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MEASURING THE EXTENT OF RUST ON STEEL AFTER ABRASIVE BLASTING: A FEASIBILITY STUDY

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Prepared for:
Tri-Service Facilities Coating Committee

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ABSTRACT

The service life of a coating on steel is known to depend upon the condition of the surface prior to painting. Factors used to assess surface preparation include extent of rust remaining on the surface, roughness, and concentration of inorganic contaminants. This report is only concerned with assessing the extent of rust. Presently, the extent of rust is determined using standard definitions and visual standards, a subjective procedure. Since a more objective procedure is desirable, video imaging and infrared thermographic techniques were assessed. It was concluded that infrared thermography does not provide the basis for a simple, sensitive method for assessing the extent of rust but that video imaging shows promise to meet this need.

Keywords: abrasive blasting; cleanness; coatings; emissivity; imaging; infrared thermography; roughness; rust; steel; surface

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1. INTRODUCTION

The service life of a coating on steel depends on the procedure used to prepare the steel prior to painting [1]. Criteria used to assess surface preparation include the extent of rust (e.g., SSPC Surface Preparation Standards [2]), roughness, and concentration of inorganic contaminants [3, 4]. This report is only concerned with assessing the extent of rust remaining on the surface, although roughness and contamination are also important. Presently, the extent of rust is determined using standard definitions and photographs. This procedure is subjective and a more objective procedure is desirable. Essential attributes for a more objective procedure are: 1) quantitative, 2) provide precise or sensitive and accurate results, 3) independent of operator and 4) suitable for use in the field. Several additional attributes are desirable, including 1) non-destructive, 2) relatively fast, 3) easy to use, and 4) relatable to current evaluation procedures.

Based upon recent literature, reflective and emissive properties of a rusted surface may be useful for assessing the extent of rust [5]. Infrared thermography is often used in the field to measure the emissivity and reflectivity of a surface in a limited spectral range, typically in the 3-5 μm or 10-15 μm ranges. Since a procedure based upon infrared thermography or video imaging could meet many of the criteria mentioned earlier, their feasibility in quantifying the extent of rust on a steel surface was studied.

2. EXPERIMENTAL PROCEDURE

2.1 Specimens

The specimens used in this study were 150 x 150 x 6 mm hot-rolled steel panels that had been prepared in conjunction with a Steel Structures Painting Council (SSPC) study to develop improved visual standards for assessing the extent of rust on steel surfaces prepared by abrasive blasting. The panels were cut from a hot-rolled steel sheet covered with both rust and mill scale and abrasively blasted to various levels of surface cleanness, as judged by visual appearance. (There was a gradual change in visual appearance, such that one of the authors (McKnight) was able to place the panels in the same order as the person who prepared them.) In all, twelve panels were prepared. The larger the panel number, the greater the degree of rust removal; that is, Panel 1 represents steel obtained directly from the sheet, Panel 12 corresponds to a white-metal finish [2] while Panels 6 and 7 were judged by McKnight to correspond to a commercial blast [2]. After the panels were blasted, they were wrapped in rust-inhibitive paper and stored in a desiccator except for the few hours during which they were being examined.

NACE Standard-TM-01-75 [6] Panels[1], centrifugally blast cleaned with either steel grit or steel shot, were also evaluated using the video-based method. These panels consist of two sets, one for each of the two blasting media, representing 1) white, 2) near-white, 3) commercial, and 4) brush-off surface preparations.

2.2 Equipment

An infrared camera with standard video output and a 20 degree camera-lens system with an extender ring was used in assessing the emissivities of the specimens. The camera was equipped with an indium antimonide photon detector sensitive to radiation in the 2.5-5.5 μm range. The field of view (FOV) was approximately 25 by 25 mm. The panels were heated from behind by placing the panels on an electrical resistance pad, covered with a 150 x 150 x 3 mm (3 mm thick) brass plate. The surface temperature of the panel in an area adjacent to the FOV was measured using a thermocouple taped to the front of the panel. The thermocouple output device displayed temperature to the nearest tenth of a degree Celsius.

The video camera used was a DAGE-MTI model 68 camera with RS-170 output. The RS-170 signal was digitized by a minicomputer-based imaging system which has been described in detail elsewhere [7]. The camera field of view is digitized into a 512 x 240 array of pixels, each of which is assigned a greylevel of 0 (black) to 255 (white) based on the local video signal intensity.

