

# **Failure Analysis of Paints and Coatings**

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## **Abstract**

In this introductory survey failure analysis methodology will be applied to the principal mechanisms by which paints and coatings fail during service. How to conduct a failure analysis, stages of analysis, proper techniques for sample removal, destructive and non-destructive techniques, primary causes and modes of failure, and specific case studies will be discussed.

## **Introduction**

A tremendous amount of financial loss is incurred every year as a result of premature failures of paints and coatings. The cost to repair such failures far outweighs the initial cost of painting, since excessive rigging may be needed to access the failing areas. Additional liability may also be expected if a facility must stop operation for the necessary repairs to be made. Coating failures can occur for dozens of reasons, although they are typically a result of poor application, a defective coating, or an inadequate specification. A determination of the fundamental causes behind coating failures is critical. Not only does this help in assigning financial responsibility, but knowing how a coating has failed is often the first step in planning how to fix it.

To investigate a failure, and analyze the conditions that promoted the failure, important information must be collected on the failed paint or coating. Background information on the coating type and application procedure, the service history and environment, and physical evidence of the failed coating are necessary to determine why, how, when, and where a failure may have occurred. If these answers are provided during the course of the investigation, future failures may be better understood or possibly prevented.

The conditions that promoted the failure are essential in identifying the underlying factors that may have initiated the failure. Other elements that may not be readily acknowledged in failure analysis, yet are no less important, are common sense, a critical and unbiased mode of thinking, experience, knowledge, and experimental observation.

Provided in this survey is a step by step approach to paint and coating failure analysis investigation. The accepted theories and mechanisms, which cause paints and coatings to fail, will be explored in this paper.

## **Failure Analysis**

A failure analysis investigation is much like the work of a detective. Clues or relevant facts pertaining to the investigation must be gathered, analyzed, explored, and studied to make a knowledgeable determination. As in the case of a good detective, first hand field experience is of the utmost important, yet academic studies are also essential.

### **Failure Analysis – Sequence of Events**

Justification for conducting paint or coating failure analysis investigations is the most important issue for a failure analyst. Corrosion protection, aesthetic, production, or litigation related purposes provide excellent examples for justification.

If the investigation is fully justified, the method for evaluation proceeds with the second step in the process. This step involves gathering relevant information and facts concerning the failure. The questions listed serve as a guide to follow during the investigation. When the information has been obtained it must be carefully organized, labeled, and documented in a logical format for future reference.

The failure analyst should question why failure occurred, how to get the building, facility, or equipment repair coated quickly if necessary, how to prevent a recurrence of the problem, and if more information is needed, how can the information be readily obtained.

With these steps taken a plan of attack can be formed. This is the single most important step in the method of evaluation. A logical plan for the investigation to follow must be developed and implemented. Each investigation will be different from the last and many variables will make it necessary to make decisions based on the investigation at hand. If an analyst is hasty in his decisions and does not have a solid plan the entire project may be ruined. By simply cutting or analyzing a sample carelessly an analyst could destroy his only useful evidence.

The stages of analysis performed when conducting a paint or coating failure analysis investigation should begin with the collection of background data and sample removal. This step includes site inspection, information regarding the current history of the failure, all relevant record keeping, and records on past failures if applicable.

A preliminary examination of the failed coating and the substrate, as well as a non-destructive examination of the failure, with extensive photographic documentation, precedes any destructive laboratory evaluation and analysis. The preliminary examination does not change or damage the failed coating or substrate in any way.

At this point in the investigation the specimens should be selected and identified for further laboratory testing and analysis. Management should be notified of any specimens collected from a paint and coating failure, including the underlying substrate, are often damaged, and of little use after testing.

There is a wide variety of testing methods currently available for failure analysis of paints and coatings. Sophisticated and highly calibrated laboratory equipment can detect the slightest imperfections on a specimen, and accurately identify the inherent characteristics.

A macroscopic examination of the surface of the selected specimen begins this stage of analysis, followed by a microscopic examination. A close examination of failed paint and coating chips using a stereo microscope at magnification of 50x or less may reveal that one of the layers is brittle and full of cracks, or perhaps that an entire layer of paint is missing. An examination of failed and non-failed samples may reveal that all of the failed samples are of improper thickness. A microscope at magnifications ranging from 50x to 1000x magnification can be used to examine the cross section of failed paint and coating samples for voids or inclusion, as well as observation of underlying corrosion products on substrates.

A chemical analysis of the paint or coating, as well as the substrate and corrosion products is usually the next step. Chemical analysis techniques typically used in the laboratory for paint and coating failure analysis are Fourier transform infrared spectroscopy (FTIR) for organic functional group analysis, scanning electron microscopy (SEM) with associated energy dispersive x-ray spectroscopy (EDS) for elemental analysis, and Auger electron spectroscopy (AES) for surface elemental analysis.

Fourier transform infrared (FTIR) spectrometers record the interaction of infrared radiation (light) with experimental samples, measuring the frequencies at which the sample absorbs the radiation and the intensities of the absorptions. Determining these frequencies allows identification of the sample's chemical makeup, since chemical functional groups are known to absorb infrared radiation at specific frequencies.

The scanning electron microscope (SEM) is a microscope that uses electrons rather than light to form an image. There are many advantages to using the SEM as an adjunct to the optical (light) microscope. The SEM has a large depth of field, which allows a large amount of the sample to be in focus at one time. The SEM also produces images of high resolution, which means that closely spaced features can be examined at a high magnification. Preparation of the samples is relatively easy since most SEMs only require the sample to be electrically conductive.

Energy dispersive x-ray spectroscopy (EDS) systems are used in the characterization of materials through the use of ionizing radiation to excite a sample. This excitation generates x-ray energies that identify the elemental composition of the sample. Using x-ray detection equipment to count the number of x-ray photons emitted by this technique, an EDS system is able to characterize and quantify in an approximate manner the elemental composition of the sample.

Auger electron spectroscopy (AES) determines the elemental composition of conductive and semi-conductive surfaces, and can provide elemental depth profiles through sputtering. This information can then be utilized to solve problems associated with surface appearance, cleanliness and bonding. In principle, an electron beam bombarding a solid surface excites electrons from core electronic energy levels of atoms. A deep core electron is knocked out of an atom, a shallower level electron drops into the deep core level hole, and its energy loss is transferred to another shallower-lying electron which can be ejected (the Auger electron). The kinetic energy spectrum is used to identify the atom of origin and its concentration.

Accelerated environmental exposure tests, such as salt spray (fog) tests, humidity tests, and ultraviolet light (QUV) exposure tests can help to confirm the proposed failure mechanism of a painted or coated substrate sample. Accelerated exposure testing can be complemented with electrochemical impedance spectroscopy (EIS). In the EIS technique capacitance and electrical properties of the coating are measured as a function of time. If the impedance ratio does not change as a function of time, then one can with high degree of confidence conclude that the coating is not altered and performs very well under actual

service conditions. The advantage of this technique is that we will not accelerate the test such that conditions will result in the failure of coating system. The test will provide reliable data in a short time of exposure. The data from this test can also provide data for calculating permeation rate and minimum coating thickness and cure schedule requirements for adequate corrosion resistance.

Analysis of the evidence, and a review of the existing data and documentation are the final stages of failure investigation. All information is gathered and analyzed to form a determination on the mode and probable cause of the failure. Identification of the mode and cause of failure provide the source for recommendations for corrective action. A final report including all relevant data, analyses, and recommendations are compiled and presented to the client. In litigation investigations, the client may not be interested in the recommendations section of the report.

### **Collection of Background Data**

The failure analyst should determine when, where, and how the paint or coating failure occurred. Interview all users and operators involved in the failure with point-related questions. Examples of point-related questions include “how was the coating-substrate handled after failure?” and “was it protected?”

### **Sample Removal**

The decision to remove a sample specimen of a paint or coating, or of the underlying substrate, is a very important part of the failure analysis investigation. Sample selected should be characteristic of the coating and/or substrate and contain a representation of the failure or corrosion attack. For comparative purposes, a sample of the intact coating and/or substrate should be taken from a sound and normal section. In conjunction, for a complete microscopic and chemical evaluation and analysis, samples from the failure, adjacent to the failure, and away from the failure are necessary.

The sample must be removed without changing the surface conditions or characteristics of the sample, nor inflicting physical damage of any kind. The sample is the basis on which the investigation and analysis rely, and extreme care must be taken not to destroy any of the sample's properties.

Upon removal of the sample, the exact location where it was obtained must be documented both in writing and by photography. Any corrosion product found on the coating or the substrate should also be collected and examined. If necessary, the corrosion product may be removed carefully from the substrate and sent with the removed sample. When the sample has been removed from the structure or the component, it should be carefully packaged in a water-tight container appropriate to the size of the sample, identified and labeled.

## **Paint and Coating Failures**

The majority of paint and coating-related failures can be attributed to six primary causes. These causes are as follows.

1. Improper surface preparation – the substrate surface is not adequately prepared for the coating that is to be applied. This may include cleaning, chemical pretreatment or surface roughening.

2. Improper coating selection – either the paint or coating selected is not suitable for the intended service environment, or it is not compatible with the substrate surface.
3. Improper application – this can be a problem with either shop-applied or field applied coatings, and occurs when the required specifications or parameters for the application are not met.
4. Improper drying, curing and over coating times – again, this problem relates to a lack of conformance to the required specifications or parameters.
5. Lack of protection against water and aqueous systems – this is a particularly serious problem with aqueous systems containing corrosive compounds such as chlorides.
6. Mechanical damage – which results from improper handling of the painted or coated substrate, resulting in a breach in the paint or coating.

There are innumerable possible failure modes which can result from these primary causes. For the purposes of this review paper, the failure modes will be divided into three general categories, as follows.

1. Formulation-related failures.
2. Substrate-related failures.
3. Physical defect-related failures.

These three general categories of failure modes will be described briefly.

### **Formulation-Related Failures**

There are many types of paint and coating failures for which the coatings or corrosion engineer has little or no control over. These types of failures are related to the formulation of the coating itself. If the coating system that is selected by the engineer is formulated inadequately, the coating will most likely fail regardless of all efforts made in an optimal application. These formulation-related failures occur as a result of the ingredients used and their formulation in the paint or coating. These ingredients include the resins used, the pigments used, as well as the solvent formulation. Several specific types of formulation-related failures are presented in Table 1, as well as appearances, causes, and problem prevention. They include chalking; erosion; checking; alligatoring; cracking; mud crack; wrinkling; biological failure; and discoloration for organic coatings; and checking; mud cracking; and pinpoint rusting for inorganic (zinc) coatings.

**Table 1. Formulation-Related Failures**

<b>Organic Coating Failures</b>	<b>Failure Appearance</b>	<b>Cause of Failure</b>	<b>Problem Prevention</b>
1. Chalking	Surface soft & powdery. Easily wiped away.	UV degradation of resin. Improper pigmentation.	Use UV-resistant resins and non-chalking pigments.
2. Erosion	Similar to chalking. High spot removal & brush marks.	Chalking & surface weathering.	Use chalk-resistant coating with good flow.
3. Checking	Uneven, small, non-continuous coating fissures.	Surface stresses caused by shrinkage.	Use weather-resistant resins and inert pigments.
4. Alligatoring	Large macro-cracking and cross-hatching.	Internal stresses with greater surface shrinkage.	Apply thin coats and thoroughly dry before reapplication.
5. Cracking	Small breaks in coating to substrate of various geometries.	Stresses due to continued polymerization/oxidation.	Use non-reactive resins and pigments.
6. Mud Cracking	Large macrocracking and curling.	Rapid drying of highly filled coatings.	Use coatings with strong adhesion and proper drying conditions.
7. Wrinkling	Furrows and ridges in coating surface.	Surface dries more quickly than underlying coating.	Use coatings with even, thorough drying characteristics.
8. Biological Failure	Softening or slime reaction. Blotchy brown or black spots.	Bacterial or fungal degradation.	Use permanent fungicides or bactericides in coating.
9. Discoloration	Yellowing, graying, or darkening.	Weathering or chemical reaction.	Use color stable resins and pigments.
<b>Inorganic (Zinc) Coating Failures</b>	<b>Failure Appearance</b>	<b>Cause of Failure</b>	<b>Problem Prevention</b>
1. Checking	Fine visible or microscopic checks that do not penetrate to substrate.	High zinc pigment/binder ratio. Rapid drying conditions.	Use reinforcing pigments, thin layer application and proper drying.
2. Mud Cracking	Fine to large segments flaking from surface.	Too thick application. Too rapid drying.	Use recommended thickness and proper drying method.
3. Pinpoint Rusting	Pinpoint spots of corrosion. early failure can be catastrophic.	Improper zinc/binder ratio. Uneven coating thickness.	Remove and reapply more satisfactory coating at first indication.

**(Source: Steel Structures Painting Council, Causes and Prevention of Paint Failure, Chapter 23, Good Painting Practice, Steel Structures Painting Manual, 1982.)**

**Substrate-Related Failures**

A substantial percentage of paint and coating failures are related to the substrate to be coated and its proper preparation prior to coating. To eliminate this class of paint and coating failure, it is imperative that

the painters and coating applicators take great care in following specified methods of surface preparation. There is no substitute for proper surface preparation if long service lifetime is expected from the paint or coating. Several specific types of substrate-related failures are presented in Table 2, as well as appearances, causes, and problem prevention. They include previously used steel; galvanized or metallic zinc surface; aluminum; copper; wood; and concrete.

