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Timothy J. Bencic
Glenn Research Center, Cleveland, Ohio

June 2000

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APPLICATION OF PRESSURE-SENSITIVE PAINT TO ICE-ACCRETED WIND TUNNEL MODELS

Timothy Bencic
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

SUMMARY

Pressure-sensitive paint (PSP) has been successfully used to measure global surface pressures on an ice-accreted model in an icing wind tunnel at NASA Glenn Research Center. Until now, the PSP technique has been limited to use in normal wind tunnels and clear flight environments. This is the first known application of PSP directly to ice in subfreezing conditions. Several major objectives were achieved in these tests. The procedure for applying the coating in the subfreezing tunnel environment was verified. Inspection of the painted ice surface revealed that the paint did not alter the original ice shape and adhered well over the entire coated area. Several procedures were used to show that the paint responded to changes in air pressure and that a repeatable pressure-dependent calibration could be achieved on the PSP-coated surfaces. Differences in pressure measurements made simultaneously on the ice and the metal test model are not yet fully understood, and techniques to minimize or correct them are being investigated.

INTRODUCTION

When unprotected aircraft fly through clouds under freezing conditions of supercooled water droplets, the droplets impinge on exposed surfaces and ice accumulates. The accumulation of ice decreases the lift of the aircraft and can severely increase the drag. This degradation in aircraft performance can ultimately lead to catastrophic failures and even loss of life (ref. 1). To prevent these icing accidents, researchers at NASA Glenn Research Center are studying the effects of ice in the Icing Research Tunnel (IRT) (ref. 2).

Glenn Research Center's IRT, featuring a 6- by 9-ft test section, is the largest refrigerated icing tunnel in the world (ref. 3). This facility plays a significant international role in air safety through ground-based icing tests. Testing is performed at the IRT to determine the effect of ice accretion on the aerodynamic performance of aircraft components, to develop and validate ice prediction codes, and to test and verify deicing systems. To perform these tests, it is necessary to measure the pressure distribution on the iced surface.

Currently, two techniques are used to measure the effects of ice on test article performance. First, a dry wake survey probe is used to measure the drag on the iced and noniced model. The second procedure requires mounting the model on a force balance to measure the lift and drag properties during testing. Mounting and calibration of a test article on this force balance can take as long as a week. Moreover, these techniques only measure the overall performance of the test article; individual contributions from components are not known.

Pressure-sensitive paint (PSP), originally developed in the early 1990's, has become a useful tool to augment conventional pressure taps in measuring the pressure on the surface of aerodynamic components in normal wind tunnel testing (refs. 4 and 5). In the IRT, application of PSP will allow surface pressure measurements on actual ice accretions. The PSP technique offers the advantage of a nonintrusive global mapping of the surface pressure, providing unique knowledge of the pressure distribution of an iced component. Integration of the pressure on the surface would give researchers insight into the loss of performance (decreased lift and increased drag) from accumulated ice.

The extension of PSP to icing research requires study of the feasibility of making global pressure measurements in harsh icing conditions. Currently, a mold is created of an ice shape grown in the IRT to measure the influence of the ice shape on an aerodynamic surface. Only one or two molds can be created per day. A casting is made from the mold and reattached to the test article. Experiments on this modified test article are then run in a different aerodynamic wind tunnel to determine the changed performance characteristics attributable to the ice. This procedure can take as long as a year after the original IRT test is performed because of scheduling constraints and test article preparation.

The use of PSP will allow surface pressure measurements to be made on the original ice shape, producing preliminary information in less than 30 min. Measurement of the pressure over the entire test article surface would allow the aerodynamic performance to be calculated by integrating the pressures over a three-dimensional surface. A three-dimensional pressure profile could be generated by mapping multiple two-dimensional views on a three-dimensional computational grid. This technique has been used successfully by several aircraft manufacturers in traditional aerodynamic wind tunnel tests and could be used for code verification and integrated surface pressure loads, leading to safer aircraft performance in foul weather.