2.3 Measurement Method

2.3.1 Infrared Thermography

Before performing any measurements on the experimental panels, the stability of the infrared camera was checked. This was done by repeatedly measuring the thermal level of a black body for several consecutive days. For a camera to be stable, the thermal level associated with a given temperature of the black body must remain constant. For the camera used in this study, the change in thermal level over three days was less than 0.5 thermal level unit for black body temperatures less than 55°C. Calibration of the camera was carried out using procedures described in the instruction manual [8]. Briefly, an isotherm level was set at the zero point of the thermal range (i.e., midway between black

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[1]Certain commercial products are identified in this paper in order to adequately specify the experimental materials and procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is necessarily the best available for the purpose.

and white on the greylevel scale) and the camera gain (thermal level setting) adjusted so that the image just filled in with "white spots." The "white spots" marked all areas of the image having the thermal level associated with the isotherm. This procedure was repeated for several black-body temperatures.

From preliminary measurements, it was determined that the greylevel of the pixels making up the image of a blasted surface varied considerably over the image [9]. For abrasively cleaned surfaces, the mode of the greylevel/pixel distribution of an image should provide the greatest distinction between the surfaces cleaned to different degrees. However, since the objective of this study was to determine if infrared thermography could be used as a field method to assess degree of cleanness, and it would not be feasible to quantitatively determine the mode of the distribution in the field, another procedure for determining a representative parameter was required. Experimentally, it was found that the thermal level associated with the mode greylevel and the average of the thermal levels of areas having the greatest emissivity and of areas having the least emissivity were about the same. Hence, since the minimum and maximum thermal levels of a surface could be measured in the field, they were used to calculate the average thermal level for this study.

The average thermal level associated with the field of view of each panel was determined at five surface temperatures, roughly 30°, 35°, 40°, 45° and 50°C. A visually representative area of the sample was selected as the FOV. The back heating plate was adjusted to obtain the desired panel surface temperature. The following method was used to determine the maximum and minimum thermal levels of the FOV of a panel. First, an isotherm level was set at the zero point of the range. Next, the camera gain was increased until "white spots" (areas having a thermal level corresponding to the setting on the thermal level knob) appeared on those areas of the image having the highest emissivity. This value was recorded and then the gain was increased until "white spots" appeared on those areas of the image having the lowest emissivity. This value was also recorded, and the average was determined.

2.3.2 Video

To evaluate the blasted panels, the video camera was used in a manual mode of operation. Both the gain and black level were held constant throughout the evaluation. Each of the panels was viewed, a digitized image created by the imaging system, and the average greylevel determined for the image.

Since the camera was operated in manual mode, the average greylevel should provide a direct measurement of degree of rusting (or cleanness). Briefly, simply considering non-rust areas to have one greylevel value, GR_{steel}, and rusty areas a second (lower) greylevel, GR_{rust}, GR_{ave} can then be established as

$$GR_{ave} = GR_{steel}(1 - f_{rust}) + GR_{rust}f_{rust} \tag{1}$$

where f_{rust} is the fractional surface area which contains rust. Furthermore, for the SSPC panels, considering panel 1 to be totally rusted and panel 12 (white-metal finish) to be totally clean, the above equation may be rearranged to obtain

$$f_{rust}(\text{panel } i) = \frac{GR_{ave}(\text{panel } 12) - GR_{ave}(\text{panel } i)}{GR_{ave}(\text{panel } 12) - GR_{ave}(\text{panel } 1)} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1 Infrared Thermography

Based upon the calibration measurements using a black body, calibration constants were determined using the following equation:

$$TL = Ae^{B/T}, \tag{3}$$

where TL is the thermal level which is proportional to the number per unit time of photons detected by the camera, A and B are calibration constants, and T is the absolute blackbody temperature in degrees Kelvin. Figure 1 shows the experimental points and the line calculated from the constants obtained by using a linear least squares regression on the natural logarithm of the thermal level and the reciprocal of the absolute temperature.

The experimental data of thermal level versus the visual degree of rust removal are shown in table 1 and illustrated in figure 2. Although there is considerable variation in thermal level between the uncleaned and best cleaned panel for temperatures between 40° and 50°C, the change is not monotonic and much of the change is associated with the initial removal of rust and mill scale. Thus, based upon these data, it appears that a method that compares thermal levels would not provide a sensitive procedure for comparing degree of rust removal. Inasmuch as the thermal level measurement depends on both roughness and degree of rusting, the question arises as to whether a material parameter that depends only on the degree of rusting can be determined from these data.