**Table 2. Substrate-Related Failures**

<b>Coating Failure</b>	<b>Failure Appearance</b>	<b>Cause of Failure</b>	<b>Problem Prevention</b>
1. Previously Used Steel	Blistering, rust, tubercles, loss of adhesion.	Retention of minute amounts of corrosion product; even after abrasive blast.	Wash blasted surface with water or dilute phosphoric acid and re-blast. Use anti-corrosive primer with strong adhesion.
2. Galvanized or Metallic Zinc Surface	White zinc corrosion product forming under coating or breaking through.	Formation of zinc salts underneath coating.	Brush blast zinc surface or use commercial zinc treatment. Use anti-corrosive primer with strong adhesion.
3. Aluminum	White corrosion product, loss of adhesion, possible blistering.	Smooth aluminum oxide surface. No physical adhesion.	Light blast aluminum surface or use aluminum treatment. Use anti-corrosive primer with strong adhesion.
4. Copper	Grey-green corrosion product, loss of adhesion.	Smooth copper oxide surface. No physical adhesion.	Brush blast copper surface or use copper treatment. Use anti-corrosive primer with strong adhesion.
5. Wood	Checking, cracking, and flaking of coating. Blistering from trapped Moisture in wood.	Expansion and contraction of wood due to varying temperatures and humidity.	Start with clean newly sanded surface. Use elastic, highly penetrating paint with high moisture permeability.
6. Concrete	Blistering, peeling, or loss of adhesion. Formation of calcium salts under coating.	Chemical reactivity, moisture content and porosity of concrete.	Concrete surface should be clean and dry. Acid etch or light blast. Use elastic, highly penetrating paint with alkali resistance (epoxy).

**(Source: Federation of Societies for Coating Technology, Pictorial Standards of Coating Defects, Chalking Resistance, Erosion Resistance, Mildew Resistance, Philadelphia, PA)**

## Physical Defect-Related Failures

Many specific types of physical defects have been categorized and studied by the paint and coatings industry and by coatings and corrosion engineers. Many of these physical defect-related failure types overlap with the formulation-related failure and substrate-related failure types discussed above. However, these physical defect types and their nomenclature as discussed here are traditionally considered by the paint and coatings industry, and they merit a separate category. Several specific types of physical defect-related failures are presented in Table 2, as well as appearances, causes, and problem prevention. They include blisters; bubbles and craters; color mismatch; dirt; fisheyes; gloss variations; mottle; orange peel; runs, sags, and curtains; paint adhesion loss; soft paint films; solvent popping, boiling, and pinholes; and solvent wash.

**Table 3. Physical Defect-Related Failures**

<b>Defect Failure</b>	<b>Failure Appearance</b>	<b>Cause of Failure</b>	<b>Problem Solution</b>
1. Blisters	Dome-like raised area containing moisture or other liquids.	Contamination on surface prior to painting or coating. Moisture in wood substrate.	Clean surface prior to painting. Other means of moisture escape for wood substrates.
2. Bubbles and craters	Bubble: dome-like raised area containing vapor. Crater: concave area once covered by bubble.	Solvent or moisture entrapment during drying or baking.	Application of coating in thin layers. Sufficient flash time before baking.
3. Color mismatch	Color deviations from one area/part to another.	Variations of film wetness and build, substrate, thickness, application and agitation.	Consistency required in film wetness, build, thickness, application and agitation.
4. Dirt	Any contaminants found in paint or on painted surfaces.	Inadequate facilities, poor housekeeping, poor painting practices.	Improved housekeeping and attention to painting practices and procedures.
5. Fisheyes	Small depression with a central mound.	Caused by residual oil or grease, especially silicone types.	Keep painting area free of silicone products. Use fisheye eliminators.
6. Gloss variations	Gloss deficient patches of paint film.	Basecoat wet spots, improper oven conditions, insufficient film build.	Control bake oven conditions, proper application, consistent film thickness.
7. Mottle	Metallic paint; color pigments separate from metallic flake.	Application of paint too thick or excessively wet.	Do not apply the paint too wet.
8. Orange peel	Repetitive bumps and valleys similar to an orange surface.	Freshly applied paint film does not flow out smoothly.	Proper paint spray atomizing pressure, paint viscosity, and film thickness.



9. Runs, sags and curtains	Downward flow of paints prior to film hardening.	Application of coating too thick or too wet.	Proper spray gun cleanliness and operation. Correct solvent amounts.
10. Paint adhesion loss	Premature separation of paint film from substrate.	Contaminants, excessive bake time, condensed moisture.	Cleanliness, correct bake parameters, prevent condensed moisture.
11. Soft paint films	Coatings cured to hardness below a designated specification.	Improper oven/cure parameters, softening contaminants, excessive solvents and film builds.	Correct bake parameters, avoid softening agents, proper solvent amount and film build.
12. Solvent popping, boiling and pinholes	Tiny surface craters on paint films. Small versions of bubbles and craters.	Overly rapid solvent loss from the wet paint, escaping as “bursts.”	Avoid pigment clusters, controlling solvent evaporation rates and oven temperatures.
13. Solvent wash	Paint voids or areas with thin paint due to solvent condensation.	Excessive solvent evaporation on entry area of oven, condensation on cool area of part.	Sufficient flash time before painted parts enter an oven.

(Source: **Industrial Painting Principles and Practice, Second Edition, Norman Roobol, Hanser Gardner Publications, Cincinnati, OH, 1997.**)

### **Case Study Analysis of Paint and Coating Failures**

Six case studies concerning paint and coating failures will be the focus of the following section. The approach adopted for each case study will provide the principal characteristics of the failure, main identifying features, basic problem solving techniques, and applied aspects of the failures.

#### **Case Study I – Corrosive Industrial Environment**

A major power company requested an investigation to determine the cause of paint failures on the two storage tanks and associated piping at a trucking company facility. Peeling, or delamination, was experienced. The trucking company, which was approximately 1 mile distant from the client’s coal-fired power plant, was laying the blame on the power plant’s stack emissions for peeling paint on the trucking company’s storage tanks and associated piping.

In discussions with the power plant’s engineering department, it was determined that the plant was meeting the mandated gaseous emissions requirement of less than 1.2 pounds SO<sub>2</sub> per million Btu output, which led to water vapor droplets containing sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and sulfate compounds. The actual measured stack emission averages 100 to 200 parts per million SO<sub>2</sub>. The plant emission of NO<sub>x</sub> ranged between 0.05 and 0.35 pound NO<sub>x</sub> per million Btu output. The particulate emissions from the stack were primarily silicon, aluminum, and iron oxides (87.7 weight percent), with small amounts of calcium, magnesium, sodium, and potassium oxides. Some water and sulfur trioxide was also present, and the loss on ignition was 5.4 weight percent.

Discussions with the trucking company representative focused on an attempt to obtain information concerning the type of paint applied and when the paint was applied to the storage tanks and piping. The representative had insufficient knowledge to answer either of these questions.

A site visit was made to the trucking company, and discussions were held with the client and a representative of the trucking company. Peeling paint was observed on both storage tanks, as well as on the associated piping, and a pipeline flange. Photographs of the failures were taken, as illustrated in Figures 1 through 3. Several measurements of the paint thickness were made on the pipeline, one tank, and a flange. All of the thickness measurements ranged between 4.5 mils (0.0045 inch) and 7 mils (0.007 inch). Samples of the peeling paint were collected from one tank, the pipeline, and a flange. Also, a dark soot sample was collected from the wall of one tank with tape.

Fourier transform infrared (FTIR) spectroscopy was performed on the top sides of the paint chip samples using the attenuated reflectance (ATR) technique. The under sides of the paint chips were too contaminated with rust for FTIR analysis. All of the paint chip samples appeared to be of similar paint resin chemistry, and were phenoxy-based resin, as shown in the FTIR given in Figure 4.

Energy dispersive x-ray fluorescence spectrometry (EDS) was conducted on both sides of each of the three paint chips, as well on the soot sample at 20 kV accelerating potential. Figures 5 and 6 present EDS spectra for the top side and under side of a paint chip from tank #1. Figure 7 presents an EDS spectrum of the soot sample. Sulfur was found on both sides of the paint chips, as well as in the soot. Sulfur is not present in this paint composition as a pigment, resin, or additive, and so it must have been deposited from the local environment. The power plant and/or other industrial plant(s) in the area may have been potential sources. Chlorine/chloride was also found on both sides of the paint chips, as well as in the soot. Chlorine/chloride is also not present in this paint composition, and also must have been deposited from the local environment. The elemental composition of the soot matched closely the elemental composition of the fly ash from the power plant.

A sample of the pipe paint chip was mounted in cross section in epoxy, polished, and examined under an optical microscope. The chip examined did not display defects or trapped vapor bubbles. The chip appeared to possess two layers or coats of paint, with approximate thicknesses ranging from 1.2 to 3.0 mils for the top layer and 2.1 to 4.9 mils for the bottom layer.

The coating system originally selected for the trucking company storage tanks and piping was not resistant to the combination of industrial stack emissions and moisture present in the local environment. Sulfur and chlorine/chloride penetration to the steel substrate surfaces appears to be a contributing factor in the delamination and peeling of the paint at the facility. Sulfur and chlorine in the form of chemical compounds may diffuse through an organic coating over time and reach the metal substrate, forming metallic corrosion products, which will delaminate the coating from the substrate.

The source(s) of the sulfur and chlorine/chloride cannot be proven with complete certainty. Based on the known sulfur emissions of the nearby coal-fired power plant, it is highly likely that the power plant does contribute a share of the atmospheric sulfur which ultimately deposits at the trucking company site. However, it is not certain whether or not other local sources of sulfur and chlorine/chloride exist, which may be contributing to the problem.

Based on past experience a coating resistant to industrial pollution should have been applied at this location. Recommendations were made here to mitigate the effects of sulfur on the tanks and piping at the trucking company, with regard to repair and replacement coating. A known successful plant maintenance coating system utilized for coal-fired power plants should also be used here for the trucking company storage tanks and pipeline. Adequate surface preparation would include a water blast at a minimum pressure of 4500 psi using a rotary turbo nozzle to remove all loose paint, dirt and loose rust. This would be followed by application of the optimized primer, intermediate, and finish coats.

## **Case Study II – Rural Environment**

Corrosion failure occurred on a galvanized and painted sheet steel roofing material, measuring 16 inches wide by 25 inches long, which had experienced corrosion and red rusting. The roof was located on an elementary school building, in a rural setting in the northeastern United States, and was not subject to any chemical fumes or salt spray. The roofing material was a 29 gauge, galvanized, 1-1/4 inch standing seam roof (SSR). Laboratory investigation of the failed galvanized and painted sheet steel roofing sample included visual examination, Fourier transform infrared spectroscopy (FTIR), low magnification stereo optical microscopy, high magnification cross sectional optical microscopy, and scanning electron microscopy – energy dispersive x-ray spectrometry (SEM-EDS).

Visual examination of the roofing material was undertaken. The sample was coated green on one side, and light blue on the opposite side. Close-up examination was conducted and photographs were taken, as illustrated in Figures 8 and 9. In general, the red rust appeared to be localized on one end of the length of the panel, as seen in the photographs. Also, the rust was found in the same locations on opposite sides of the panel in a regularly spaced pattern; both on the green and light blue sides. A slight amount of red rusting was also found on fabrication ridges on the green side.

Low magnification stereo optical microscopy of the surfaces of both sides of the roofing sample was conducted on from two small sections cut from the sample. One section was cut from an apparently uncorroded, or “good” area; one section was cut from a corroded area. The good area of the green coating appears to be highly uniform. The good area of the light blue coating showed the presence of dark spots. The corroded area of the green coating had small, spotty patches where the coating was still intact. The corroded area of the light blue coating possessed an area of continuous corrosion, with an adjacent area of spotty corrosion at the boundary.

Fourier transform infrared (FTIR) spectroscopy was performed on the green and light blue coatings on the opposite sides of the roofing sample using the attenuated reflectance (ATR) technique. Based on the FTIR spectral analysis, the green coating appeared to be a purified isophthalic acid type polyester coating and the light blue coating appeared to be a saturated polyester coating, possibly phthalic anhydride/glycerine type. These were consistent with the available literature concerning the manufacturer’s 1-1/4 inch SSR product specifications.

Cross sections of the substrate-coating systems from the “good” and corroded areas of the roofing sample were cut, cold mounted in epoxy resin, ground, and polished in accordance with standard procedures. High magnification cross sectional optical microscopy of the substrate-coating system was conducted on the good and corroded sections and digital optical micrographs were taken.

Aside for a corrosion pit in the galvanized layer under the green coating, which is seen in Figure 10, the “good” sample met the manufacturer’s specifications for the 1-1/4 inch SSR. Severe corrosion was present on the light blue side, as seen in Figure 11, and the galvanizing was beginning to be attacked on the green side. The galvanized layer average thickness (1.6 mils both sides) corresponded to a coating weight of 0.94 ounces per square foot, or a G 90 coating designation, as given in ASTM A 525, “General Specification for Steel Sheet, Zinc-Coated by the Hot-Dip Process.”

Scanning electron microscopy – energy dispersive x-ray spectrometry (SEM-EDS) was performed on the “good” and corroded cross sections. On the “good” cross sectional sample shown in the SEM micrograph of Figure 12, sulfur, a corrosive element, was found in three locations surrounding the corrosion pit in the galvanized layer underneath the green coating layer. Figure 13 presents an EDS spectrum of one area showing high sulfur levels. On the corroded cross sectional sample shown in the SEM micrograph of Figure 14, chloride, a corrosive element, was found on both the light blue coating and in the corrosion product underlying the green coating. Figure 15 presents an EDS spectrum of an area possessing substantial chloride.

Based on these laboratory observations, no evidence was found for cause of the corrosion failure being due to quality of application or manufacturing defects. The presence of the corrosive elements sulfur and chlorine certainly appeared to be responsible for the accelerated corrosion. However, the source of these elements could not be identified in this laboratory investigation.

Also, based on the presence of the regularly spaced pattern of corrosion, or red rust, which was found at one end of the roofing sample, and on both the green and light blue sides, it seemed most reasonable to conclude that some means of superficial mechanical damage occurred which disrupted the coating – galvanizing system. In the presence of corrosive chlorine/chloride and sulfur, accelerated corrosion attack in the superficially damaged area would occur. Thus, the damage must have been of a relatively recent origin in comparison to the time of purchase 10 years ago.