PRESSURE-SENSITIVE PAINT BASICS

Global techniques like the measurement of surface pressures using PSP have dramatically increased the amount of information realized during wind tunnel testing over that obtained with point measurements, which may in turn decrease aircraft design cycle time. These paints contain a luminescent compound (luminophore) or dye that is quenched by oxygen and is dispersed in an oxygen-permeable polymeric binder. The luminescence is induced by excitation of the dye with an appropriate wavelength light, typically in the ultraviolet to blue region. The emitted intensity or brightness of the PSP is inversely proportional to the partial pressure of oxygen. The relationship between the intensity of the luminescence and the partial pressure of oxygen or air can be expressed by

$$\frac{P}{P_{REF}} = A\left[\frac{I_{REF}}{I}\right]^2 + B\left[\frac{I_{REF}}{I}\right] + C$$

where I_{REF} is "wind-off" intensity at constant pressure P_{REF}; I is "wind-on" intensity at pressure P; and A, B, and C coefficients are determined experimentally.

The intensity technique requires that two data points, I_{REF} and I, be acquired to determine the unknown pressure P. (This technique holds true whether the acquired intensity data is from a single point detector or two-dimensional intensities from a charge-coupled device (CCD) camera. Since all the data presented in this paper were acquired with a cooled CCD camera, the data points will be referred to as images.) The reference image is acquired at a constant known pressure, usually at ambient conditions, and is commonly referred to as the wind-off image. The image of the unknown pressure is referred to as the wind-on image. These images must be spatially aligned to subpixel accuracy for a true representation of the surface pressure before applying the equation above (ref. 6). The image ratio of wind-off by wind-on corrects for the nonuniform application of the paint and the illumination light field.

TECHNICAL APPROACH

The method of applying PSP to ice-accreted aerodynamic surfaces has been structured into a multiphase developmental process. The steps of this process include the following (current development has reached steps 4 and 5):

1. Develop a paint that cures and adheres to an ice surface at subfreezing temperatures and responds to changes in air pressure. The paint formulation was developed by the University of Washington through a grant from NASA.
2. Test application procedures and the durability of the coating on actual ice accretions. Evaluate the coating for uniformity, adhesion, and ice shape retention.
3. Record the luminescent intensity of the PSP with a digital camera during testing in the IRT to confirm that the paint responds to changing pressures. Utilize conventional point pressure measurements to determine the pressure over the entire painted area of the test article (in situ calibration).
4. Develop repeatable calibration information for the paint from data gathered in a pressure chamber located in a cold-room environment (a priori calibration).
5. Investigate alternate data acquisition methods to minimize errors for measurements made on iced and noniced test articles.

6. Record multiple image views and create a three-dimensional pressure mapping to calculate aerodynamic loads.
7. Develop the PSP technique into a useful IRT tool.

EXPERIMENTAL PROCEDURE

The investigation was carried out in three parts. The University of Washington developed the PSP formulation used in the tests. This PSP utilizes platinum octaethyl porphyrin (PtOEP) solution as the pressure-sensing probe in a silicone polycarbonate copolymer binder. An initial feasibility test was carried out to determine if the PSP technique could be applied in the environmental conditions of the IRT without altering the ice accretion produced on a test model. The second test focused on the technique for acquiring surface pressure data on a model in the test section and on the operational procedures needed to integrate this technique into the standard operation of the IRT. The third test was to determine a reliable calibration for measuring the surface pressures on an iced model where no on-model instrumentation is available for an in situ calibration.

Feasibility Test

The initial feasibility test involved verification of the paint application procedures, as described in step 2 in the Technical Approach section above. It was first necessary to know whether it was possible to apply PSP to an actual ice sample. The test involved the evaluation of procedures for paint application, curing times, and ice surface retention for applying PSP to ice at subfreezing temperatures. Once the accretions were produced in the IRT test section, the samples were moved to an adjacent cold room for the PSP application.

Three different samples of ice were accumulated on lengths of aerodynamic tubing attached to the ceiling of the IRT test section. The samples consisted of glaze ice (formed at a tunnel temperature of –0.7 °C), mixed ice (–8.2 °C), and rime ice (–15.4 °C). These three types of ice have significantly different physical and optical properties, and each had to be evaluated for compatibility with the PSP technique. Each sample was removed from the wind tunnel and stored in the IRT cold room at a temperature of –8 °C. The PSP was cooled to the cold room temperature and applied to the samples using an automotive spray gun in a temporary spray chamber, which exhausted the fumes from the cold room to the atmosphere. Cold nitrogen was used to provide the atomization pressure for the spray gun. The paint curing time was nearly instantaneous, but the sample was not disturbed for approximately 3 min. Figure 1 shows a painted rime ice sample on an airfoil section. Visual inspections of the paint showed that it provided a uniform coating that preserved the detailed structure of the mixed and rime ice samples.