Sparrow, Albers and Eckert [10] have developed a theory to describe how varying shapes of holes in a surface affect radiant energy leaving it. Although the geometries of the blasted surfaces are very complex, the ideas Sparrow et al. developed may be applied to this situation.

Briefly, the theory expresses the increased radiation leaving a hole, which is caused by the increased reflectivity within a hole, in terms of an apparent emissivity. The apparent emissivity, ϵ_{app}, is defined as the ratio of the actual energy leaving the surface to the energy leaving a black body at the same temperature. Thus, in our case, the TL expressed in terms of apparent emissivity becomes

$$TL = \epsilon_{app} A e^{B/T_S} + \rho_{app} A e^{B/T_A}, \tag{4}$$

where T_S is the absolute surface temperature and T_A is the absolute ambient temperature. If one assumes that the reflectivity, $\rho_{app} \approx \rho_{actual} = 1 - \epsilon_{actual}$, then ϵ_{app} and ϵ_{actual} can be calculated for each panel using a linear regression model with a forced zero intercept. The results of these calculations are shown in figure 3. The fit of the data to this model as characterized by standard regression coefficients is shown in table 2. One notes that the calculated emissivity of the specimens varies from nearly one for the visually most rusted panel (p-1) to about 0.5 for the visually cleanest one (p-12). The difference between the apparent and "actual" emissivity is related to the effect of roughness on the thermal level. Although this model provides a means of obtaining a material-based parameter using a measurement procedure that would be possible to carry out in the field, the change in emissivity for Panels 6 through 11 is still too small and not monotonic.

3.2 Video

Figure 4 shows a plot of area fraction rusted, as determined using equation (2), for the video-based evaluation of the twelve SSPC panels. In general, as the panel number increases, the area fraction rusted monotonically decreases (with one exception - Panel 10) suggesting that the video-based procedure does provide a means for quantifying the degree of cleanness of blasted steel. Figure 5 shows a plot of average greylevel vs. panel classification for the two sets of NACE blasted panels. Once again, as the degree of blasting is decreased, the average greylevel decreases monotonically in an approximately linear fashion. From these preliminary results, it appears that an assessment procedure based upon video imaging may be more sensitive to changes in the degree of cleanness than one based upon infrared thermography.

4. CONCLUSIONS AND RECOMMENDATIONS

For steel specimens cleaned to visually different degrees by abrasively removing rust, the thermal level of a specimen (measured using an infrared camera) generally decreased as the degree of rust removal increased; this was expected since rust has a higher emissivity than clean steel. The difference in thermal levels between specimens was found to increase as the surface temperature of the specimens increased. Although comparisons of thermal levels of steel surfaces having the same temperature could provide a measure of the relative degree of cleanness, the procedure was not sensitive in its ability to discriminate between neighboring panels. Thus it was concluded that thermographic imaging would not provide a feasible procedure for quantitatively comparing extent of rust on abrasively blast-cleaned steel surfaces.

Since relative field measurements are not always possible or feasible, the data were analyzed to estimate a material parameter based upon a model developed by Sparrow et al. [9]. This model included the effect of roughness on the emittance properties of a surface. Two parameters were obtained, an apparent emissivity and an "actual" emissivity. However, the change in actual emissivity as calculated was small for panels having degrees of cleanness similar to commercial to near-white (Panels 6-11). Thus, it was concluded that, for these levels, determining degree of rust removal from abrasively-cleaned steel using an infrared camera did not appear to be feasible.

In contrast to the thermographic data, it appears that an assessment procedure based on a video image may have sufficient sensitivity to measure changes in the extent of rust present on blast-cleaned surfaces. Further, these results were obtained with a black-and-white video camera. It is expected that a color image, in which some colors could be used separately from others, would provide a basis for an assessment procedure that would offer a more sensitive measure of the degree of cleanness of blast-cleaned steel surfaces than that obtained using a black-and-white image. Thus, it is recommended that the feasibility of assessing the degree of cleanness of blast-cleaned steel surfaces using a color video camera be investigated.

