Surface Preparation & Coating Application Inspection Instruments

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Instruments

Preface
Chapter 1 of this eBook provides information on the proper use of test instruments and kits for verifying the quality of surface preparation of new steel in the shop, as well as previously coated structural steel, prior to the application of protective coatings. Verifying the quality of coating application both during and post-application is the subject of Chapters 2 and 3, respectively.

Successful corrosion prevention using protective coating systems is based in part on the quality of the surface preparation and the coating system installation. To verify quality, we rely heavily on data generated by coatings inspection instruments and on visual inspection of the prepared surfaces. We rely on this same information to determine contractual compliance with the project specification.

This eBook was prepared with both the novice and the experienced coatings professional in mind. While it does not include every inspection instrument from every manufacturer, it does contain a cross-section of common instruments and test kits, with references to industry standards throughout. Instrument use however is only part of the coatings inspection equation. It must be combined with thorough knowledge of the project specification and field practicality. Formal training in coatings inspection techniques remains a critical component. This publication is not intended to replace formal training, but
rather to supplement the learning process before, during and after training.

Chapter 1
Verifying the Quality of Surface Preparation

Introduction
Common quality control checkpoints associated with surface preparation include:

- Grease/Oil Removal (SSPC-SP 1)
- Abrasive Cleanliness
- Compressed Air Cleanliness (ASTM D4285)
- Surface Profile (ASTM D4417/NACE SP0287/SSPC-PA 17)
- Surface Cleanliness (SSPC/NACE/ISO)
- Surface Soluble Salt Detection

The focus of Volume 1 is on the use of instruments, kits & visual guides associated with four of the six checkpoints itemized above, including:

- Verifying Abrasive Cleanliness
- Measuring Surface Profile (ASTM D4417/NACE SP0287/SSPC-PA 17)
- Verifying Surface Cleanliness (SSPC/NACE/ISO)
- Detecting Surface Soluble Salt Concentrations

In addition, the importance and value of measuring peak density (in addition to the peak-to-valley depth) is discussed, and the instrumentation is described. Both traditional methods and novel techniques for verifying quality are explored.
Abrasive Cleanliness

Abrasive cleanliness is an indirect or automatic requirement of the SSPC/NACE surface cleanliness standards for abrasive blast cleaning. Further, the SSPC Abrasive Standards (AB 1, AB 2, AB 3 and AB 4) all require the abrasive (whether new or reused) to be clean. There are two parameters associated with abrasive cleanliness, including oil contamination and water-soluble contaminants resulting in elevated conductivity.

**Verifying Abrasive Cleanliness - Oil.** ASTM D7393, “Standard Practice for Indicating Oil in Abrasives” describes a method for determining whether an abrasive is contaminated with oil. To perform this test, place about 1” of abrasive into a clear glass or plastic container, then add clean tap water one inch above the abrasive level (Figure 1). The water should be between 68° and 95°F. Cover and shake the abrasive/water sample vigorously for one minute, then remove the cover and allow the abrasive to settle for up to 5 minutes. Observe the surface of the water for an oil film or sheen. Discard the abrasive and document the results.

**Verifying Abrasive Cleanliness - Water Soluble Contaminants.** The second parameter for assuring an abrasive is clean is described in ASTM D4940, “Standard Test Method for Conductimetric Analysis of Water Soluble Ionic Contamination of Blasting Abrasives.” To perform this test, add 300mL of distilled water (available from most
grocery stores) to 300 mL of abrasive. Stir the abrasive/water slurry for one minute, then allow the slurry to sit undisturbed for 8 minutes. Re-stir for an additional one minute (total extraction time of 10 minutes), then filter and discard 10 mL of the extract solution through laboratory-grade filter paper (e.g., Whatman). Filter the remaining extract and test the solution for conductivity using a temperature-compensating conductivity meter. Test the water used for the extraction for conductivity, and subtract this value (known as the “blank”) from the conductivity value obtained from the abrasive extract. A kit containing all of the equipment and supplies for conducting 25 abrasive ionic contamination tests is shown in Figure 2. If the project specification references SSPC/NACE surface cleanliness standards for abrasive blast cleaning and/or the SSPC abrasive (AB) standards listed above, the maximum allowable threshold of water-soluble contaminants is 1,000 microsiemen (µS), which is 1 millisiemen (mS). Annual calibration of the conductivity meter is critical to achieving confidence in the data that is generated on the abrasive, as is verification of accuracy of the meter prior to each use. Procedures for calibration and verification of accuracy are described next.
Calibration and Verification of Accuracy of the Conductivity Meter

Calibration of the temperature-compensating conductivity meter (Figure 3) using standard solutions across the range of the meter for its intended use (in this case up to 1,000 µS) can be performed by an instrument supplier or an accredited calibration laboratory. Annual calibration is recommended. A Certificate of Calibration is typically provided listing the calibration checkpoints and tolerance relative to the standard solutions used, along with the manufacturer’s stated accuracy of the meter. Readings that fall outside of the combined tolerance of the meter and standard solution(s) often indicate that the probe is defective and that the meter should be replaced.

Verification of accuracy should be performed by the inspector prior to each use (if multiple tests are performed daily, then once daily is adequate). A single standard solution (mid-range, e.g. 445 µS) is adequate. This standard solution is provided in the kit shown in Figure 2. Place a small amount of the standard solution in the cap of the conductivity meter, then place the cap over the probes. The value displayed should match the standard solution value (+/- 5 µS, or 440-450 µS for the 445 solution). Readings that fall outside of the acceptable range often indicate that the probe is defective and that the meter should be replaced.
Measurement of Surface Profile

The surface profile, anchor pattern, or roughness is defined as the maximum average peak to valley depth (or valley to peak height) created during surface preparation. The terms are most commonly associated with abrasive blast cleaning and are the result of the impact of the abrasive onto the substrate. Some impact-type power tools can also produce a roughness in a steel surface. Surface profile is important because it increases the surface area to which the coatings can adhere, providing a mechanical anchor to enhance the adhesion of the coating. Generally, heavier coatings require a deeper surface profile than coatings of lesser thickness.

Surface profile determinations are commonly made in the field or shop using one of three instruments: a visual comparator, a depth micrometer, or replica tape. All three methods are described in ASTM D4417, “Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel.” Recent advances in technology enable acquisition of peak density measurements directly from replica tape using a Replica Tape Reader. Traditional and novel methods of quantifying surface roughness characteristics are explored next.
Two of the more traditional methods for measuring surface profile depth include the use of a depth micrometer (Method B in ASTM D4417) and replica tape (Method C in ASTM D4417). Each is briefly described below.

A depth micrometer (Figure 4) consists of a 60° conical pin that projects from a flat base. First, zero the instrument on a float glass plate (included with the instrument) and verify accuracy using a specially-designed shim placed onto the glass plate (with a notch of a known depth, also included with the instrument) prior to each use. Next position the probe of the instrument on the blast cleaned substrate, resting the base on the tops of the "peaks" and push downward (slightly) so that the 60° conical pin projects into the valleys of the profile. The depth of the profile, relative to the height of the peaks is displayed by the gage. Obtain a minimum of 10 readings in each area, and report the maximum value after discarding any outliers, which are unusually high or low readings that cannot be repeated. That is 12-14 readings may be required to obtain 10 representative readings. The average of the ten readings may also be reported. It is important to pick the instrument up and place it down for each reading, rather than drag it across the profile; otherwise, the point can become blunted, yielding erroneous readings.

Note: According to ASTM D4417, SSPC-SP 15 (Commercial Grade Power Tool Cleaning) and SSPC-SP 11 (Power Tool Cleaning to Bare Metal), Method B is the only suitable method for quantifying the surface profile depth generated by impact-type power tools.
Newer models have a remote probe (Figure 5) for taking surface profile measurements in difficult access areas, like the underside of a pipe.

**Calibration**

Calibration of a depth micrometer can be performed by the instrument manufacturer, authorized service dealer or an accredited calibration laboratory. Annual calibration is recommended. A Certificate of Calibration is provided listing the manufacturer’s stated accuracy, the readings from the instrument and the associated deviation (if any). The calibration often includes a visual inspection of the probe for wear. Probe tips are replaceable. Based on the degree of variation from the manufacturer’s stated accuracy, the calibration provider may recommend repair or replacement of the instrument.

*Replica tape* is described in ASTM D4417, Method C and NACE SP02-87, Field Measurement of Surface Profile of Abrasive Blast-Cleaned Steel Surfaces Using a Replica Tape. The Testex Press-O-Film Replica Tape consists of compressible foam attached to a uniform, 2 mil film of Mylar® (a polyester film). The tape is available in three ranges: "Coarse" for profile measurements from 0.8 to 2.5 mils; "X-Coarse" for measurements from 1.5 to 4.5 mils; and “X-Coarse Plus” for measurements from 4 to 5 mils. The X-Coarse Plus tape may be used to measure surface profile
up to 6 mils or so, provided the tape is pre-measured to verify adequate compressible foam is available.

Remove the paper backing and attach the tape to the blast cleaned steel surface, foam side down. Using medium pressure, vigorously rub the Mylar with a burnishing tool (Figure 6). The peaks and valleys of the profile conform to the compressible foam and the peaks will ultimately touch, but not alter the thickness of the Mylar, as the Mylar is non-compressible. Remove the tape from the surface once the white Mylar is uniformly gray and measure the compressed foam and Mylar using a light spring-loaded micrometer, which provides a reading from the upper or outermost surface of the Mylar to the high spots on the foam (corresponding with the valleys of the profile). Subtract 2 mils from the gage dial to determine the maximum surface profile depth (e.g., 3 mils in Figure 7). The gage dial may be preset to “8” (-2) to auto-correct for the Mylar thickness. Obtain a minimum of 2 readings per area.

The replica tape will reportedly retain the impression indefinitely, provided it is stored in a cool area with no pressure applied. Conceivably, replicas of profile depths could be kept on file permanently for future reference.
A Testex linearizing micrometer specially designed to be used with Testex Press-o-Film Replica Tape effectively removes the need to preset the dial to 8 (-2) or deduct 2 mils from the gage reading, provided the gage indicator is set properly (as shown in Figure 8). Note however that the maximum surface profile depth that can be measured using this micrometer is 5 mils, so use of the X-Coarse Plus replica tape beyond 5 mils (as described above) is not feasible with the linearizing micrometer.

A Replica Tape Reader (RTR; Figure 9) can be used in lieu of the standard micrometer and the linearizing micrometer. Insert the burnished replica tape into the slot and press the gray button. The surface profile is displayed (in mils or microns). The Mylar thickness is automatically subtracted; therefore, no user correction is necessary. Additional information such as peak density\(^1\) can be acquired from the same replica tape and Advanced Model Replica Tape Reader.
Optical Grade Replica Tape
A special Optical Grade Replica Tape (when used in conjunction with an Advanced Model Replica Tape Reader) can provide 3-dimensional images of peak density, or Pd (Figures 10a and 10b).

![Figure 9](image)

Figure 9

Figure 10a (Pd of 5/mm²)  Figure 10b (Pd of 16/mm²)

It is important to realize that there is little correlation among the methods described herein because each takes in a different peak count or surface area for its measurement. Therefore, it is advisable that all parties agree upon the method that will be used to determine the surface profile and not deviate from it. Oftentimes project specifications will dictate the method of surface profile measurements.