The PSP technique worked well for the rime and mixed ice shapes but required modification for the glaze shapes. The paint was applied to the glaze ice sample immediately after the sample was moved from the test section to the cold room area. As seen in figure 2, the paint surface shows significant pooling. This was caused by the amount of liquid water in the glaze, which was produced at temperatures close to the freezing point. Allowing the sample to remain in the lower cold room temperature for several minutes before application of the paint solved this problem. It was concluded that the tunnel temperature would have to be lowered to use the technique for glaze ice, so that the remaining liquid water would solidify prior to PSP application. This procedure will not alter the ice shape, but it will require that the wind-off and wind-on data be taken at lower temperatures.

After paint application in the cold room, the luminescent response of the paint was recorded with a CCD camera. The camera was fitted with a longpass (>600 nm) filter mounted to the front of the lens. A bandpass-filtered halogen lamp (475 > x > 530 nm) was used for excitation of the PSP. Reference images of the coated ice-accreted strut were acquired at atmospheric pressure in the cold room. A data image was then acquired with a low-pressure nitrogen (N_2) jet impinging on the painted ice. The nitrogen source helps verify that the PSP is responding to changes by simulating a change in air pressure. Nitrogen is used often because it displaces the local oxygen and, since no oxygen quenching occurs, gives the appearance of a low-pressure region of air. Figure 3 shows the reference image of rime ice from figure 1 taken in the cold room with the tube for introducing the N_2. Figure 4 shows an intensity ratio image (air image versus nitrogen jet image) of the nitrogen jet impinging on the ice and spilling onto the aluminum airfoil section. The success of the application and response test yielded optimism that the technique was feasible.

Wind Tunnel Test

The next phase of testing performed in the IRT covered steps 2 and 3 listed above in Technical Approach using two GLC 305 airfoils mounted vertically in the test section. Two different models were used because these tests had to be run concurrently with the ongoing scaling comparison tests in the IRT. A 914-mm-chord airfoil section was used initially for this test. A section of the airfoil was painted with a white background prior to the PSP test to provide diffuse scattering. Registration marks were applied on both sides and on the leading edge of the airfoil using a black paint marker. The initial test involved only one ice shape to determine the feasibility of making the PSP measurements on the airfoil. Figure 5 shows the setup of the PSP acquisition equipment around the test section (ref. 7). Two CCD cameras were used to view the pressure and suction sides of the airfoil, and a third CCD camera was used to view the leading edge. The airfoil was illuminated from the sides with six filtered lamps, which provided uniform illumination from the leading to the trailing edges. One advantage of testing in the IRT is that there is ample optical access for making PSP measurements.

The testing sequence used in the PSP tests was designed to minimize the impact on the normal operating procedures of the facility. First, the wind tunnel was started and brought to the desired temperature and velocity. Once the conditions had stabilized, a spray was initiated for a given droplet size and spray time (this combination determines the amount of liquid water that impinges into the test model). When the spraying was complete, the tunnel velocity was set to zero to document the ice formation (in the standard IRT test, the typical sequence usually calls for the ice to be cleaned from the model to get it ready for the next spray condition, but a different procedure was followed for the PSP test). After documentation of the ice shape, the PSP was applied to the ice and airfoil using the same application technique described in the feasibility test. Then the test section was closed, and all six excitation sources were turned on. The three cameras viewing the wing acquired wind-off images. The images were taken simultaneously from the three views at a series of model angles of attack ranging from –0.4° to 3.6°. Once the reference images were acquired, the tunnel was once again brought to the same velocity and temperature for which the ice shape was created.

The entire process of painting the model and acquiring the reference images took less than a quarter of an hour. The tunnel drive fan was kept on idle after the paint was applied to help keep the temperature constant in the facility. The procedure of using a very low wind tunnel wind velocity as a pseudo wind-off reference condition has been used successfully at NASA Ames (ref. 8). Wind-on images were acquired for the same model attitudes used for the reference images. The tunnel was then shut down, the ice and PSP were removed from the airfoil, and normal testing resumed.