5. ACKNOWLEDGMENT

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Table 1. Thermal levels for
SSPC specimens for five surface temperatures

	Temperature, °C				
Panel no.	30	35	40	45	50
1			28.8	34.3	40.4
2	21.1	23.4	27.5	32.1	37.8
3	19.5	22.4	25.9	30.5	35.3
4	19.4	23.1	25.2	29.1	33.3
5	20.0	22.9	26.3	30.8	35.7
6	20.1	22.4	25.8	31.4	34.6
7	19.5	21.9	25.3	28.7	33.2
8	19.5	21.6	24.5	28.0	31.8
9	19.4	21.2	24.0	28.0	32.0
10	19.5	22.0	24.8	27.9	32.3
11	19.3	21.8	24.5	28.0	30.8
12	19.5	21.5	24.0	26.7	30.0

Table 2. Statistical parameters of linear regressions of data to model based on Sparrow et al's theory

Panel no.	ϵ_{app}	ϵ_{actual}	σ_y	r^2	σ_{x1}	σ_{x2}
12	0.50	0.42	.06	1.00	0.004	0.007
11	0.55	0.49	.33	1.00	0.020	0.039
10	0.60	0.55	.23	1.00	0.014	0.026
9	0.61	0.59	.43	0.99	0.025	0.049
8	0.59	0.55	.17	1.00	0.010	0.020
7	0.65	0.61	.20	1.00	0.024	0.024
6	0.72	0.68	.79	0.99	0.047	0.091
5	0.75	0.71	.20	1.00	0.012	0.023
4	0.64	0.58	.50	0.99	0.030	0.416
3	0.75	0.75	.20	1.00	0.012	0.024
2	0.80	0.74	.48	1.00	0.029	0.056
1	1.01	1.02	.50	1.00	0.020	0.035

Notation:
ϵ_{app} - the apparent emissivity obtained from the model,
ϵ_{actual} - the actual emissivity obtained from the model,
σ_y - the estimated standard deviation of the y variable, thermal level
r_2 - the square of the correlation coefficient
σ_{x1} - the estimated standard deviation of the dependent variable, ϵ_{app}, and
σ_{x2} - the estimated standard deviation of the dependent variable, ϵ_{actual}

