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Failure Analysis of Coatings

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ABSTRACT

Failure analysis of coatings reviews several incidents from the USA. Through the review of individual case studies, the audience will see the utility of various analysis techniques, laboratory tests and equipment to determine the mechanism of failure of protective coating systems. Case studies will include examples from a global fast food chain's headquarters in the USA, Oil & Gas storage in California, Demineralized water tanks in Indiana, Coal Process units in Oklahoma, High Rise (30+ floors) apartments in Chicago, MIC accelerated corrosion multiplying the rate of corrosion by a factor of over 40, Pipeline breach and explosion of a home in New York and heavy metals abatement on the US Capital Dome. Techniques will discuss the use of scientific methods in analysis. Use of test results from an overspray legal claim involving over 300 autos will also be discussed. The case studies will reveal related issues to coatings which are the unexpected results such as regulatory action and defense not often reported in journals.

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INTRODUCTION

No test of coatings can match actual use in service. We can theorize coating performance based upon the chemistry of the coating and determine how long the coating SHOULD provide protection of the substrate. In service, a plethora of variables arise that can derail the intended performance. The variables can range from preparation, mixing, application and design errors. Through the use of scientific method, correct use of testing equipment and review of design we can determine the root cause, proximal cause and contributing factors of a coating failure. In the following cases, look for the technologies and methods employed to determine the causes.

CASE STUDY 1 – THE CASE OF THE UGLY PAINT

The case of the ugly paint job was found at a major hotel brand on the campus of the corporate headquarters of a global fast food company. This fast food company sells franchises and requires the new owners and their managers to attend training at their corporate campus. To house these business owners, a major USA hotel brand runs a hotel on the campus. Certainly the expectation is to have a very good looking paint job so be aesthetically pleasing to the guests. This case involved a vestibule entry way into the main lobby constructed of concrete columns and visible steel beams for a ceiling/roof structure. Tempered glass panels were installed as the roof between the beams. Inside the structure water began to drip and small stalactites formed. When the customer investigated the top of this structure from the outside, several areas of the beams had failed coatings. The coatings contractor repaired these areas by applying more of the top coat of paint. This repeated an additional time and failed a third time all within 18 months. The coatings contractor then engaged an engineering company that engaged my services to determine what had gone wrong and how to repair it. The following is the report given to the client and the owner.

Generally, coatings may be used to protect the substrate from corrosion, for aesthetics or for safety. The coating in question was used for all three types of protection. During this review, I discovered not only cosmetic issues, but substantive issues that could affect life safety.

DISCUSSION

This review was not a liability investigation. The relationships between the parties and timelines are not part of this analysis. The relevant issues are that the Owner's representative determined that Brand X was the intumescent coating to be installed in this location. Brand X is known for high quality coatings within the industry. Brand X advertises this product was tested by UL for external use. UL's certification has nothing to do with being an appropriate coating for outdoor use. UL offers no such certification. It merely certifies that after exposure to relative humidity, salt spray, UV light, carbon dioxide, etc. that it retains 75% of its fire rating. UL does not evaluate any coating for any other property than fire resistance. None of the test conducted by UL includes water pooling on flat surfaces nor snow and ice doing the same. Further, that this product BRAND X must not be applied over galvanized steel per manufacturer's application instructions.

Section 6.1 of the manufacturer's instructions states that an approved primer be used prior to installing BRAND X. This primer must be approved by Brand X. The next section, Section 6.2, states the conditions the surface or substrate must be in before BRAND X may be applied. All of these conditions take into account that a primer be used. Even with an approved primer, number 6 under Section 6.2 cautions that the product not be applied over galvanized steel.

A coating contractor installed the system as the Applicator. The Applicator received approval from the manufacturer for surface tolerant epoxy to be used as a primer with BRAND X. Surface tolerant epoxy is an epoxy high solids material. These materials develop surface tension as they cure. Without sufficient anchor profile in the substrate, they can check and crack. This was found in Lab samples. (See Lab report Sample No. 1, page 3; Sample No. 2, page 3; Sample No. 12, page 4.) The surface tolerant epoxy product data sheet calls for waiting 6 months for galvanizing to weather (although the manufacturer of BRAND X states to not apply it over a primer on galvanized steel), this is not the recommended practice for coating galvanized steel. The cracking is evidence that the Microcopy had no anchor pattern or profile upon which to attach itself and as the tension of the curing epoxy continued, the Surface tolerant epoxy ripped itself apart creating the cracking. This is not uncommon on epoxies generally when applied over galvanizing in these circumstances. Most standards, NACE, SSPC, ASTM, call for the removal of the passivation layer of the zinc. To understand this, we must take a look at galvanizing.