Initial data reduction of the image data showed a significant problem with this test. The six filtered lamps mounted to excite the painted surface caused a considerable error that became evident in the intensity ratio images. The PSP-coated ice portion of the model had significantly higher ratios than expected. This was attributed to forward scattering of the light through the ice from the opposite side. Normally, the excitation light impinges on the coated surface and scatters back to the CCD camera. Because of their translucent nature, however, the iced surfaces allow a significant amount of forward-scattered light to overpower the back-scattered signal from the side of interest.

A second attempt to measure the surface pressures on a smaller scale airfoil was made the following day. Figure 6 shows a 457-mm-chord wing section with an ice accretion created by an air velocity of 103 m/s at a total temperature of –8.0 °C with the airfoil at a –0.4° angle of attack. The airfoil was subjected for 5.4 min to a PSP cloud with a liquid water content of 0.9 g/m^3 and a median volumetric droplet diameter of 28 mm. A tracing of the resultant ice shape on the leading edge of the airfoil is shown in figure 7. Application of the PSP to the iced model using a spray gun and cooled N_2 took less than 10 min this time, including the time for the coating to cure.

The procedure for acquiring the images was changed during this test to eliminate the problems from the prior test. The wind-off images were acquired in a sequential pattern corresponding to the switching of the excitation sources. Initially, the pressure-side images were taken with the three filtered lamps on the pressure side turned on and the suction-side filtered lamps turned off. Similarly, the suction-side images were then acquired with their associated sources turned on and the pressure-side sources turned off. Lastly, the leading edge images were taken with only the upstream lamps on, illuminating the ice shape from the front. The wind tunnel was restarted to the original velocity and temperature from the beginning of the test, and data were taken in the same sequence as the wind-off data were acquired.

One drawback to sequencing the illumination sources is the requirement for repeatability and stability of the illumination field. Typically, the illumination sources are allowed to stabilize for 10 to 15 min before any images are acquired. Switching of the light sources will eventually require a remotely operated shutter that would block the light while allowing the sources to operate at a stable condition.

The two-dimensional pressure data acquired during the second test from the suction side of the airfoil at 3.6° are shown in figure 8. The image was calibrated using the active pressure ports on the wing to generate an in situ calibration. Comparisons of the pressure measurements from the PSP with the conventional pressure taps across the airfoil are shown in figure 9. The static ports on the model are typically covered prior to an icing run to prevent the taps from becoming plugged with ice during the spray. During this test, low-pressure purge air was forced through the ports to prevent moisture from getting into the taps. There is a very good agreement between both of these measurement systems on the aluminum airfoil shown. A total root-mean-square pressure coefficient error of 0.075 was calculated between the measured static ports and the PSP. However, the calibration of the paint on ice and aluminum shows a difference that can be seen on the ice at the leading edge (left side) of the airfoil in figure 8. The use of pressure taps during wet subfreezing testing is not recommended and often results in unreliable pressure data, even when actions are taken to keep water out of the taps. For this reason, a reliable calibration of the PSP that does not rely on model instrumentation is needed.

Calibration Cell Tests

An experiment was performed to develop a repeatable calibration, often referred to as a priori calibration, that does not rely on model instrumentation. For this series of tests, sample ice accretions were formed on small aerodynamic tube sections similar to those used in the feasibility study. The airfoils were painted white and registration marks were added prior to creating the ice accretions. The accreted ice samples of the airfoil sections were painted with PSP and placed in a calibration cell in the cold room. The 168-mm-diameter glass calibration cell allows small PSP-coated test articles to be calibrated while providing a 360° view of the test specimen. This calibration cell covers the pressure range typically experienced in the IRT and is limited to a pressure range between 0 and 1 atm, since the top is not restrained for pressures above atmospheric pressure and cold room temperatures.