This did not account for the appearance of slight red rusting found on the fabricated ridges of the green side. However, as the material was within weeks of expiration of the manufacturer’s 10-year warranty, this seemed to be a minor issue given the presence of the corrosive elements chlorine/chloride and sulfur obviously found in the local environment.

It was recommended that consideration be given to repainting the corroded areas with a zinc-rich coating system. This would serve as a suitable repair coating for the corroded painted and galvanized sheet steel roofing.

### **Case Study III – Indoor Moisture Accumulation**

Paint failure in the form of widespread cracking and peeling, or delamination, was experienced on the walls and the ceiling of a large cathedral in the northeastern United States. Recommendations to solve the problem were required, as the cathedral would soon be undergoing renovation and repainting. Background information was collected from the client, an engineer of the cathedral’s contracted architectural firm, and from the cathedral maintenance manager during both face-to-face and telephone conversations.

Details concerning the paint brand or composition were not known. However, it was known that the paint was applied approximately 10 years ago by a contractor, who has not been able to be contacted. The paint peeling problem first appeared about 5 years ago, a short time after a new 25 ton air conditioning system was installed on the rear roof of the cathedral. Also to be noted is that since the installation of the new air conditioning system, the rear and side windows in the choir loft had been always kept closed. Before the installation of the air conditioner, the windows were opened for ventilation and air circulation, and no paint peeling had occurred. The peeling first started to occur at the rear of the cathedral, but moved forward over time toward the front of the cathedral.

In current practice at the time of this investigation, the air conditioning system was programmed for operation primarily on Sundays from 6 AM to 2 PM. There was a dome fan, which will activate when the dome temperature reached 90° F. The setpoint for warm season air conditioning was 73° F. During the heating season, steam heating was employed with ground level heating vents. The heat was usually turned on Saturday to achieve a temperature of 68° to 70° F. During the weekdays, winter temperatures in the cathedral may have been in the 50° to 60° F range.

A site visit was made to the cathedral for examination and sample collection. Paint cracking and peeling was observed throughout the cathedral. The peeling problem was most pronounced near the rear ceiling air conditioning vents, as seen in the photograph of Figure 16. Inasmuch as peeling was found around all of the walls and ceiling, the peeling problem was more pronounced toward the back of the cathedral, and more pronounced at higher elevations in the cathedral. Figures 17 and 18 present photographs of paint peeling on the upper walls behind the altar and near a stained glass window, respectively. The adhesion of the cracking and peeling areas of paint was very poor, as shown by the tape adhesion test. Samples of the peeling paint, both lighter and darker colors, were obtained from the walls for Fourier transform infrared (FTIR) spectroscopy, energy dispersive x-ray spectrometry (EDS), and cross sectional optical microscopy.

A second site visit was made a month later to conduct a surface moisture survey of the painted walls using a surface moisture probe. A survey was conducted of both the ground floor and the choir loft. Clearly, there was a correlation between the visual observation of degree of paint peeling with surface moisture as a function of location, as both peeling and moisture were more substantial toward the back of the cathedral, and at higher elevations. For example, in the ground floor of the cathedral, moisture levels were generally 1% or less. In the choir loft, which occupied the second floor, rear of the cathedral, moisture levels were measured in excess of 5%

Fourier transform infrared (FTIR) spectroscopy was performed on both the light and dark paint chips. By means of a solvent extraction with tetrahydrofuran (THF), the paint resins were deposited as a thin film on glass slide and subjected to FTIR by means of the attenuated reflectance (ATR) technique. Two spectra were obtained, one of the light paint and one of the dark paint. Both spectra appeared to be vinyl acetate based polymers. The FTIR spectrum of the dark paint binder, given in Figure 19, had a more intense carbon-hydrogen absorption band at around 2900  $\text{cm}^{-1}$ , which might indicate that it was vinyl acetate copolymerized with ethylene. The strong oxygen-hydrogen absorption band at 3350  $\text{cm}^{-1}$  is suggestive of substantial absorbed water.

Energy dispersive x-ray spectrometry (EDS) was conducted on the samples of peeled light and dark paint. Results indicated the presence of titanium dioxide, calcium carbonate, and aluminosilicates. Titanium

dioxide is a primary white pigment. Calcium carbonate and aluminosilicates are typically used as pigment extenders.

The light and dark paint chips were mounted in cross section in epoxy, polished, and examined under an optical microscope. Neither chip examined microscopically displayed defects or trapped vapor bubbles. The light chip appeared to possess three layers or coats of paint, with approximate thicknesses of 1.5 mils, 3.5 mils, and 4.5 mils. One mil equals 0.001 inch. The dark chip appeared to possess thirteen (13) layers of paint with an overall thickness of approximately 38 mils.

As the paint consisted of a conventional vinyl acetate binder with typical pigments, and displayed no microscopic defects in cross section, the paint itself or its application could not have been considered the root cause of the peeling problem. However, the environmental conditions in the cathedral were a concern. Certain factors, discussed earlier, pointed to excessive moisture buildup and retention as being the root cause of the paint cracking and peeling problem.

Since the installation of the new air conditioning system, the rear and side windows in the choir loft were always kept closed. Before the installation of the air conditioner, the windows were opened for ventilation and air circulation, and no paint peeling had occurred. Also, the degree of paint cracking and peeling and surface moisture levels appeared to be directly correlated, as both peeling and moisture are more substantial toward the back of the cathedral, and at higher elevations.

Recommendations to solve this paint peeling problem were of two types. The first type involved building operation, and the second type was in the selection of an appropriate paint for renovation and repainting.

Ventilation is crucial. Because it was heated only one or two days a week, moisture from the atmosphere and the congregation condensed on cold walls and ceilings. Good ventilation during the week could reduce condensation problems. Opening windows could help to minimize condensation and dampness, but this requires a dedicated staff person to monitor external weather changes and ensure closure when rain occurs.

Coating materials such as sealers, dense or vinyl emulsions or oil based paints which are impermeable to moisture and water vapor should not be used, because the likelihood is that they will be lifted from the wall by the pressure of moisture trying to dry out internally. Some suitable types of coatings include the following.

- Lime-wash - one of the most effective materials for use on old stone walls and plaster and breathes very well.
- Lime and tallow – not as easy to use as lime wash and does not touch up without leaving water marks.
- Distemper – it is easy to use and is good for old walls; there are different types of acceptable distemper.
- Emulsion paints – may be suitable for churches built over the last 50 years that have damp courses and cavity walls.
- Micro-porous paints – they may be suitable for some churches, but will flake if applied over softer paints.

## Case Study IV – Coating Incompatibility with Primer

Urethane touch-up paint failures were experienced on the seat standards in the upper level east and west sections in a football stadium in the northeastern United States, shown in the photograph of Figure 20. Extensive delamination was experienced on approximately 20 percent of the seat standards that received the touch-up. The touch-up paint used was a two part urethane furnished by a particular supplier, designated here as supplier #1. According to the client, they followed recommended mixing proportions of 4 parts paint to 1 part catalyst. The color was a specially blended yellow. Paint was used in pots in one cup lots. Prior to applying the touch-up urethane, a commercial primer was spot applied to exposed metal areas on the standard. This was a primer furnished by another supplier, designated here as Supplier #2. Another urethane touch-up paint manufactured by the same company as the primer, Supplier #2, was used earlier, but, since it was not the right color, the touch-up work was switched over to the paint supplied by the Supplier #1. Reportedly, no problems were encountered with the original touch-up paint.

The base paint system used on the stadium seat standards was a water borne two part epoxy paint “E-coat” system, with a 1,3,5 triglycidyl isocyanurate (TGIC) topcoat. The coating is applied by electrostatic spray and cured by baking for 15 minutes at 375° F.

A site visit was made to the football stadium. At this time, the client and a representative of the touch-up paint supplier #1 were met. Examination included the seating areas where failures were occurring, including close-up examination and photographs, as well as observation of the pressure washing operation. A close-up photograph of the peeling paint on a seat standard is given in Figure 21. Samples were obtained from the client, including painted metal chair standards with and without peeling urethane touch-up paint, designated Samples No. 1 and 2, respectively, as well as samples of Supplier #1’s liquid paint and catalyst.

Photographs were taken of the stadium seat standard with peeling touch-up paint, which was removed and returned to the lab. The adhesion of the remaining Supplier #1 paint to the original yellow paint was very poor, and it could be easily flaked off by probing with an X-acto knife. This is seen clear in the close-up photograph of Figure 22. A photograph of a delaminated touch-up paint chip was also taken.

When the back side of the delaminated Supplier #1’s touch-up paint was examined with a stereo microscope with magnification to 30X, it was smooth, clean, and glossy. Likewise, the surface of the original yellow paint from which it delaminated was also smooth, clean, and glossy. The delaminated paint consisted of a single yellow coat approximately 2 mils thick, with no evidence of voids or porosity. Exposure to a drop or two of methyl ethyl ketone (MEK) resulted in some swelling and curling of the chip after about 309 seconds, but it did not dissolve.

The solvent resistance of the original yellow topcoat on Sample No. 1 was evaluated by rubbing with a cotton Q-tip and MEK. The solvent resistance was fair, as 50 double rubs resulted in moderate color transfer, and dulled and slightly softened the coating.

Sample No. 2 was another bright yellow metal chair standard, reportedly where the touch-up paint had not failed. An area of the Supplier #1’s touch-up paint had been marked on the front face, or edge, of the standard, and an area of the Supplier #2’s touch-up paint, of a markedly different shade of yellow, had been marked on the armrest area. Both touch-up paints were apparently intact. However, when probed with a

knife, the Supplier #1's touch-up paint was found to have very poor adhesion, and it could be easily peeled from the original yellow paint.

In contrast, the Supplier #2's touch-up paint had good adhesion. The delaminated Supplier #1's touch-up paint consisted of a single yellow coat approximately 2 mils thick. The back of it, as well as the surface of the original paint from which it delaminated, were clean, smooth, and glossy. The flaking paint had similar resistance to MEK as did the flaking paint from Sample No. 1.

Fourier transform infrared (FTIR) spectroscopy was performed on a sample of the delaminated touch-up paint. The technique involved combining sample scrapings with potassium bromide powder and forming into pellets under high pressure. The pellets were then placed in the optical path of the spectrometer, and spectra obtained over the range  $4000\text{ cm}^{-1}$  to  $400\text{ cm}^{-1}$ . Two spectra were obtained. The analysis revealed that the failing Supplier #1's touch-up paint from Sample No. 1, shown in Figure 23, is virtually identical to the properly mixed (4:1 mix ratio) liquid control sample of Supplier #1's touch-up paint, shown in Figure 24. The coatings are a urethane, as seen by absorption bands near  $1730$ ,  $1690$  (a weak shoulder), and  $1530\text{ cm}^{-1}$ .

Energy dispersive x-ray spectrometry (EDS) was conducted on the sample of delaminated touch-up paint at 20 kV accelerating potential. The carbon and oxygen present are characteristic of the urethane resin. Also present were elements corresponding to the presence of titanium dioxide, a primary white pigment, and aluminosilicates, typically used as pigment extenders.

The liquid control sample of the Supplier #1's touch-up paint was mixed at the proper 4:1 ratio and brush applied to a small area of the original yellow paint on Sample No. 1. Test patches were also applied at the wrong mix ratios of 2:1 and 8:1. After curing for one week, the patches were tested for adhesion in accordance with ASTM D 3359, "Method for Measuring Adhesion by Tape Test," Method B. This involves scribing a cross hatch pattern into the sample, and applying a special pressure sensitive adhesive tape. The tape is then rapidly removed, and the amount of coating detachment assessed in accordance with the method's visual rating scale. This ranges from a 5B for no loss of adhesion, to a 0B for 65% or more loss of adhesion.

Supplier #1's touch-up paint was found to have extremely poor adhesion to the original yellow paint, with a rating of 0B. Indeed, it was flaking during the cutting operation, without the need for tape, and when tape was applied and removed, it completely removed the touch-up paint, even beyond the area of the actual crosshatch pattern. This was true regardless of the mix ratio of the touch-up paint.

Based on the laboratory investigation of the samples, the root cause for the delamination of the Supplier #1's touch-up paint from the original yellow topcoat is a basic incompatibility between the touch-up paint and the TGIC powder coating originally applied to the seat standards. This was indicated by the fact that the Supplier #1's touch-up paint, which was thought to have good adhesion to a seat standard, was actually found in the laboratory to have extremely poor adhesion, but had simply not fallen off by itself as of yet.

Furthermore, when properly mixed Supplier #1's touch-up paint was applied in the laboratory to the original yellow paint on a section of a seat standard, it was also found to have extremely poor adhesion. This ruled out any factors related to poor application of the touch-up paint, and clearly demonstrates that it is simply incompatible with the existing, original yellow topcoat. Indeed, there was no visual or microscopic



evidence of contamination on either the back of the failing topcoat from a stadium seat standard, or on the original, underlying topcoat.

FTIR spectroscopy showed that the failing touch-up paint matched the properly mixed control sample provided to the laboratory. The observation that both the back of the delaminating paint and the front of the underlying TGIC topcoat paint were smooth and glossy suggest that the solvents in the touch-up paint never softened or bit into the original TGIC topcoat paint adequately enough to provide good adhesion.

One possibility to improve the adhesive properties of the urethane touch-up paint without impacting the desired color may be to modify the solvent blend to permit softening of the underlying TGIC topcoat, with subsequent improved adhesion of the touch-up paint to the topcoat.