Galvanizing is a layer of zinc over steel. In this case, it was metallurgical bonded to the steel by dipping the steel into a molten vat of nearly pure zinc. When done correctly, it gives from 10 to 70 years protection to the steel from corrosion depending on the environment. Part of this protection is the forming of a zinc oxide layer as the zinc coating is exposed to relative humidity and oxygen. This loose layer is called passivation and slows the progression of additional oxygen and moisture from getting through this layer. Because it is loosely adherent, it weathers and fresh zinc passivates as it is exposed. Another method of protecting the steel is called sacrificial or galvanic corrosion. Zinc is a more reactive substance than steel. When in contact with steel, the zinc will 'sacrifice itself' to protect the steel. This action occurs when the zinc has a hole down to the steel and both are exposed to moisture. This reaction will continue until the zinc near the steel is depleted, at which time nothing is left to protect the steel.

Another issue with coating galvanized steel is the use of oil based paints. I mention this to illustrate the pH of Zinc as it passivates. Because zinc oxide is a base of about a 10 pH, one should not apply oil based coatings because the oils and the high pH of the zinc oxide cause saponification, or form soaps. (Just like animal fats and fire ash was used to make soap.) Thus, the coating will not adhere to anything but the soap film and fall off over time.

With this knowledge of galvanized steel, we return to the installation at hand. The Lab report showed water had migrated into the BRAND X material. There were several breeches of the sealing coat and the upper coats of UV protective coatings. The Lab report shows that most samples had lower than manufacturer recommended seal coat thicknesses and one that may have been less than 3 mils. (See Lab report, page 5 No. 7 KBr pellet, shows that all samples except for No. 12 unless it was less than 3 mils, also page 6.) This may have accounted for the moisture migrating into the BRAND X. If so, the moisture would cause the BRAND X to swell. Thus creating additional stress on the Surface tolerant epoxy to galvanized steel layer. These additional stresses could have caused the disbanding of the Surface tolerant epoxy from the galvanized steel as found in the Lab analysis. (See Lab report, page 6.) However, these issues with coating application only

highlighted the ultimate failure of this system. This system should not been applied over galvanized steel.

The proximate cause of this failure is the reaction of the materials in the BRAND X and the zinc of the galvanizing. Surface tolerant epoxy was the approved primer. This installation resulted in a cracked primer, most likely from stress caused during cure as discussed. Certainly, added stress from blistering would not help the situation. The moisture and material from the BRAND X that is water soluble could migrate through the cracked primer and reach the zinc. Further, the same result is possible without the cracks. Epoxies are organic binders. All organic binders are water permeable over time. That being the case, water bearing soluble components of BRAND X could leach through the primer and react with the zinc. What would this mean?

Two of the components from the BRAND X are Phosphorous and Carbon. (See Lab report scanning electron microscopy with X-ray microanalysis showed the Brand X intumescent composition contains phosphorous and carbon, page 5 under No. 3.) Phosphorous with water can form Phosphoric Acid. Acid on the zinc oxide reacts. Phosphorous has a pH of 1, extremely acidic. Zinc oxide is about a pH of 10, so it's a base. The reaction between the zinc oxide and phosphoric acid would have attacked each other and depleted the zinc. This was seen on the surface where Sample No. 12 was taken.

This is consistent with the manufacturer's instructions that this material must not be applied over galvanized steel even with an approved primer. This reaction is born out from the mineral formations found inside the vestibule.

Just as stalactites form in caves when water permeates through the ground above, water picks up carbon and calcium. Here, the water has picked up carbon and phosphorous and formed similar structures. The reaction is evidenced in the trace presence of galvanizing products as the zinc was depleted. (See Lab report, No. 3, page 5.) We can see this is not related to the concrete and that the water has taken the mixture around the caulked glass panels.