1 Research indicates that increased peak density can improve coating system adhesion and provide greater resistance to corrosion undercutting when the coating is damaged in service.
**Calibration**

Calibration of the Testex micrometers and the Replica Tape Readers can be performed by the instrument manufacturer, authorized service dealer or an accredited calibration laboratory. Annual calibration is recommended. A Certificate of Calibration is provided listing the manufacturer’s stated accuracy, the readings from the instrument and the associated deviation (if any). Based on the degree of variation from the manufacturer’s stated accuracy, the calibration provider may recommend repair or replacement of the instrument. The Testex micrometers can be verified for accuracy in the shop or field using the same certified or measured shims that are used to verify the accuracy of electronic dry film thickness gages.

**Frequency of Measurement**

While ASTM D4417 prescribes the number of readings to take per area, it does not prescribe the number of areas to measure. SSPC-PA 17, “Procedure for Determining Conformance to Steel Profile/Surface Roughness/Peak Count Requirements” fills this gap. It states, “Unless otherwise specified, select a minimum of three 6 x 6-inch locations in which to take readings for each specific surface preparation apparatus used during each work shift or twelve-hour period, whichever is shorter. For the purpose of this standard, “apparatus” is defined as an individual blast pot (which may supply multiple nozzles), individual self-contained abrasive recycling/blast cleaning units (which may contain multiple pots), individual stationary or mobile centrifugal cleaning unit, or individual power tool.”
Assessment of Surface Cleanliness

All surfaces should be visually inspected after surface preparation to ensure compliance with the cleanliness requirements of the governing specification. The SSPC Surface Preparation Standards describe the appearance of various methods of surface preparation (e.g., hand and power tool cleaning, abrasive blast cleaning, etc.), including the type and percentage of residues or stains permitted to remain on the surface.

The written definitions for abrasive blast cleaned surfaces are supplemented by SSPC-VIS 1 Guide, which photographically depicts the surface appearance of various grades of blast cleaning over four initial mill scale and rust conditions of steel and three conditions of coated steel (Figure 11). The images in the Guide are visually compared with the prepared surface to determine the degree of cleanliness. SSPC has also produced a visual guide for hand- and power-tool cleaned surfaces (SSPC-VIS 3; shown in Figure 12). Other visual guides for surface cleanliness evaluation include the ISO Pictorial Standards (8502-1); however, these are only used when ISO surface cleanliness standards (e.g., Sa 1, Sa 2, Sa 2½ and Sa 3) are specified.

Using SSPC-VIS 1, Guide and Reference Photographs for Surfaces Prepared by Dry Abrasive Blast Cleaning

SSPC-VIS 1 is a collection of color reference photographs depicting various initial conditions and different levels of dry...
abrasive blast cleaning. To use the SSPC VIS 1 visual standard, follow these four basic steps:

**Step 1: Determine the initial condition of the steel surfaces:**
Determine what the existing steel looks like before it is prepared by abrasive blast cleaning. To do this, locate the reference photographs in the visual guide illustrating the seven possible initial conditions of the steel. The SSPC-VIS 1 Guide illustrates seven *Initial Conditions*, including:

**Condition A:** Steel surface completely covered with adherent mill scale; little or no visible rust.

**Condition B:** Steel surface covered with both mill scale and rust.

**Condition C:** Steel surface completely covered with rust; little or no pitting visible.

**Condition D:** Steel surface completely covered with rust; pitting visible.

**Condition G₁:** Weathered coating system over mill scale with extensive pinpoint rusting

**Condition G₂:** Weathered coating system over mill scale with moderate pitting

**Condition G₃:** Weathered coating system over mill scale with severe pitting
Select one or more of the “before” reference photographs that best illustrates the condition of the steel (the steel may be represented by more than one condition).

**Step 2: Determine the level of surface cleanliness the specification requires:** After you select a reference photograph(s) that depicts the existing condition of the steel surfaces (the “before photograph”), reference the project specification to determine the degree of surface cleanliness required. The degree of surface cleanliness will typically appear in the project specification as one of five possible “levels,” including SSPC-SP7, Brush-off Blast; SSPC-SP14, Industrial Blast; SSPC-SP6, Commercial Blast; SSPC-SP10, Near-White Metal Blast; or SSPC-SP5, White Metal Blast. At this point, you should have both a code for the initial condition (A, B, C, D, G₁, G₂ or G₃) and a code for the surface cleanliness (SP7, SP14, SP6, SP10 or SP5).

**Step 3: Locate the reference photograph in the visual standard.** The SSPC-VIS 1 visual guide illustrates various levels of surface cleanliness (after abrasive blast cleaning is completed) for each of the conditions in Step 1. We’ll call these “after photographs.” Table 1 provides the combinations of initial conditions (before photographs) and surface cleanliness levels (after photographs)
<table>
<thead>
<tr>
<th>Rust Grade</th>
<th>Surface Cleanliness Levels Depicted in the Reference Color Photographs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Near-White Metal Blast (SP10) and White Metal Blast (SP5)</td>
</tr>
<tr>
<td>B</td>
<td>Brush-off Blast (SP7); Commercial Blast (SP6); Near-White Metal Blast (SP10); and White Metal Blast (SP5)</td>
</tr>
<tr>
<td>C</td>
<td>Brush-off Blast (SP7); Commercial Blast (SP6); Near-White Metal Blast (SP10); and White Metal Blast (SP5)</td>
</tr>
<tr>
<td>D</td>
<td>Brush-off Blast (SP7); Commercial Blast (SP6); Near-White Metal Blast (SP10); and White Metal Blast (SP5)</td>
</tr>
<tr>
<td>G₁</td>
<td>Brush-off Blast (SP7); Industrial Blast (SP14); Commercial Blast (SP6); Near-White Metal Blast (SP10); and White Metal Blast (SP5)</td>
</tr>
<tr>
<td>G₂</td>
<td>Brush-off Blast (SP7); Industrial Blast (SP14); Commercial Blast (SP6); Near-White Metal Blast (SP10); and White Metal Blast (SP5)</td>
</tr>
<tr>
<td>G₃</td>
<td>Brush-off Blast (SP7); Industrial Blast (SP14); Commercial Blast (SP6); Near-White Metal Blast (SP10); and White Metal Blast (SP5)</td>
</tr>
</tbody>
</table>

Select the reference photograph in the visual guide by combining the code for the initial condition (from column 1 in Table 1) and the code for the specified surface cleanliness level (from column 2 of Table 1).
**Step 4: Assess the prepared surfaces.**

Use the reference photograph selected in Step 3 to determine whether the prepared surface(s) meet or exceed the specified level of surface cleanliness. Here are two examples:

**Example 1:** If the steel surface contains both mill scale and rust, select Condition B (image within yellow circle). Assuming the specification requires a Commercial Blast (SSPC-SP 6), select level SP6. Combine the two codes (B SP6). Locate the section of the SSPC-VIS 1 visual guide that contains the “before” photograph Rust Grade B and the “after” photographs of the four levels of surface cleanliness. Select the “after” photograph that contains the complete code (e.g. B SP6; red circle). Use this reference photograph to help assess whether the minimum surface cleanliness has been achieved (Step 4).
**Example 1 Images**
**Example 2:** If the steel contains a weathered coating system over mill scale with severe pitting, select Initial Condition G₃ (image within green circle). Assuming the specification requires a Near-white Blast (SSPC-SP 10), put the two codes together to arrive at the complete code (G₃ SP10), and locate the section of the SSPC-

**Example 2 Images**

VIS 1 visual guide that contains the “before” photograph Rust Grade G₃ and the “after” photographs of the five levels of surface
cleanliness. Select the “after” photograph that contains the complete code (e.g. G₃ SP10; image within black circle). Use this reference photograph to help assess whether the minimum surface cleanliness has been achieved (Step 4).

Using SSPC-VIS 3, Guide and Reference Photographs for Surfaces Prepared by Power and Hand Tool Cleaning

SSPC-VIS 3 is a collection of color reference photographs depicting seven initial conditions and three degrees of cleaning for each condition. To use the SSPC-VIS 3 visual guide follow these five steps.

**Step 1: Determine the initial condition of the steel surfaces:** Determine what the existing steel looks like before it is prepared by hand- or power-tool cleaning. Locate the reference photographs in the visual guide illustrating the seven possible initial conditions of the steel. These “before photographs” depict the condition of the steel before it was hand- or power-tool cleaned. The SSPC-VIS 3 guide illustrates seven *Initial Conditions*, including:

Condition A: Steel surface completely covered with adherent mill scale; little or no visible rust (Rust Grade A).

Condition B: Steel surface covered with both mill scale and rust (Rust Grade B).
Condition C: Steel surface completely covered with rust; little or no pitting visible (Rust Grade C).

Condition D: Steel surface completely covered with rust; pitting visible (Rust Grade D).

Condition E: Previously painted steel surface; mostly intact, light-colored paint applied to a blast cleaned surface.

Condition F: Previously painted steel surface; mostly intact, zinc-rich paint applied to a blast cleaned surface.

Condition G: Paint system applied to mill scale bearing steel; system thoroughly weathered, blistered or stained.

Select one or more of the “before” reference photographs that best illustrates the condition of the steel (the steel may be represented by more than one condition).

**Step 2: Determine the level of surface cleanliness the specification requires:** After you select a reference photograph(s) that depicts the existing condition of the steel surfaces (the “before photograph”), reference the project specification to determine the degree of surface cleanliness required. The degree of surface cleanliness will appear in the project specification as one of four possible “levels,” including SSPC-SP2, *Hand Tool Cleaning*; SSPC-SP3, *Power Tool Cleaning*; SSPC-SP11, *Power Tool Cleaning to Bare Metal*; or SSPC-SP15, *Commercial Grade Power Tool Cleaning*. 
Step 3: Locate the reference photograph in the visual guide: The SSPC-VIS 3 visual guide illustrates various levels of surface cleanliness (after hand or power tool cleaning is completed) for each of the conditions in Step 1. We’ll call these “after photographs.” Table 1 provides the combinations of initial conditions (before photographs) and surface cleanliness levels (after photographs).
Table 2 - Combinations of Initial Conditions and Surface Cleanliness Levels in SSPC-VIS 3

<table>
<thead>
<tr>
<th>Rust Grade/Initial Condition</th>
<th>Surface Cleanliness Levels Depicted in the Reference Color Photographs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hand Tool Cleaning (SP 2) and Power Tool Cleaning (SP 3)</td>
</tr>
<tr>
<td>B</td>
<td>Hand Tool Cleaning (SP 2) and Power Tool Cleaning (SP 3)</td>
</tr>
<tr>
<td>C</td>
<td>Hand Tool Cleaning (SP 2) and Power Tool Cleaning (SP 3)</td>
</tr>
<tr>
<td>D</td>
<td>Hand Tool Cleaning (SP 2) and Power Tool Cleaning (SP 3)</td>
</tr>
<tr>
<td>E</td>
<td>Hand Tool Cleaning (SP 2); Power Tool Cleaning (SP 3); Commercial grade Power Tool Cleaning (SP 15) and Power Tool Cleaning to Bare Metal (SP 11)</td>
</tr>
<tr>
<td>F</td>
<td>Hand Tool Cleaning (SP 2); Power Tool Cleaning (SP 3); Commercial grade Power Tool Cleaning (SP 15) and Power Tool Cleaning to Bare Metal (SP 11)</td>
</tr>
<tr>
<td>G</td>
<td>Hand Tool Cleaning (SP 2); Power Tool Cleaning (SP 3); Commercial grade Power Tool Cleaning (SP 15) and Power Tool Cleaning to Bare Metal (SP 11)</td>
</tr>
</tbody>
</table>

Select the reference photograph in the visual guide by combining the code for the initial condition (from column 1 in Table 2) and the code for the specified surface cleanliness level (from column 2 of Table 2).
**Step 4: Assess the prepared surfaces.**

Use the reference photograph selected in Step 3 to determine whether the prepared surface(s) meet or exceed the specified level of surface cleanliness. Here are two examples:

*Example 1:*
The surface contains 100% rust with little or no visible pitting:
Select Condition C

The specification requires SSPC-SP 2 Hand Tool Cleaning:
Select Image C SP2

*Example 2:*
The surface contains a thoroughly weathered paint system:
Select Condition G

The specification requires SSPC-SP 15 Commercial Grade Power Tool Cleaning:
Select Image G SP15

Agreement on the desired appearance of a cleaned surface using commercially available reference photographs is often difficult to achieve because of shadows and hues caused by the abrasive used, the pattern and degree of prior rusting and numerous other factors unique to each project. As a result, jobsite standards are often developed to reach agreement on the appearance prior to beginning production work. Sections of the structure (or test panels of a similar nature) are prepared and all parties involved ultimately select the panels or areas that are representative of the desired end-result.
Using ISO 8501-1, Preparation of Steel Substrates Before Application of Paints and Related Products -- Visual Assessment of Surface Cleanliness -- Part 1: Rust Grades and Preparation Grades of Uncoated Steel Substrates and of Steel Substrates After Overall Removal of Previous Coatings

The ISO 8501-1 Visual Guide (Figure 13) is similar in use to the SSPC VIS 1 and VIS 3 Guides previously described, however the images in the guide conform to the ISO surface cleanliness standards and not the SSPC surface cleanliness standards. Therefore, the images in the ISO 8501-1 guide should only be used when ISO surface cleanliness standards are specified.