### **Case Study V – Poor Paint Adhesion**

A painted galvanized square tube section of bridge railing and other similar parts had been rejected by a transportation department because of a loss of paint adhesion. The client reportedly purchased the hot dip galvanized square tube railing, blasted the surface with steel shot to provide the specified 1.0 to 2 mil surface profile and then washed the surfaces with a trisodium phosphate (TSP) solution prior to painting. A gray colored two component epoxy primer was used followed by a black colored aliphatic acrylic-polyester polyurethane top coat. The time intervals between steps was reported to be approximately no less than 24 hours. It was reported that after the application of the primer no problems were noticed by the on-site inspector. After the application of the top coat some blistering was observed. Observed blisters were repaired by locally removing the paint down to the galvanized surface, spot repriming and top coating. No further loss of adhesion had been observed at the repair locations.

Other blisters occurred after being shipped and stored at the job site. It was also reported that post beams painted at the same time have not experienced any evidence of poor adhesion. At a later date a second rail section was submitted that had been repair coated in his shop as well as a large paint chip that had been sent from the job site.

The rail section exhibited a few areas of paint loss due to poor adhesion. The loss of adhesion occurred at the galvanizing/primer interface. The areas were usually observed near the ends of the rail section with the exception of one area near the center of the rail section where the loss of adhesion occurred at the location of an intentional X cross cut. See Figure 25. A few repaired blister areas were also observed as shown in Figure 26. No blisters were observed in the as received sample.

At locations where the paint was absent the underlying galvanized surface exhibited a pock marked texture caused by the shot blasting. These indentations resulted in a corresponding raised pattern on the underside of the primer. An X cut was made through the paint in an area where no previous failure of the paint had occurred. Separation occurred readily at the galvanizing/primer interface. On the underside of the paint film considerable particulate material was observed as shown in Figure 27.

The particulate material observed on the underside of the primer at the plane of delamination was analyzed for its elemental composition using a scanning electron microscope (SEM) equipped with an energy dispersive x-ray spectrometer (EDS). A spectrum of the particulate material is shown in Figure 28. The particulate material was found to consist primarily of iron and zinc which is indicative of shot blasting

material debris from the shot blasted galvanized surface. Chromium was also found in association with the particulate material.

A spectrum of the underlying surface of the primer at the plane of delamination, without any significant surface contamination, is shown in Figure 29. A spectrum of the surface of the galvanized coating at the plane of delamination, in an area without any significant surface contamination, is shown in Figure 30. No chromium, indicative of a chromate conversion coating, was detected on either mating surface. Also, the surface of the galvanized coating at the plane of delamination was also further examined by Auger electron spectroscopy (AES) which is a surface sensitive method of elemental analysis. Again no chromium was detected. A spectrum of the primer plane of delamination could not be obtained.

Transverse cross sections through the painted galvanized rail were prepared for subsequent metallographic examination. The samples were examined in both the as polished condition and again after etching with a one percent nital solution which revealed the microstructure of the galvanized coating. The structure of the galvanized zinc coating consisted of an outer layer of metallic zinc above an iron-zinc alloy layer at the steel-galvanizing interface. The depressions, or pock marks, in the galvanizing caused by the steel shot blasting are shown in Figure 31. The coating thickness was measured optically using a calibrated filar eyepiece micrometer. The average thickness of the primer was measured to be 0.0041 inches (4.1 mils). The average thickness of the top coat was measured to be 0.0031 inches (3.1 mils). These values do conform to the specified minimum intermediate (ie. primer) and finish coat dry film thickness (DFT) values of 3.0 mils as per paragraph 708.06.1.1 of NHDOT Galv-Paint Spec, Amendment to Section 708-Paints.

The paint was found to have very poor adhesion at all locations examined with the plane of delamination occurring at the primer-galvanized coating interface. Considerable debris from the shot blasting operation was observed at the plane of delamination which exhibited a greater tendency to adhere to the underside of the primer. No chromium, indicative of a chromate conversion coating, was detected on the clean mating primer and galvanized surfaces. The only chromium detected was found to be associated with the iron blasting shot suggesting that the iron shot contains chromium as an alloying element. The cause of the adhesion failure appears to be the result of the corrosion of the blasting shot and to a lesser extent, the surface of the galvanized coating.

## **Case Study VI – Mechanical Damage**

Three painted galvanized roofing samples were subjected to failure analysis. All three of the galvanized roofing samples were from the same roofing panel, removed from the roof of a building in a city in the east-central part of the United States.

A visual examination of the three roofing samples was undertaken. Figure 32 presents photographs of the three samples. Two of the three samples had obvious localized corrosion in the coatings. The localized corrosion areas on the lesser localized corroded sample were believed to be representative of, and similar to the start of the localized corrosion on the most severely corroded sample. Low power microscopy using a stereo microscope revealed that the one sample that didn't clearly appear to have localized corrosion also contained very small areas of localized corrosion. The localized corrosion initiated from perforations in the coatings caused by mechanical damage most likely while in service or during installation. Examples of the mechanical damage may be found in Figures 33.

The perforations in the coating expose the galvanized panel to the atmosphere. As an exposed panel corrodes under the coating a blister is formed in the coating. The atmosphere attacks the galvanized substrate via the perforation in the coating's surface. The zinc sacrificially corrodes first, as designed, creating a layer of white rust on the substrate. However, as the white rust builds up, the localized galvanic reaction will decrease and the steel substrate begins to corrode leaving the ringed corrosion products shown in Figure 34.

Cross-sectional optical microscopy was used to determine whether the coating properties contributed to the corrosion of the roofing samples. The coatings were found to be relatively uniform with no porosity or delamination occurring within the coating layers. A micrograph of a typical cross-section is given in Figure 35. Grain boundary precipitates were observed within the galvanized layer. Paint, primer, and galvanized layer thickness measurements using a filar unit eyepiece and an optical light microscope at 1000x magnification to determine whether inhomogeneous coating practices were a contributing factor to the extent of corrosion of the galvanized roofing panels since the samples were all from the same roofing panel. The thickness measurements were similar, suggesting that the coating thickness may not be a major factor in the corrosion of the roofing panels.

Scanning electron microscopy - energy dispersion x-ray spectroscopy (SEM-EDS) was used to determine the elemental composition of the corrosion products on the roofing samples. Two localized corrosion areas from the severely corroded sample were analyzed. Corrosion products were found to be zinc corrosion products on the rim of the localized corrosion and iron corrosion products in the center of the localized corrosion area. Orange and white crusts from the outside of the localized corrosion area were taken and analyzed. The white crust was found to be zinc oxide and the orange crust contained iron, zinc, and oxygen. Sulfur was found on the outermost rim of each analyzed corrosion area, as seen in the EDS spectrum in Figure 36.

Fourier transform infrared (FTIR) spectroscopy was used to determine the chemistry of the paint and the primer coatings. The paint was found to be a poly(vinylidene fluoride) and the primer was a polyester.

Pencil hardness tests were performed on the roofing samples per ASTM D 3363 to determine whether fluctuations in the roofing panel's coating hardness were present. The measurements for all of the samples were in the same range. Cross hatch adhesion testing of the coatings was performed per ASTM D 3359. All of the samples were classified as 5B, meaning that the edges of the cuts were completely smooth and none of the squares in the lattice were detached. No unforeseen areas of underlying corrosion were found.

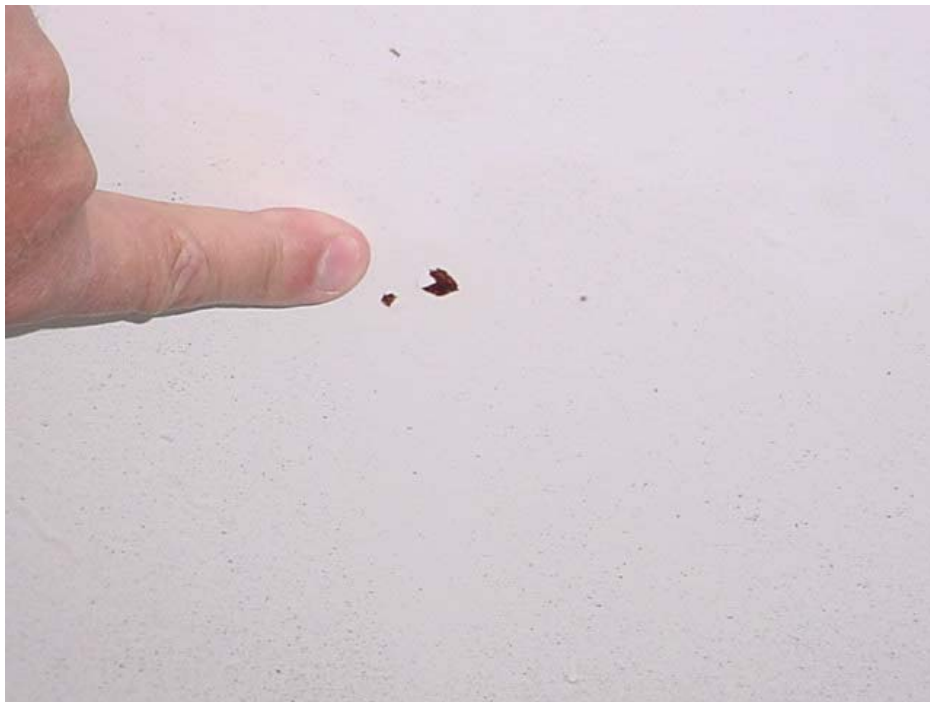
In summary, localized corrosion was found on all three galvanized roofing samples. There were no irregularities in the coating layers. The observed small localized corrosion areas formed due to mechanical damage to the coating exposing the steel substrate to the corrosion from the atmosphere. Due to the loss of the overlying paint film for the larger corroded areas, no direct evidence of mechanical damage was observed at these locations. However due to the absence of any evidence to the contrary, it appears that similar circumstances (i.e. mechanical damage) occurred at these locations also which resulted in corrosion of the substrate under the paint film.

## **Conclusion**

This paper emphasized the basic problems and applied aspects of the failures encountered in paints and coatings. Six separate types of failures were presented detailing the factors and mechanisms affecting the failures.



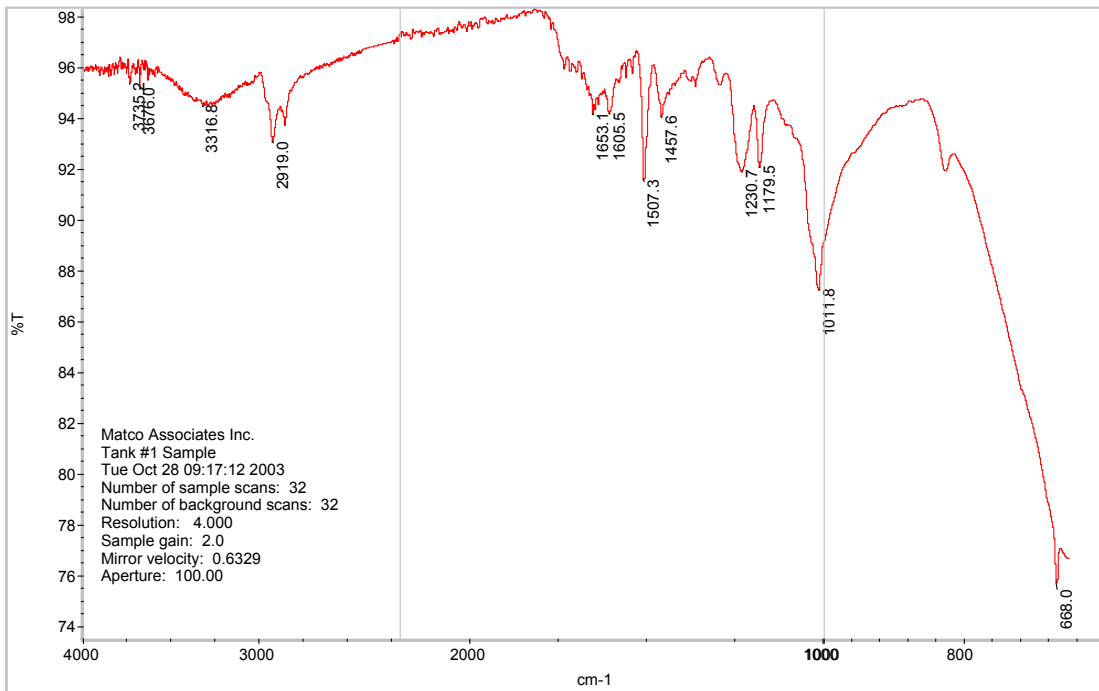
**Figure 1. Photograph of peeling paint from pipeline.**



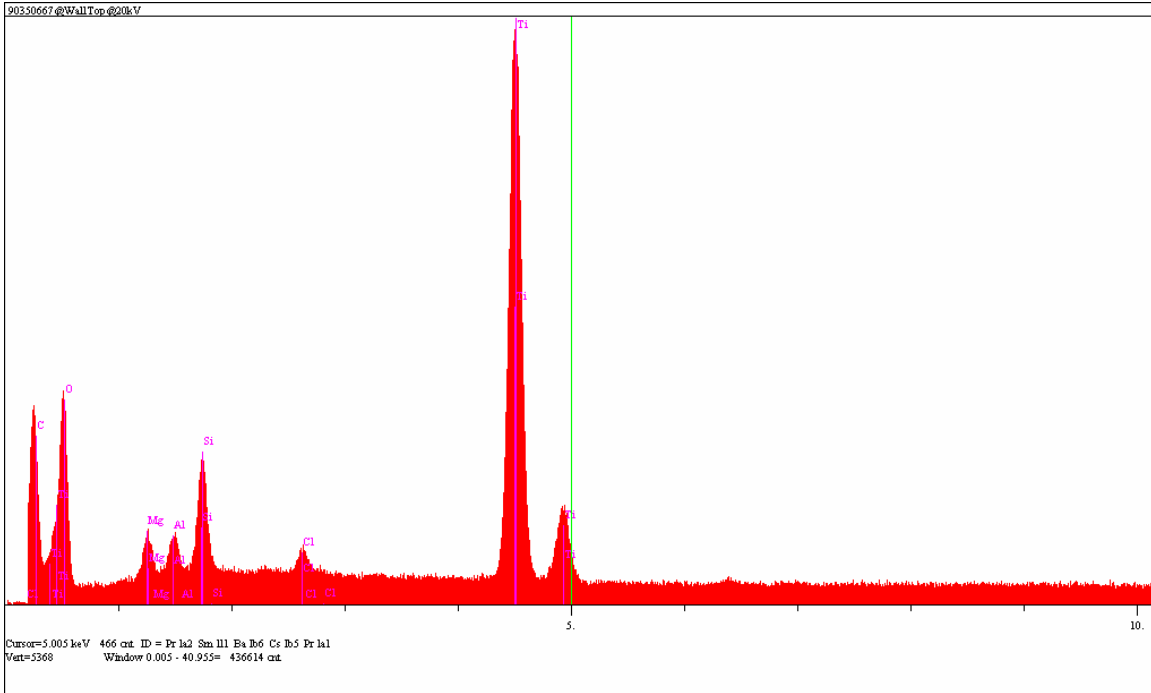
**Figure 2. Photograph of peeling paint from tank.**