Further field testing with an adhesion pull off gage, Elcometer F106, found that some interesting results. Three pull tests were done. The target is 322 psi per the manufacturer's literature. If the target is reached, the implication is that the system is functioning as intended and was thus applied sufficiently in mixing and adhesion. We expect to see a target reached and expect to see failure at the weakest link. With an intumescent we expect to see a cohesive failure within the intumescent. Again this is expected and as long as the target value is reached, all is well. If we find an adhesive failure, it is an indication that the adhesion between those two layers is the weak link.

Pull Test No.	PSI at failure	Location of failure
1 (original installation)	~350	25% cohesive failure of BRAND X 35% adhesive failure of top coats 40% glue failure
2 (earlier repair w/BRAND X)	>450	75% cohesive failure of BRAND X 15% adhesive failure of top coats 5% glue failure
3 (original installation)	>950	100% adhesive failure of BRAND X from galvanized steel

Pull test Nos. 1 and 2 show, where blisters are not present, the coating has adhesion as advertised. One would assume performance as tested by UL. However, test No. 3 brings to light the issues found in the blistered areas. Test No. 3 had a complete adhesive failure at the primer to galvanized bond. The galvanized surface was found to be moist to the touch and appeared white rather than grey or silver. Zinc turns whitish when water has remained for any length of time. The surface temperature was just below freezing, if a chemical reaction was taking place on the surface of the galvanizing, this temperature would have kept the water from freezing, as observed. The high psi value is likely from the support of the surrounding coating. When initial tension was placed on the test apparatus, a 'pop' was felt, yet the visible top coating did not separate. It was not until the full pressure reading of over 950 psi that the visible paint ripped free. This often happens when an underlying component fails under the adjoining coating to the test site. Thus pressure is relieved and the apparatus is no longer pulling against a 20 mm area, but a much larger area.

The evidence found during this review shows that the system should not be installed over galvanized steel, just as the manufacturer's literature states. I would not have recommended this material for this application. This system of BRAND X, the top seal, the approved Surface tolerant epoxy primer are all organic binders that are water permeable. Given time, water would have reached the galvanized steel carrying with it the phosphorous which likely reacted with the zinc oxide and caused the weak link observed in the Lab tests and was in accord with the field tests. While application errors included a deviated surface preparation and a seal coat that was not per the manufacturer's recommendation, these issues only accelerated the eventual failure of the system over galvanized steel. This has had the effect of bringing to light what may have been a life safety issue in the event of a fire.

This product, BRAND X is rated for up to 4 hours by UL. It functions by swelling when exposed to extreme heat and this swelling insulates the steel. This is important because direct fire contact with steel can weaken the steel up to a factor of seven. Insulating the steel allows the steel to keep its strength and thus its structure so that persons can escape the building. With the suspected reactions these materials had, it is very possible that in its current condition, if a fire were to contact the coating system, the stresses of the swelling could pull the entire thickness off the steel. This would provide no protection from the weakening effects of the heat.

SUMMARY

Based on field observation and laboratory analysis, I have the following conclusions. The coating is not appropriate for this location. The use of this coating, although a quality coating, in this situation resulted in failure. Further, the application of the coating did not meet the manufacturer's instructions for installation. However, the deficiencies in application of the system brought to light the underlying life safety and potential property damage issues. A more detailed specification review by a coatings specialist and/or inspection of the installation by a certified coatings inspector may have prevented these issues.

This case highlights the use of field and laboratory testing to ascertain the mechanisms of the failure. A general knowledge of basic science allows us to piece together the timeline of events that lead to the failure. The root cause in this case was the poor specification and design of the coating system. The owner decided to remove the system and apply a different system which has successfully performed for two years thus far.

CASE STUDY 2 – THE CASE OF THE DISAPPEARING?REAPPEARING RUST

At an alternative energy plant supporting an oil refinery, demineralized water is used. The tank holding the Demin water has rust breaking through the internal coating inside the tank every two years regardless of the paint system used. After four repairs to the original paint installation, an eight years period, the owner engaged a coatings consultant who could not determine the cause of the failures. That consultant engaged my services to determine why the failures happened and how to prevent this expensive repair cycle. The following is the discussion of the issues.

On 13 August 2013, Tank A was inspected in the Demin Plant at Brand Y Oil Company Clean Energy. Tank A at Brand Y presented with several failures on the first 4 feet of the walls and floor. The majority of these failures were through previous repairs.

At the man way prior to entry, I found coatings that had chipped off. I began with a sounding using a steel hammer to check for audible changes which could indicate a loss of adhesion of the coating to the substrate. What occurred was a full thickness delamination of the previous coatings. A leopard pattern of dark corrosion product was found on the steel. See attached photographs.