The first configuration calibrated in the vacuum cell was an ice accretion on a white aluminum airfoil prepared for the PSP technique as if for a normal wind tunnel test. The airfoil with ice accretion was painted with PSP with no surface preparation after the sample was moved to the cold room. The painted sample was placed in the chamber, and the pressure was controlled over a range of 0.33 to 1 atm. One camera and one excitation source were mounted to view only the side of the ice accretion and airfoil. The intensity ratio image of the calibration sample at a constant cell pressure of 0.33 atm is shown in figure 10. The difference between the measured intensity ratio level on the ice and on the aluminum airfoil section is clearly shown in the figure 11 plot of a spanwise line from the trailing edge to the leading edge of the image in figure 10. The intensity ratio is approximately 2 percent lower over the iced region than over the clean aluminum section. The difference between the two materials was consistent over the entire pressure range and resulted in a pressure-dependent error. The error associated with the PSP on ice always indicates a lower intensity ratio that converts to a higher indicated pressure level.

Figure 12 shows the calibration plot of the image intensity ratio versus pressure level for the PSP applied to the two different materials over the pressure range typically experienced in the IRT. The data point values were calculated by determining an ensemble average over two regions of interest for each pressure. The two regions were chosen over an area containing a similar background material, avoiding the interface where the ice is bonded to the airfoil. The indicated pressure difference between the ice and airfoil ranged from less than 0.1 percent at 1 atm to 3.8 percent at 0.33 atm. This is not an acceptable accuracy and would lead to large errors when surface pressures were integrated to determine the aerodynamic performance.

To determine the contributing factors of this difference, the optical properties of the two materials were investigated first. An attempt was made to produce a typical model surface that more closely matched the scattering properties of the ice surface. A white basecoat containing titanium dioxide in the same silicone polycarbonate copolymer binder was developed at the University of Washington. The new basecoat was applied over a simulated acrylic sample accretion prior to the application of the PSP. The purpose of this test was to eliminate the physical properties that occur at the boundary of the ice-paint interface of an actual accretion. The surface of the acrylic block was sandblasted to give it an optical quality or visual surface opacity similar to ice accretions created in the IRT.

Figure 13 shows the results of the scattering background paint calibration on the simulated acrylic ice shape. The data shows that the addition of the scattering background had a minimal effect on the intensity ratios measured. A maximum difference of 0.4 percent exists between the coated and uncoated areas at a pressure of 0.33 atm. Therefore, it seems that the optical qualities of the ice background are not the major source of the error observed in the wind tunnel and calibration cell tests. A test using the scattering layer on an ice sample was not possible due to the shutdown of the IRT for a facility modification. Future calibration tests will focus on the application of the white scattering layer to actual ice shapes to determine if this undercoating helps correct the variation measured across the ice region shown in figure 11.

The physical factors that might contribute to the difference in the measured ice and model surface pressures are being studied. Significant emphasis will be placed on the theory that the change in surface pressure is due to the sublimation of the ice, which has been noted as a large potential source of errors. The sublimation into water vapor of the ice in direct contact with the PSP would account for a difference in the measured partial pressure of oxygen. A thorough understanding of the physical processes that occur on the surface of the PSP-coated ice will help determine the best way to minimize or compensate for the difference.

CONCLUSION

The results from the initial testing indicate that it is feasible to apply the PSP technique to iced models in an icing tunnel. The paint developed by the University of Washington met all requirements for the initial series of tests performed. The proof-of-concept tests at the Glenn IRT showed that the paint formulation adheres to both the ice shapes and cold aluminum models, provides a uniform coating that preserves the detailed ice shape structure, cures quickly, and responds to simulated and actual wind tunnel pressure changes.

The results from the PSP on the aluminum airfoil showed excellent agreement with conventional pressure measurements. The capability of making global pressure measurements on ice as well as on a solid model would represent a promising research tool. Once the measurements have been made, mapping the multiple views to a three-dimensional grid and integrating the surface pressures to get aerodynamic loads would be a simple computational exercise. However, one difference in the pressure measurements made simultaneously on ice and on aluminum is not fully understood at this time. This difference is less than 0.1 percent at 1 atm and rises to 3.8 percent at a pressure of 0.33 atm.

The addition of a scattering layer to a simulated ice surface showed that changing the optical properties of the translucent surface had minimal effect. The physical characteristics of the ice-PSP interface and variation in the ice geometry are being investigated.