Four initial conditions are shown:
Condition A: Steel surface completely covered with adherent mill scale; little or no visible rust.

Condition B: Steel surface covered with both mill scale and rust.

Condition C: Steel surface completely covered with rust; little or no pitting visible.

Condition D: Steel surface completely covered with rust; pitting visible.
Two levels of hand and power tool cleaning are shown for each condition:
St 2: Thorough Hand/Power Tool Cleaning
St 3: Very Thorough Hand/Power Tool Cleaning

Four levels of dry abrasive blast cleaning are shown for each condition:
Sa 1: Light Blast Cleaning
Sa 2: Thorough Blast Cleaning
Sa 2 ½: Very Thorough Blast Cleaning
Sa 3: Blast Cleaning to Visually Clean Steel

Use the ISO 8501-1 guide to inspect prepared surfaces using these three steps:
Step 1: Select the image that closely represents the existing condition of the surfaces.
Step 2: Determine the specified degree of cleanliness for the project specification.
Step 3: Select the image in the ISO visual guide that references both the initial condition code and the surface cleanliness code. Here are two examples:

Example 1:
Surface contains 100% adherent mill scale
Select Condition A

Very thorough Blast Cleaning is specified (Sa 2 ½)
Select Image A Sa 3

Example 2:
Surface contains 100% rust
Select Condition C
Thorough Hand/Power Cleaning is specified (St 2)
Select Image C St 2

**Assessing Surface Dust**

After the specified level of surface cleanliness has been achieved and the surface profile depth has been measured and recorded, the prepared surfaces should be examined to assess whether they contain levels of dust that may interfere with coating adhesion.

Dust and debris remaining on the surface is frequently removed by brushing, compressed air blow down (or double blow down), or by vacuuming. If the compressed air is used, it must first be verified for cleanliness per ASTM D4285, “*Standard Test Method for Indicating Oil or Water in Compressed Air.*” While a “white glove” test is not necessary nor recommended, if gloved fingers are traced across the surfaces and tracks are visually evident on the surface, then excessive dust remains and can interfere with primer adhesion and/or cause application defects. Alternatively, ISO 8502-3: *Preparation of Steel Substrates Before Application of Paints and Related Products – Tests for the Assessment of Surface Cleanliness, Part 3: Assessment of Dust on Steel Surfaces Prepared for Painting (pressure-sensitive tape method)* can be used to evaluated the presence of surface dust.

To perform this test, a special type of clear, pressure sensitive 1-inch wide adhesive tape, a special spring-tensioned roller, a 10X illuminated magnifier and a white backing (e.g., bright white cardboard or paper) are needed. The spring-tensioned roller is not required by the standard unless the testing procedure or
results are being disputed. The roller can be replaced by thumb pressure applied to the tape, as described below.

Step 1: Discard three full turns of tape from the roll.

Step 2: Remove a test piece of tape approximately 8-inches long, being certain to only touch the two ends (1-inch at each end). Attach (press) approximately 6-inches of the tape (excluding the two – 1-inch ends) to the surface.

Step 3: Press the tape to the surface by placing your thumb at one end of the tape, then move your thumb along the tape length (at a constant speed and pressure) three times in each direction (each stroke should take between 5 and 6 seconds to complete). Leave the two 1-inch ends of the tape up from the surface. Only the middle 6-inches of the tape should be attached.

Step 4: Remove (peel) the tape from the surface at a 180° angle (to the surface). Attach the peeled tape to a white backing.

Step 5: Rate the quantity of dust attached to the tape using the Dust Quantity Ratings figure provided in the standard (Figure 14) and compare the results to the specification requirements for the maximum dust rating. The standard requires one test for every 200 square feet of prepared surface that is ready to be primed.
Surface Soluble Salt Detection

Chemical contaminants on a surface can include chloride, ferrous ions, sulfates and nitrates, among others. These chemicals are deposited onto surfaces while the structure is in service, or during transportation of new pipe/steel to the fabrication shop. These chemicals are soluble in water, so they can typically be removed from surfaces by pressure washing. The effectiveness of the washing step is dependent on the condition of the surface. That is, contamination is relatively easy to remove from smooth surfaces, but may be more challenging if the surfaces are pitted or are configured with difficult-access areas, as contamination will tend to concentrate in these areas. If the salts are not detected or are not adequately dissolved and rinsed from the surfaces, they can become trapped beneath a newly-installed coating system. If there is a sufficient quantity of water in the environment, the water-soluble contaminant trapped beneath the coating system will draw the water through the coating film by a process known as “osmosis.” This drawing force
will continue until the concentration of salt in water is the same on both sides of the coating film (the concentration reaches equilibrium). This process creates a build-up of water and pressure beneath the coating film, oftentimes enough to cause blistering of the coating (known as osmotic blistering), underfilm corrosion and premature coating failure.

Additionally, if soluble salts on the surface are not sufficiently removed prior to abrasive blast cleaning, recycled abrasive media can become contaminated.

It is for these reasons that many specifications are now requiring testing of surfaces for chemical contaminants after surface preparation is complete, but before application of the primer. Because this type of contamination cannot be detected visually, the surface must be sampled and the “surface extraction” tested for the contaminant(s) of concern. There are several methods to choose from. SSPC Guide 15, “Field Methods for Retrieval and Analysis of Soluble Salts on Steel and Other Nonporous Surfaces” describes common methods for sampling and analysis of soluble salt contamination, with the intent of assisting the user in selecting an extraction and analysis procedure.

This eBook highlights two procedures, including a non-ion-specific method (conductivity) and an ion-specific method for chloride, sulfate and nitrate contamination. Specific step-by-step instructions are too lengthy to provide in this eBook, but the ISO standard and/or the manufacturer’s instructions are relatively easy to follow.
Non-ion specific Analysis (Latex Patch/Conductivity per ISO 8502-6/8502-9)

For this procedure, attach a latex patch (Bresle Patch, Figure 15; DeFelsko Patch or PosiPatch, Figure 16) to the prepared, uncoated surface using an adhesive or a magnet. Inject the prescribed amount of distilled water into the patch and agitate the water inside the patch (Figure 17a/17b). Once the extraction is complete, remove the solution from the patch and place it onto a conductivity bridge (Figure 18) or Soluble Salts Tester (Figure 19). Conductivity results are displayed in microsiemens/cm ($\mu$S/cm) or millisiemen (mS/cm); surface concentrations are displayed in $\mu$g/cm$^2$ or mg/m$^2$. Either can be compared to the maximum allowable contamination referenced in the project specification.
This test will not reveal the type of surface contamination; only that some type of water soluble ionic contamination was extracted from the surface, causing an increase in the conductivity of the distilled water used for the extraction.
Ion-specific Analysis – Chloride-Sulfate-Nitrate (CSN) Test Kit

If ion-specific testing for chloride, sulfate and nitrate surface contamination is required, then a special kit is required to perform both the extraction and analysis. The CSN kit contains latex sleeves, pre-measured extraction liquid, chloride ion detection tubes (Kitagawa), nitrate test strips, and pre-measured chemicals and a meter for sulfate analysis.

A premeasured amount of extraction solution is emptied into the latex sleeve (Figure 20) and the sleeve is attached to the prepared, uncoated surface (Figure 21). An extraction is performed (Figure 22), the latex sleeve removed and the solution analyzed for chloride (Figure 23), nitrate (Figure 24) and/or sulfate (Figure 25). Because the opening of the latex sleeve is 10 cm$^2$ and the premeasured amount of solution is 10 mL, these values cancel one another, so the reading from the tube, strip and meter (in PPM) is the same as µg/cm$^2$. 
Conclusion

Surface preparation is considered the foundation for the coating system. In this case, installing a solid “foundation” includes verifying that the surface is prepared according to the project specification prior to application of the primer. This frequently involves quality control check points to verify conformance and to correct deviations before they become nonconformities. Common quality check points include those described in Chapter 1 of this eBook series - *Surface Preparation and Coating Application Inspection Instruments*. 
Chapter 2: Verifying the Quality of the Application of Protective Coatings
Introduction

Common quality control checkpoints associated with coating application include:
• Measuring Prevailing Ambient Conditions & Surface Temperature
• Measuring the Coating Temperature
• Calculating and Measuring the Wet Film Thickness
• Measuring Dry Film Thickness

Measuring Ambient Conditions & Surface Temperature

The measurement of air temperature, relative humidity, dew point temperature, and surface temperature is oftentimes required before and during coating application activities (Figure 1, right). Air or surface temperatures above/below the manufacturer’s specified range, as well as excessive or inadequate moisture levels in the air (humidity) can contribute to application challenges, inadequate curing and performance problems. In addition, a surface temperature at or below the dew point temperature can result in moisture condensation on the surface. Therefore, it is important to verify that the
The temperature of the surfaces to be coated is at least 5°F (3°C) higher than the temperature of the dew point, and to verify that the air and surface temperatures, as well as the relative humidity, are all within the coating manufacturers’ specified range or as required by the project specification. These values (air temperature, relative humidity, surface temperature and dew point temperature) can be obtained using sling (Figure 2, top left) or battery-powered psychrometers (Figure 3, top right) in conjunction with US Weather Bureau Psychrometric Tables (Figure 4, bottom left) and surface temperature.
thermometers (Figure 5, right) or can be obtained using electronic psychrometers equipped with surface temperature probes (Figures 6 below and 7 very bottom). Each of these procedures is described herein.
Ambient conditions should be measured and recorded prior to mixing the coating materials and at 4-hour intervals thereafter, unless conditions appear to be declining. In this case, more frequent checks may be required. The prevailing ambient conditions at the actual location of the work should be assessed. The location, date, time of day and the conditions of air temperature, relative humidity, dew point temperature, and surface temperature should be recorded.

Traditional and least expensive methods of measuring the prevailing ambient conditions include the use of whirling psychrometers in accordance with ASTM E337, *Standard Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)*, psychrometric charts, and dial-type surface temperature thermometers.