Inside the tank, I used the hammer (10 light to moderate blows) over patching repairs and dis-bonded a significant amount of coatings from the substrate. Again the corrosion products were found along and in addition pits of 1/8 inch depth. This was repeated for a total of 2 sites on the floor and 1 site on the wall, all underneath previous repairs. One additional location showed similar results under a prior coating that did not present with a repair patch. I ran conductivity

salts tests at one floor location, one wall location and on the man way. Results were Man way @ 16.3 micro Siemens, wall under a repaired area @ 34.9 micro Siemens and floor under repaired area @ 88.8 micro Siemens. A conference call to Paint Manufacturer Q's Technical

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Representative found their recommendation to be to allow no more than 15 micro Siemens on the surface when applying their product.

I suspect a high concentration of soluble salts has caused this condition. Soluble salts contribute to accelerated corrosion by a factor of up to 30 times greater than water alone on bare steel. Several areas on the walls and tank floor have what appear to be dimples. These are blisters. Given the conductivity readings found, they are likely osmotic blisters caused when moisture reaches through the coating (often permeating) and reacts with soluble salts trapped under the coatings. Because rust has an expansion factor of 7 to 1, the paint is pushed off the steel by the expanding corrosion and a blister is formed. International has listed allowable concentrations of soluble salts on their Application Guide for Q's Paint 1234.

Because of the lack of adhesion of the existing coating, I recommend abrasive blast to remove the existing coating on the walls 4 feet up, floor, all carbon steel appurtenances and all stainless steel appurtenances. While the connected portions of welded carbon steel and stainless steel will continue to be a site of galvanic corrosion concern, isolation from electrolytes (or moisture) and product will greatly slow the reaction between the two. Further a thorough post-cleaning of the steel with Brand Z Salt Remover additive by pressure washer to remove soluble salts to levels complying with Q's Application Guide for Q's Paint 1234. Industry practice under ISO standards referenced in Q's Application Guide are 5 salts tests per 1000 sq.ft. Ideally, Q might give a hard micro Siemens number so we could test for all three salts with the one conductivity method.

The environmental conditions for this assessment were ambient temperature: 71 F; Dew Point 56.4 F; Relative Humidity 60%.

SUMMARY

This case illustrates the importance of verifying non-visible contamination of the substrate. No blasting standard in the industry requires this verification. In this case it was ignored and resulted in great expense to the owner. It was an easy fix once it was identified. By following ques (blistering, disbonded areas and knowing only clean water was the material stored), the evidence led to ruling out salts contamination. Contamination could not be ruled out based on the high conductivity. The installation of the new coating was done after proper cleaning and verification of a near salt free substrate. Unfortunately, repeating the same procedure hoping for a different outcome is a common practice.

CASE STUDY 3 – THE CASE OF THE BLASTED?UNBLASTED TANKS

This case illustrates the lack of surface preparation and the lack of verification by inspection. Two reactor tanks were shop coated without inspection and installed at an electric generating plant in rural Oklahoma. A field check by the owner found the total paint thickness was less than specified. A consulting company was called to identify where the coating needed more paint and any other defects that may be present. That consulting engaged my services and the tanks were investigated on site. The report follows.

DISCUSSION

Mill Scale

From June 10th to 11th, 2015, an evaluation took place at Owner B fossil fuel power plant in Chouteau, Oklahoma. This examination began with a visual observation. Multiple areas of mechanical damage were evident and provided access to the substrate. All areas which had exposed substrate presented with what appeared to be mill scale. Mill scale acts as a cathode relative to the steel underneath. Thus, once an electrolyte such as moisture is present, the steel will corrode to protect the mill scale. Modern high performance coatings, such as the systems listed in the General Contractor's specification, rely on the mill scale being removed in order to perform. A Zinc rich primer, as used in this system, will act as an anode and sacrifice itself to protect the steel. However it cannot do so if it is in contact with mill scale. The zinc will instead protect the mill scale and when depleted, the steel will become the anode and protect the mill scale. One can see the importance of removing the mill scale. That is why the specification required Commercial Blast (SSPC SP-6). SP-6 requires all visible mill scale to be removed. This is the middle level of abrasive blast cleaning. Not only was mill scale visible within the viewing window of a Coating Inspector Gage, but the mill scale completely covered the exposed areas. Multiple cuts in the coating system were made at various elevations on both tanks and copper sulfide testing was done.