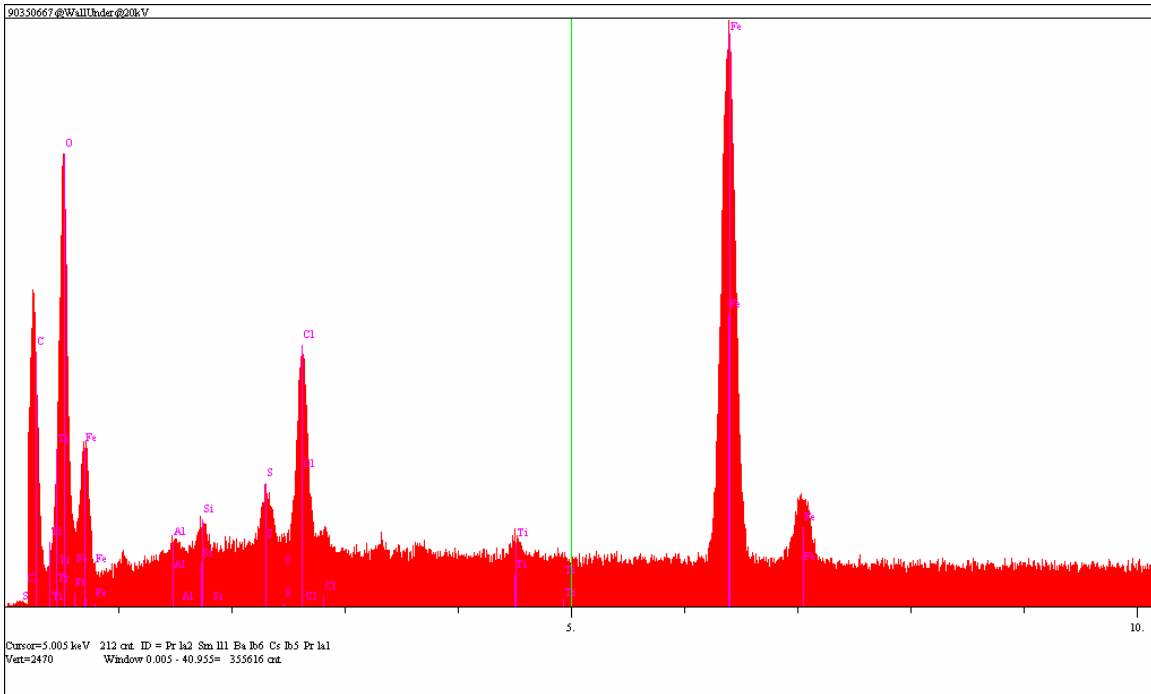
**Figure 3. Photograph of peeling paint from flange on pipeline.**



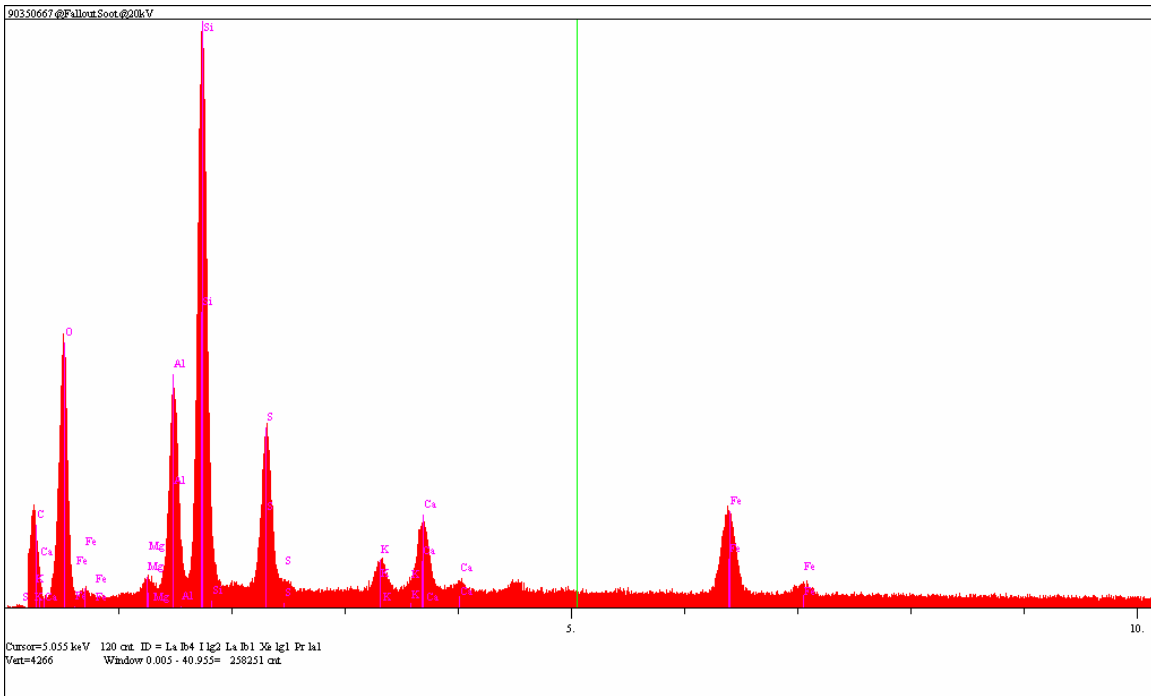
**Figure 4. FTIR spectrum of peeled paint chip from tank, top side.**



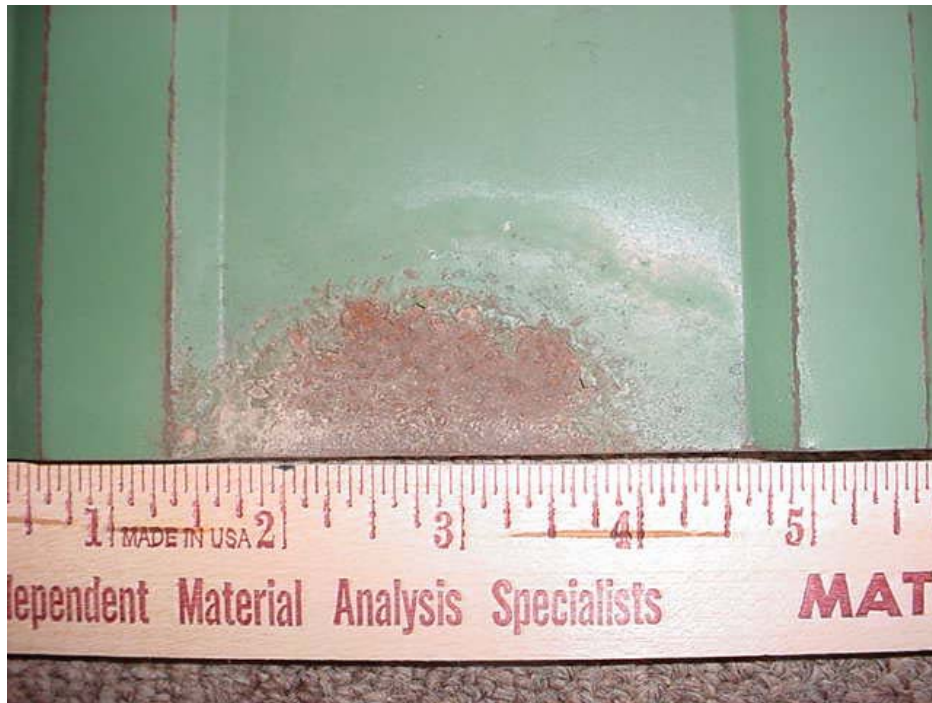
**Figure 5. EDS spectrum of tank wall paint chip, top side.**



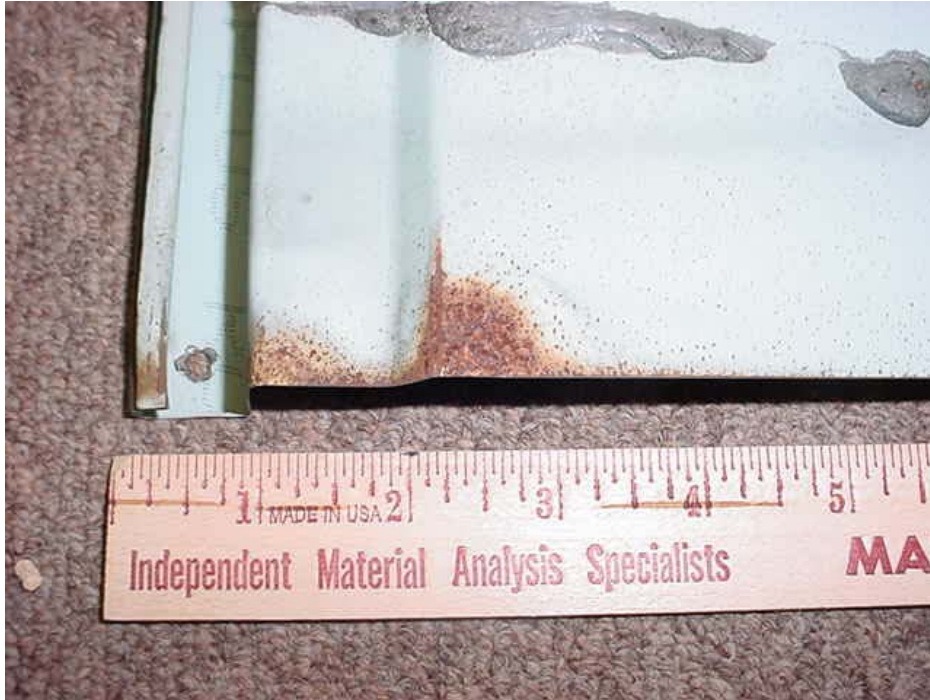
**Figure 6. EDS spectrum of tank wall paint chip, under side.**



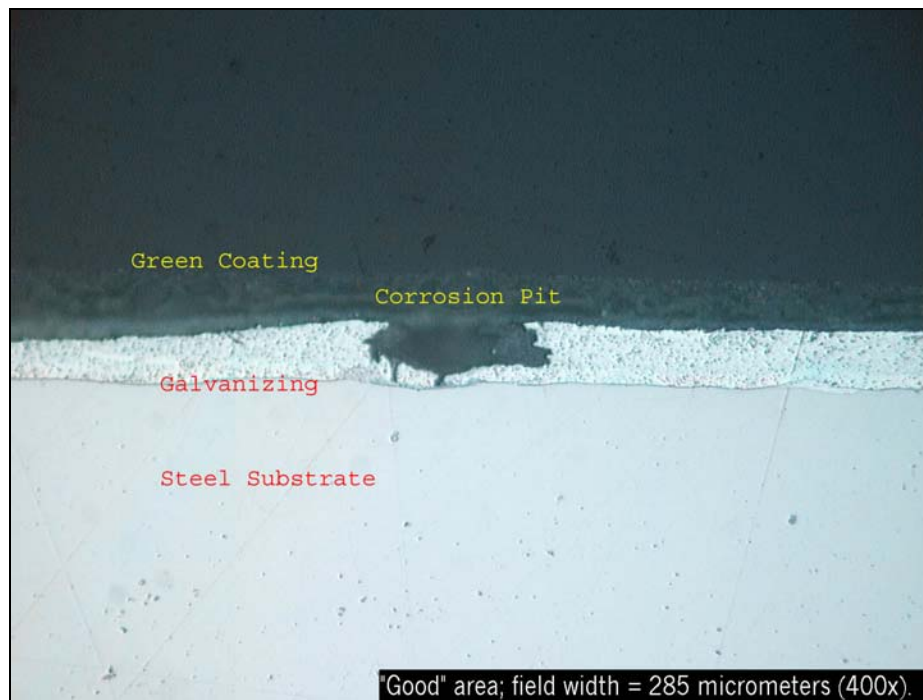
**Figure 7. EDS spectrum of dark fallout soot particle.**



**Figure 8. Close-up photograph of red rust spot on green side.**



**Figure 9. Close-up photograph of red rust spot on light blue side.**

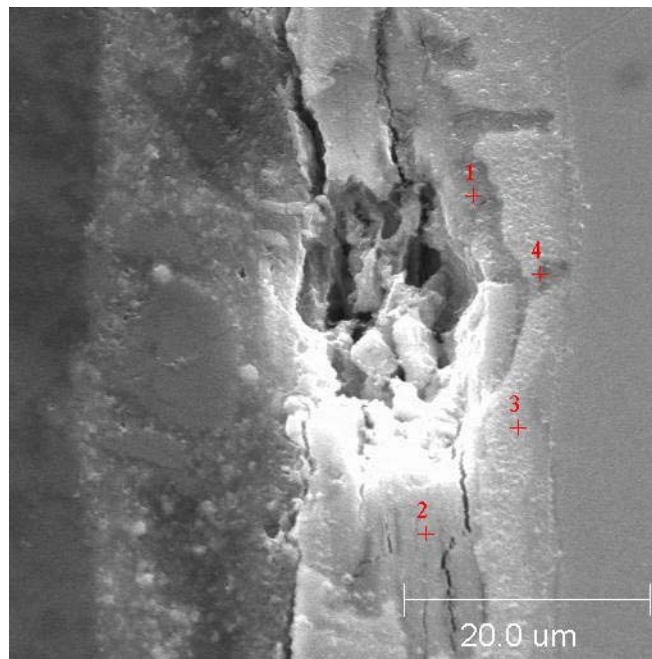


**Figure 10. Cross sectional optical micrograph of corrosion pit in galvanized layer under green coating; field width = 285 micrometers (400x).**

