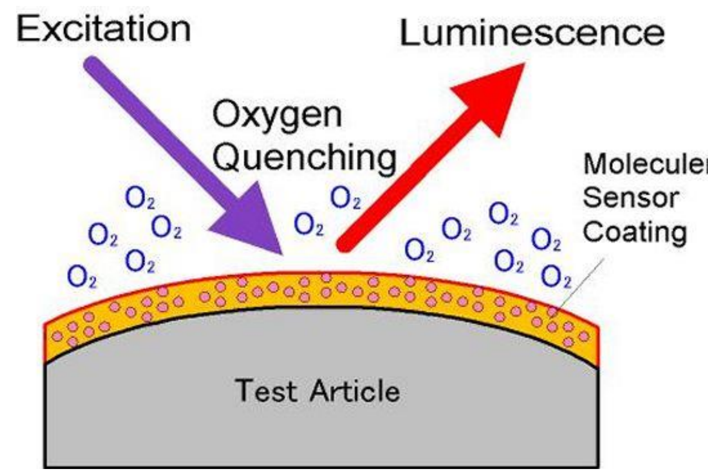


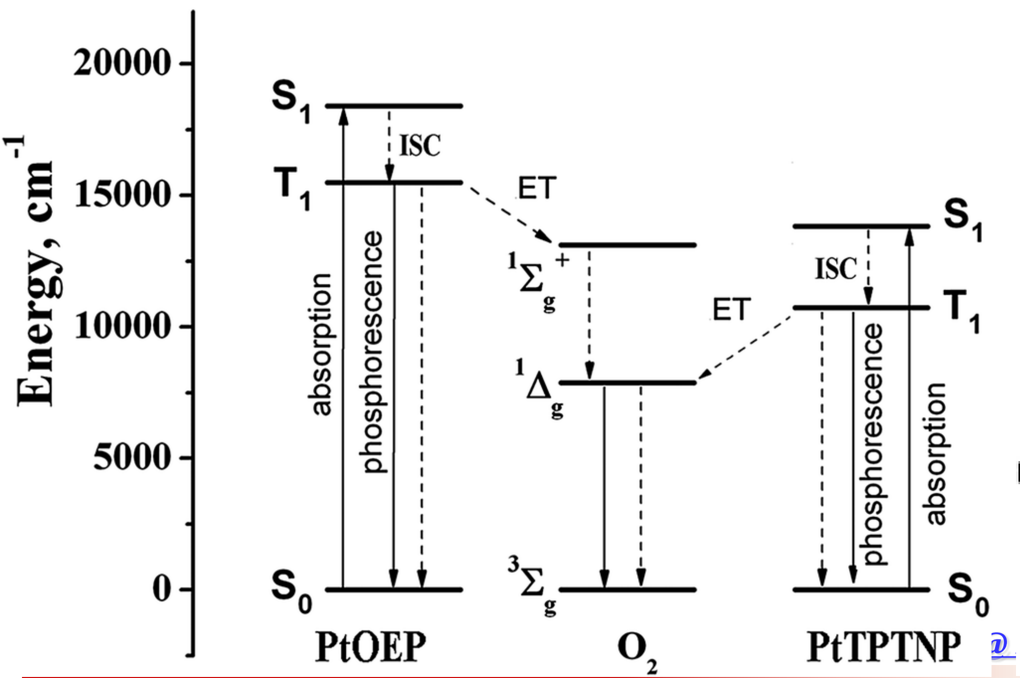
❑ BASIC PRINCIPLES OF PRESSURE SENSITIVE PAINT (PSP)

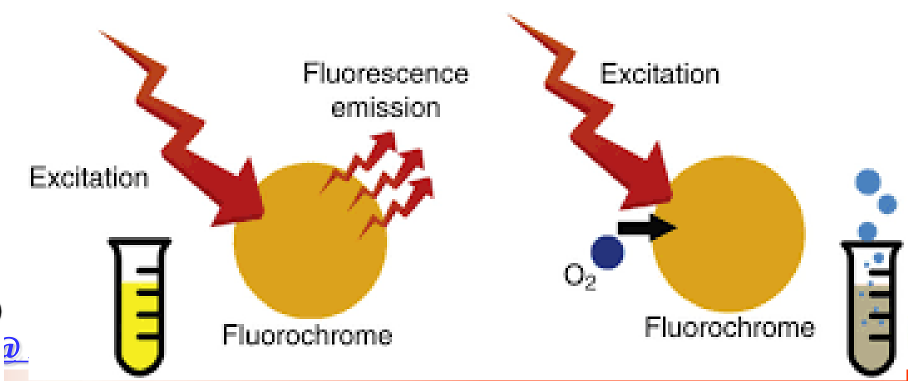
- ***For oxygen quenching, the intensity decrease can be described by the well-known Stern-Volmer equation:***

$$\frac{\tau_0}{\tau} = 1 + K_{SV} Q \qquad \text{or} \qquad \frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2}$$

- ***τ is the lifetime, I is the intensity***
- ***K_{SV} is the Stern-Volmer constant***
- ***Q is the quencher or partial pressure of oxygen***

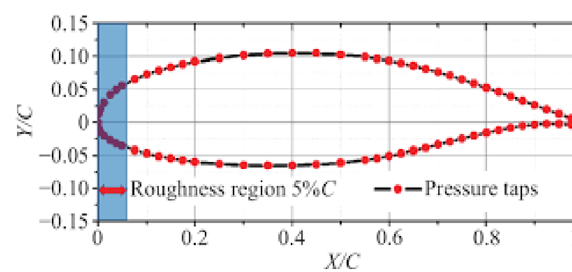


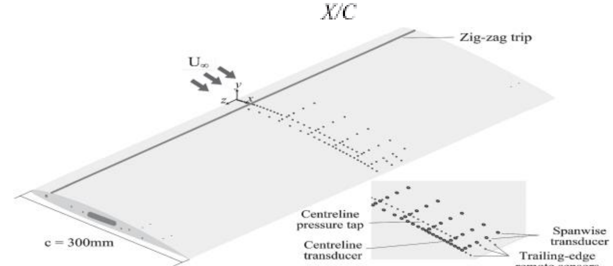




❑ Advantages of Pressure Sensitive Paint (PSP)

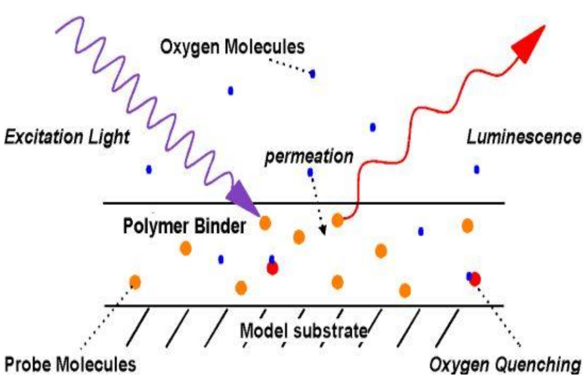
- *Pressure sensitive paint has numerous advantages over conventional pressure taps and transducers.*
  - *PSP is a field measurement technique, allowing for a surface pressure determination over the entire model.*
  - *PSP provides a much greater spatial resolution than pressure taps, and disturbances in the flow are immediately observable.*
  - *Use of PSP does not affect the flow around the model, allowing its use over the entire model surface.*
  - *The use of PSP eliminates the need for a large number of pressure taps, leading to less time and money for surface pressure measurements*
  - *Since holes do not need to be drilled in the model for the installation of pressure taps, the model strength is increased, and higher Reynolds numbers can be obtained.*
  - *Not only does the PSP method reduce the cost of the model construction, but it also reduces the cost of the instrumentation needed for data collection.*
  - *The equipment needed for PSP costs less than pressure taps, but it can also be easily reused for numerous models.*
- *PSP has the potential to save both time and money in aircraft design.*
  - *The continuous data distribution on the model provided by PSP can easily be integrated over specific components, which can provide detailed surface loads.*
  - *Since a model for use with the PSP technique is faster to construct, this allows for load data to be known much earlier in the design process.*

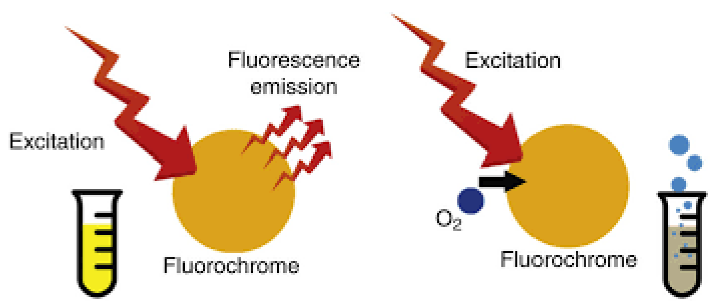


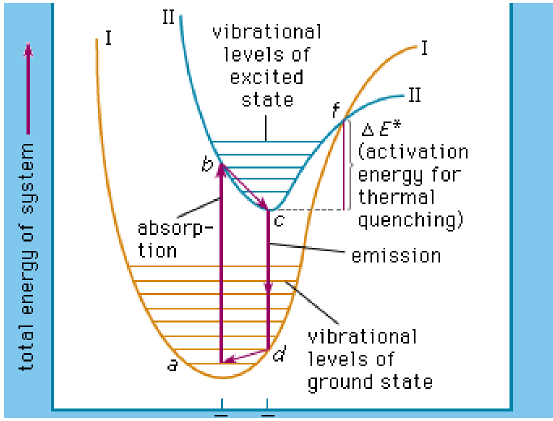


❑ Disadvantages of Pressure Sensitive Paint (PSP)

- *One of these characteristics is that the response of the luminescent molecules in the PSP coating degrades with time of exposure to the excitation illumination.*
  - *This degradation occurs because of a photochemical reaction when the molecules are excited.*
  - *Eventually, this degradation of the molecules determines the useful life of the PSP coating.*
  - *This characteristic becomes more important for larger models, as the cost and time of PSP reapplication becomes a significant factor.*
- *A second undesirable characteristic of PSP is that the emission intensity is affected by the local temperature.*
  - *This behavior is due to the effect of temperature has on the energy state of the luminescent molecules, and the oxygen permeability of the binder.*
  - *This temperature dependence becomes even more significant in compressible flow tests, where the recovery temperature over the model surface is not uniform.*



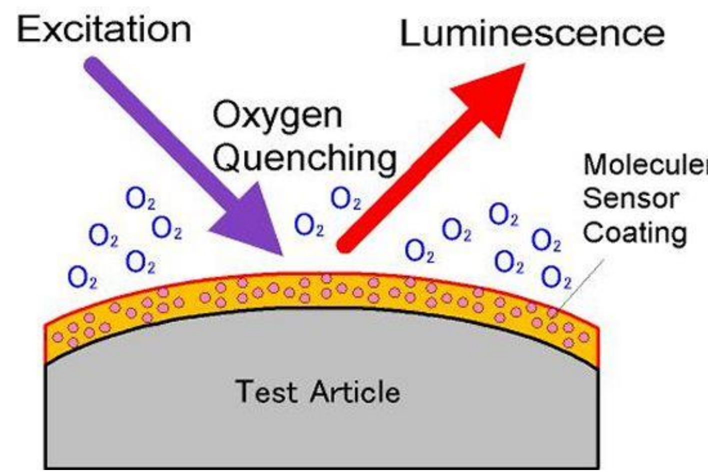




• Oxygen quenching effect

• Thermal quenching effect

❑ Basic Principles of Pressure Sensitive Paint (PSP)



- *Intensity based Methods (most common)*
  - *Full-field using camera*
  - *Point systems using scanning laser*

- *lifetime based Methods (lifetime decay)*
  - *Full-field using camera*
  - *Point systems using scanning laser*