The whirling or battery-powered psychrometer is used to measure the air temperature and to assess the latent heat loss caused by water evaporation from a wetted sock on the end of a bulb thermometer. The psychrometric tables are used to look-up the relative humidity and dew point temperature (based upon temperature readings from the psychrometer and the barometric pressure).
Sling and the battery-powered psychrometers are each equipped with two bulb thermometers. The two thermometers are identical, except that one has a wick or sock covering the end of the bulb. This thermometer is called the wet bulb. The thermometer without the wick is called the dry bulb thermometer (Figure 8 above). Follow Steps 1 through 3 below to obtain the dry bulb and wet bulb temperatures.

Step 1 - Verify that the wick surrounding the wet bulb thermometer is relatively clean.

Step 2 - Saturate the wick with distilled water, or fill the water reservoir at the end of the sling psychrometer (Figure 9, above).
Step 3 –
For the sling psychrometer, whirl the instrument (Figure 10, left) through the air (away from your body) for approximately 15 or 20 seconds, then obtain a reading from only the wet bulb thermometer. *Without* re-wetting the wick, whirl the instrument for another 10 or 15 seconds and obtain another temperature reading from the wet bulb thermometer. Repeat this process until the two consecutive temperature readings are within 0.5°F of one another. This is considered a stable wet bulb temperature. Then read and record the dry bulb (air) temperature.

If you are using a battery-powered psychrometer, a fan draws the air across the thermometers, rather than whirling them through the air. Allow the fan to operate for approximately 2 minutes, then record the wet bulb temperature after it stabilizes, as well as the stable dry bulb (air) temperature.
Determining the Dew Point Temperature and Relative Humidity

The next step is to determine the relative humidity and the dew point temperature. The relative humidity is the amount of moisture in the air, relative to total saturation at the given temperature. This is expressed as a percentage (e.g., the relative humidity is 56%). The dew point is the temperature that moisture in the air will condense on a surface. The surface temperature needs to remain warmer than the dew point temperature for coating work to begin or continue to be assured that moisture is not present. If the temperature of the surface is at or below the dew point, condensation will form, and it may not even be visible.

The US Weather Bureau Psychrometric Tables contain charts that are used in conjunction with dry bulb temperature and the depression of the wet bulb thermometer from the dry bulb (air) temperature to determine the relative humidity and dew point temperature.

One set of charts is used for calculating relative humidity and another set is used for calculating dew point. The names of the charts are at the top of each page. First, locate the charts of interest (e.g., dew point temperature), and select the ones that correspond to 30-inches barometric pressure. If the exact barometric pressure where the project is located is known (e.g., 29 inches), use those charts instead.

Locate the dew point chart at the appropriate barometric pressure (say 30 inches) and find the dry bulb temperature (air temperature) reading in the far left-hand column, entitled “air
temperature $t'$. Subtract the wet bulb reading from the dry bulb reading. The difference is the “depression of the wet bulb thermometer” ($t-t'$). Locate the depression of the wet bulb thermometer across the top row of the table. Intersect the depression of the wet bulb thermometer (along the top row) with the air temperature (down the left column). The intersection of the two values represents the dew point temperature in °F (*Figure 11, next page*). Repeat this same process using the relative humidity charts at the appropriate barometric pressure (*Figure 12 on two pages from now*).
### TABLE VI.—Relative humidity, percent—Fahrenheit temperatures—Continued

[Pressure=20.0 inches]

<table>
<thead>
<tr>
<th>Air temperature f</th>
<th>Depression of wet-bulb thermometer ((t' - t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
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<tr>
<td>2.0</td>
<td></td>
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<td>2.5</td>
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<td>7.0</td>
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<td>9.0</td>
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<td>9.5</td>
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</tr>
<tr>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>10.5</td>
<td></td>
</tr>
</tbody>
</table>

Example data entries might include: 20°F, 85%, 70°F, 62°F, etc.
Use of Digital Psychrometers to Assess Ambient Conditions

As an alternative to sling and battery-operated psychrometers, digital psychrometers can be used to determine the prevailing weather conditions (*Figure 13, top left*). These gages digitally display the air temperature, relative humidity, dew point temperature and surface temperature essentially at the push of a button. One manufacturer features a hot wire probe to monitor wind speed (*Figure 14, bottom left*). Although the digital psychrometers provide “instantaneous” results, before taking any readings, they must be acclimated to the environmental conditions in the location of use for up to 30 minutes. This means you should not take the instrument from an air-conditioned office trailer and expect to take readings a few minutes later outside. This is often overlooked, resulting in inaccurate readings. In comparison, the sling and battery-operated psychrometers do not have to be acclimated to the environment before use.
Use of Surface Temperature Measuring Instruments

There are a variety of instruments for measurement of surface temperature, including analog and digital contact thermometers as well as non-contact infrared pyrometers. As discussed earlier, most digital psychrometers have surface temperature measurement capability.

A common surface temperature thermometer is analog and contains a bi-metallic, temperature-sensing spring on the back of the thermometer that expands and contracts with the temperature of the surface (*Figure 15, above left*). Since the spring is attached to the indicator needle on the front side of the thermometer, the needle moves across the temperature scale, indicating the surface temperature. Magnets attached to the back of the thermometer enable self-attachment to vertical steel surfaces, although this thermometer can be used on almost any surface, by taping it in place if necessary. Thermocouple digital surface temperature gages are quicker and more accurate than the analog type.
Non-contact infrared pyrometers (Figure 16, left) can also be used to measure surface temperature. These gages are often equipped with laser sightings, so that the user can target the location on the surface to be measured. However, the further away from the surface that the “gun” is held, the larger the area of measurement, causing potential error. Also, there is a maximum distance, depending on the make and model of the thermometer.

Calibration of Equipment for Measuring Ambient Conditions and Surface Temperature
Calibration and/or verifying the accuracy of any coating inspection instrument is paramount to the reliability of the data it produces. This section describes the calibration and verification procedures for instruments used to assess ambient conditions and surface temperature.

Calibration of Psychrometer Thermometers
The bulb thermometers in sling and battery-operated psychrometers cannot be “calibrated” per se. However, their accuracy can be routinely verified by comparing the
thermometer readings with that of a thermometer traceable to the National Institute of Standards and Technology (NIST), or in a controlled temperature chamber.

Cover the bulb thermometers and the traceable thermometer with a dry cloth until stabilization occurs (30 minutes minimum). The wick must be removed from the end of the wet bulb before placing the thermometers beneath the dry cloth. Uncover the thermometers and quickly compare the readings of the two psychrometer bulbs to the traceable thermometer reading. If the readings are outside of the tolerance of the psychrometer bulbs (typically +/- 1°F), the psychrometer bulb(s) should be replaced.

Calibrating Analog Surface Temperature Gages
Analog surface temperature gages also cannot be calibrated, but the accuracy against a traceable thermocouple-type surface temperature probe can be plotted on a curve.

Calibrating Digital Psychrometers and Surface Temperature Thermometers/Pyrometers
Digital psychrometers and surface temperature thermometers can be calibrated either by the equipment manufacturer, an accredited calibration laboratory or an authorized service center. Annual calibration is recommended by most manufacturers. Unfortunately, field verification of accuracy is not possible with this type of equipment.
Measuring the Coating Temperature

The induction time and pot life of a mixed coating is based on the temperature of the coating material. Additionally, some coating manufacturers list a minimum coating material temperature for application on their product data sheets. So, the ability to measure the temperature of the mixed coating is an important consideration. Stem-type paint thermometers, immersion-type thermocouples and non-contact infrared pyrometers can all be used. The stem-type thermometers (*Figure 17, top left*) will require a few minutes to stabilize and the infrared pyrometers only measure the surface of the coating in the container.

Calculating Wet Film Thickness

Prior to mixing, thinning and applying the coating, the target wet film thickness (WFT) should be determined. Some coating manufacturers list the WFT on the product data sheet (PDS) but many do not. Even when the target WFT is listed on the PDS, the contractor will need to verify that the dry film thickness (DFT) in the PDS that it is based on is the same as the DFT.
specified for the product. Further, if the coating will be reduced (thinned), the target WFT must be adjusted based on the amount of thinner added, so the target WFT in the PDS will no longer be accurate. While in most cases the facility owner is concerned with the dry film thickness and not the wet film thickness, the contractor must ensure that the proper wet film thickness is applied so that the specified dry film is achieved. If it is discovered that the coating is too thin or too thick after it dries, costly rework is often required. It is better to confirm that the proper amount of paint is being applied to begin with.

The step-by-step instructions provided below are for calculating a target wet film thickness of both un-thinned and thinned coating, based on the specified dry film thickness (from the specification or PDS), the volume solids content of the coating (from the PDS), and when applicable, the amount of thinner added to the coating.

**Calculating the WFT when using a coating as manufactured**

To calculate wet film thickness, you will need two values:

Value No. 1: The target dry film thickness (DFT) from the specification or PDS

Value No. 2: The solids by volume content of the coating material from the PDS

Formula: \( WFT = \frac{\text{DFT}}{\% \text{ solids by volume}} \)
Enter the values into the formula to arrive at the wet film thickness range.

**Example:** *DFT range of 2-4 mils with no thinner added (solids by volume of 75%):*

2 mils $\text{DFT} \div 0.75 = 2.7$ mils WFT  
4 mils $\text{DFT} \div 0.75 = 5.3$ mils WFT  

Therefore, the applicator should apply the coating in the range of 3-6 mils WFT to achieve a DFT of 2-4 mils.

**Calculating the WFT when using a coating that is thinned**

To calculate wet film thickness, you will need *three* values:

Value No. 1: The target dry film thickness (DFT) from the specification or PDS  
Value No. 2: The solids by volume content of the coating material from the PDS  
Value No. 3: The amount of thinner that will be added to the coating (indicated on the PDS)

Formula: \[ \text{WFT} = \frac{\text{DFT}}{\left[ \frac{\% \text{ solids by volume}}{100\% + \% \text{ thinner added}} \right]} \]

This formula has two steps:

Step 1: \[ \frac{\% \text{ solids by volume}}{100\% + \% \text{ thinner added}} = \text{adjusted volume solids content} \]

Step 2: \[ \text{DFT} \div \text{adjusted volume solids content} = \text{WFT} \]
Enter the values into the formula to arrive at the wet film thickness range.

**Example – DFT range of 4-6 mils, Volume Solids 65% with 15% thinner added:**

\[(65 \div 115) = 0.57\] adjusted volume solids content

4 mils DFT \(\div 0.57 = 7.0\) mils WFT

6 mils DFT \(\div 0.57 = 10.5\) mils WFT

Therefore, the applicator should apply the coating in the range of 7-11 mils WFT. Even with the addition of 15% thinner, the coating should reduce to 4-6 mils once dry.

The solids by volume content (as a percentage of the total coating material) remains a key component in the calculation of the wet film thickness. However, the published value may be “theoretical” and based on the formulation, or may not account for complete coating film shrinkage. Therefore, the contractor may choose to apply a test area of the coating (thinned if appropriate), measure the wet film thickness, then after the coating dries on the test area, measure the dry film thickness. This will provide the applicators with a “practical” wet film target. If the resulting dry film thickness meets the requirements of the specification, the actual volume solids content of the coating material becomes a moot point. Conversely, if the resulting dry film thickness is too low or too high, the actual percentage of volume solids can be calculated, provided the wet film and dry film thickness is known. Then the revised target wet film thickness can be calculated. This is
illustrated below. Concurrently, the applied coating film can be evaluated for flow characteristics, resistance to sag, etc.