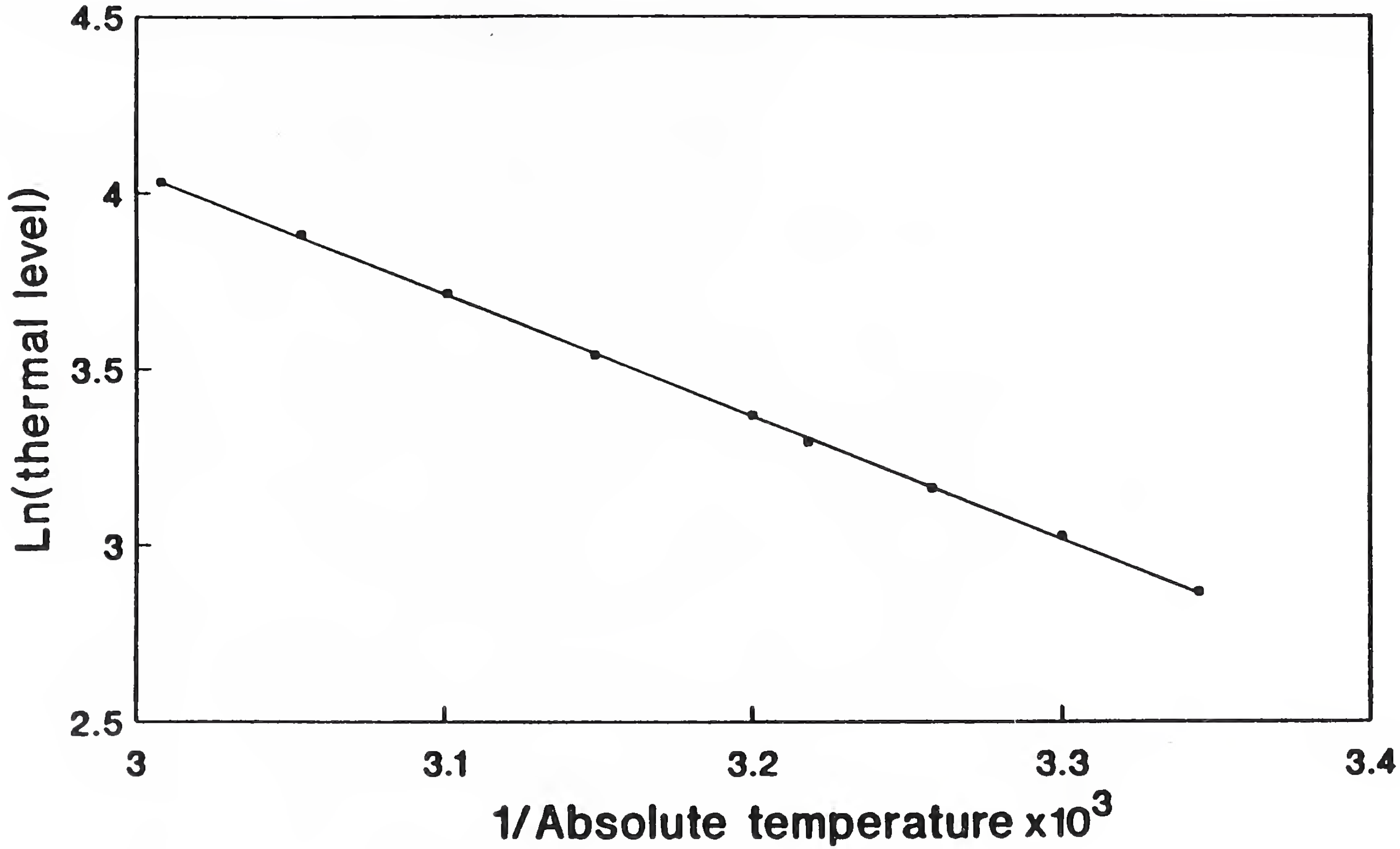

Figure 1. Calibration curve for IR camera showing experimental points and linear regression line