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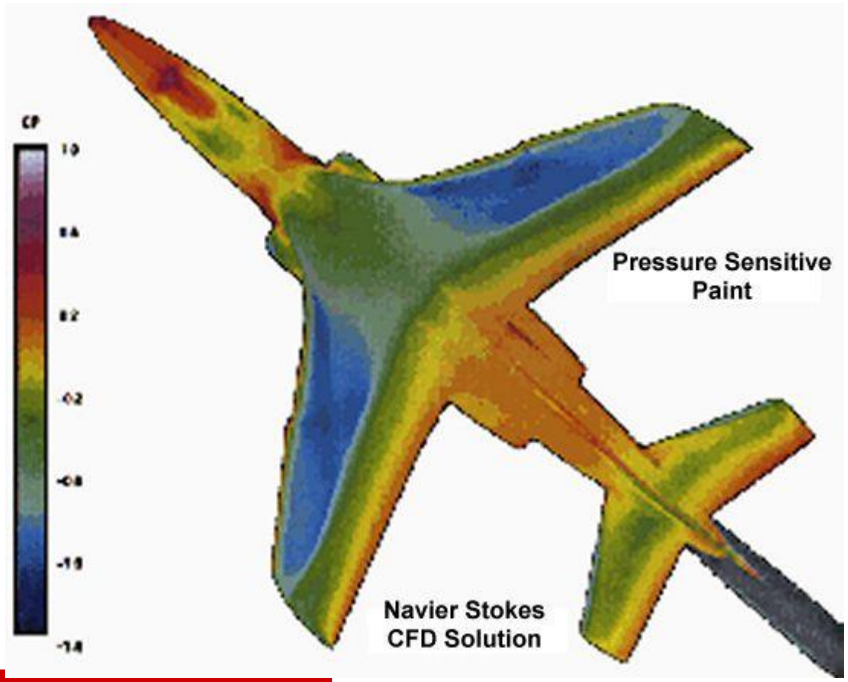
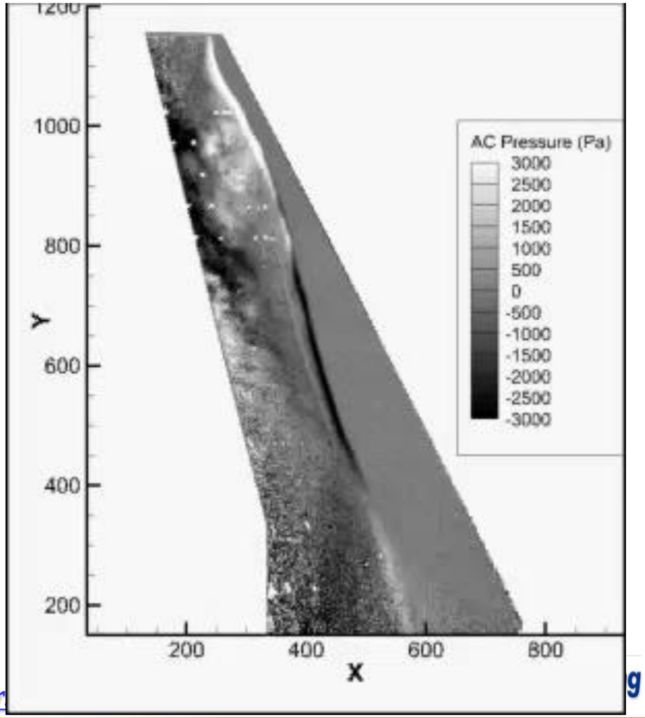


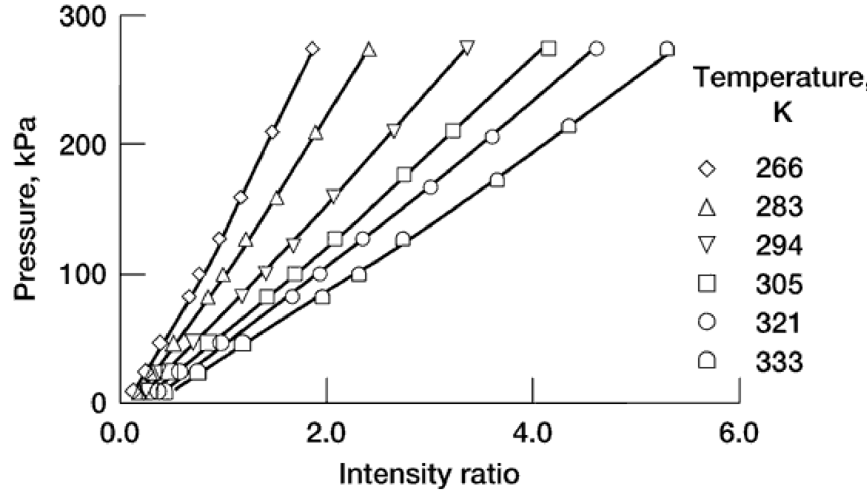


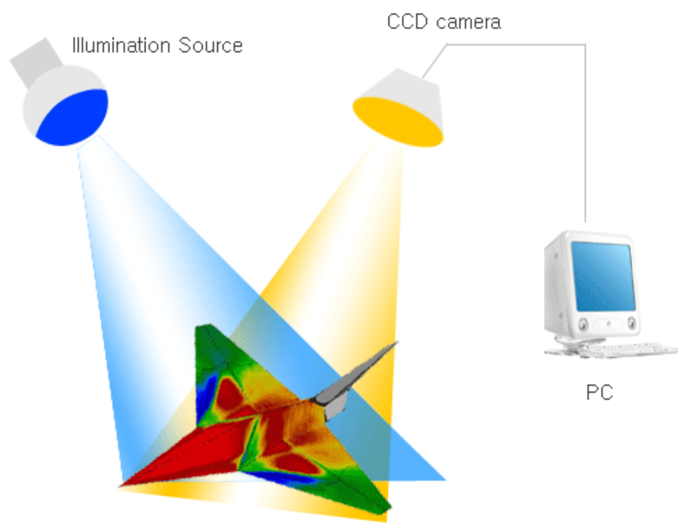
❑ INTENSITY-BASED PSP

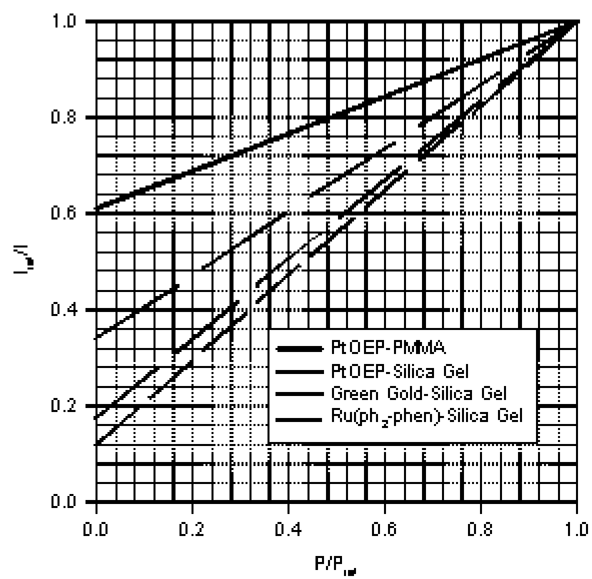
- *The Stern-Volmer equation is rewritten in the popular intensity ratio form:*

$$\frac{P}{P_{REF}} = A + B\frac{I_{REF}}{I}$$

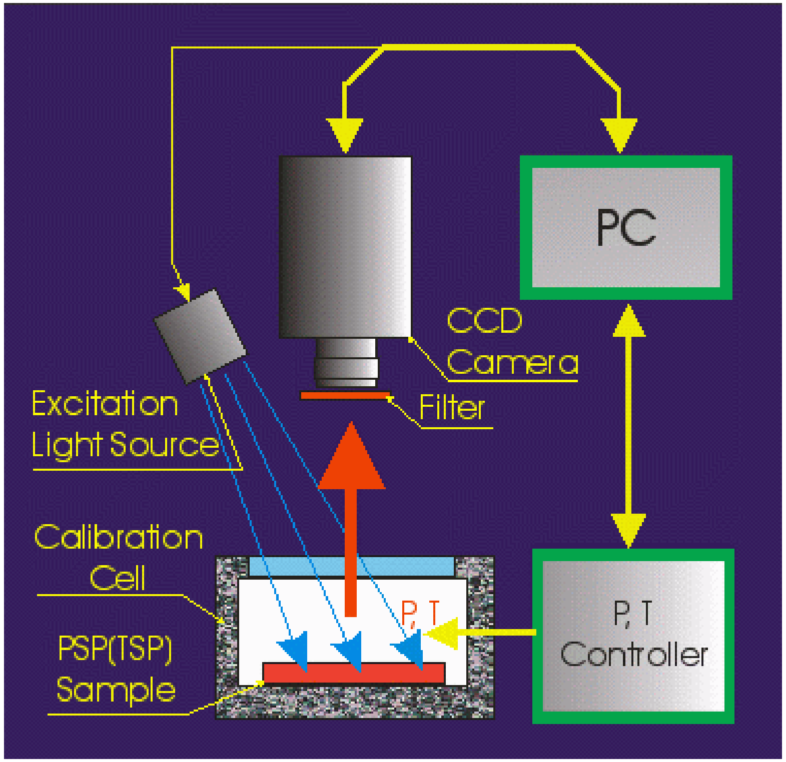
- *A and B are highly dependent on the luminophore and binder material as well as the temperature sensitivity of the materials used to make the paint. A 2nd order curve generated from calibration data is most often used.*

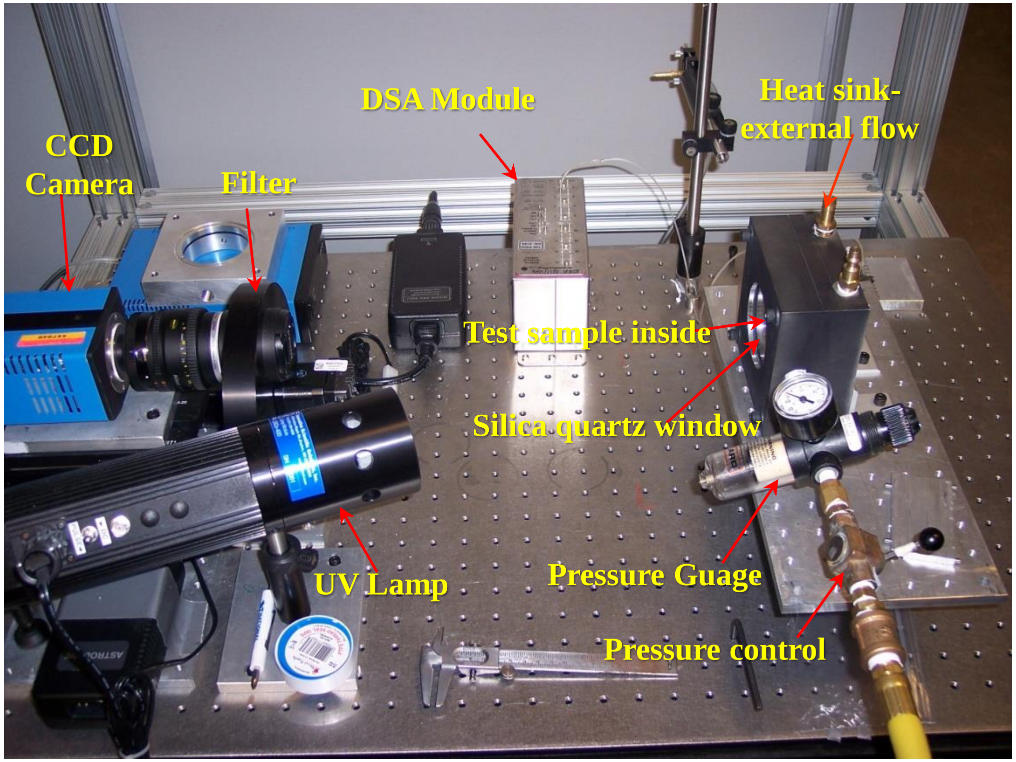






❑ Calibration setup for PSP measurements



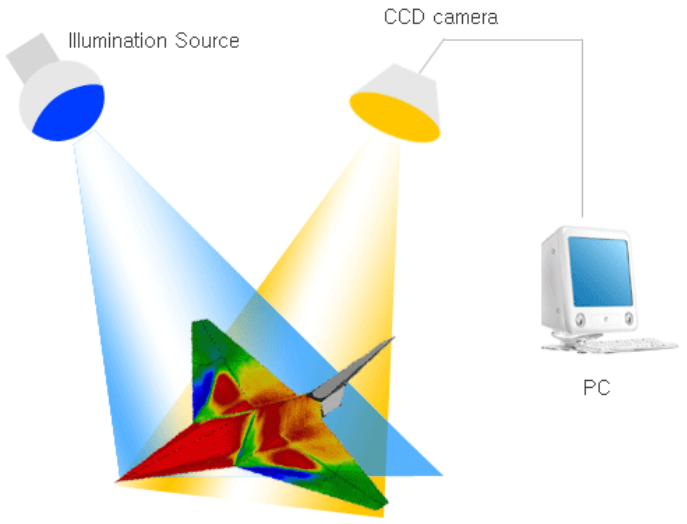


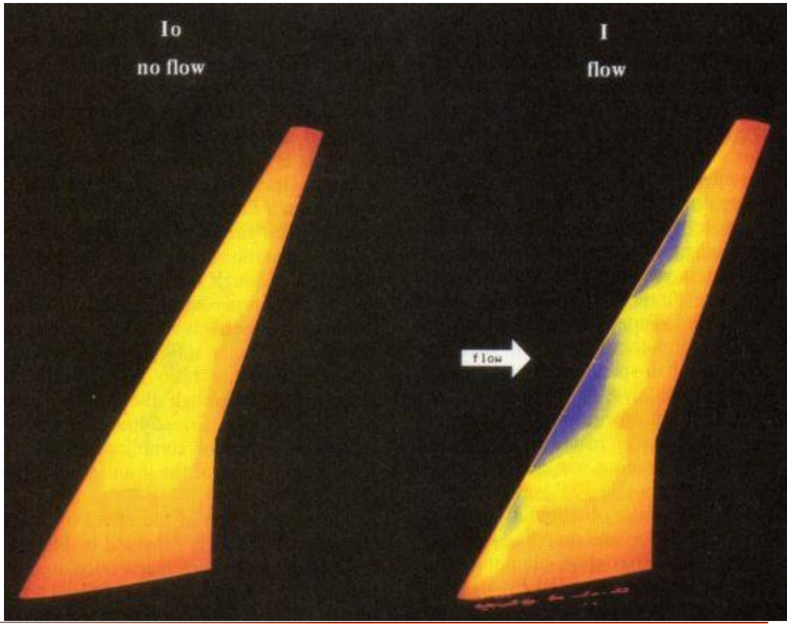
- *Pressure air pipe to control the pressure in the chamber*
- *Water recirculation to control the temperature on the sample plate*