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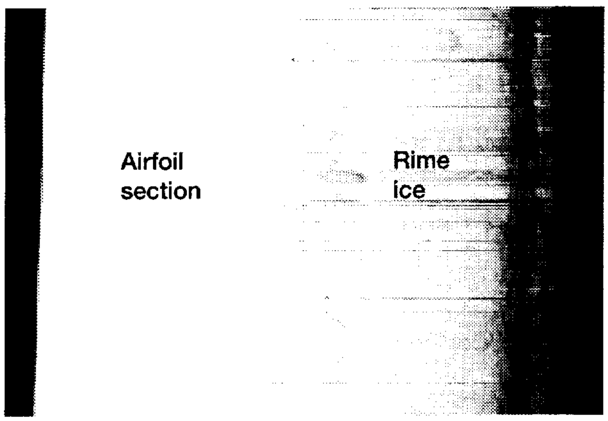

Figure 1.—Closeup of pressure-sensitive paint (PSP) applied to airfoil section and rime ice accretion.

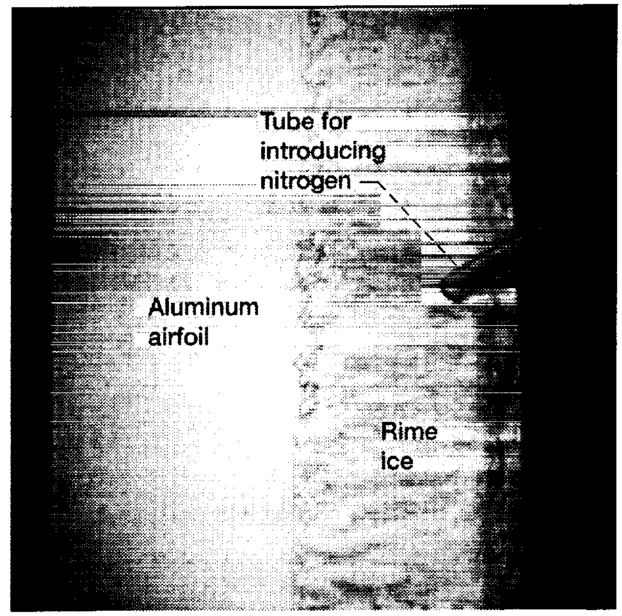

Figure 3.—Reference image of painted rime ice from figure 1.


Figure 2.—Closeup of PSP applied to airfoil section and glaze ice with significant pooling caused by liquid water.

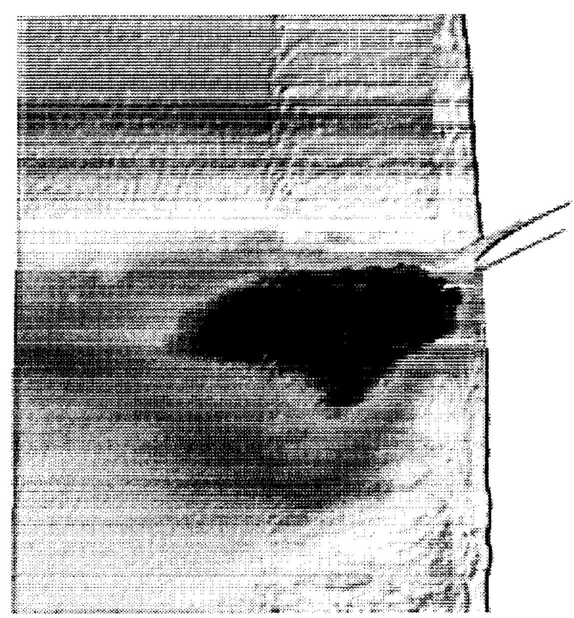
Figure 4.—Intensity ratio image of nitrogen jet impinging on ice surface.

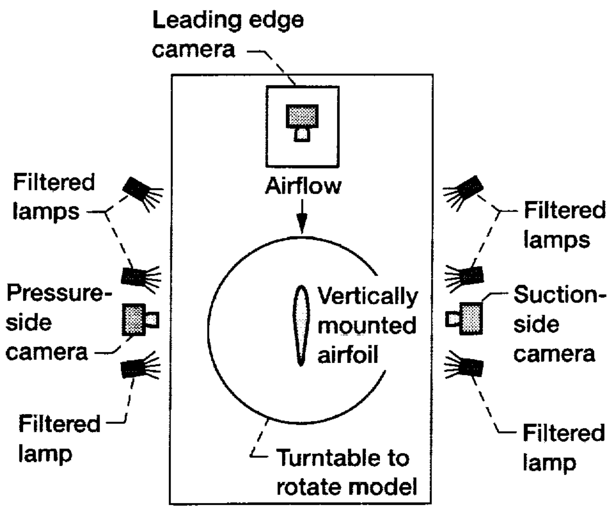

Figure 5.—Pressure-sensitive paint acquisition equipment setup in the IRT.