**Target DFT (from the specification): 5 mils**
**Calculated Target WFT (based on 50% solids by volume): 10 mils**
**Actual WFT (measured): 10 mils**
**Actual DFT (measured): Only 4 mils**

\[
\frac{\text{Actual DFT} \times \text{Actual WFT}}{100} = \text{Adjusted Percent Volume Solids Content}
\]

\[
\frac{4}{10} \times 100 = 0.40 \text{ or } 40\%
\]

**Revised Target WFT = 5 mils DFT / 0.40 = 12.5 mils WFT**

**Measuring Wet Film Thickness**

Once the target WFT is calculated, the thickness of the wet coating film can be monitored as it is applied using a wet film thickness gage. These are known as notch-type gages and conform to ASTM D4414, *Standard Practice for Measurement of Wet Film Thickness by Notch Gages*.

All notch-type gages contain four or eight faces with a series of steps, with notches between the steps. Each step is numbered. The number corresponds to the wet film thickness in mils (0.001”) or micrometers (µm). There are 25.4 µm in 1 mil.
The traditional aluminum (Figure 18, top left) and hardened steel (Figure 19, bottom left) wet film thickness gages have four (4) measuring faces. Each face contains a different wet film thickness range. The chart below provides the measuring ranges for each of the four faces, for both the aluminum and hardened steel type gages.
<table>
<thead>
<tr>
<th>WFT Gage Type</th>
<th>WFT Range on each Face</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Face 1</td>
</tr>
<tr>
<td>Hardened Steel (low)</td>
<td>½ - 2 mils</td>
</tr>
<tr>
<td>Hardened Steel (medium)</td>
<td>4 - 10 mils</td>
</tr>
<tr>
<td>Hardened Steel (high)</td>
<td>10 - 40 mils</td>
</tr>
<tr>
<td>Aluminum (Side 1-mils)</td>
<td>1 - 6 mils</td>
</tr>
<tr>
<td>Aluminum (Side 2-µm)</td>
<td>25-150 µm</td>
</tr>
</tbody>
</table>
Two limitations of traditional WFT gages are: (1) there isn’t a single, accurate gage that includes the full range in both mils and microns, and (2) the tolerance of the steps is unknown (Certificates of Accuracy are either not available or very costly). A precision 4-in-1 wet film gage (Figure 20, top) eliminates the need for multiple gages to measure the full range, and the need for a gage in mils and another in micrometers. With mils on one side and microns on the other, the gage essentially has eight faces. Even more importantly each gage comes with a Certificate of Traceability that illustrates the precision of the gage, making wet film thickness measurement more reliable and reducing the chances for rework.
**Precision 4-in-1 WFT Gage**

<table>
<thead>
<tr>
<th>Face</th>
<th>Mils</th>
<th>Micrometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>1-5 mils</td>
<td>25-125 µm</td>
</tr>
<tr>
<td>B₁</td>
<td>6-10 mils</td>
<td>150-250 µm</td>
</tr>
<tr>
<td>C₁</td>
<td>11-15 mils</td>
<td>275-375 µm</td>
</tr>
<tr>
<td>D₁</td>
<td>16-20 mils</td>
<td>400-500 µm</td>
</tr>
<tr>
<td>A₂</td>
<td>22-30 mils</td>
<td>550-750 µm</td>
</tr>
<tr>
<td>B₂</td>
<td>32-40 mils</td>
<td>800-1,280 µm</td>
</tr>
<tr>
<td>C₂</td>
<td>42-50 mils</td>
<td>1,050-1,250 µm</td>
</tr>
<tr>
<td>D₂</td>
<td>52-60 mils</td>
<td>1,300-1,500 µm</td>
</tr>
</tbody>
</table>

Immediately after the wet coating film is applied, insert measuring face into the wet coating, perpendicular to the surface (*Figure 21, left*). The two “end steps” on the face selected must penetrate down to the previous layer, or the substrate if measuring the thickness of the first coat. Withdraw the gage from the wet film. The two end steps that penetrated down to the previous layer will be coated with paint. Observe the numbered steps between to the two end steps. The
highest numbered step containing wet paint is the wet film thickness (Figure 22, left). If all numbered steps are coated, then choose a face on the gage that represents a higher wet film thickness range. If none of the numbered steps are coated, then choose a face on the gage that represents a lower wet film thickness range. Clean the gage, then repeat this step in several other areas and/or as application progresses to verify that the WFT remains consistent.

**Measuring Dry Film Thickness (DFT) on Coated Steel**

There are two common standards that are frequently referenced in project specifications for measuring DFT, including ASTM D7091, *Standard Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals* and SSPC-PA 2, *Procedure for Determining Conformance to Dry Coating Thickness Requirements*.

The current version of the ASTM standard (2013) focuses on proper gage use, while SSPC-PA2 focuses primarily on the
frequency and acceptability of the measurements. These two documents do not contain conflicting information; they were written to complement one another and are designed to be used in conjunction.

**Traditional Coating Thickness Measurement**

There are two common types of coating thickness gages including Type 1 (magnetic pull-off) (top left) and Type 2 (electronic, with integral probes) (bottom left).
Type 1 Magnetic Pull-off Gages

For the Type 1 magnetic pull-off gages (Figure 24, left), a permanent magnet is brought into direct contact with the coated surface. The force necessary to pull the magnet from the surface (created by tightening a calibrated, helical spring) is measured and indicated as the coating thickness on an analog scale. The principle is quite simple - less force is required to remove the magnet from a thick coating, compared to a thinner coating, since the magnet is closer to the steel and will have greater attraction.

Calibration and Verification of Accuracy

The ASTM D7091 standard practice and the SSPC-PA 2 standard describe three steps associated with assuring accurate measurement processes, including gage calibration, verification of accuracy and adjustment. Each of these steps must be completed before coating thickness measurements are made.

Calibration

Coating thickness gages must be calibrated by the manufacturer, an accredited calibration laboratory or a manufacturer’s authorized service center. A Test Certificate or
other documentation showing traceability to a national metrology institution is required. There is no standard time interval for re-calibration, nor is one absolutely required. Calibration intervals are usually established based upon experience and the work environment. A one-year calibration interval is a typical starting point suggested by gage manufacturers.

**Verification of Accuracy**

To verify the accuracy of Type 1 gages, the thickness of a series of coated reference standards covering the expected range of coating thickness is measured (Figure 25, above). To prevent acquiring measurements with an inaccurate gage, the gage should be checked at least at the beginning and the end of each work shift. If the gage is dropped or suspected of giving erroneous readings during the work shift, its accuracy should be rechecked. Unless a gage manufacturer explicitly allows it, certified shims used to verify the accuracy of Type 2 electronic gages (described later) are not permitted to be used with Type 1 gages.
Single Point Verification

When verifying the accuracy of Type 1 or Type 2 gages, the user can employ a single point or two-point process. For single point verification, a single reference test block is selected that is at or close to the thickness to be measured. For example, assuming the coating thickness to be measured is 4-6 mils, a reference standard of approximately 5 mils should be used to verify gage accuracy.

Two-Point Verification

For two-point verification, two reference standards are selected - one above and one below the expected film thickness to be measured. For example, assuming the coating thickness to be measured is 5 mils, reference standards of 3 mils and 7 mils are appropriate for establishing a range of accuracy.

When documenting gage adjustment processes, the serial number of the gage, the reference standard used, the stated thickness of the reference standard as well as the measured thickness value obtained, and the method used to verify gage accuracy are recorded. If the same gage, reference standard, and method of verification are used throughout a job, they only need to be recorded once, but the stated value of the standard and the measured value must be recorded each time accuracy is verified.

Adjustment

Type 1 gages have nonlinear scales, whereas any adjusting feature is linear. As a result, any adjustment of these gages will
limit the DFT range for which the gage will provide accurate readings and is not recommended. Furthermore, the application of a single “correction value” representing the full range of the gage to compensate for a gage that is not measuring accurately is not appropriate, since the correction will also be non-linear. Therefore, if the gage reading is outside of the combined tolerance of the gage accuracy and the coated reference standard accuracy, it should be removed from service and repaired or replaced. For example, if the manufacturer’s stated accuracy for the gage is ± 5% and the tolerance of the traceable coated standards is ± 3%, the combined tolerance is 5.8% (the calculated square root of \[5^2 + 3^2\]). Therefore, the gage reading on a 10-mil coated reference standard can range from 9.4-10.6 mils. A reading outside of this range indicates that the gage is out of tolerance and should not be used, or that the exposed magnetic probe has become contaminated.

Compensating for Surface Roughness

Once the Type 1 thickness gage is verified for accuracy, the next step is to measure and record the Base Metal Reading or BMR, since Type 1 gages cannot be adjusted. This is accomplished by placing the gage magnet on the prepared, uncoated substrate and obtaining a measurement (Figure 26, above).
Let’s explore this concept a little closer. The specified dry film thickness of each coating layer is to be measured from the tops of the peaks of the surface profile. However, most coating thickness gages must reach down into the surface roughness to satisfy the magnetic properties of the gage. As a result, the effect of the surface profile (roughness) on the thickness gage must be measured using the same DFT gage and subtracted from the coating thickness measurement. This is known as a base metal reading or BMR. Think of it as a background reading that the prepared, uncoated metal provides.

The BMR is the effect of surface roughness on a coating thickness gage – it is not surface profile. There is no correlation between surface profile depth and the effect of this roughness on a coating thickness gage. The BMR will vary widely, ranging from 0.1 mil to over 1 mil. Therefore, minimum of 10 measurements of the base metal are made and the average BMR is calculated. The average BMR is subtracted from the thickness of each coat, to determine the thickness of the coating film above the peaks of the surface profile.
Type 2 Electronic Gages with Integral Probes

Type 2 electronic gages use electromagnetic principles and electronic circuitry to convert a reference signal and display it as coating thickness (Figure 27, above). Generally, Type 2 gages are more accurate than Type 1 gages, are not susceptible to vibration, and data acquisition is typically much faster. Also, most Type 2 gages can store readings and provide statistical analysis of the data, and once the data is generated and stored, it can be uploaded into a computer software program or downloaded to a printer. Measurement frequencies such as those described in SSPC-PA 2 are often programmed into Type 2 gages. The gage probe is placed onto the coated surface and the measurement is revealed on the display (in mils or micrometers).

Calibration

Like Type 1 gages, Type 2 coating thickness gages must be calibrated by the manufacturer, an accredited calibration laboratory or a manufacturer’s authorized service center. A Test Certificate or other documentation showing traceability to a national metrology institution is required. There is no standard time interval for re-calibration, nor is one absolutely required. Calibration intervals are usually established based

![Type 2 Electronic Gage](image-url)
upon experience and the work environment. A one-year calibration interval is a typical starting point suggested by gage manufacturers.

**Verification of Accuracy**

To verify the accuracy of Type 2 gages, the thickness of a series of coated reference standards covering the expected range of coating thickness is measured (*Figure 28, left*) using either the single point or two-point verification process, described earlier for the Type 1 gage. However, in this case, unless strictly prohibited by the manufacturer, the gage is adjusted to match the thickness of the standards. To prevent acquiring measurements with an inaccurate gage, the gage should be checked at least at the beginning and the end of each work shift. If the gage is dropped or suspected of giving erroneous readings during the work shift, its accuracy should be rechecked. As an alternative to certified coated standards, certified shims placed on a smooth steel surface used to verify the accuracy of Type 2 electronic gages.
Adjustment

The final step in verifying gage accuracy is to align the Type 2 gage to a known value to improve gage accuracy on the specific type and design of surface or within a specific measurement range. Some refer to this step as gage optimization. In this case, the gage is adjusted (when permitted by the gage manufacturer) to match the value on a measured shim or certified shim by placing the shim(s) directly onto the prepared, uncoated structure or part under the same conditions of air and surface temperatures that the coating will be measured under (*Figure 29, previous page*). This also compensates for curvature of the component or structure, the alloy of the steel, surface roughness (profile), proximity to edges or other surface conditions.