❑ Intensity-based PSP

$$\frac{P}{P_{REF}} = A + B\frac{I_{REF}}{I}$$

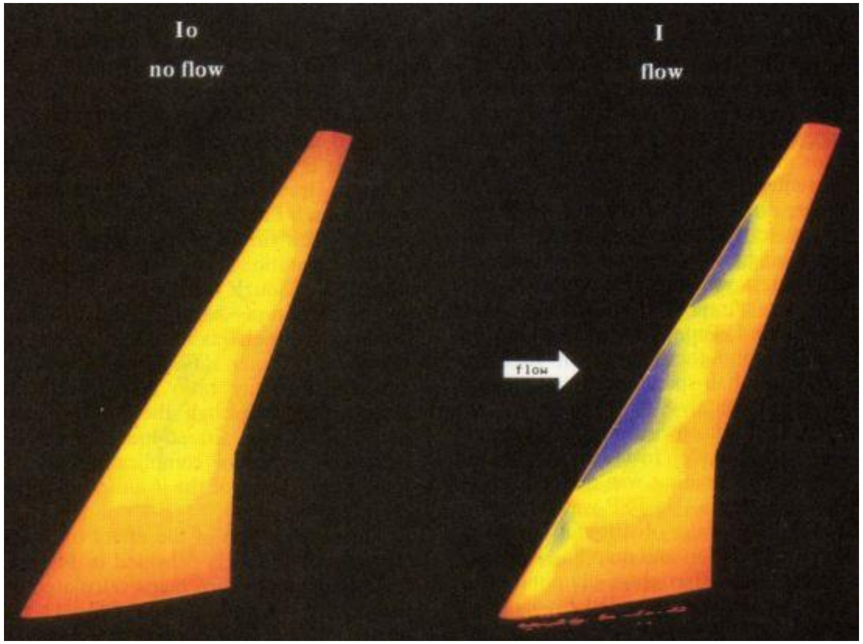
- *Requires two readings, a reference at constant pressure (wind off) and an unknown data point (wind-on)*
- *Ratio of intensities I_{REF}/I is inversely proportional to the air pressure*
- *The excitation and detection systems must be spectrally separated, (>10-6 attenuation in stop band).*
- *Simplest technique, most sensitive*
- *Very sensitive to motion between wind-off and wind-on*
- *A long period of time can elapse between reference and data.*
- *images resulting in significant changes in contamination of paint, light stability, etc. that cannot be normalized by the reference condition.*





❑ INTENSITY-BASED PSP

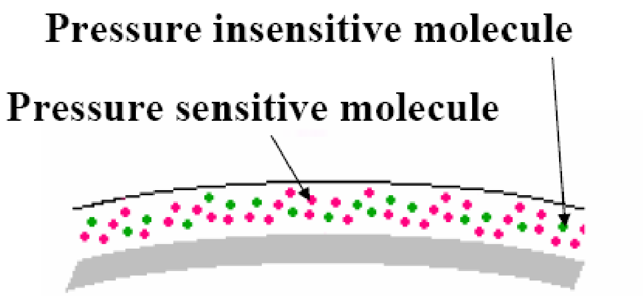
$$\frac{P}{P_{REF}} = A + B\frac{I_{REF}}{I}$$



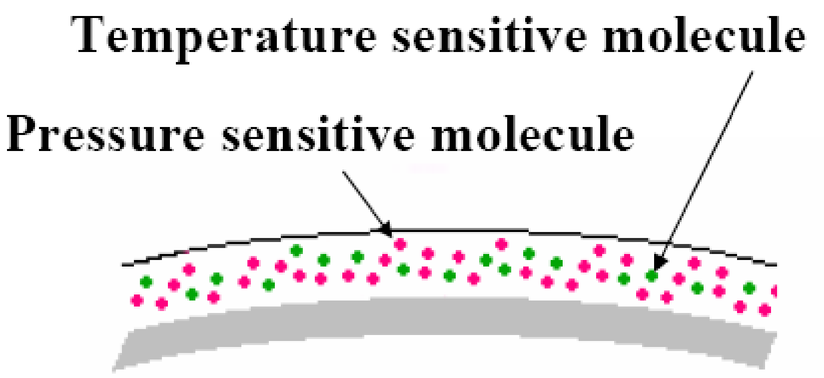
Advantages:

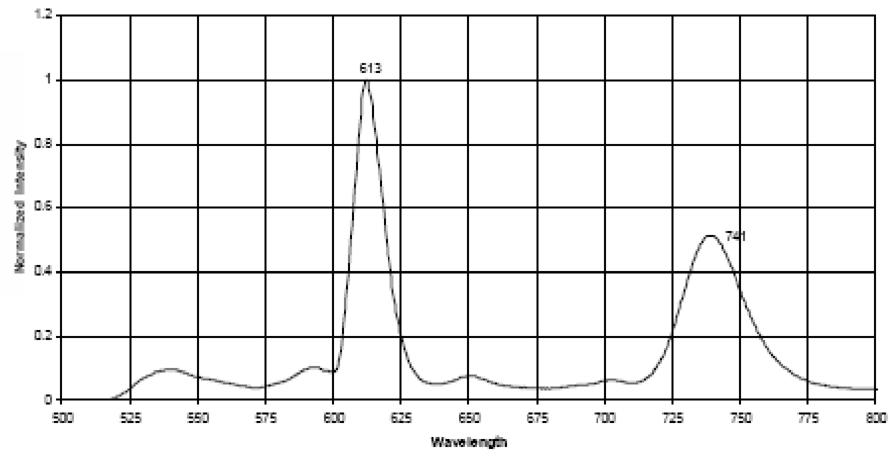
- *Eliminate wind off images and image registration problems. It works in theory*
- *In practice, due to homogeneity problems of dispersing of two kinds of molecules, it actually requires a double set of ratios, often called ratio of ratios method.*

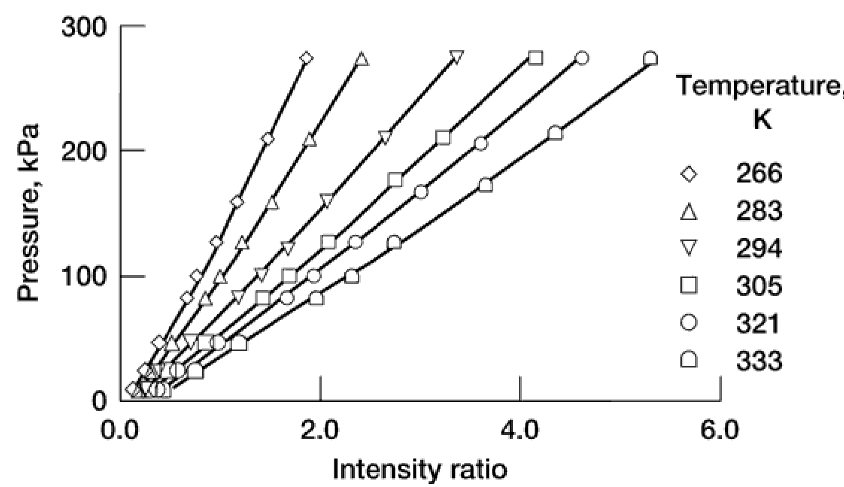
Self-Referencing paints



❑ Intensity based PSP-temperature compensation





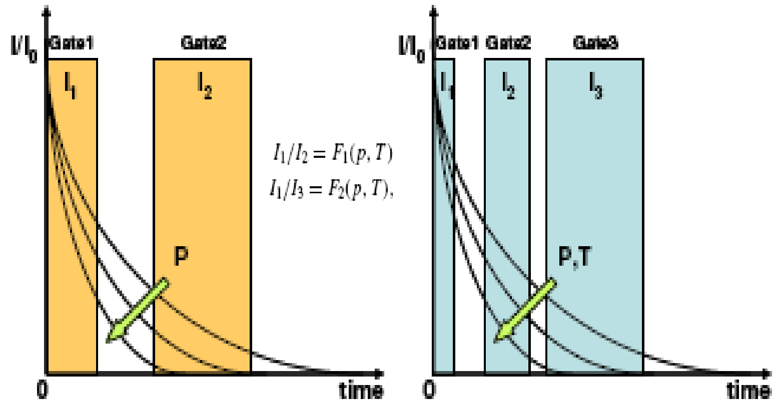


Advantages:

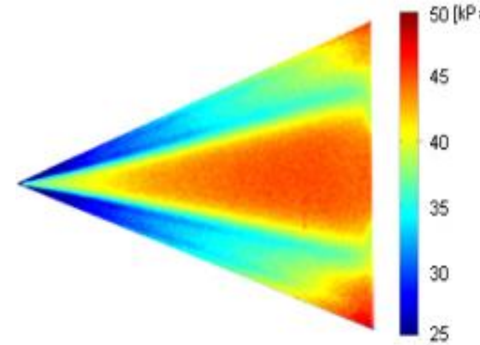
- ***Measure temperature to compensate for temperature sensitivity of PSP.***
- ***This technique requires all four images to be aligned.***

❑ LIFETIME-BASED PSP MEASUREMENTS

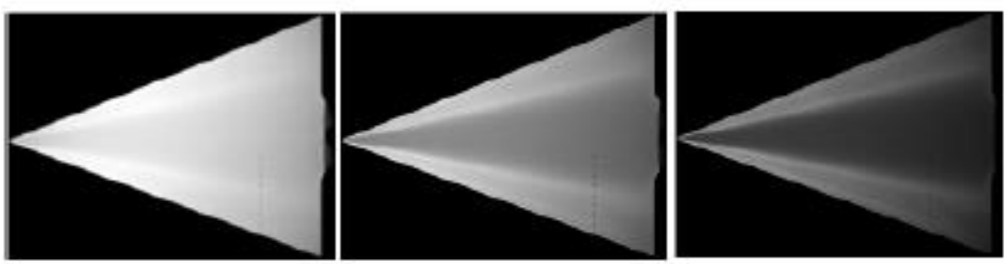
- *Easiest to do with a point measurement but can use time resolved cameras to measure lifetime decays of the probe molecules.*
- *Point measurements require a pulsed light source and detector (PMT, PD)*
- *Time resolved imaging requires a double pulse type experiment to measure the decay times (gated camera, interline transfer camera capable of multiple flash integration).*



(*a*) Two gate method (*b*) Three gate method

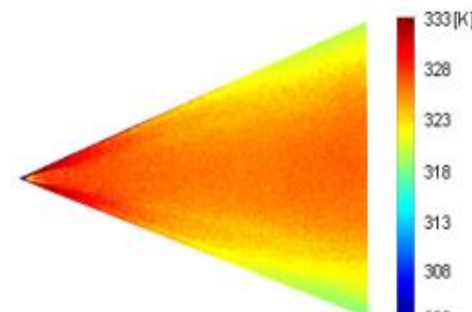


(*b*)



(*a*) I_1 (*b*) I_2 (*c*) I_3

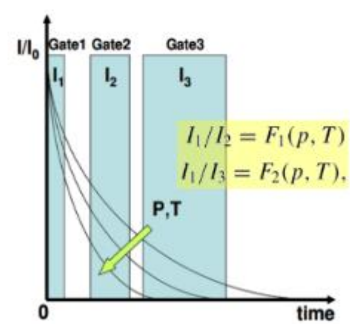
Figure 14. PSP luminescent lifetime images of (*a*) I_1, (*b*) I_2 and (*c*) I_3.



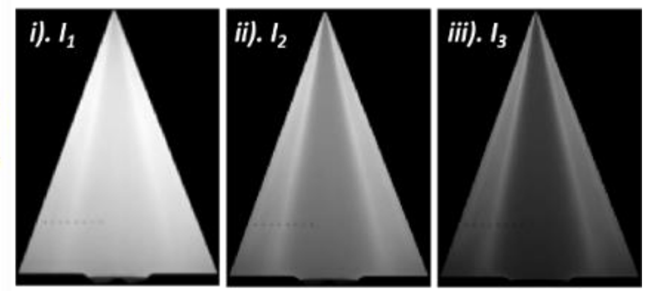
❑ Lifetime-based PSP

- ***Benefits:***
  - *Eliminates the need for aligning two or three images since the pair of (or three) images are taken at the same condition relatively close in time (micro-seconds).*
  - *Pressure and temperature distributions can be determined simultaneously.*

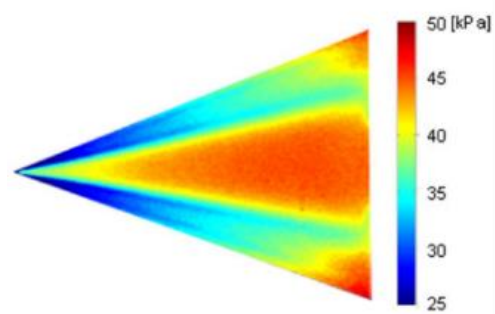
- ***Disadvantages:***
  - *Requires three gates to generate two equations of gate ratios to solve for pressure and temperature at each point (pixel).*
  - *Camera noise is much higher, especially gated intensified cameras.*
  - *Paints have tended to be more spatially noisy from lifetime differences between molecules (homogeneity problem).*



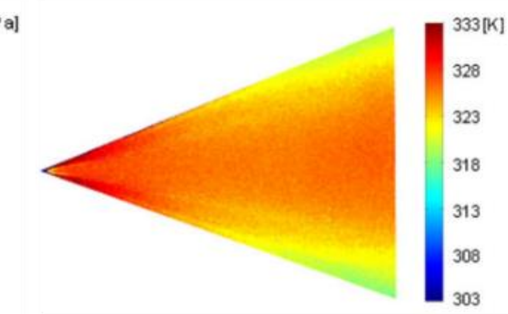
(a). Timing chart for the 3-gated lifetime-based PSP measurements