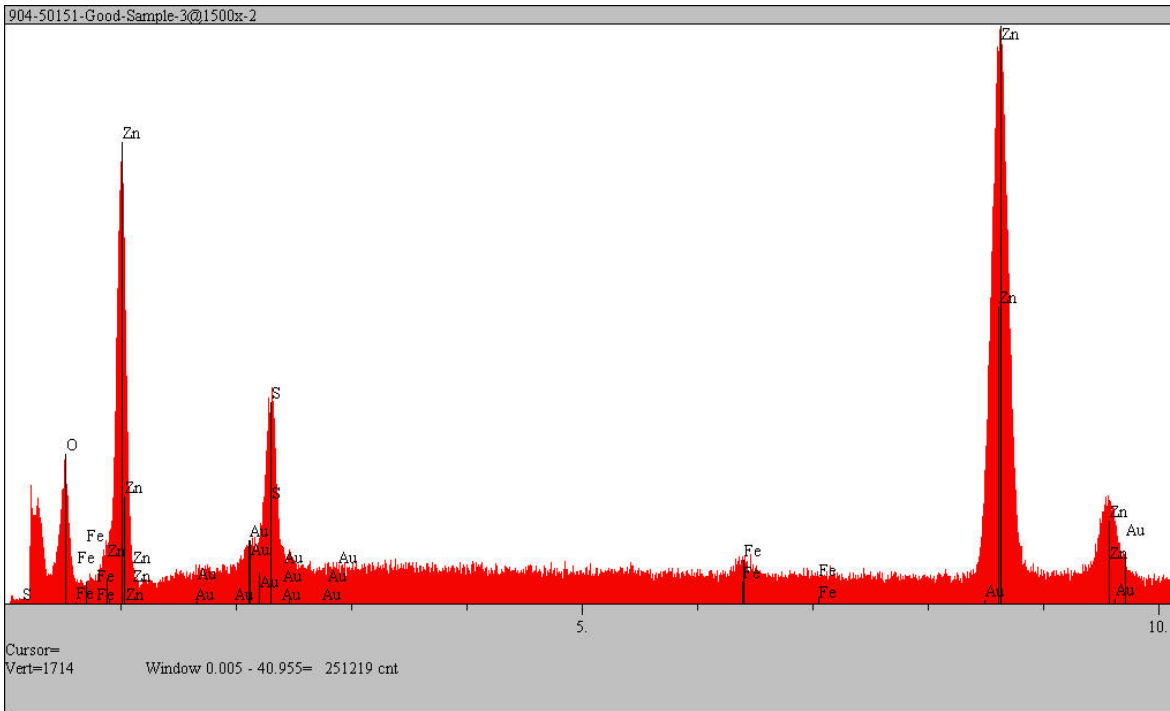




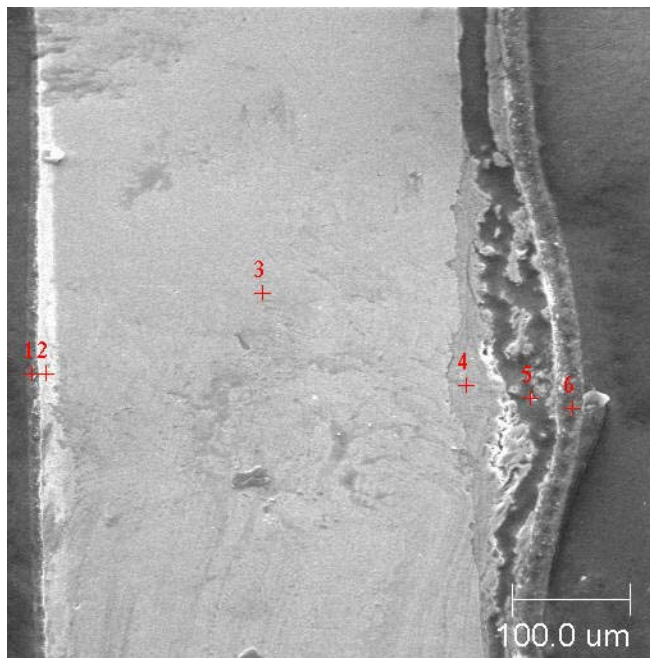
**Figure 11. Cross sectional micrograph of severe corrosion present on light blue side; field width = 285 micrometers (400x).**



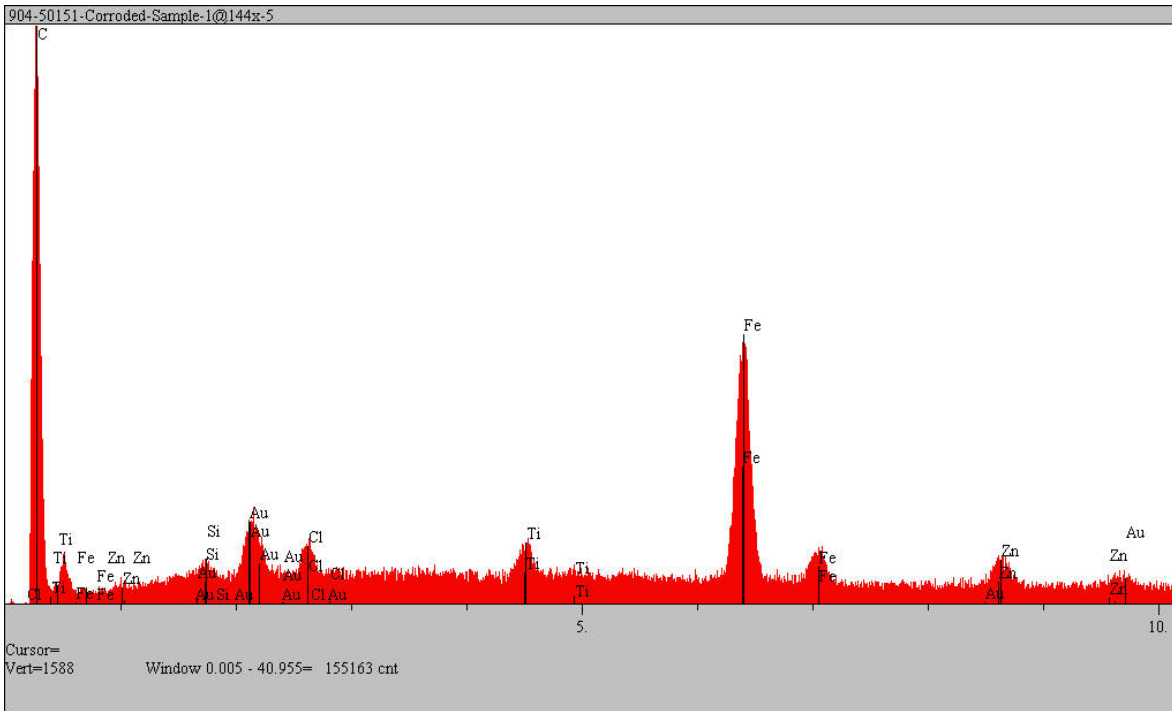
**Figure 12. Scanning electron micrograph of corrosion pit in “good” area with locations marked for EDS analysis.**



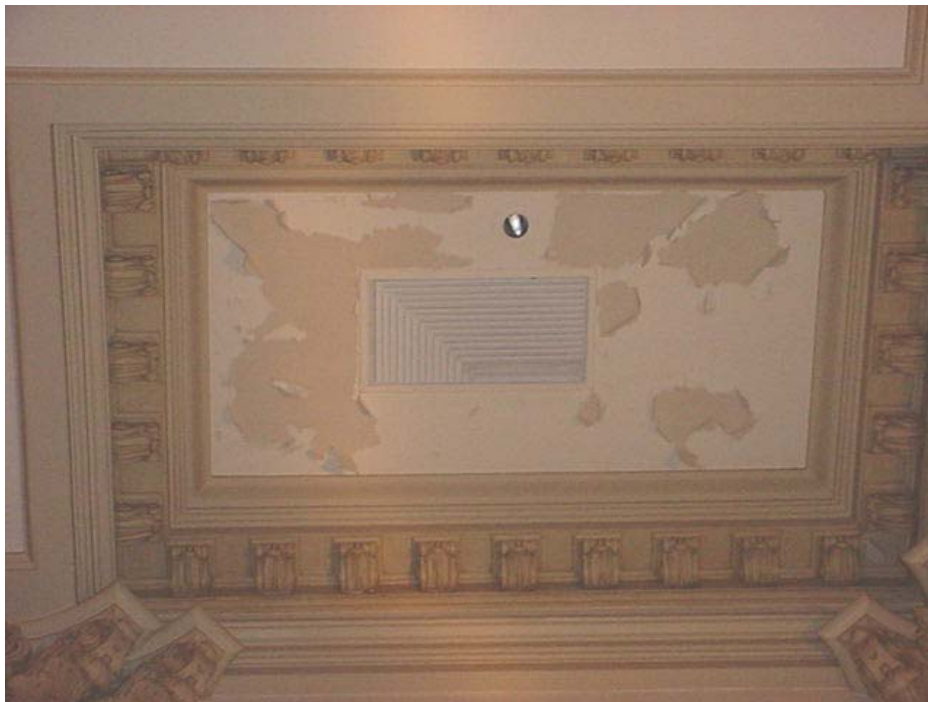
**Figure 13. EDS spectrum of location 2 from “good” area as shown in Figure 12.**



**Figure 14. Scanning electron micrograph of corroded area with locations marked for EDS analysis.**



**Figure 15. EDS spectrum of location 5 from corroded area as shown in Figure 14.**



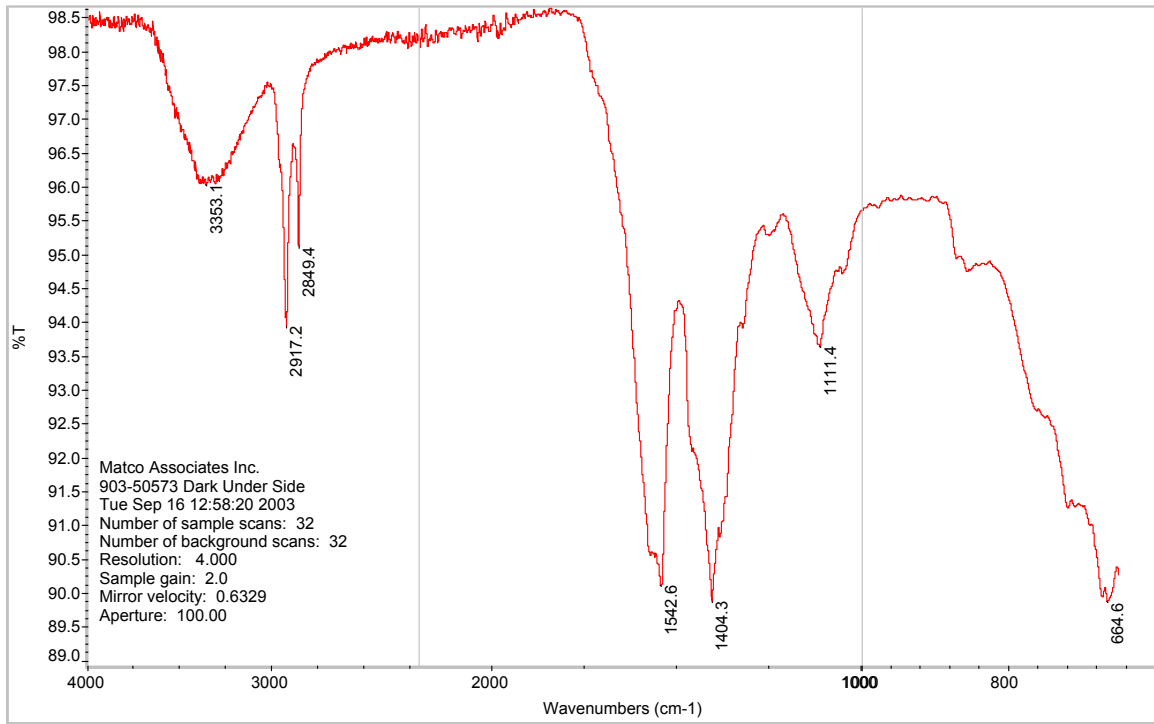
**Figure 16. On-site photograph; ceiling near vent.**