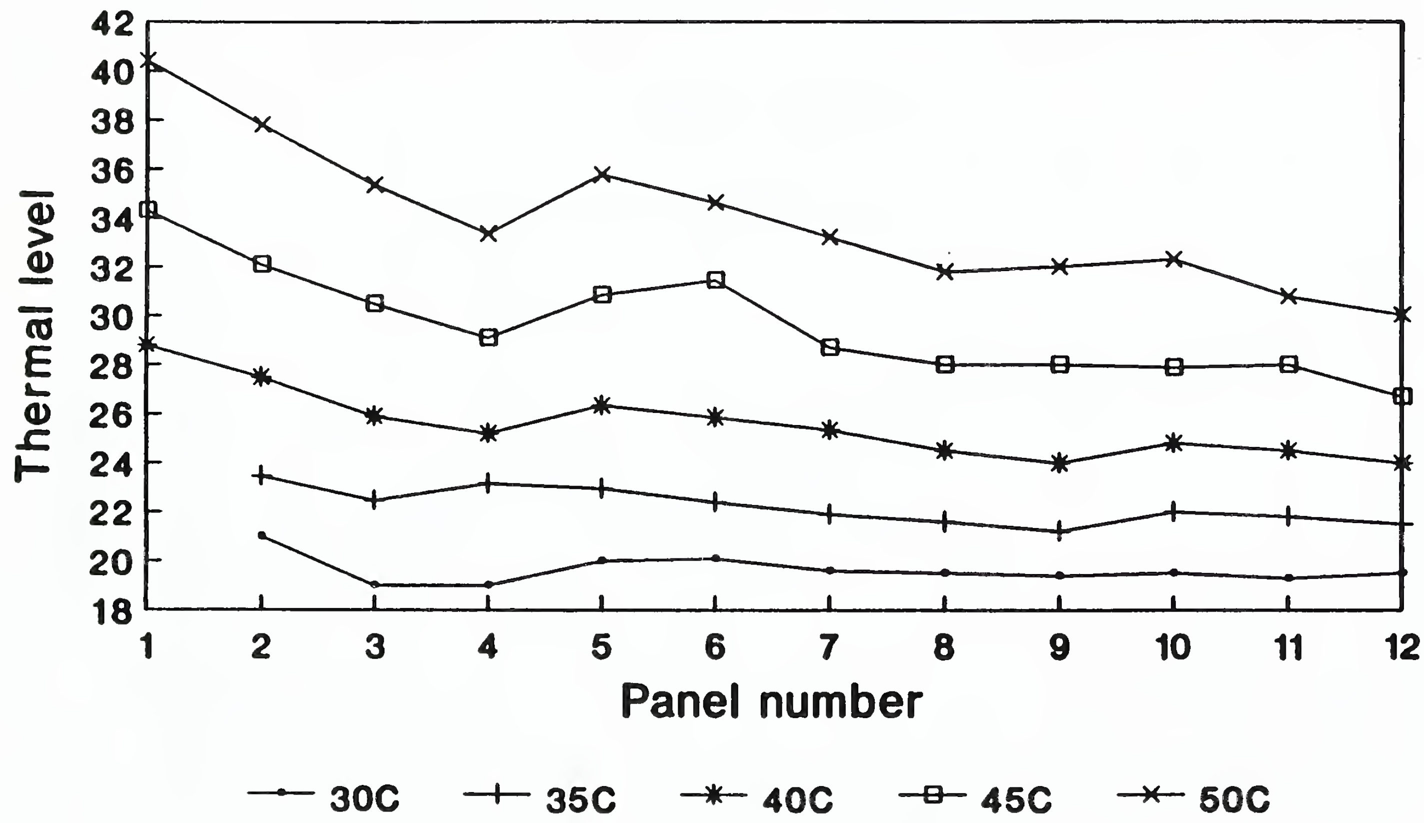

Figure 2. Thermal levels of SSPC specimens for five surface temperatures: 30°, 35°, 40°, 45° and 50°C

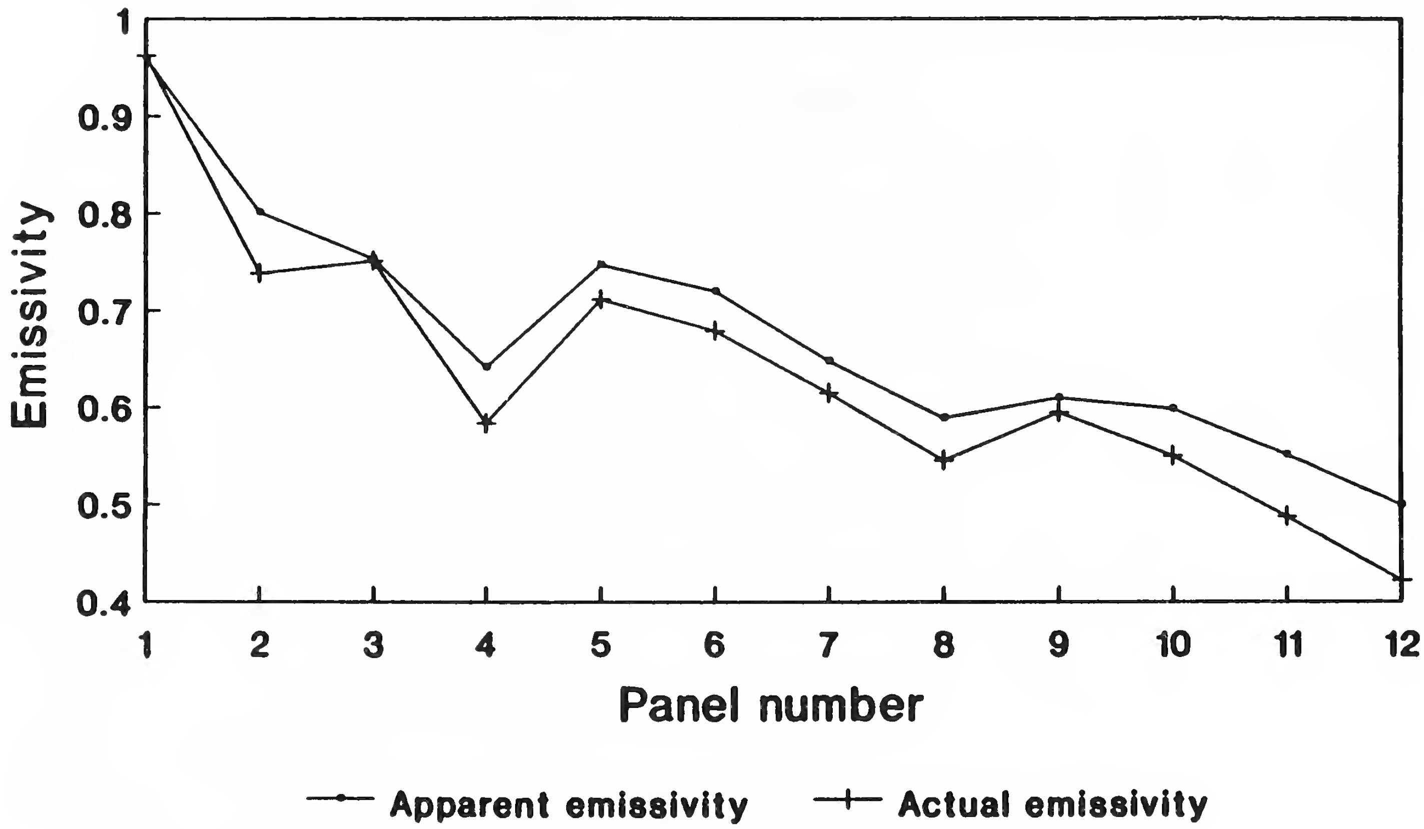

Figure 3. Actual and apparent emissivity of SSPC specimens calculated using model based upon theory of Sparrow Albers and Eckert