(b). Acquired raw images for the 3-gated, lifetime-based PSP measurements



(c). The measured pressure distribution over the test model

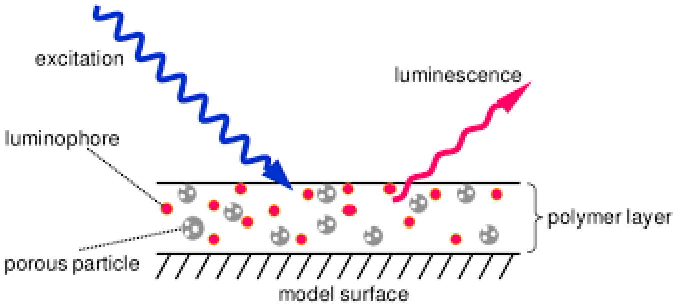


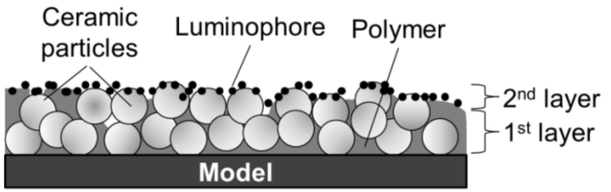
(d). The measured temperature distribution over the test model

❑ PSP/TSP COATINGS

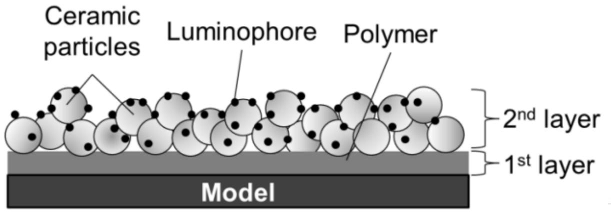
- *PSP coatings used at NASA GRC*
  - *Boeing PF2B – ruthenium bathophenanthroline in silicone rubber binder (soft*
  - *paint, chlorinated solvent)*
  - *UW (ISSI) FIB – PtTFPP in FIB copolymer binder (hard, good steady state paint)*
  - *NASA Langley – PtTFPP in FEM (very hard, very smooth finish)*
  - *ISSI sol-gel – Ru(ph2-phen) and PtTFPP on sol-gels (higher frequency response)*
  - *Anodized aluminum – dip coated Ru(ph2-phen) on anodized surface (very high freq. response)*
  - *UW PtOEP in MAX acrylic copolymer (ice paint)*

- *TSP coatings*
  - *Boeing TSP (range: 0 to 100°C, sensitivity ~ -3%/°C)*
  - *EuTTA in commercial clear or shellac (-20 to 80°C, ~ -4%/°C)*
  - *Thermographic phosphors in high temp binders (-20 to >1000°C)*





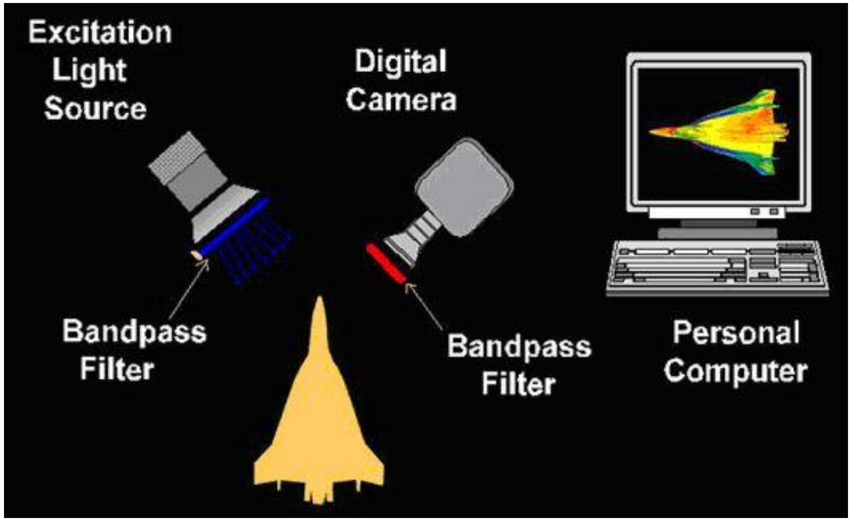
(a)

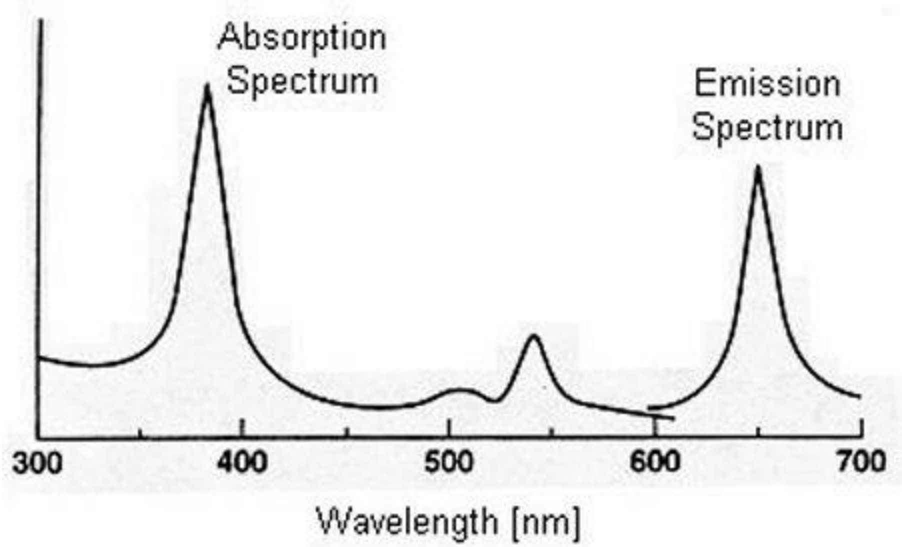


(b)

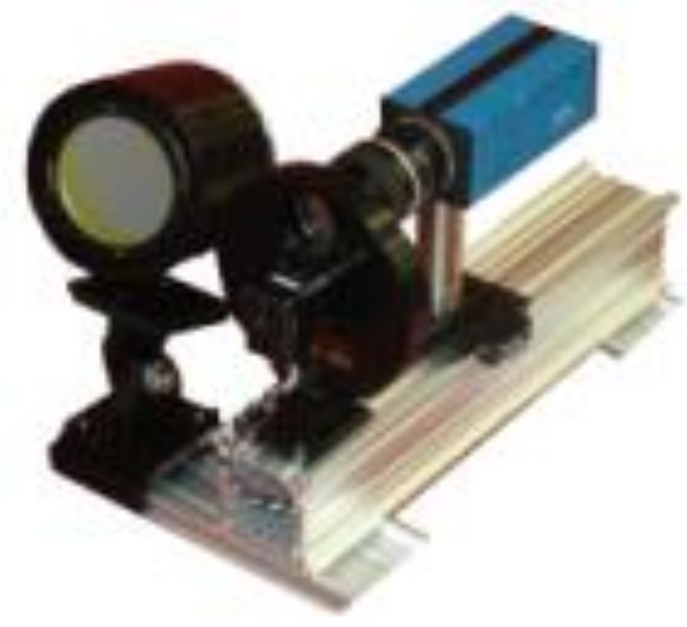
❑ Intensity based PSP

- *Excitation:*
  - *Continuous Sources: LEDs, Filtered lamps (Halogen, Xenon), Lasers*
  - *Pulsed Sources for instantaneous or periodic measurements: LEDs, Xenon, strobes/flash*
- *Detectors*
  - *Cooled Scientific grade CCD cameras (slow scan, low noise), PMT, PD*





Typical PSP absorption and emission spectra
[from McLachlan and Bell, 1995]



❑ Calibration for PSP

A-priori Calibrations

- *Paints are typically calibrated in a cell that varies pressure and temperature and has a reference measurement – this calibration is used when no on-model instrumentation exists.*

In-situ Calibration

  - *Uses standard on-model instrumentation to calibrate the paint/images in place*
  - *Compensates for temperature differences from reference data, spatial temperature differences are averaged among all the points used to generate a calibration*

- *In practice both calibrations are typically used*

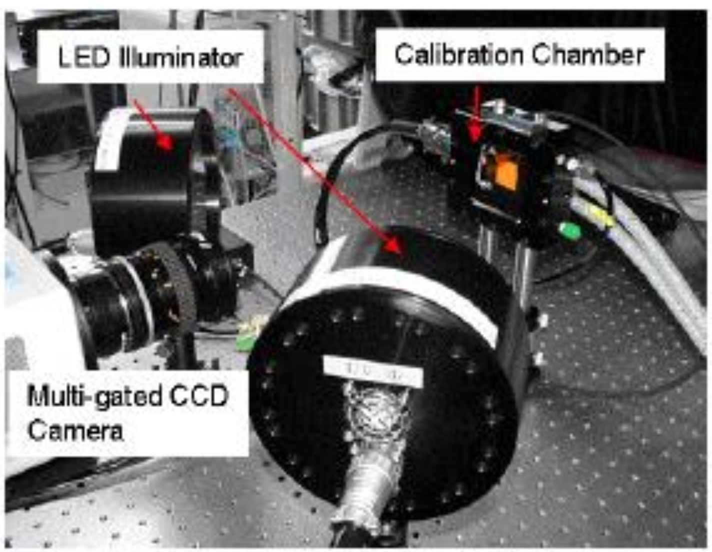
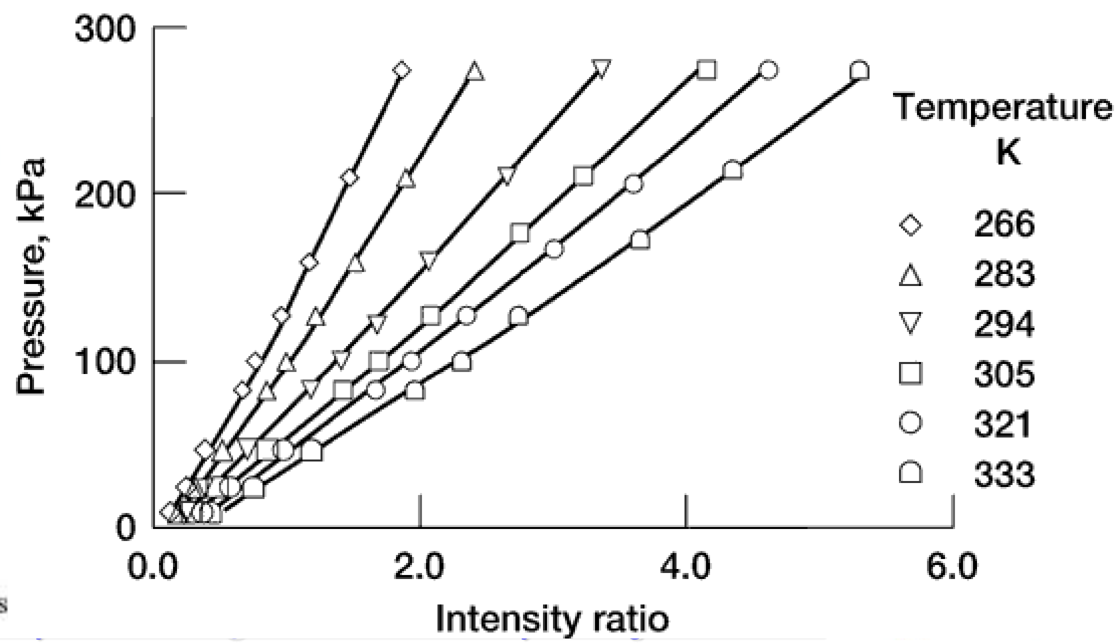
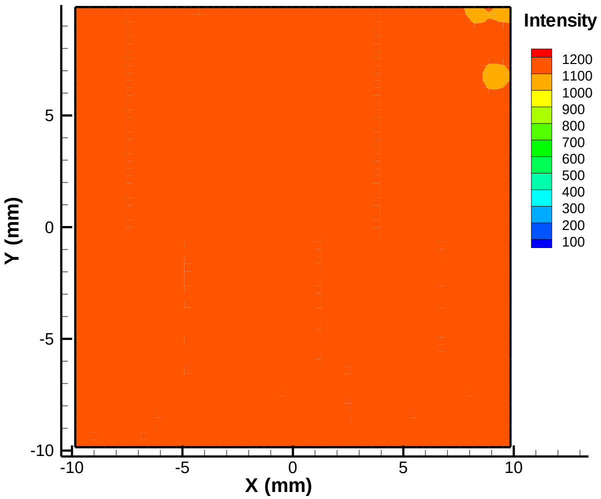


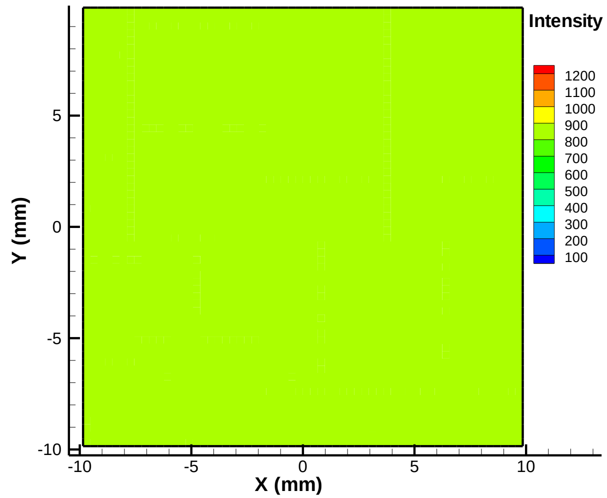
Figure 3. Photo of a multi-gated camera and LED illuminators