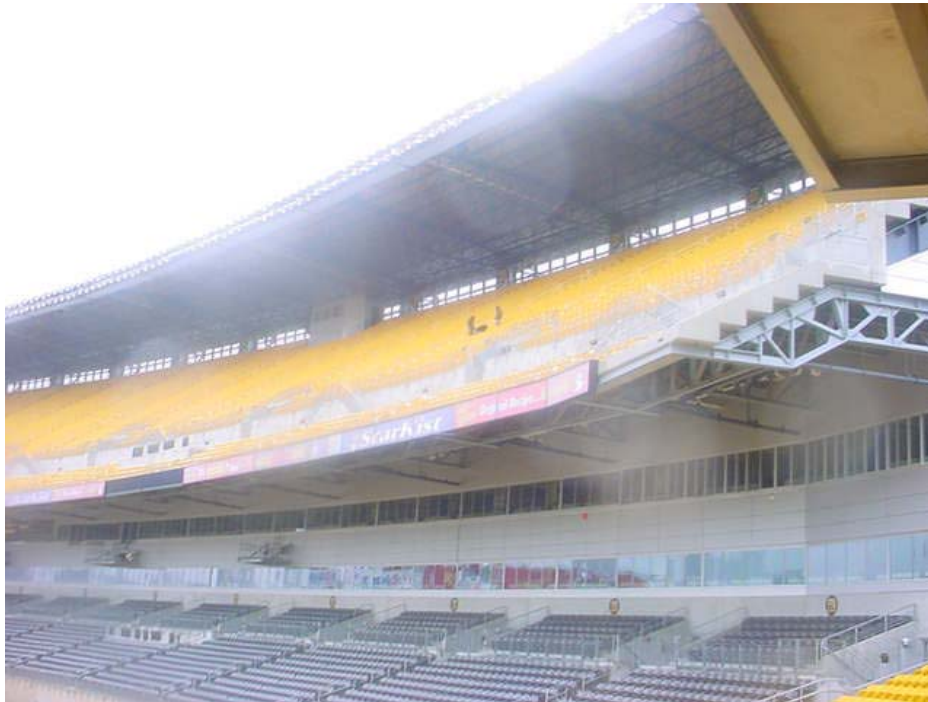
**Figure 17. On-site photograph; wall near altar.**



**Figure 18. On-site photograph; wall near stained glass window.**



**Figure 19. FTIR spectrum of under side of dark peeled paint.**



**Figure 20. Photograph of area of football stadium with failing yellow touch-up paint.**



**Figure 21. Close-up field photograph of failed touch-up paint on seat standard.**



**Figure 22. Close-up laboratory photograph of peeling paint on seat standard.**

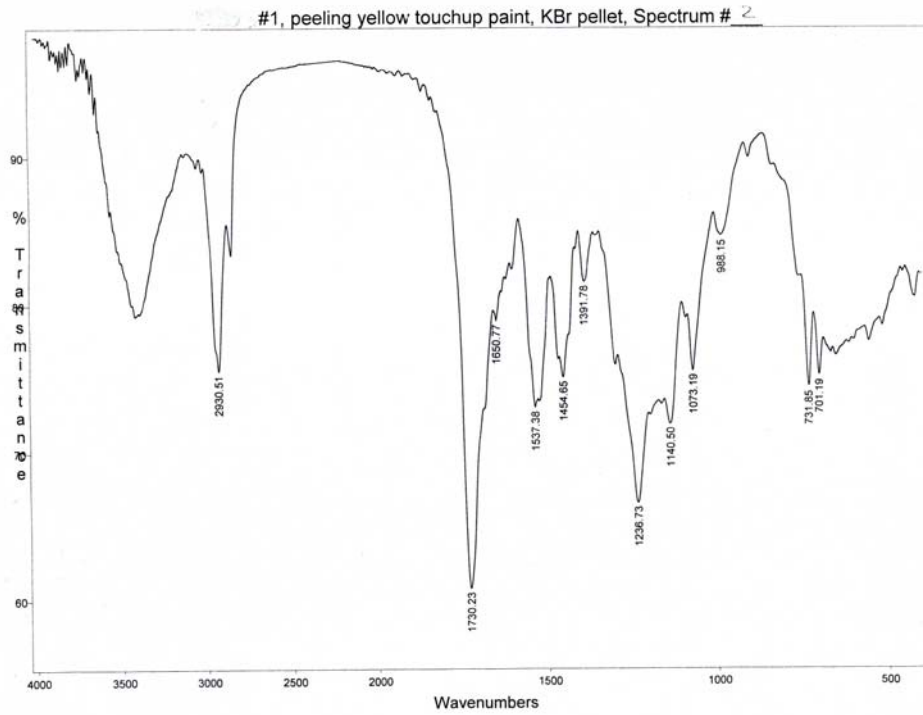


Figure 23. Fourier transform infrared spectrum of delaminated paint chip sample.

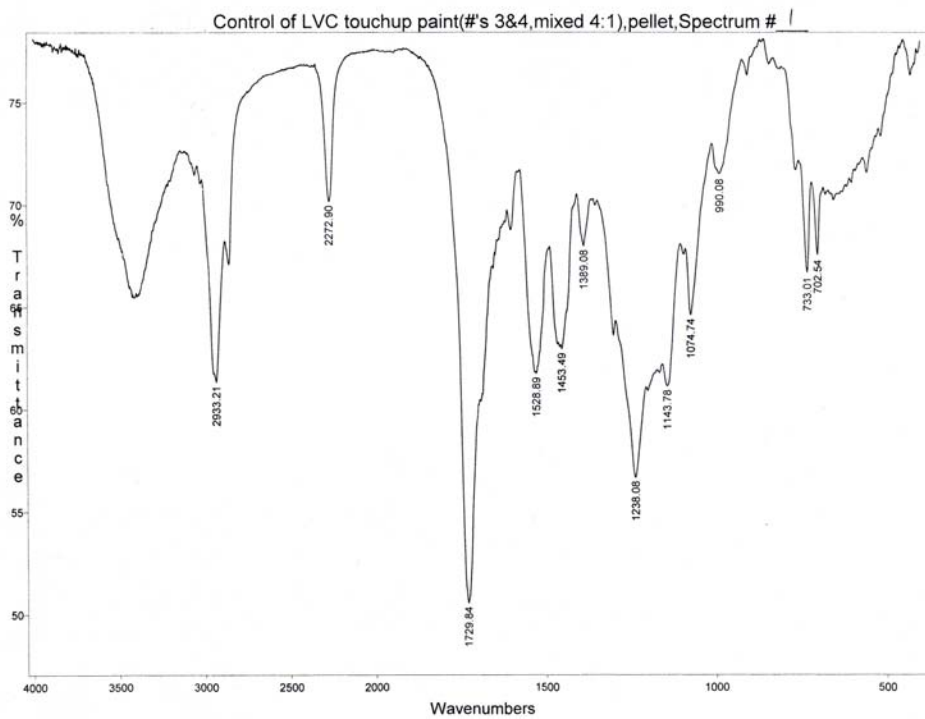


Figure 24. Fourier transform infrared spectrum of control sample, mixed 4:1 ratio.

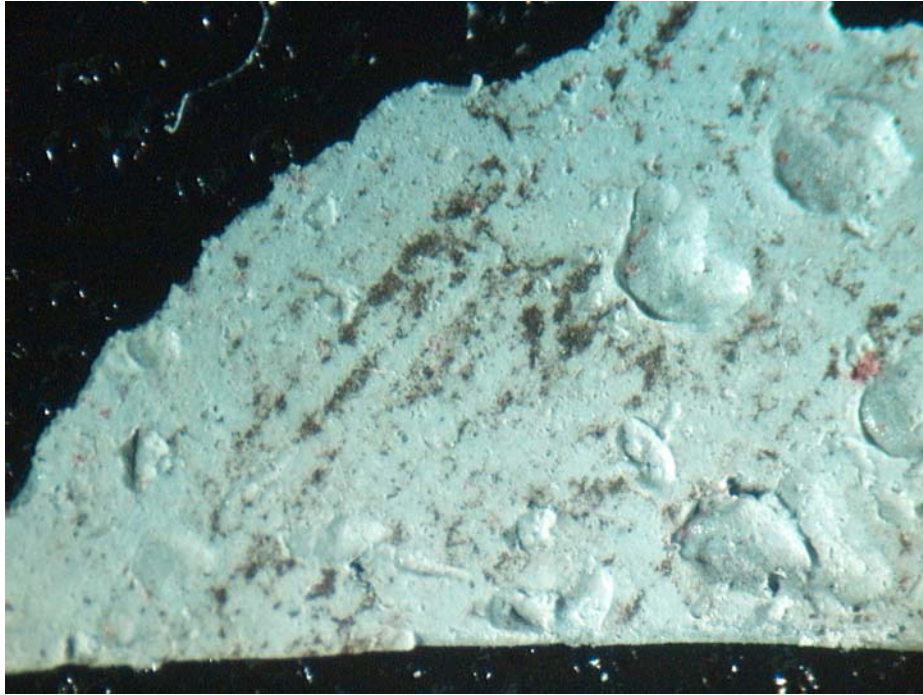


**Figure 25. Photograph showing the as received painted galvanized rail section.**

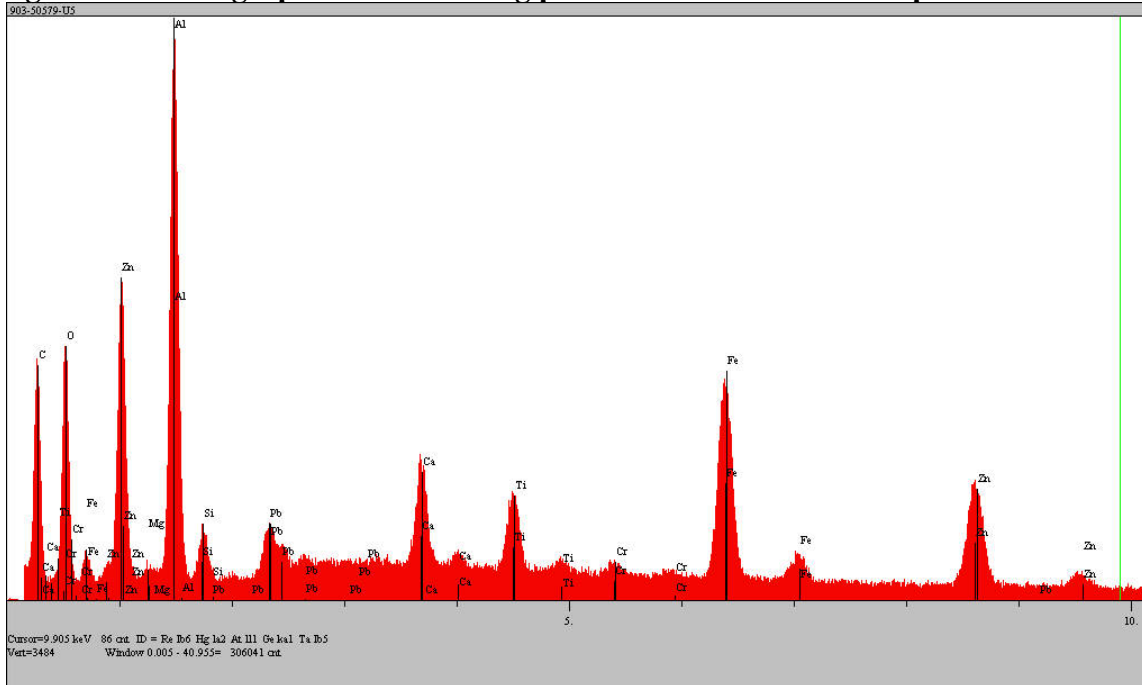


**Figure 26. Photograph showing a repaired blister area.**

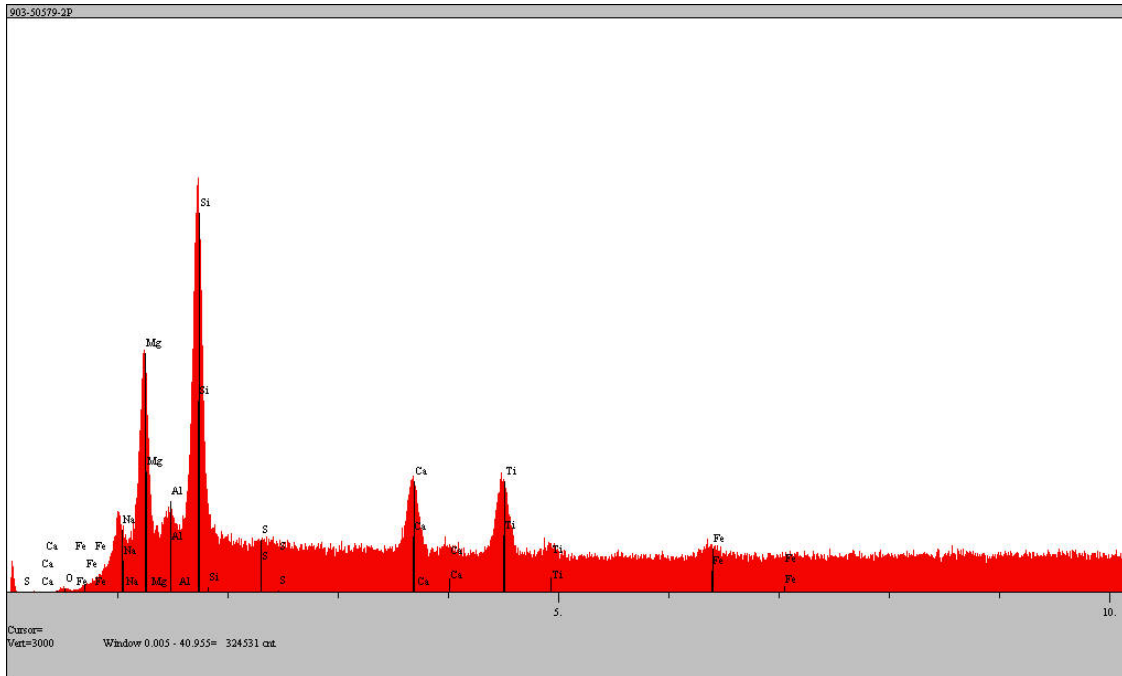




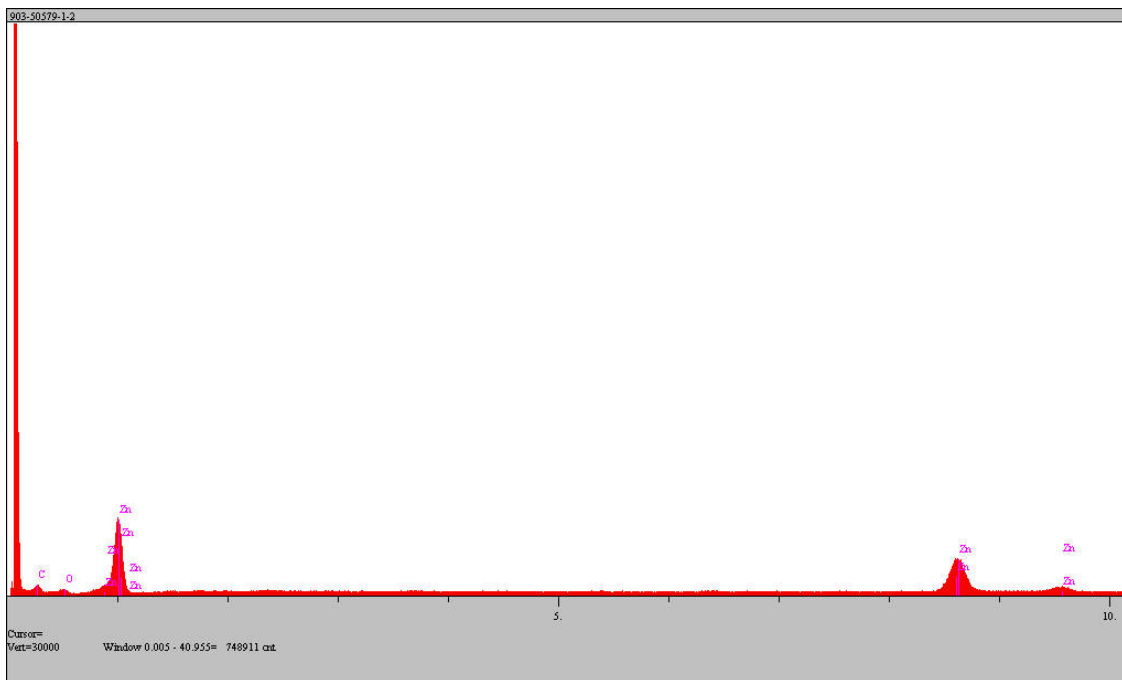
**Figure 27. Photograph at 10X showing particulate material on the primer underside.**