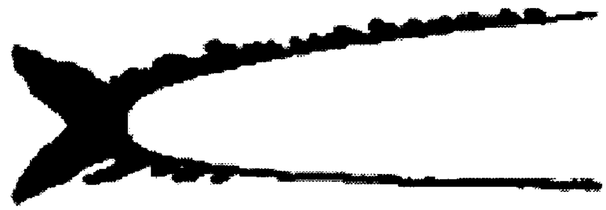

Figure 7.—Tracing of ice shape on leading edge of model shown in figure 6.

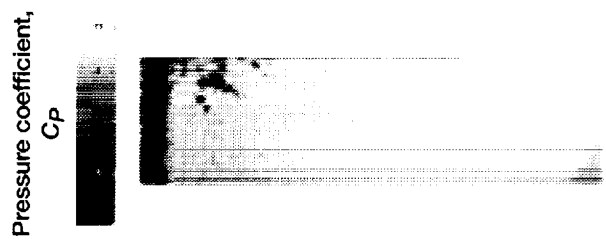

Figure 8.—Two-dimensional pressure data from top or suction side of wind tunnel model at 3.6° angle of attack.

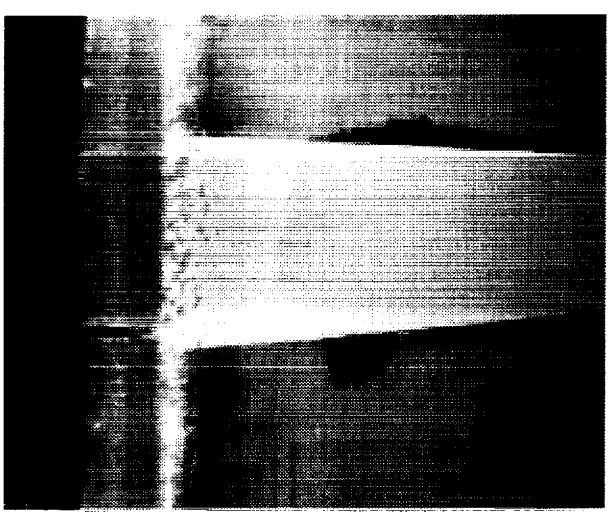

Figure 6.—Ice accretion on 457-mm-chord wing section with PSP application.

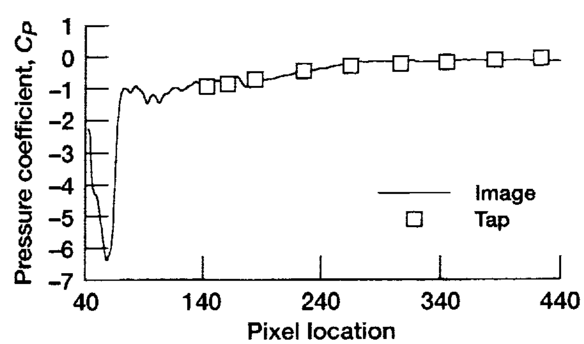

Figure 9.—Pressure-sensitive paint data plotted with pressure tap measurements for pressure distribution shown in figure 8 (error = 0.075).

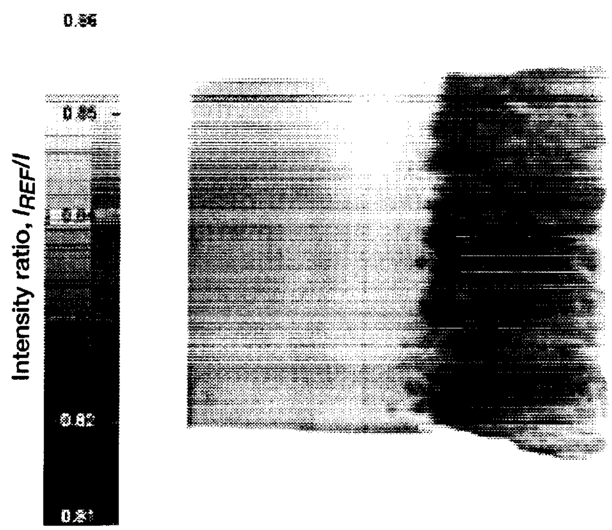

Figure 10.—Intensity ratio image of ice accretion on airfoil section at constant pressure and temperature showing the difference between PSP on ice and on aluminum. Wind-off intensity at constant pressure P_{REF}, I_{REF}; wind-on intensity at pressure P, I.