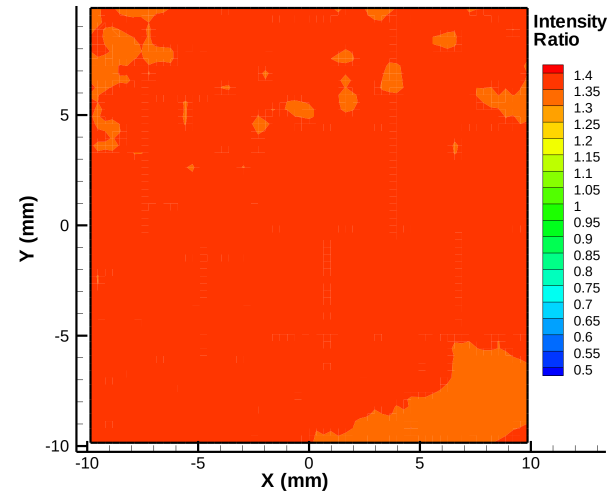
PSP calibration image process



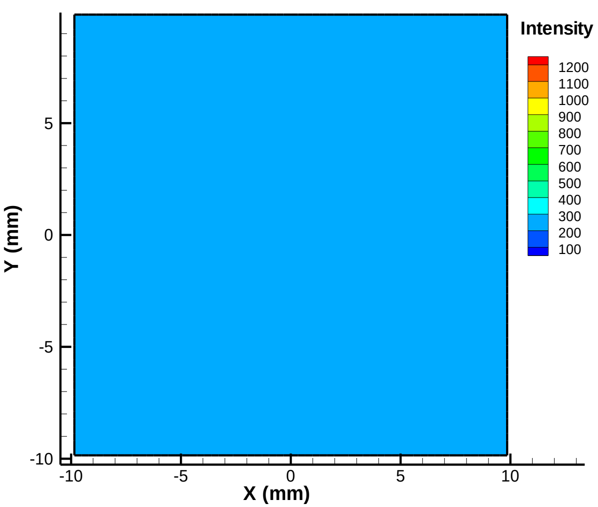
Reference Intensity: Iref



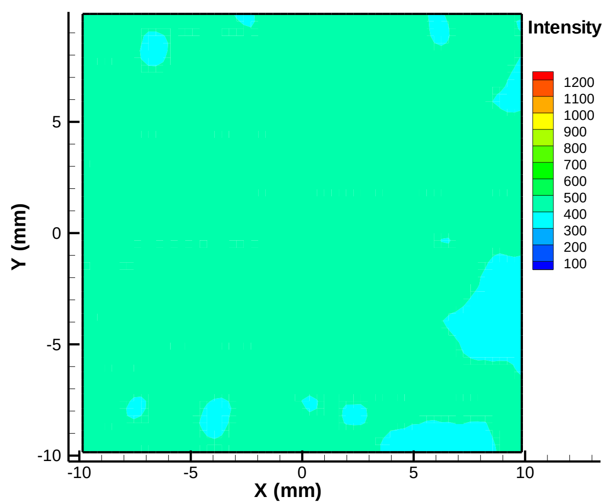
P/Pref=7.2: Intensity



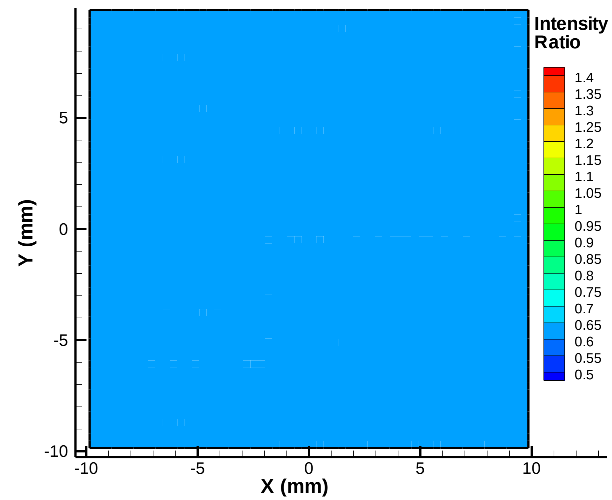
Intensity ratio: Iref/I



Reference Intensity: Iref

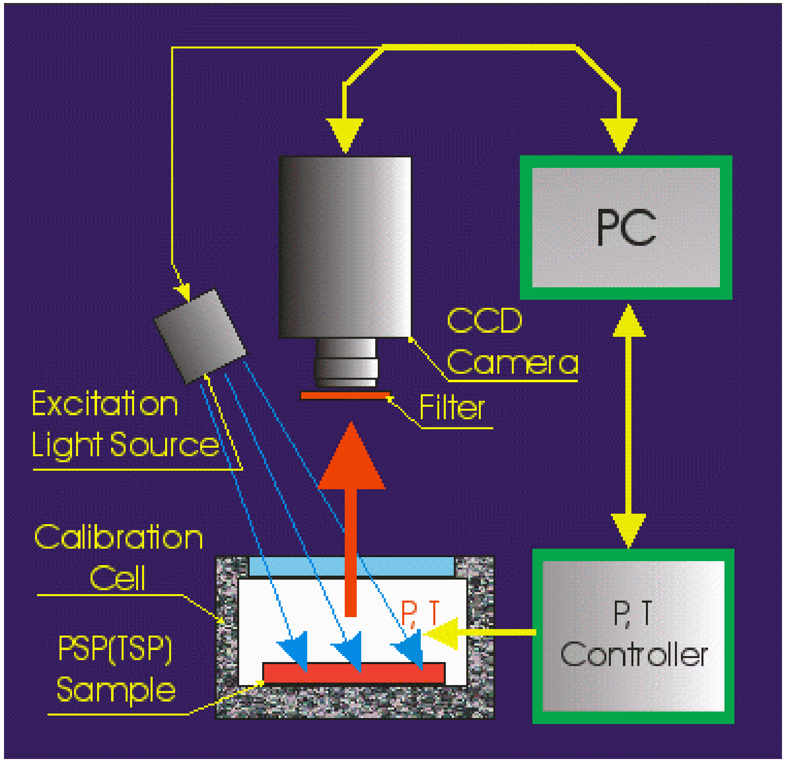


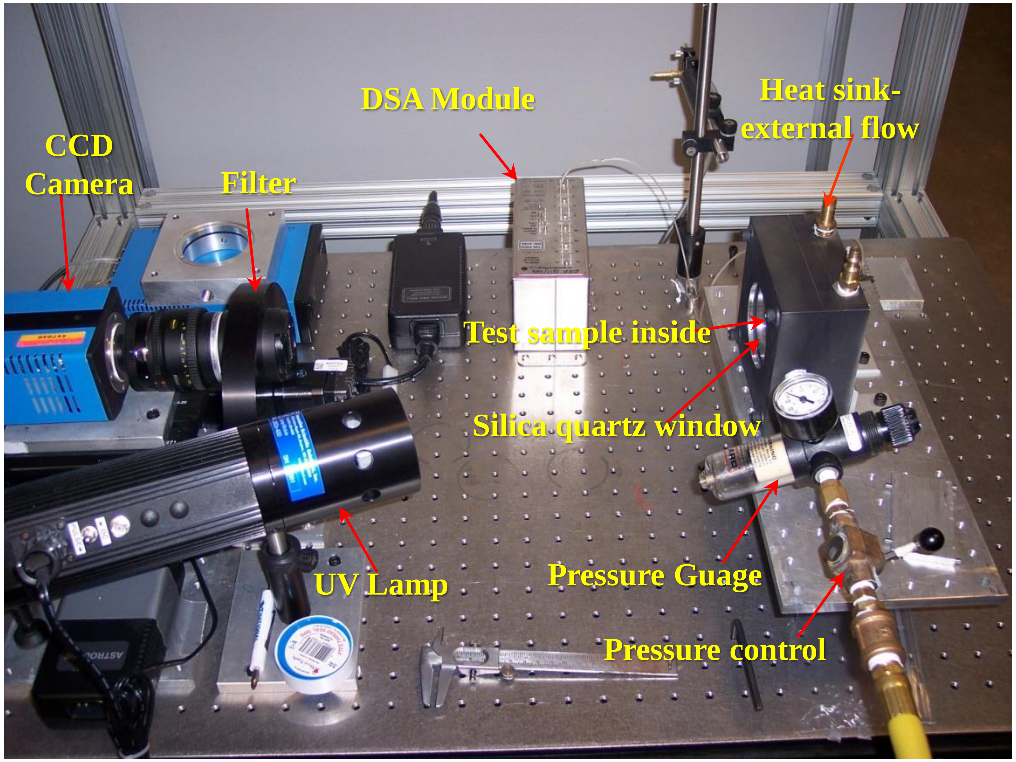
P/Pref=0.23 Intensity



Intensity ratio: Iref/I

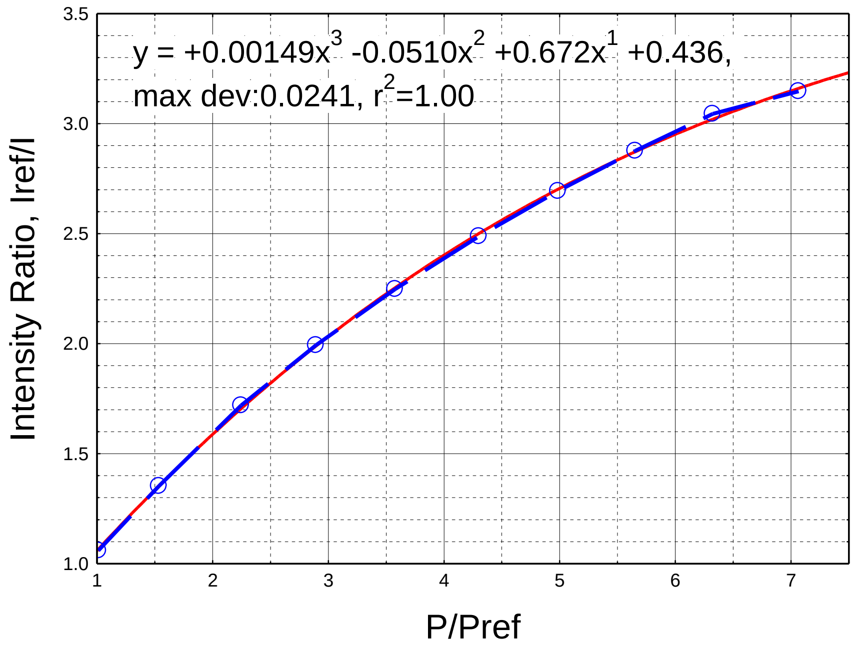
❑ Calibration setup for PSP measurements

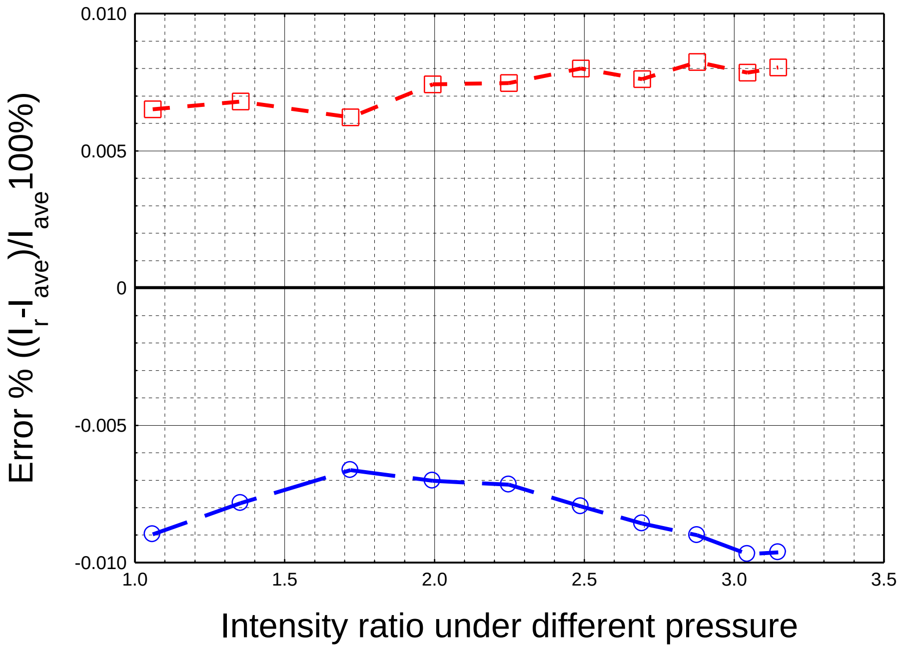




- ***Pressure air pipe to control the pressure in the chamber***
- ***Water recirculation to control the temperature on the sample plate***