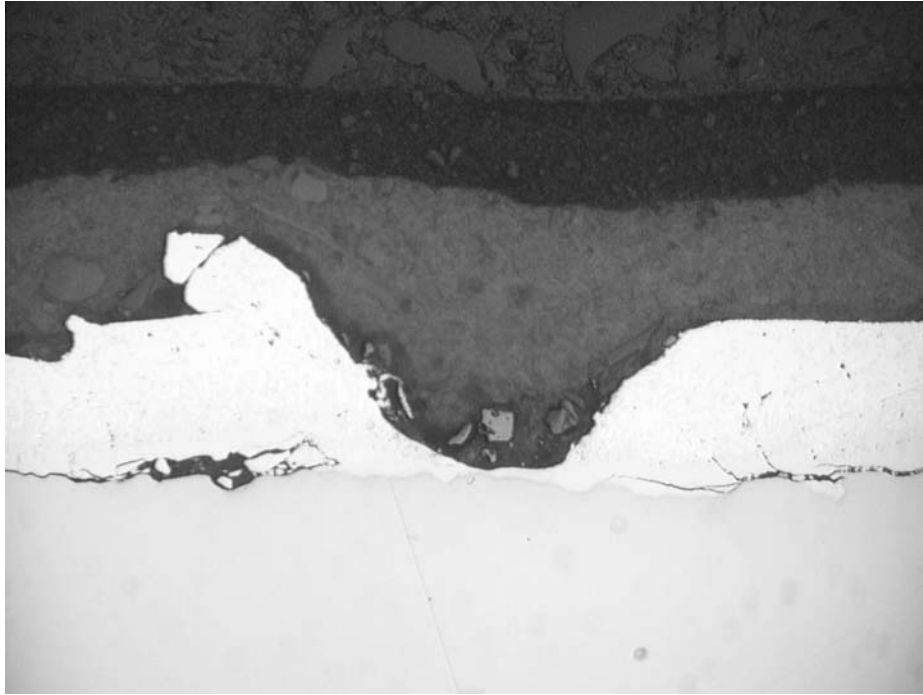
**Figure 28. EDS spectrum of particulate material on the primer underside.**



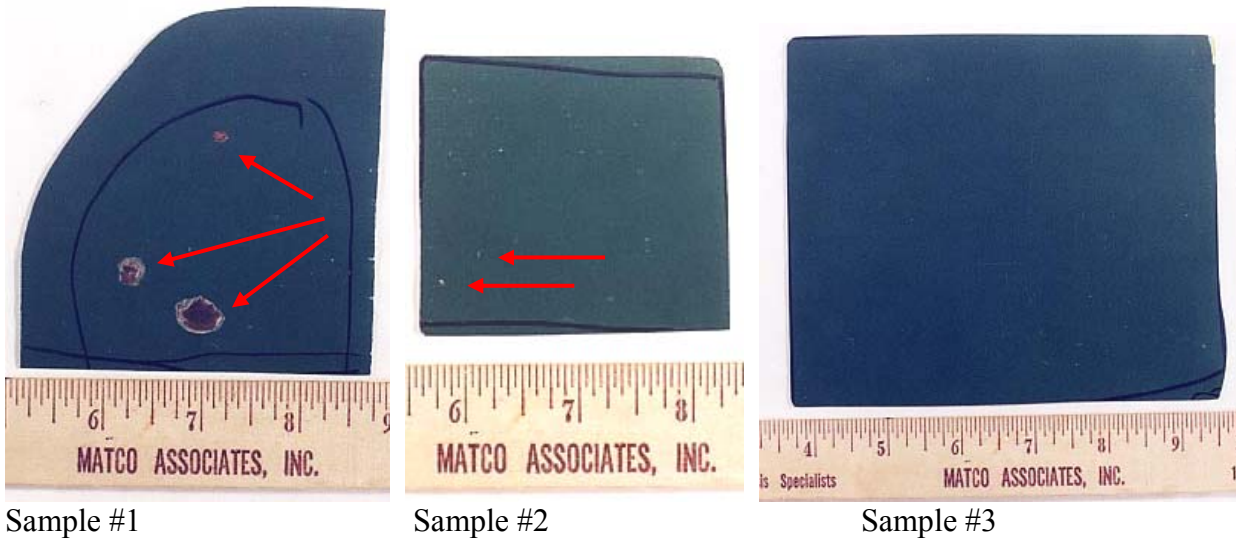
**Figure 29. EDS spectrum of the clear primer at the plane of delamination.**



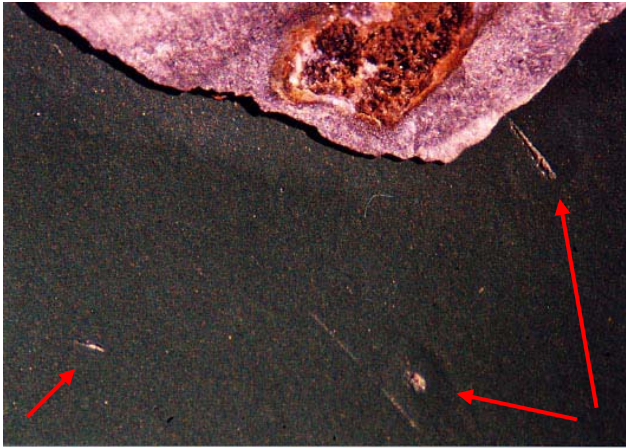
**Figure 30. EDS spectrum of the clear galvanized coating at the plane of delamination.**



**Figure 31. Photograph at 200X showing a depression in the galvanized coating due to shot blasting. as polished.**



**Figure 32. Photographs of three roofing samples.**



Mechanical Damage @ 15x

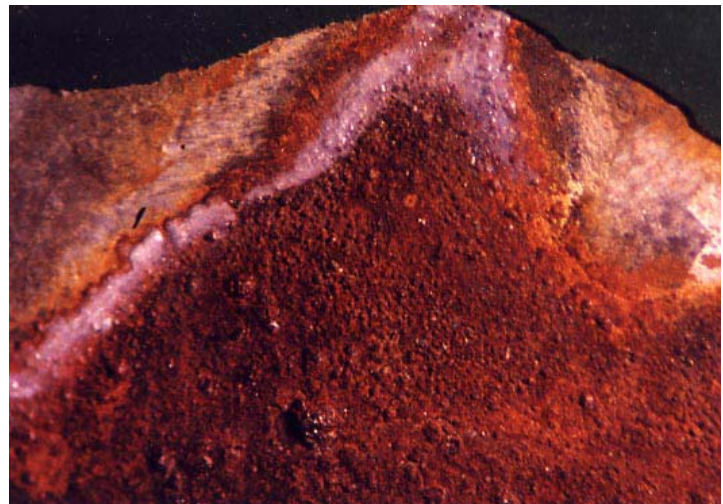


Mechanical Damage @ 22x

**Figure 33. Stereo micrographs of mechanical damage.**

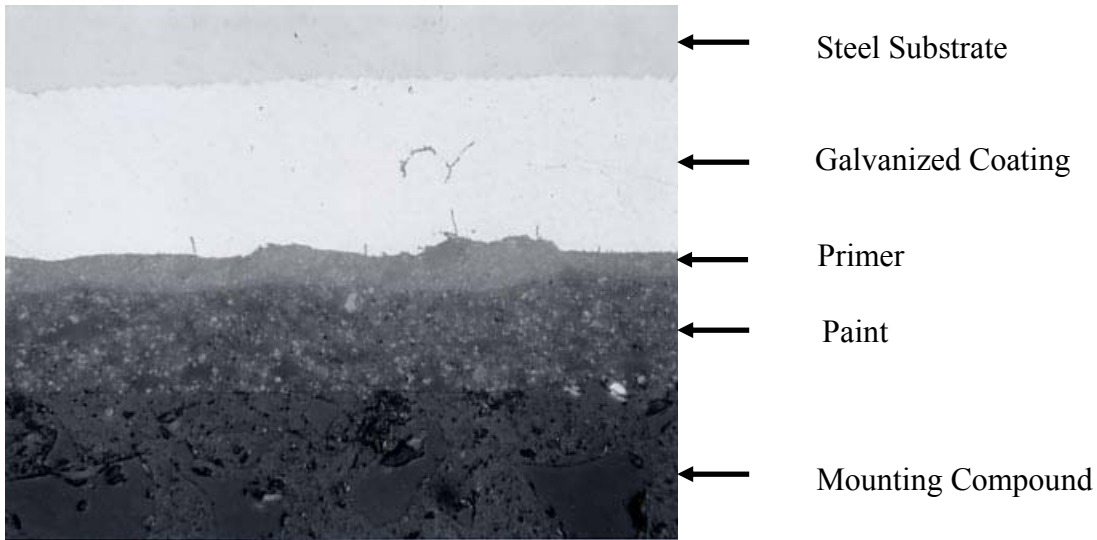


Sample #1 - Large Corrosion Pit @ 6x

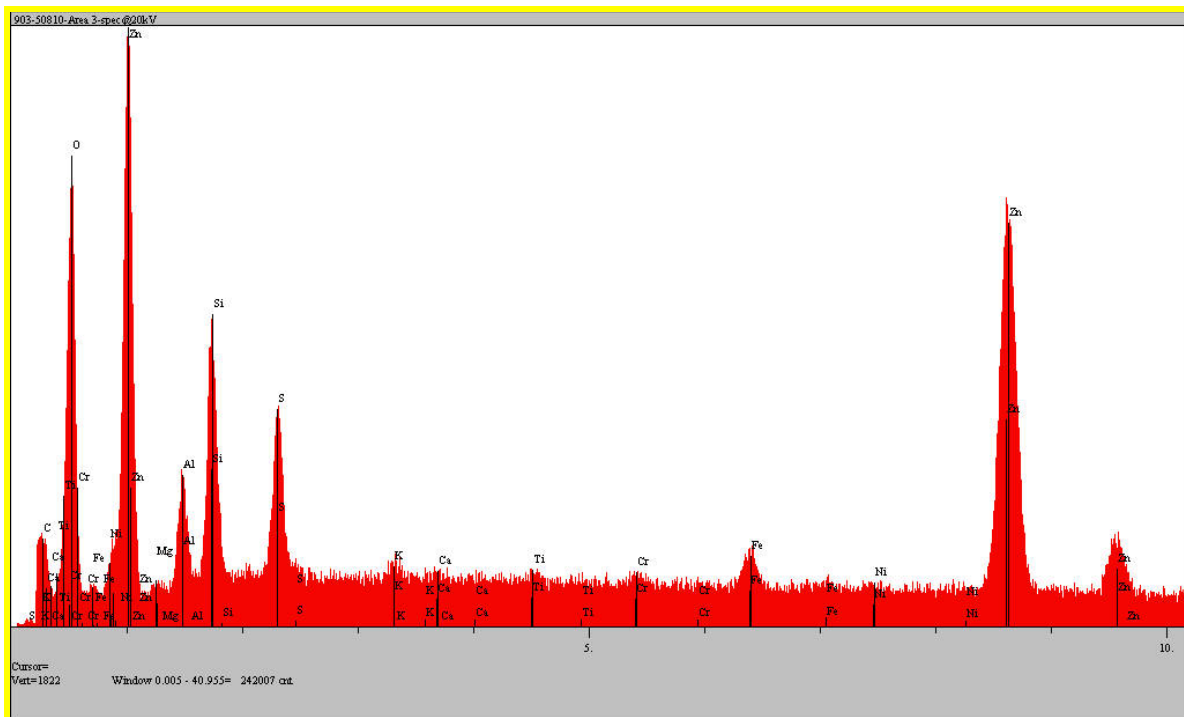


Sample #1 - Close-up of Large corrosion Pit @ 23x

**Figure 34. Stereo micrographs of ringed corrosion pits.**



**Figure 35. Typical coating cross section at 100x magnification.**



**Figure 36. EDS spectrum of outermost rim of corrosion pit showing high sulfur (S) levels.**