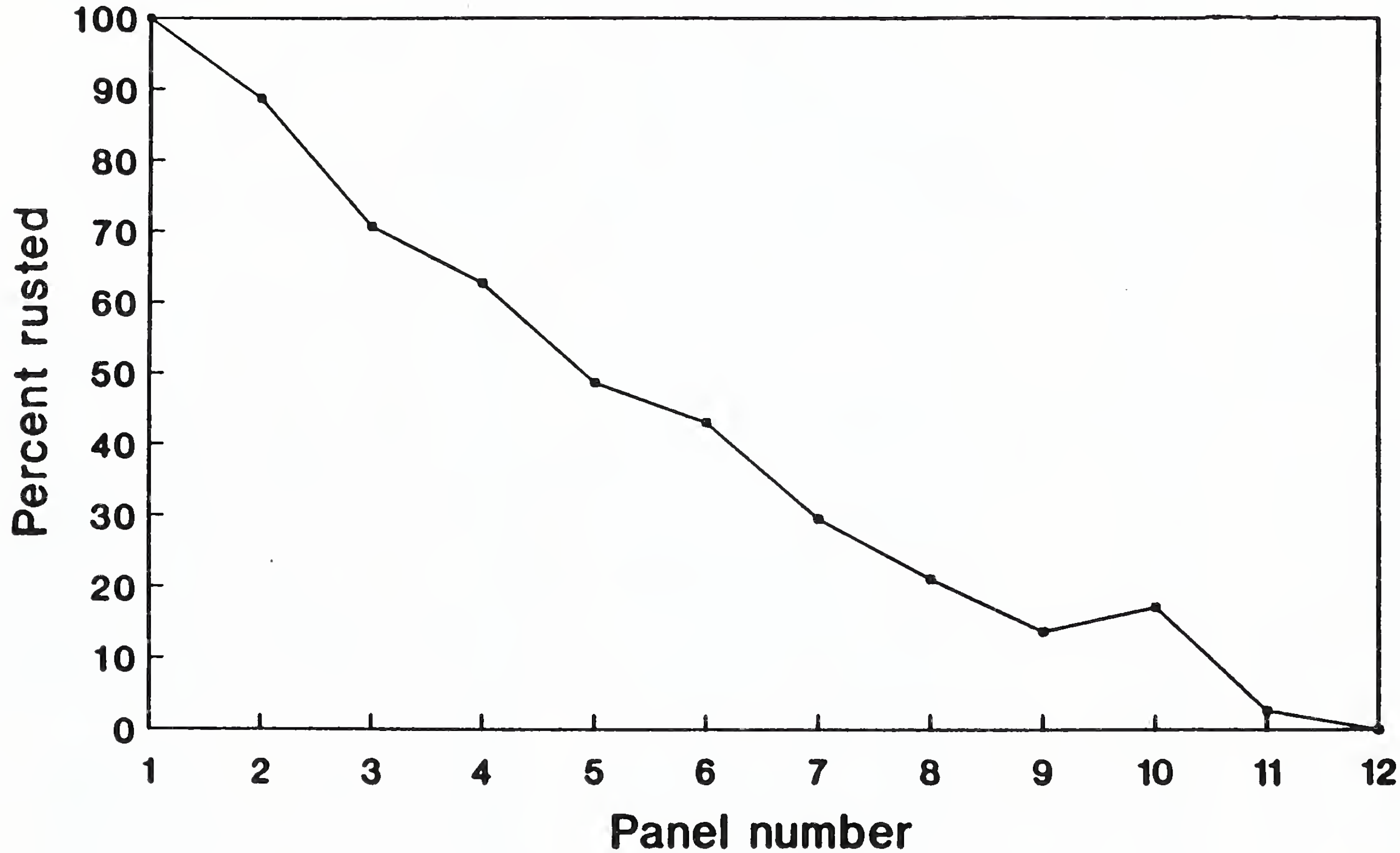

Figure 4. Average greylevel of video image for SSPC specimens

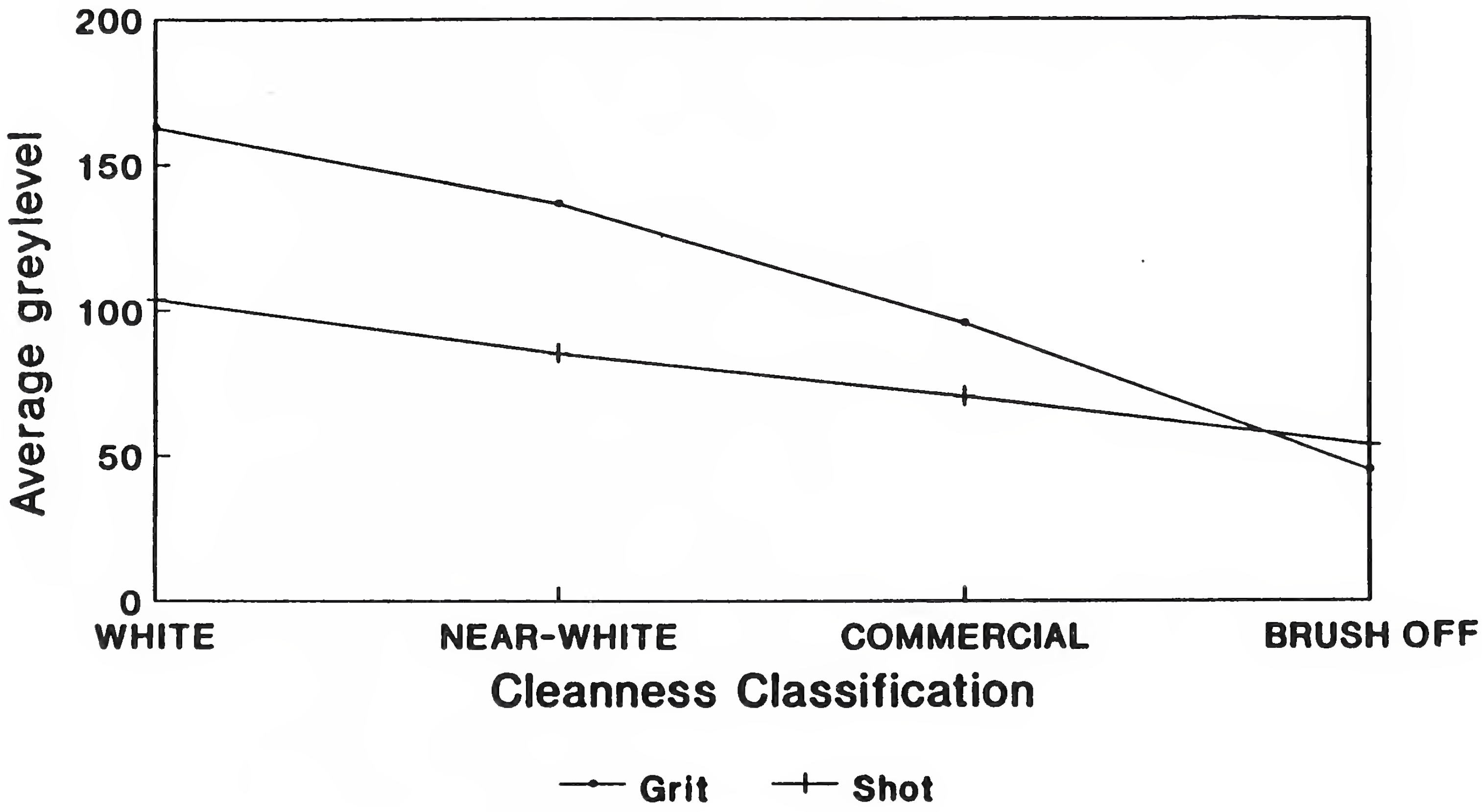

Figure 5. Average greylevel of video images for NACE standards

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The service life of a coating on steel is known to depend upon the condition of the surface prior to painting. Factors used to assess surface preparation include extent of rust remaining on the surface, roughness, and concentration of inorganic contaminants. This report is only concerned with assessing the extent of rust. Presently, the extent of rust is determined using standard definitions and visual standards, a subjective procedure. Since a more objective procedure is desirable, video imaging and infrared thermographic techniques were assessed. It was concluded that infrared thermography does not provide the basis for a simple, sensitive method for assessing the extent of rust but that video imaging shows promise to meet this need.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
abrasive blasting; cleanliness; coatings; emissivity; infrared thermography; roughness; rust; steel; surface.

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