❑ Calibration curve – Positive pressure

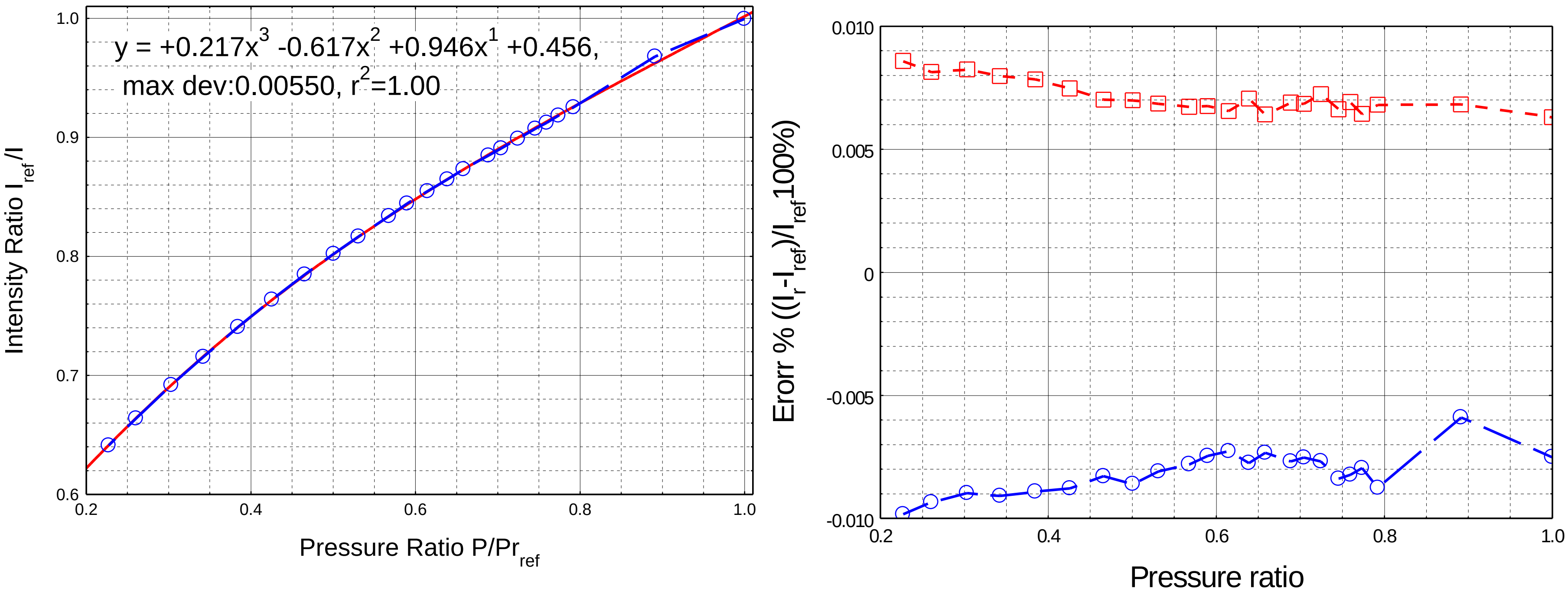




Calibration curve for the paint positive pressure and error analysis

- *Fit function: y=0.00149x^3-0.0510x^2+0.672x+0.436*
- *Error level is below 1%*

❑ Calibration curve – Vacuum pressure



Calibration curve for the PSP paint under vacuum pressure and error analysis

- Fit function: y=0.217x^3-0.617x^2+0.946x+0.456
- Error level is below 1%

❑ Uncertainty for PSP Measurements

- *Characterization of the paint and calibration errors (a-priori, in-situ calibration, photo degradation, paint contamination, paint intrusiveness, time response)*
- *Measurement system errors (detector noise, illumination spectral and temporal stability, spectral leakage)*
- *Signal analysis errors (registration from model motion and deformation, incomplete temperature compensation, self illumination, resectioning on a non-deformed grid)*
- *The major contributor is temperature uncertainty which can account for up to 90% of the total uncertainty*

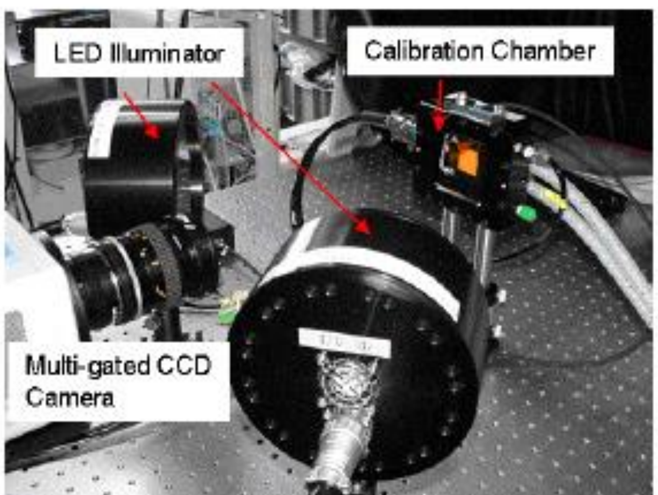
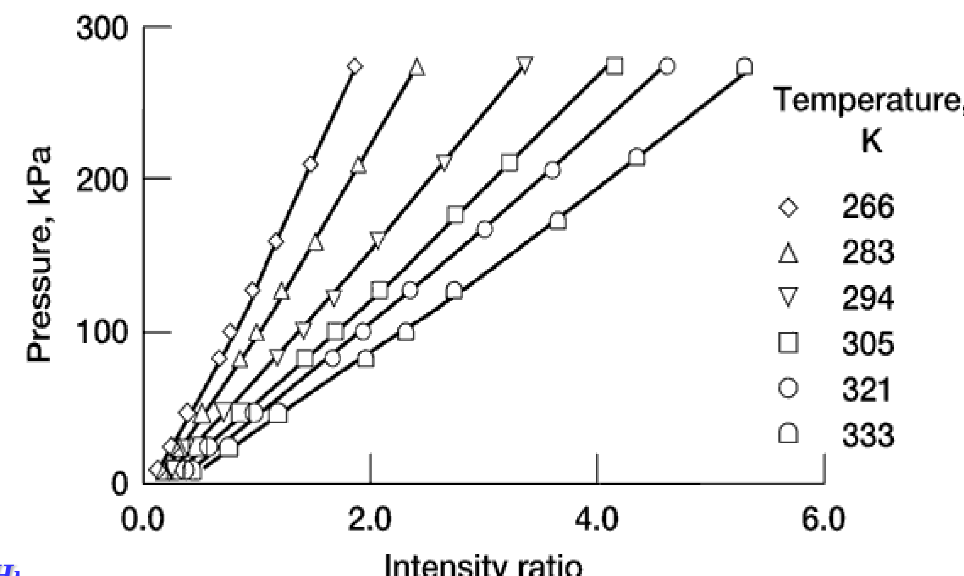


Figure 3. Photo of a multi-gated camera and LED illuminators.



❑ PSP Application Examples

National Aeronautics and Space Administration
Glenn Research Center

Rotating PSP/TSP on 22” Fan Model

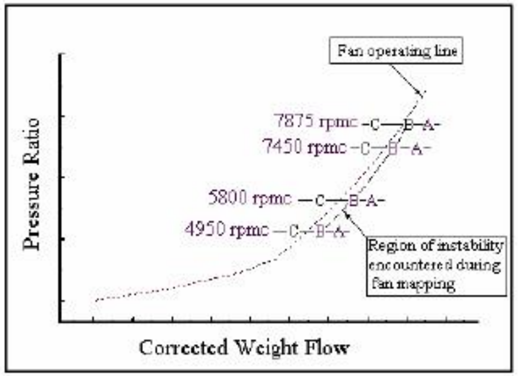
GRC 9’x15’LSWT

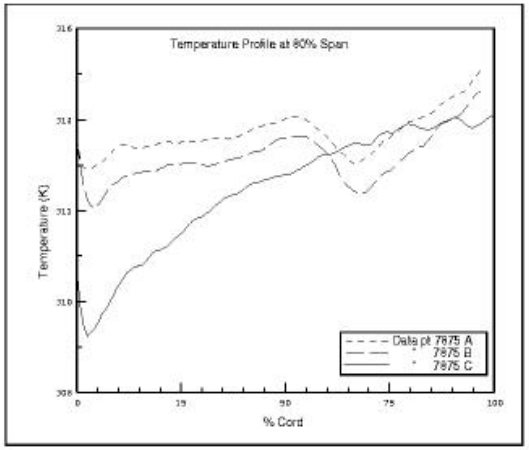
https://www.youtube.com/watch?v=T_T-njklwKE