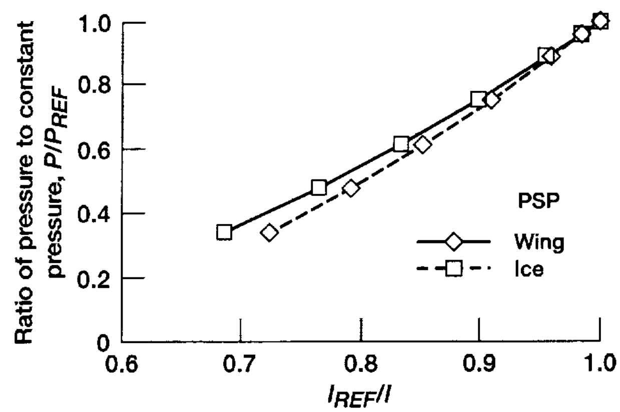

Figure 12.—Calibration cell data for PSP on airfoil and on ice with no scattering layer.

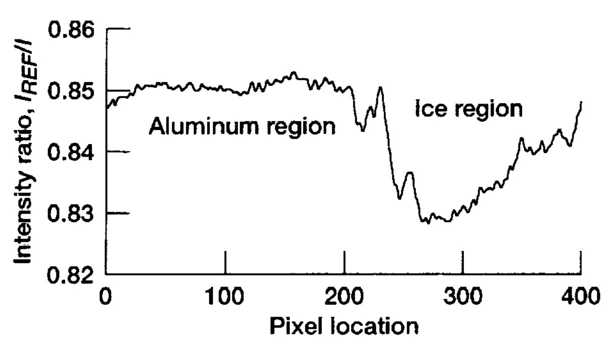

Figure 11.—Intensity ratio of ice accretion on airfoil section centerline at constant pressure and temperature showing the difference between PSP on ice and on aluminum. Wind-off intensity at constant pressure P_{REF}, I_{REF}; wind-on intensity at pressure P, I.

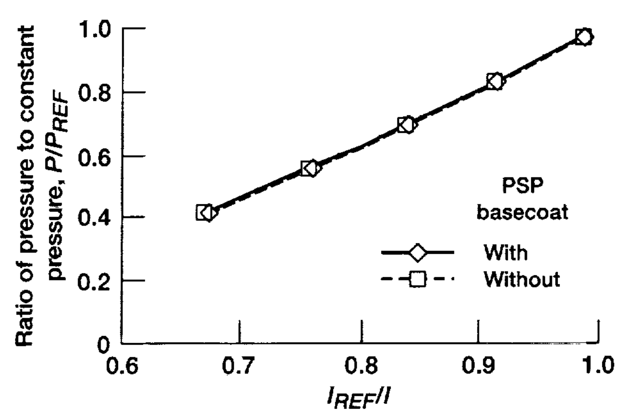

Figure 13.—Calibration cell data for PSP on simulated acrylic ice shape with scattering layer effects.

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Timothy J. Bencic

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National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

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13. ABSTRACT ***(Maximum 200 words)***

Pressure-sensitive paint (PSP) has been successfully used to measure global surface pressures on an ice-accreted model in an icing wind tunnel at NASA Glenn Research Center. Until now, the PSP technique has been limited to use in normal wind tunnels and clear flight environments. This is the first known application of PSP directly to ice in subfreezing conditions. Several major objectives were achieved in these tests. The procedure for applying the coating in the subfreezing tunnel environment was verified. Inspection of the painted ice surface revealed that the paint did not alter the original ice shape and adhered well over the entire coated area. Several procedures were used to show that the paint responded to changes in air pressure and that a repeatable pressure-dependent calibration could be achieved on the PSP-coated surfaces. Differences in pressure measurements made simultaneously on the ice and the metal test model are not yet fully understood, and techniques to minimize or correct them are being investigated.

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