**Novel Approaches to Dry Coating Thickness Measurement**

The traditional methods of dry coating thickness measurement have been in existence for decades. Type 2 electronic gages offer novel approaches to gathering DFT data, including remote probes, microprobes and scanning/continuous read probes.
Remote Probes (on a short cable attached to the gage; Figure 30, above left), enabling easier measurement access, especially on the underside of pipe, and even wireless probes that communicate with a read-out device using Bluetooth technology, including Smart Phones (Figure 31, above right).

Micro-Probes

Traditionally we have been taught to stay at least 1” away from all edges when measuring coating thickness. However, coating build on edges, known as edge retention, is a concern particularly in immersion environments. And many gage manufacturers now produce micro probes for measuring
coating thickness on small parts, as these probes are less affected by proximity to edges (Figure 32, above). Appendix 6 in SSPC-PA 2 describes a procedure for measuring coating thickness on edges, and suggests a minimum of three gage readings along 1.5 linear inches, which is equivalent to a spot measurement. The number of spots will vary depending on the total length of the edge. SSPC Guide 11, Protecting Edges, Crevices, and Irregular Steel Surfaces by Stripe Coating addresses edge preparation, stripe coating procedures and the use of edge-retentive coatings.

Scanning Probes

Several manufacturers of electronic coating thickness gages have incorporated “scanning probe” technology, and the associated support software, into the data acquisition process. This newer technology enables the gage operator to obtain large sets of coating thickness data in a relatively short time frame. To illustrate this concept, data was obtained by a certified coatings inspector on a recoating project that included 12 batches of readings (nearly 600 readings) obtained in just under 8 minutes (measurement time only). So, it may be possible to obtain a greater, more representative sampling of the coated area without impeding production. However, there are concerns with acquiring such large data sets, such as management of the data, handling outliers, determining the statistical significance of the data (i.e., what is an acceptable standard deviation), etc. The preparation of a non-mandatory appendix (i.e., Appendix 10) to the SSPC-PA 2 standard that addresses the acquisition of large data sets has been proposed.
SSPC-PA 2 describes a frequency of coating thickness measurements. Figure 33 (above) was extracted from the standard. It illustrates three gage readings taken in each of 5 spots in an area of approximately 100 square feet. The average of the three gage readings in each of the 5 spots has been calculated. The number of 100 square foot areas that are to be measured is based on the total square footage of the coated area:
➢ For areas of coating not exceeding 300 square feet, each 100-square foot area is measured. As a result, the maximum number of areas to be measured will be 3.

➢ For areas of coating greater than 300 square feet but not exceeding 1000 square feet, three 100 square foot areas are arbitrarily selected and measured.

➢ For areas of coating exceeding 1000 square feet, three 100 square foot areas are measured in the first 1000 square feet. For each additional 1000 square feet or portion thereof, one additional 100 square foot area is arbitrarily selected and measured.

Conclusion

While surface preparation is considered the foundation for the performance of the coating system, proper installation of the system is critical to the protection of the substrate, and to prevent premature coating failure and preserve structural integrity. This includes verifying that the coating system is applied according to the manufacturer’s instructions, and that the wet film and resulting dry film thickness is achieved for each coating layer. This involves quality control check points to verify compliance with the specification and to correct deviations before they become nonconformities.
Chapter 3: Verifying the Quality of the Application of Protective Coatings Post-Application
**Introduction**

Common quality control checkpoints associated with post-coating application inspection include:

- Holiday Detection
- Hardness Testing
- Adhesion Testing

**Holiday Detection** Project specifications for the application of coatings and linings to liquid and gas pipelines, tanks, vessels, tank cars frequently require a continuous coating system. Rather than relying on a visual inspection, special detectors are used to determine the number and location of skips, misses, and pinholes, so that they can be repaired prior to placing the pipeline into service. The pipeline industry frequently refers to this procedure as “jeep” testing (Figure 1). If holiday, pinhole or “jeep” testing is not performed, and there are undetected voids in the coating system, the performance of the cathodic protection system could be affected (if the voids are extensive), and the exposed substrate could corrode, with the potential for pitting corrosion, section loss, and

Pinhole or holiday detection is usually conducted after the final coat has been applied, but before it has achieved complete cure in the event repair of the coating film is required.

The terms “pinhole” and “holiday” are often used interchangeably. However, they represent two different types of “breaches” in the coating system. **Pinholes** are tiny voids in the coating that penetrate through a layer or layers of the system, potentially to the substrate. These voids allow the service environment to have direct or nearly direct access to the metal substrate via tiny “pathways.” **Holidays** are considered “skips” or “misses” in the coating/lining system (just like holidays are skips in the work calendar). These uncoated areas also permit easy access to the unprotected substrate.

Pinholes can be caused by poor wetting of the
coating on the surface during application, or out-gassing (displacement) of air without subsequent flow-out of the coating. Holidays are areas that are missed by the applicator. They may be caused by the configuration of the structure being coated (i.e., difficult to access with the application equipment), or lack of attention to detail by the applicator. Most holidays and pinholes are found on areas that are difficult to protect or access, such as edges and corners, welds, bolts, nuts and threads, behind angles and clips, inside holes, between back-to-back angles, etc. Large, flat surfaces that are easier to access and coat usually contain fewer pinholes and holidays.

There are two different types of holiday detectors, low voltage and high voltage; selection of the specific type is based on the total thickness of the coating/lining system. Low voltage or “wet sponge” holiday detectors are used on coatings/linings that are less than 20 mils (508 µm) thick. High voltage holiday detectors or “spark testers” are typically used on coatings greater than 20 mils thick. Independent of coating thickness, both detectors will only work on non-conductive coatings applied to a conductive substrate. For example, epoxy coatings applied to steel can be tested for holidays, while a zinc-rich coating applied to the same steel cannot (zinc is a conductive metal in coating).
Low Voltage (wet sponge) Holiday Detection

There are several manufacturers of low voltage holiday detectors; all operate on a similar principle, and most operate on 67.5 volts DC using battery power (Figure 2). A sponge is clamped to the end of a wand and is wetted with tap water containing a low-sudsing wetting agent (about 0.5 oz./gallon [15 mL/3.8 L]) supplied by most low voltage holiday detector manufacturers/suppliers. Kodak Photo-Flo photographic development wetting agent can also be used. The wetting agent reduces natural water surface tension, and is particularly important to use when coatings are in the 10-20 mil (254-508 µm) range. The detector unit is grounded to an uncoated area of steel using a ground wire clip. Both the wand and the ground wire are connected to the detector. The wet sponge
is scanned across the coated surface (Figure 3) at a rate not to exceed one linear foot per second. If a pinhole or holiday is present, the water from the sponge will contact the steel, complete the circuit (since the detector is grounded to the bare metal) and cause the detector to signal using a visible and/or an audible alarm.
Calibration and Verification of Continuity

Calibration of any coating inspection instrument is paramount to the reliability of the data it produces. Annual calibration by the manufacturer or an authorized service center is recommended by most instrument manufacturers. A certificate of calibration is provided.

Continuity can be verified by touching the wet sponge to the ground wire or an uncoated area, or by creating an intentional pinhole and touching the wet sponge to the area of the void. Some low voltage detectors have 80 ohm (80K) and 90 ohm (90K) resistance buttons (see Figure 4) that are used to indicate the sensitivity of the device. For the model shown, the detector should signal and the LED should light when the 80K (80 ohm) button is pressed, provided the detector is to be used on coated steel structures and it is in calibration. The 90K (90 ohm) setting is for coatings on concrete.

High Voltage (spark) Holiday Detection

The operation of high voltage holiday detectors is somewhat more complex than low voltage
detectors, since the test voltage is variable and selection of the voltage is based on the thickness of the coating to be tested and to some degree the conductivity of the surrounding air. While both NACE International and ASTM International have tables in their respective standards listing coating thickness ranges and corresponding test voltage ranges, it is best to contact the coating manufacturer to obtain their recommended voltage setting or calculate the required test voltage (discussed on Page 11), since the ranges listed in the tables are quite broad and only “suggested.” To prevent potential damage to a coating film when using high voltage test instrumentation, total film thickness and dielectric strength of the coating is considered in selecting the appropriate voltage for detection of discontinuities. Atmospheric conditions are also considered since the voltage required for the spark to “bridge” a given distance in air varies with the conductivity of the air at the time the test.

Figure 5 - Courtesy of Tinker & Rasor Company
is conducted. Newer digital detectors (Figure 5) enable the operator to select or “dial-in” the exact test voltage, versus the older models (Figure 6) that have limited operator interface with test voltage settings. For example, on older models if the calculated test voltage was 6,525 volts, the operator could only select either the 6,000 or 7,000 volts setting.

Calculating the test voltage is straightforward. Simply calculate the square root of the thickness of the applied coating (Tc), then multiply the resulting value by a constant (K) of either 525 or 1250. The constant of 525 is used when the applied coating thickness is less than (<) 40 mils (1016 µm); the constant of 1250 is used when the applied coating thickness is greater than or equal to (≥) 40 mils. An example of each is shown below:

**Tc: 25 mils (square root is 5)**

\[ 5 \times 525 \text{ (K)} = 2,625 \text{ volts (2.6 kV)} \]
Tc: 50 mils (square root is 7.1)

7.1 x 1250 (K) = 8,875 volts (8.9 kV)

Once the test voltage is established, the ground cable is attached to the uncoated substrate (or the ground cable is dragged along the ground, provided the pipe is grounded to earth and the ground cable maintains contact with the earth). The exploring electrode that will be run across the coating is then selected. Choices of electrodes include flat conductive Neoprene rubber, brass or stainless-steel brush, and half-coil or full coil springs. The electrode is coupled to the wand, the unit is powered-on and

the voltage is set. The electrode is scanned across the coated surface (Figure 7) at a rate not to exceed one linear foot per second. If a pinhole or holiday is present, a spark is generated at the precise location of the flaw and the detector signals with a visible and/or an audible alarm.
While it is acceptable to retest any repairs made to the coating, it is recommended that retesting be limited to the areas of repair, rather than the entire coated surface. Also, holiday detection should never be conducted on a wet surface, and misleading results or damage could occur when testing a coating or lining system that has been in service. ASTM D5162 specifically states, “This practice is intended for use with new coatings applied to metal substrates. Its use on a coating previously exposed to an immersion condition has often resulted in damage to the coating and has produced erroneous detection of discontinuities due to permeation or moisture absorption of the coating. Deposits may also be present on the surface causing telegraphing (current traveling through a moisture path to a discontinuity, giving an erroneous indication) or current leakage across the surface of the coating due to contamination. The use of a high voltage tester on previously exposed coatings has to be carefully considered because of possible spark-through, which will damage an otherwise sound coating. Although a low voltage tester can be used without damaging the coating, it may also produce erroneous results.”
Calibration and Verification of Continuity
Similar to the low voltage detectors, annual calibration by the manufacturer or an authorized service center is recommended by most instrument manufacturers. A certificate of calibration is provided.

Continuity can be verified by touching the electrode to the ground wire or an uncoated area, or by creating an intentional pinhole and touching the electrode to the area of the void. The actual voltage output (compared to the set point) can be verified using a Peak Reading Voltmeter (Figure 8a/8b).

To address the concerns over prevailing conductivity of the air (e.g., pressure, humidity) interfering with the test and the potential to exceed the dielectric strength of the coating...
itself, a plastic sheet comparable in thickness to the applied coating can be placed on a section of uncoated steel and an intentional pinhole created in the plastic. The voltage setting on the detector can be adjusted (as necessary) to the point where it alarms. However, if the coating has slight conductivity (e.g., carbon in vinyl ester linings) this procedure may not be viable, since the use of a lower inspection voltage may be necessary.