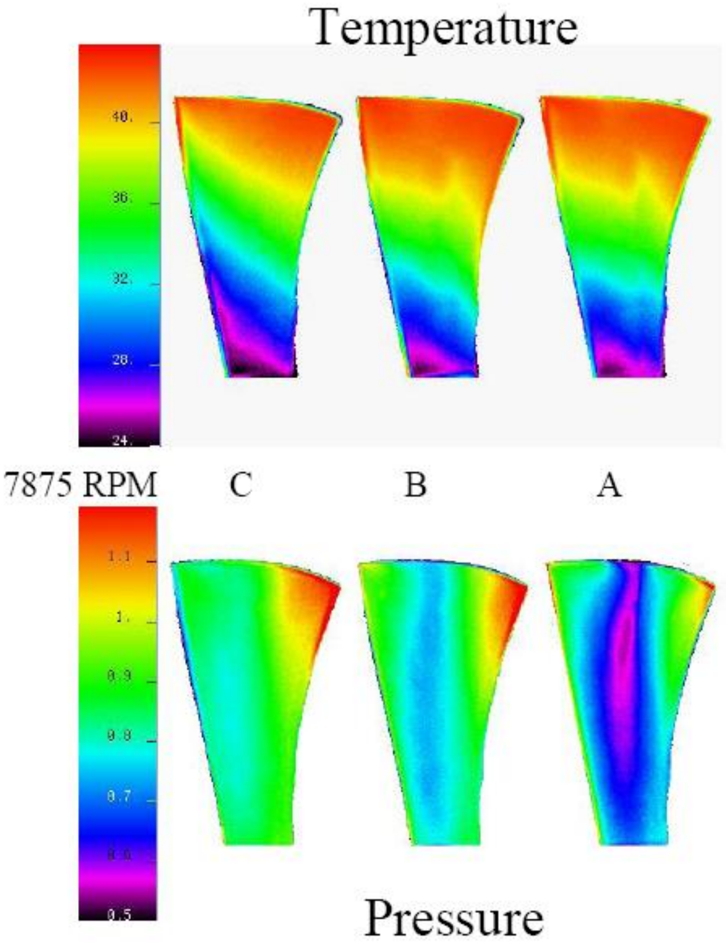
❑ PSP Application Examples

National Aeronautics and
Space Administration
Glenn Research Center

Rotating PSP/TSP



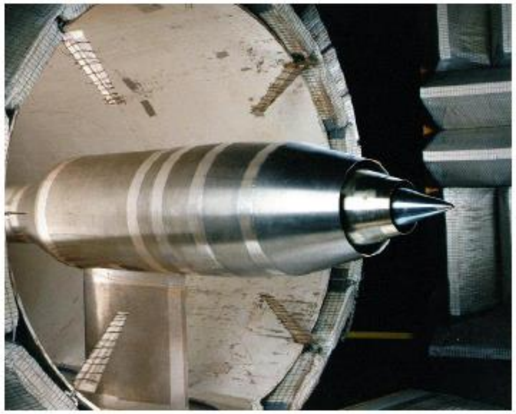


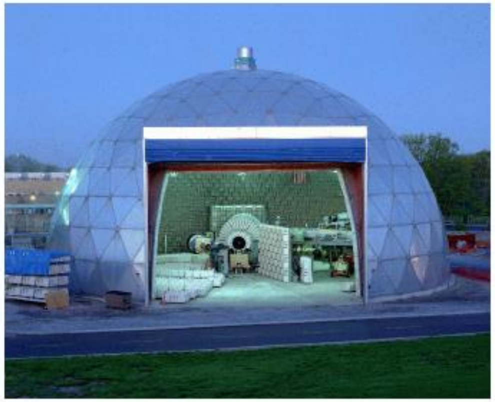


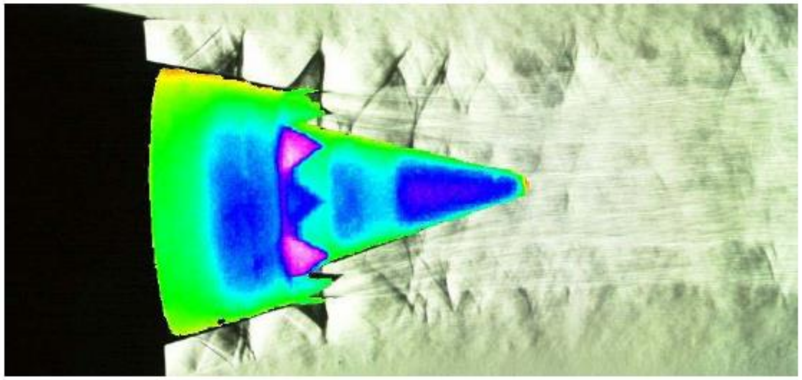
❑ PSP Application Examples

National Aeronautics and Space Administration
Glenn Research Center

Nozzle Test in APL using Lifetime PSP





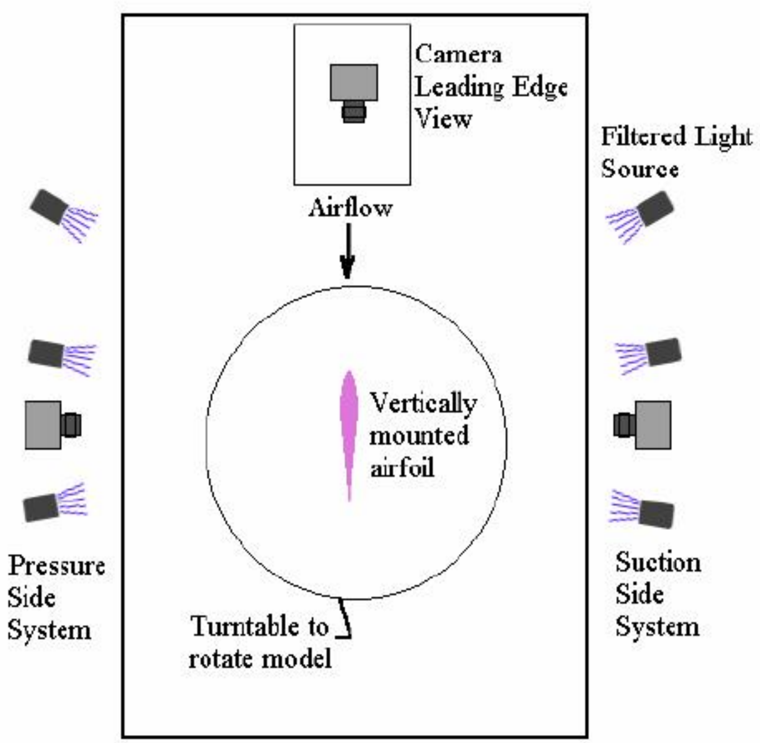


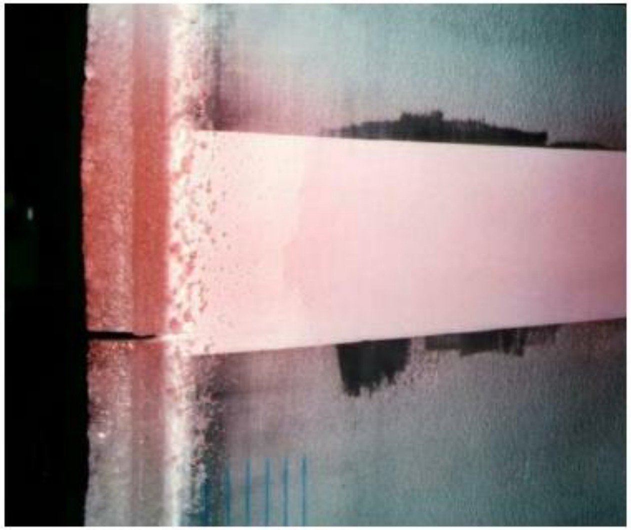
PSP Application Examples

National Aeronautics and Space Administration
Glenn Research Center

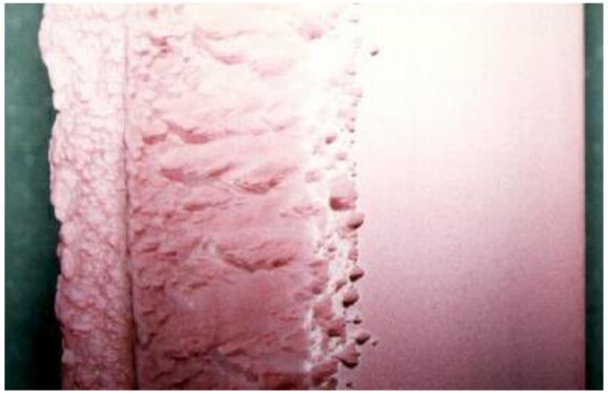
PSP on Ice

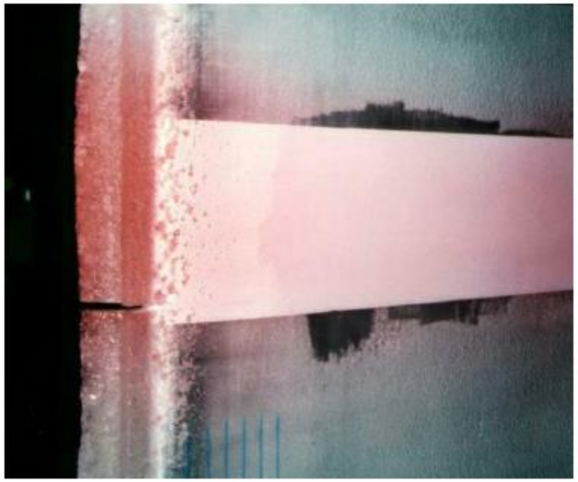
Test setup using PSP on Ice in the IRT



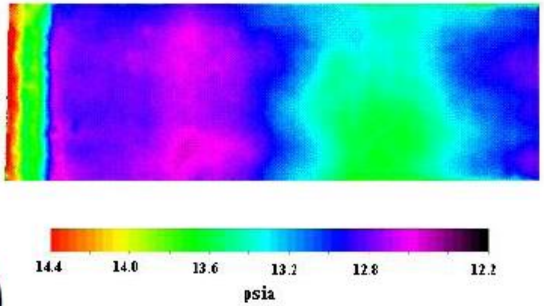


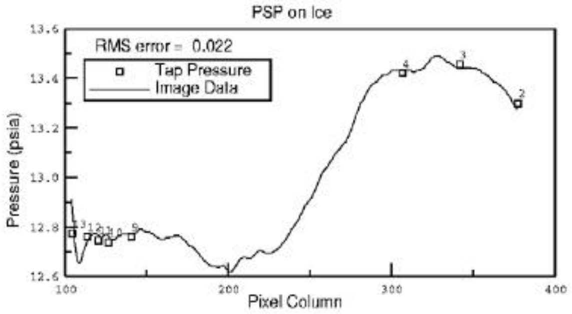
PSP Application Examples



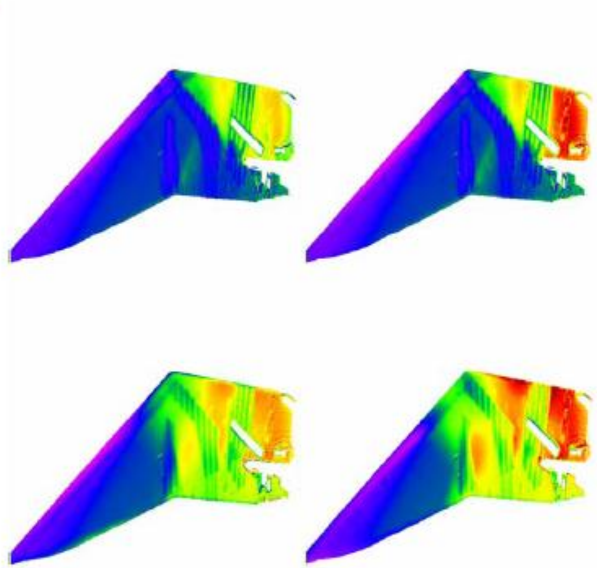


PSP on Ice in the IRT

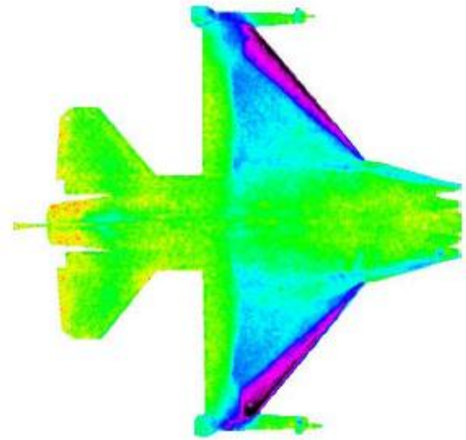




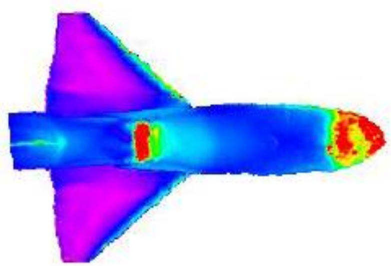
❑ PSP Application Examples



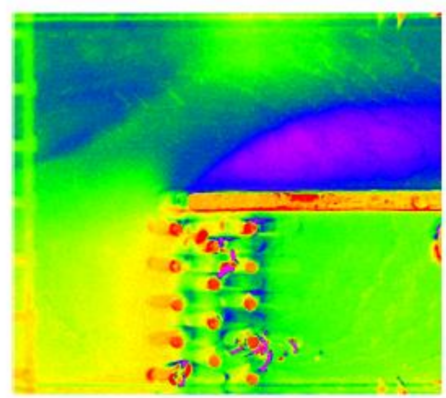
Inlet Test in the 10'X10'



Lifetime PSP F16 Test at ARC



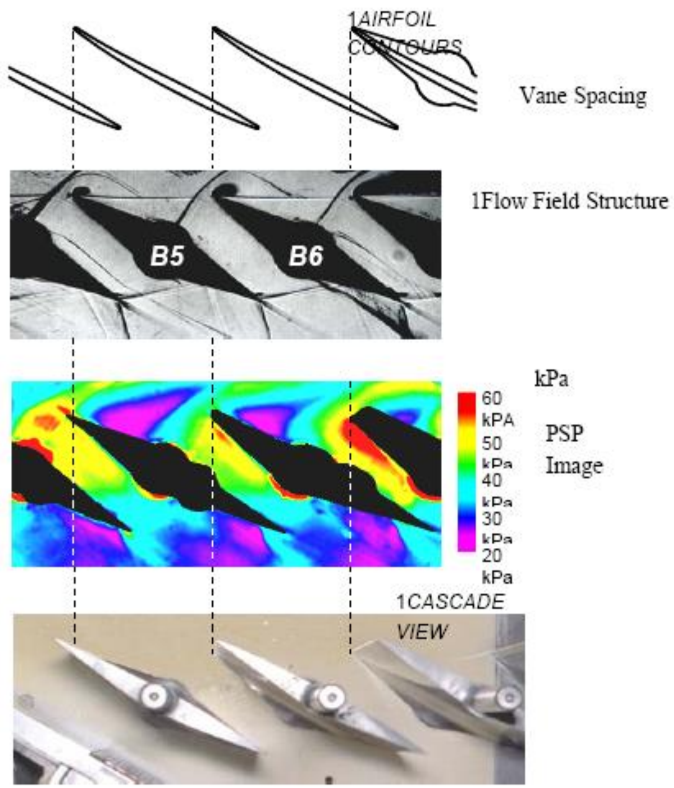
Pioneer Rocketplane in the 1'X1'



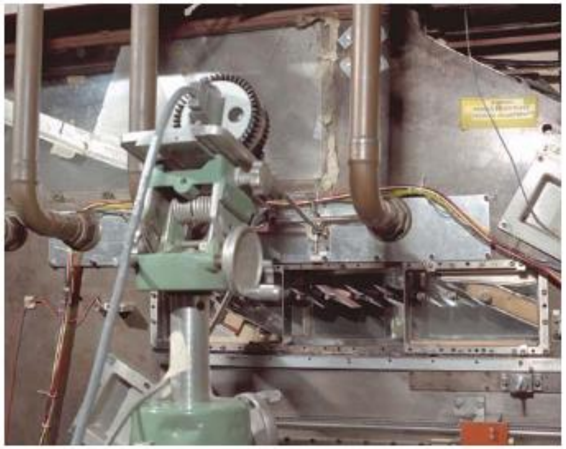
Turbine Cooling Passage simulation

❑ PSP Application Examples

Transonic Linear Cascade Facility

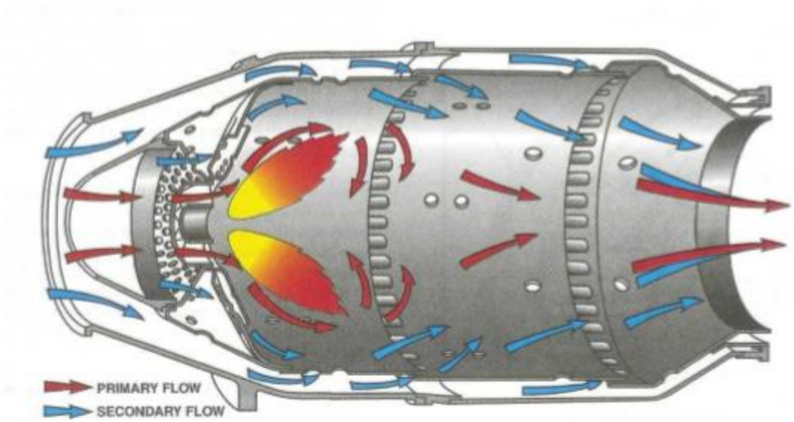


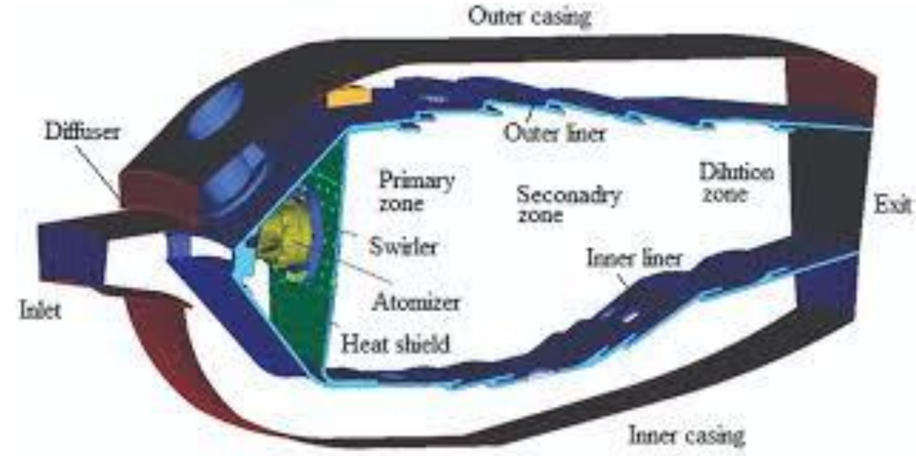
Cascade flow field for Mach number 1.3 showing relation of blades, shocks and pressure profile on the back wall.



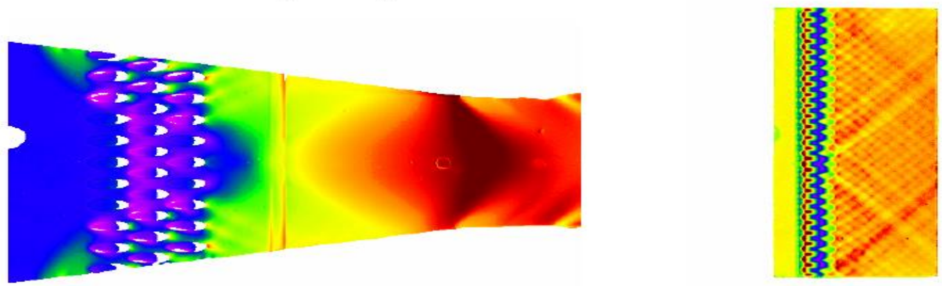
Borescope imaging of confined space surfaces

❑ PSP Application Examples

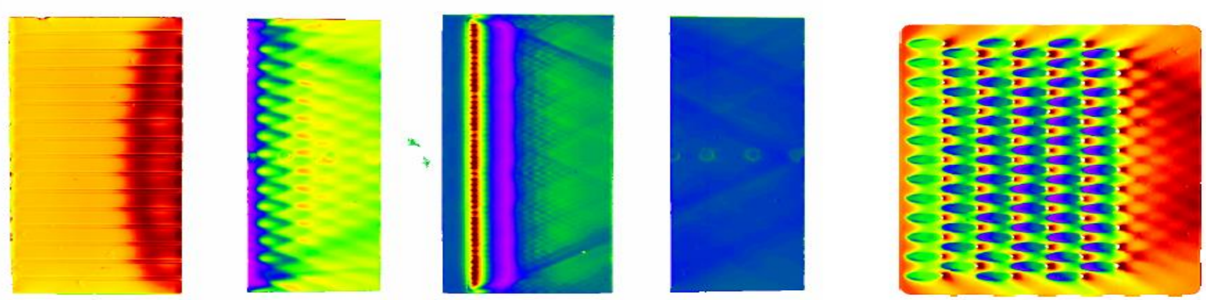




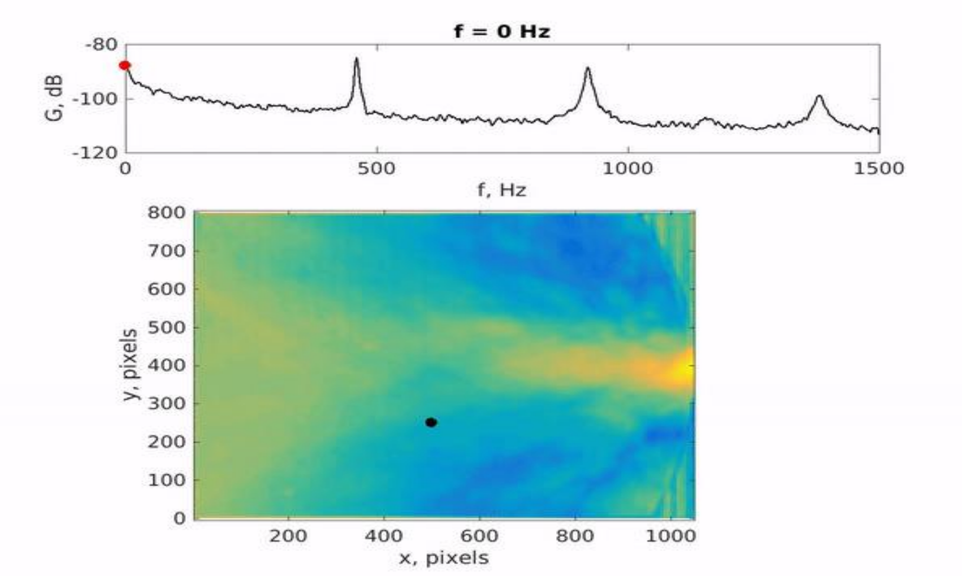
Boundary Layer Control Tests in the 1'X1'SWT

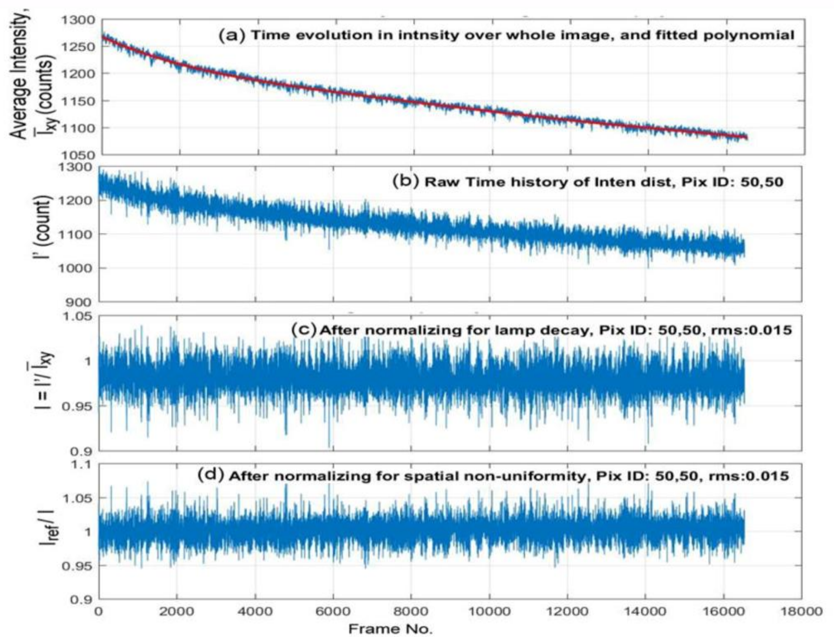


Methods using suction and blowing for boundary layer enhancement



❑ PSP Application – Unsteady pressure measurements

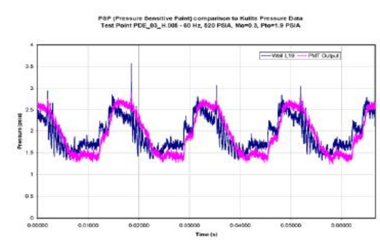




eps used to normalize PSP images. (a) Lamp intensity variation measured by a

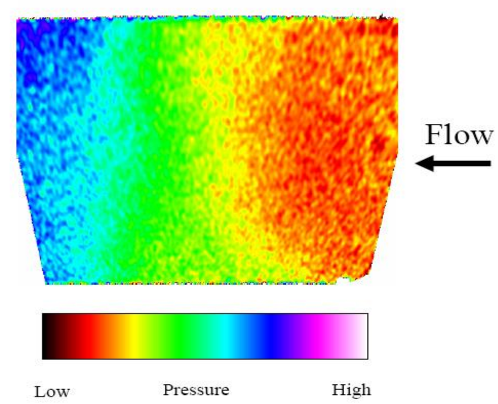
Hui H

Dynamic PSP Test: Pulse Detonation Engine Sidewall

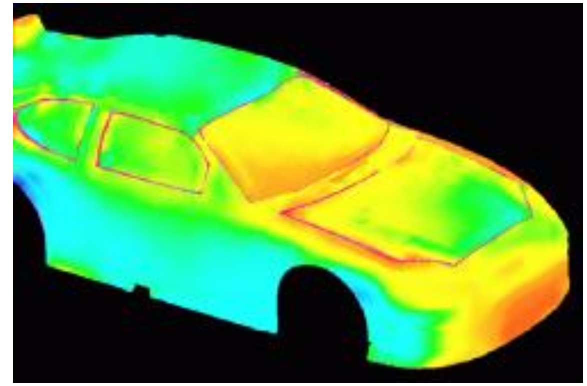


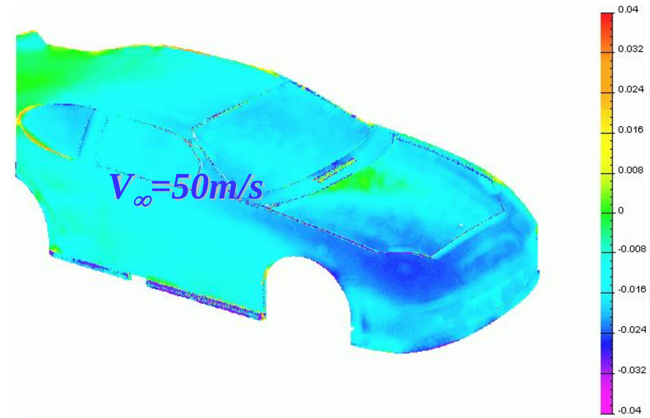
Point PSP measurements vs pressure transducer, paint has lag and ~ 1kHz response

Instantaneous image of pressure field of moving pressure wave

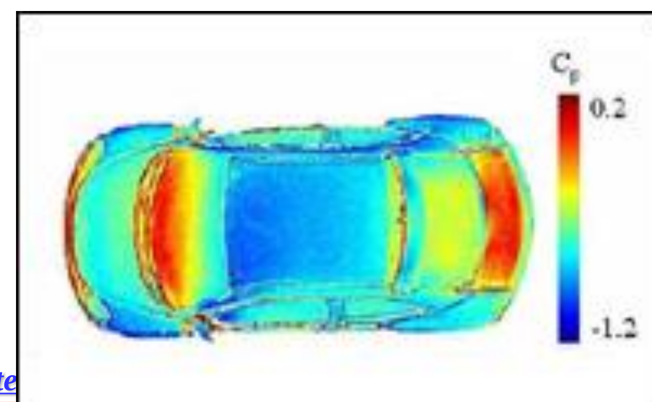


PSP Technique for Low-Speed Applications



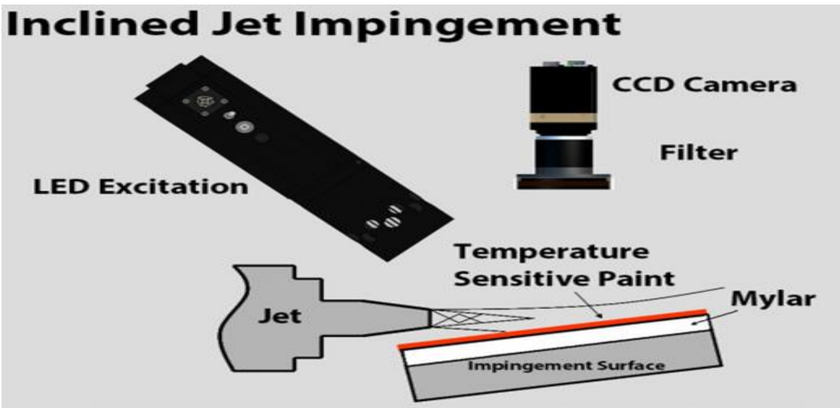


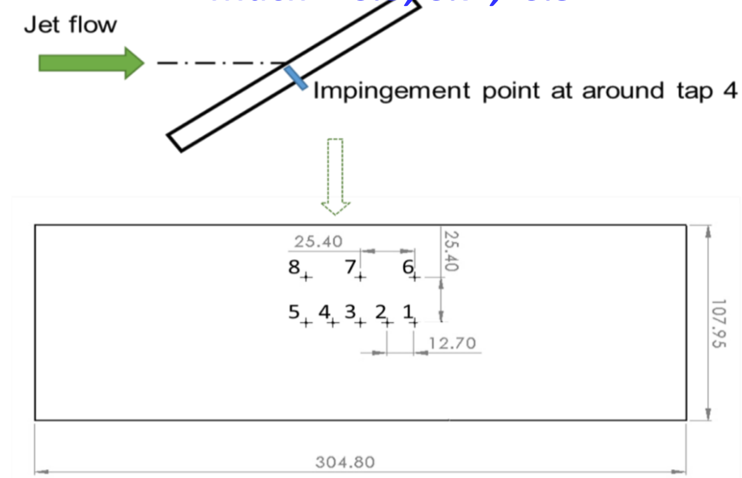
- *PSP measurements of a 2002 Ford Thunderbird*



❑ AerE545/AerE445X lab #02 – PSP Laboratory

- ***Pressure Distribution Measurements of a Transonic Impinging Jet onto a Flat Plate by using PSP technique***
    - *Mach = 0.5; 0.7 ; 0.9*





$$\frac{P_{jet}}{P_{ref}} = -0.053032170 + 0.922217040 * \frac{I_{ref} - I_b}{I_{jet} - I_b} + 0.135149696 * \left(\frac{I_{ref} - I_b}{I_{jet} - I_b}\right)^2 - 0.008236630 * \left(\frac{I_{ref} - I_b}{I_{jet} - I_b}\right)^3$$