**Hardness Testing**

The hardness of a coating material is an indication of its degree of cure and its inherent performance characteristics. Hardness testing of newly coated cut-backs at splices is often performed prior to burying the pipe, to reduce the opportunity for coating damage during the backfill process.

The hardness of thick film coatings is typically measured using an indentor-type tester, which measures the resistance to indentation under a specific spring force load. The project specification should indicate the minimum acceptable hardness value prior to placing the coating system into service. The minimum acceptable hardness value is often established by the manufacturer of the coating.
Measuring Durometer Hardness

Durometer hardness testing is performed according to the procedure described in ASTM D2240, Standard Test Method for Rubber Property – Durometer Hardness. The standard includes several types of measurement devices (Types A, B, C, D, DO, O, OO, OOO, OOO-S and R), each used for different types and hardness of materials. We will focus on the use of a Shore D Durometer, since many of the thick film, chemically resistant coatings used in the pipeline industry fall into the hardness range that a Shore D durometer can accurately measure. For softer, thick film coating materials, a Shore A durometer may be more useful since it has a lower spring force. According to the ASTM standard, hardness values obtained using durometers that are less than 20 and greater than 90 are not considered reliable and it suggests not recording them. In fact, the digital durometer described later automatically discards readings less than 20 and greater than 90. It should be noted that ASTM D2240 is written primarily for laboratory applications; however, Durometers can be used in the field.
A Shore D Durometer is a small hand-held analog device (Figure 9), or an electronic device (Figure 10) with a remote probe that is used to measure the indentation hardness of various materials like hard rubber, plastics, soft metals, and epoxy coatings. A small cone-shaped indentor protrudes from the pressor foot (the base of the tester or probe). The durometer contains a calibrated spring that is used to apply perpendicular force to the indentor. A cured, hardened coating will provide great resistance to the indentor under the force of the applied load, compared to an uncured, softer coating. This resistance to indention is displayed on the gage dial.
or digital display as a hardness value.

Verifying the Accuracy of the Durometer
Durometers should be calibrated annually by the manufacturer or their authorized service center. Some will even provide a 10-point calibration certification traceable to a National Metrology Institution like the National Institute of Standards and Technology (NIST). The operator cannot calibrate a durometer, but should verify proper operation prior to each period of use.

Test blocks are used to verify proper operation (accuracy). The set shown (Figure 11) represents hardness values of 25, 46 and 75 on the D scale. A measurement is taken on each test block and compared to the hardness value displayed on the durometer. If the value displayed by the durometer does not conform to the tolerance of the test block value (for example 25 +/- 5, which means that the displayed hardness value obtained on the test block can range from 20-30), the durometer should not be used to measure the hardness of a coating and
should be returned to the manufacturer or service center for repair and calibration.

The surface of the coating to be tested should be clean and smooth. Any inherent surface roughness can produce erroneous hardness values. Since temperature and humidity can influence the hardness value, the surface temperature of the coated surface and the relative humidity of the surrounding air should be measured and recorded prior to testing. While the temperature and humidity data is required to be reported by the ASTM standard, there is no correction of the hardness values based on the prevailing ambient conditions.

Measuring Coating Hardness (Analog Durometer)

After verifying accuracy using the test blocks and returning the red ancillary pointer to zero, the durometer is cupped in the operator’s hand and vertical pressure is

Figure 12
applied using even, steady hand/thumb pressure (Figure 12) until the base of the instrument seats evenly on the coated surface. The maximum force will be maintained by the red ancillary pointer, even though the black pointer will return to zero once the downward pressure is released. A minimum of five measurements is obtained (spaced at least ¼ inch apart), the average indentation hardness is calculated, and the results are compared to the requirements of the project specification or coating manufacturer. The analog-type durometers may be difficult to seat correctly on small diameter pipe. The durometer should always be positioned so that measurements are obtained along the length of the pipe and not across it.

Measuring Coating Hardness (Digital Durometer)

After verifying accuracy using the test blocks, the remote probe is pressed into the coating until the presser foot is in full, flat contact with the surface, and held in place (Figure 13 – Courtesy of DeFelsko Corporation).
13). After the durometer emits a single audible signal, it will display a symbol indicating a reading is in the process of being obtained. The test timer will begin counting down. When the timer reaches zero, the durometer will emit a double audible signal and display the measurement value. The probe is removed from the surface. Because of the relative small diameter of the test foot, its use is more amenable to curved surfaces; however, the full measuring surface of the probe must sit flush on the surface without rocking to obtain a reliable reading.

**Adhesion Testing**

(specifically, the 2017 version), ASTM D3359, and ASTM D6677.

**Tensile (pull-off) Adhesion Testing**

When performing a tensile or pull-off adhesion test, the strength of a coating bond is being assessed at several different “planes,” including the adhesion of the coating system to the substrate, and the adhesion of the coating layers to each other if there is more than one layer of coating on the surface. In both cases, the adhesive strength of a coating, or the bond of the layers to one another and to the substrate is being assessed. The inner-strength of each coating layer is also being assessed, which is known as the *cohesive* strength of a coating, or the ability of each layer to hold itself together or maintain its “inner-strength.”

The adhesion of a coating system to a surface is highly variable and can be influenced by a multitude of factors too numerous to list here. That is likely why there is no industry-wide standard that says that a certain type of coating must have a minimum adhesive or cohesive strength. However, project specifications may require a minimum adhesion value as a contract
requirement, and coating manufacturers will often report an adhesion value on their product data sheets that may be adopted into a project specification.

**Test Protocols**
There are two protocols that are applicable to tensile (pull-off) adhesion testing of coatings: Protocol 1 - Test to Fracture and Protocol 2 - Pass/Fail test.

**Protocol 1 - Test to Fracture:**
Protocol 1 is typically used when the minimum adhesion/cohesion properties of the coating system are unspecified. In this case, the load is applied to the fixture until detachment occurs, or the maximum capacity of the test instrument is reached. High levels of applied force may result in glue breaks prior to coating breaks (an epoxy glue is typically used to attach the test fixtures to the coated surface).

According to the 2017 version of ASTM D4541, unless otherwise agreed upon by the contracting parties, test results are discarded for all tests where the glue break is in excess of $\frac{1}{4}$ of the loading area (test fixture area).

**Protocol 2 – Pass/Fail Test:**
Protocol 2 is typically used when the minimum adhesion/cohesion properties of the coating system are specified. In this case, the load is
applied to the fixture until the specified value is attained or detachment occurs, whichever happens first. High levels of applied force may again result in glue breaks prior to coating breaks. According to the 2017 version of ASTM D4541, if a visibly detectable glue break occurs (defined as 5% or more of the loading area) and the specified minimum value is not attained, additional loading fixtures may need to be attached and pulled. If the specified value is achieved and the test fixture remains attached, the pressure is released and the adhesion tester removed. The test fixture is either left in place, or removed by tapping the side with a hammer to break the bond.

There are a variety of test instruments that can be used to assess the tensile or pull-off strength of a coating or coating system; however, all of them require that a loading fixture (a.k.a. pull stub or dolly) be attached to the surface of the coating using an adhesive (Figure 14 a and b). Once the adhesive (glue) cures, a vertical load is applied to the loading fixture,
perpendicular to the substrate using mechanical, hydraulic, or pneumatic induced pressure. The pull-off strength displayed by the instrument accounts for the applied force (e.g., pounds or megapascals) and size of the contact surface of the loading fixture.

Annual calibration of adhesion testers by the manufacturer or an authorized service center is recommended by most instrument manufacturers. A certificate of calibration is provided, frequently accompanied by a conversion table or curve so that adhesion values can be converted. Independent of the adhesion tester type or manufacturer, there is nothing that can be done to verify the accuracy of the instrument during use in the field.

Scoring the coating around the perimeter of the loading fixture is discouraged, as it may create microcracks in the coating, artificially lowering the pull-off value. Scoring may be necessary for thick-film coatings or coating systems that contain reinforcement, but is only
performed if agreeable to all parties.

The ASTM standard includes five annexes that form a mandatory part of the standard (the appendices are non-mandatory). Each annex describes the proper use of a different apparatus.

**Fixed Alignment Adhesion Testers (Annex A1)**

A fixed alignment adhesion tester (Figure 15) consists of three basic components: A hand wheel or hexagon-shaped nut at the top; a black column housing a spring or series of Belleville washers, and containing a dragging indicator pin and scale in the middle; and a
base containing three legs and a pulling “jaw” at the bottom, designed to fit the head of the loading fixture. The “jaw” of the instrument is lowered and inserted under the head of the loading fixture (Figure 16). The load is applied by rotating the handwheel (or nut, using a ratchet) clockwise. The tension on the spring or washers applies a perpendicular, upward force on the loading fixture. The tension is increased smoothly and evenly using a moderate speed not to exceed 150 psi/second (1 MPa/second). The test should be completed in 100 seconds or less. The pull-off value is read from the scale on the black column (Figure 17). The mechanical adhesion testers are fixed and cannot align with any slight mis-attachment of the loading fixture, so the force may not be applied truly perpendicular to the surface. If this happens, shear forces are applied to the loading fixture (and the coating system) instead of, or in addition to, tensile forces. In addition, the pulling forces are not applied at a constant rate since the operator cannot turn the handwheel or nut continuously. Frequently
pull-off values at the point of detachment are roughly 50% of those obtained with self-aligning adhesion testers.

**Self-Aligning Adhesion Testers**
Self-aligning adhesion testers are hydraulically or pneumatically operated; each type is described herein.

**Self-Aligning Adhesion Testers – Hydraulic (Annex A2, A4, A5)**

There are three manufacturers of self-aligning hydraulic adhesion testers. In each case a loading fixture is attached to the coated surface (as described earlier) and a self-aligning quick connect (Figure 18 and 20), or actuator (Figure 19) is coupled to

![Figure 18](image18.png)

![Figure 19](image19.png)
22 and 23) are controlled by the operator. The instruments automatically convert the force to psi or MPa based on the size of the contact surface of the loading fixture used.

Figure 20

the head of the loading fixture and hydraulic pressure is applied. The adhesion tester shown in Figure 21 applies a continuous load at a predetermined rate (not to exceed 150 psi/second) until the loading fixture becomes detached. The rate (and continuity of the rate) for the other two hydraulic adhesion testers (Figure

Figure 21 – Courtesy of DeFelsko Corporation
Pneumatic adhesion testers use an air-operated piston threaded onto the shaft of a specially-designed loading fixture to apply perpendicular, tensile forces.
force (Figure 24). There are several piston sizes; each with a corresponding range (i.e., an F-2 piston is 0-1000 psi, an F-4 piston is 0-2000 psi and an F8 piston is 0-4000 psi). Air pressure is generated using small CO₂ cartridges, which produce pressurized air that travels through a small diameter hose into the piston. The pneumatic adhesion tester shown in Figure 25 applies a continuous pressure load at a rate pre-established by the operator (not to exceed 150 psi/second) until the loading fixture becomes detached. A chart corresponding to each piston size is used to convert the burst pressure to psi or MPa.

**Loading Fixtures**

**Type:**

The manufacturers of the various test instruments (mechanical, hydraulic, pneumatic) also manufacturer the corresponding loading fixtures (Figure 26). There is no “universal” fixture. Loading fixtures are typically manufactured from aluminum, steel or stainless steel. Most operators consider the aluminum loading fixtures to be disposable, as the cost associated with

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*Figure 26*
cleaning them often exceeds the cost of new fixtures. However steel and stainless-steel loading fixtures are reusable. Coating/glue can be removed from the base of loading fixtures using chemical paint strippers, heat or abrasive blast cleaning. If cleaned by abrasive blast cleaning, care must be taken to avoid beveling or changing the shape of the contact surface of the fixture.

**Diameter:**
Twenty-millimeter (20 mm) loading fixtures are common for coatings on metal, although smaller diameter fixtures (e.g., 10 and 14 mm) are available from some of the instrument manufacturers. Fifty-millimeter (50 mm) loading fixtures are required for testing the tensile strength of coatings applied to concrete (per ASTM D7234).

**Shape:**
Many of the adhesion test instrument manufacturers can produce loading fixtures with concave and convex bases. The loading fixtures with a concave base are used on the exterior of pipe, while the loading fixtures with a convex base are used on the interior of pipe. However, since there is no universal curvature (pipe diameters vary widely), it is important to tell the equipment supplier the diameter of the pipe.
section being tested. Concave/convex loading fixtures are specially manufactured and need to be ordered well in advance of the intended test date.

**Note:** Determining the need to use curved loading fixtures is based on the diameter of the coated pipe to be tested and the diameter of the loading fixture. Concave/convex-shaped fixtures may not be required for testing the adhesion of coatings on larger diameter pipe. To determine whether curved loading fixtures are required, a fixture (of the desired diameter) with a flat surface can be placed onto the pipe surface and checked to see whether it can be rocked back and forth or whether it seats level on the surface. If rocking is evident, the use of curved fixtures is recommended.

**Frequency of Testing**

ASTM D4541 states, “At least three replications are usually required in order to statistically characterize the test area (i.e., location);” however it does not indicate how many test locations to select in order to characterize the adhesion properties of the coating system on the entire structure. Therefore, it is important to establish a test frequency upfront. Considerations may include the number of heterogeneous areas on a given structure, variations in coating thickness, etc.
A statistically significant sampling may or may not be feasible, given that these tests are destructive to the coating film and each area of test may need to be repaired. Other considerations include whether adhesion testing is part of a quality assessment (where destructive testing should be minimized), or if it is being employed to help diagnose the cause of a coating failure, where additional destructive tests have little negative impact, but can provide value in examining a problem.

**Reporting the Type and Amount of Break**

The type of break and amount of each type of break arguably provides as much information as the pull-off value itself. The types of break include adhesive, cohesive or glue, and all three may be present on a single pull test. An adhesive break is a clean break between the substrate and the first coating layer (Figure 27), or a clean break between layers (Figure 28) when there are multiple coating layers in the system. A cohesive break is a split within a given coating layer (Figure 29). A glue break (Figure 30) is the failure of the glue itself that was used to attach the loading fixture to the coated surface (may or may not require a retest, as described earlier).
The approximate percentage of each type of break that occurred should also be reported (e.g., 80% adhesive [primer/topcoat]; 20% cohesive (within topcoat layer). The total should add up to 100% of the loading area.

**Knife Adhesion Testing**

The adhesion of a coating system can also be evaluated using ASTM D6677, “Evaluating Adhesion by Knife,” which is a quick and easy way to assess adhesion in the field. Once a test area is selected, a straight edge is used in conjunction with a knife blade to make a 1.5" long cut through the coating system (down to the substrate) followed by a second cut across the first cut to

*Figure 31*
form an “X.” The legs at the top and bottom of the “X” should be approximately 1” apart, and the intersection of the “X” should be close to a 30-45° angle.

Starting at the intersection of the “X,” the tip of the knife blade is used to attempt to lift the coating from the substrate or the underlying coating layers (Figure 32).

The adhesion is rated on a scale of 10 to 0 (Figure 33).

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Coating is extremely difficult to remove. Fragments no larger than 1/32” x 1/32” removed with great difficulty</td>
</tr>
<tr>
<td>8</td>
<td>Coating is difficult to remove. Coating chips from 1/16” x 1/16” to 1/8” x 1/8” removed with difficulty</td>
</tr>
<tr>
<td>6</td>
<td>Coating is somewhat difficult to remove. Coating chips from 1/8” x 1/8” to 1/4” x 1/4” removed with slight difficulty</td>
</tr>
<tr>
<td>4</td>
<td>Coating is somewhat difficult to remove. Coating chips in excess of 1/4” x 1/4” removed using light pressure with knife blade</td>
</tr>
<tr>
<td>2</td>
<td>Coating is easy to remove. Once started with the knife blade, the coating can be grasped with fingers and easily peeled to a length of at least 1/4”</td>
</tr>
<tr>
<td>0</td>
<td>Coating is easy to remove. Once started with the knife blade, the coating can be grasped with fingers and easily peeled to a length greater than 1/4”</td>
</tr>
</tbody>
</table>
Measuring Adhesion by the Tape Test (ASTM D3359)

If the project specification or other document requires you to perform an adhesion test according to ASTM D3359, “Adhesion by Tape Test,” a metal ruler or guide, a utility knife with a new razor blade, a small brush, adhesive tape, pencil eraser, and a copy of the ASTM test method are required.

Select a Test Area. Selecting a test area is perhaps the most difficult part of testing adhesion, particularly when evaluating an older coating system that has been maintained by spot or area touch-up painting over many years. Consider testing several areas and perform replicate tests in each area to ensure representative adhesion data. If testing the adhesion of a new coating system, minimize the number of locations to reduce the amount of touch-up required. However, replicate testing (at least 3) in each area selected is recommended. Ensure the areas are free of grease, oil, dirt, chalking, or water that will interfere with the adhesion of the tape.

Determine the Thickness of the Coating System. Determine the total thickness of the coating system.

Select a Testing Method. Based on the thickness of the coating system, select a test method (A or B). Method A (“X-Cut”) and is used to test the adhesion of a coating system that is greater than 5 mils thick; Method B (“Cross-cut”) and is used to test the adhesion of a coating system that is less than, or equal to 5 mils thick.
Measuring the Adhesion using Method A (X-Cut)

1. Mount a new razor blade in a utility knife holder and extend the blade outward. Use a straight edge and make a 1.5” long cut through the coating system (down to the substrate). Make a second 1.5” long cut across the first cut to form an “X.” The legs at the top and bottom of the “X” should be approximately 1” apart. The intersection of the “X” should be close to a 30-45° angle. Remove any debris from the “X” area using a soft brush.

2. Remove two complete wraps of adhesive tape and discard. Carefully remove a piece of the adhesive tape and apply it to the “X” area.

3. Using a soft pencil eraser, rub the tape over the X-Cut to help ensure good contact between the tape and the coating surface.

4. Within 90 (+/- 30) seconds, remove the tape from the X-cut smoothly and rapidly, 180° back across the X-Cut (i.e., peel back, do not pull upwards).

5. Examine the X-Cut area for coating delamination and rate the condition of it according to the table below.
<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A</td>
<td>No peeling or removal</td>
</tr>
<tr>
<td>4A</td>
<td>Trace peeling or removal along the incisions</td>
</tr>
<tr>
<td>3A</td>
<td>Jagged removal along the incisions up to 1/16&quot; (1.6mm) on either side</td>
</tr>
<tr>
<td>2A</td>
<td>Jagged removal along most of the incisions up to 1/8&quot; (3.2 mm) on either side</td>
</tr>
<tr>
<td>1A</td>
<td>Removal of most of the coating from the area of the “X” under the tape</td>
</tr>
<tr>
<td>0A</td>
<td>Removal of coating beyond the area of the “X”</td>
</tr>
</tbody>
</table>

Classify the location of the delamination as “adhesion” (A distinct break between coating layers or a distinct break between the substrate and the first coating layer) or cohesion” (A split within a coating layer). Usually this can only be done if the adhesion is rated 3A or lower.

**Measuring the Adhesion using Method B (Cross-Cut)**

1. Mount a new razor blade in a utility knife holder and extend the blade outward. Use a straight edge or the KTA Cross-Cut Guide and make a series of 6 or 11 parallel knife blade cuts through the coating system (down to the substrate). The number of cuts and the amount of space between the cuts is based on the total thickness of the coating system. Determine
the number of cuts and the spacing between the cuts using the chart below.

<table>
<thead>
<tr>
<th>Coating Thickness</th>
<th>Number of Cuts</th>
<th>Spacing Between Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 2 mils</td>
<td>11</td>
<td>1 mm</td>
</tr>
<tr>
<td>2-5 mils</td>
<td>6</td>
<td>2 mm</td>
</tr>
<tr>
<td>&gt;5 mils</td>
<td>6</td>
<td>5 mm or X-Cut (Method A)</td>
</tr>
</tbody>
</table>

Turn the straightedge or guide 90° and make a second series of parallel knife cuts over top of the first set of cuts, but perpendicular to the first set to form a grid, cross-hatch or “Cross-Cut” pattern. If 11 cuts are made, a 10 x 10 grid, or 100 squares will be generated; If 6 cuts are made, a 5 x 5 grid, or 25 squares will be created. Remove any debris from the “Cross-cut” area using a soft brush.

2. Remove two complete wraps of adhesive tape and discard. Carefully remove a piece of the adhesive tape and apply it to the “Cross-cut” area.
3. Using a soft pencil eraser, rub the tape over the cross-cut area to help ensure good contact between the tape and the coating.

4. Within 90 (+/- 30) seconds, grasp one end of the tape and remove it from the cross-cut area smoothly and rapidly, 180° back across the grid (i.e., peel back, do not pull upwards).

5. Examine the cross-cut area for coating delamination and rate the condition according to the table below. The ASTM D3359 standard provides a chart similar to the one shown below that illustrates the various percentages of delamination described in the table. Classify the location of the delamination as “adhesion” or “cohesion” described earlier.
<table>
<thead>
<tr>
<th>Rating</th>
<th>Percent Delamination</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5B</td>
<td>0% (none)</td>
<td>Edges of the cuts are completely smooth</td>
</tr>
<tr>
<td>4B</td>
<td>&lt; 5%</td>
<td>Small flakes of coating are detached at the intersections</td>
</tr>
<tr>
<td>3B</td>
<td>5-15%</td>
<td>Small flakes of coating are detached along the edges and intersections</td>
</tr>
<tr>
<td>2B</td>
<td>15-35%</td>
<td>Coating has flaked along the edges and on parts of the square</td>
</tr>
<tr>
<td>1B</td>
<td>35-65%</td>
<td>Coating has flaked along the edges of the cuts in large ribbons and whole squares have detached</td>
</tr>
<tr>
<td>0B</td>
<td>&gt;65%</td>
<td>Flaking and detaching worse than Rating 1B</td>
</tr>
</tbody>
</table>
Conclusion

Proper surface preparation/inspection (the foundation for the coating system), proper application/inspection of the coating system and post-installation inspection are critical to the protection of the substrate, and to prevent premature coating failure and preserve steel integrity. This approach to quality is illustrated in the Venn Diagram below.
About the Author

Bill is the Chief Operations Officer for KTA-Tator Inc. (KTA), where he has been employed since 1979. He holds an AD in Business Administration from Robert Morris University. He is an SSPC Certified Protective Coating Specialist, an SSPC Level 3 Certified Protective Coatings Inspector, an SSPC Level 2 Certified Bridge Coatings Inspector, as well as a NACE Level 3 Certified Coatings Inspector. He is an approved training course instructor for both SSPC and KTA. Bill authored the first, second and third editions of the KTA publication, Using Coatings Inspection Instruments. He received SSPC’s Coating Education Award in 2006, the SSPC John D. Keane Award of Merit in 2011, an ASTM Committee D01 Award of Appreciation in 2016, and the SSPC President’s Lecture Series Award in 2017. He is the Chair of the SSPC Dry Film Thickness Committee and Chair of the SSPC Education and Certification Committee. He is also a member of ASTM Subcommittees D01.23 and D01.4.