Copper sulfide at 5-10% solution reacts with steel. The reaction takes place because the iron in the steel replaces the copper in the solution. The displaced copper then reforms on the surface and shows as a copper color. Thus, if the solution is placed on bare steel, the surface will turn a copper color immediately. Were the substrate was exposed, no color change was observed. A control area on the North Tank was used. This area was exposed by mechanical damage through the paint layers and the mill scale, perhaps by a grinder removing welding slag. When the copper sulfate solution was applied, the entire exposed surface turned a bright copper color confirming the solution and method. From the evaluation made on the above dates, it appears that both tanks are completely covered in mill scale in nonconformity with the specification and industry custom and practice.

ABRASIVE BLASTING

With the presence of mill scale, there is an obvious question, was blasting even done to this steel? Observation of the surface where paint had flaked off was done with a 50x microscope and showed a piece of steel shot, often used in automated blasting machines in shops that apply coatings. Another piece was observed on a nearby area. Both were approximately 0.08 mm in diameter. At this size, shot would not be expected to remove mill scale and would only leave a very shallow anchor profile, perhaps less than half a mil. This is far below the specified 1 to 2 mils in the specification or the 1 to 3 mils recommended by the paint manufacturer.

If the abrasive was larger in the blast machine, then the presence of this fine residue would be an indication of an air separator (used to remove small debris from the machine) was not working or not adjusted properly. Other residue was observed under magnification. One residue appeared to be that of coal slag. What appeared to be coal slag was also found embedded in the finish coat at multiple locations. No information was available on what was used to blast this steel, but the presence of two very different media indicates a contaminated shop. The presence of mill scale also indicates that the machine was not properly set to remove the mill scale.

BLISTERING AND OTHER DEFECTS

Various blisters were observed across the surface of both tanks. Blisters, and the other defects listed here, have a common issue in so far as measurement of the paint thickness is concerned. The standard measurement technique is to use a Type II Dry Film Thickness Gage (electromagnetic). But because the blisters are elevated along the entire surface, we cannot get a true reading of the paint thickness with this type of gage.

Further, the blisters present several varieties. One type is a gaseous bubble. These are likely caused by poor mixing technique that injects air bubbles when the paint is mixed. Possibly they are solvent blisters caused by adding too much solvent or too high of a surface temperature. While the causes are varied, the result is a void in the paint where the bubble is which provides much less protection, broken blisters where the substrate is exposed and possible entrapped solvents. Cratering was seen in many areas as well. Craters happen when gaseous bubbles burst before the paint has dried, but after the paint is no longer fluid. The resulting rim around the base is left and presents as a crater. Of course the paint has less thickness and will not provide the intended protection of the steel.

Another blister that is possible here is an osmotic blister. This type is formed when soluble salts are not removed. The three soluble salts we are concerned with are chlorides, sulfides and nitrates. Understand that all organic paints are permeable by water vapor, eventually. Sometimes after one or two years. If the surface was cleaned properly we will still see service lives of 10 years or longer because pure water is a poor conductor and corrosion is very slow. If salts were left on the surface, when the water gets through and mixes, acids will be formed; Hydrochloric, Sulfuric and Nitric. These accelerate corrosion by up to 30 times. Additionally, corrosion of steel has an expansion factor of up to 7 to 1. Meaning that as steel corrodes it expands by seven times. Literally the paint is pushed off of the steel by the rust. There may be this type of blister now, but there will likely be this blistering later. I can state this because of a conductivity test done on site.

I took a conductivity reading from an area that had been mechanically damaged. This was the same area where I performed the confirmatory copper sulfide test, but the conductivity test was done first. I used a Brestle patch to apply distilled water and flushed salt deposits from the steel. The process is outlined later in this report. The result was significant; 18 times the allowable level of Chloride salts, 9 times the allowable level of Sulfide salts and 14 times the allowable level Nitrate salts; per the manufacturer's recommendations.

Also, Dry Spray was found in many areas. Dry spray is the result of too much pressure at the spray gun, high application temperatures, or other anomalies that cause the paint to begin to dry rapidly as it leaves the spray gun on the way to the surface. Normally the paint would hit and splatter out combining with the other splatters to form a consistent film of wet paint. However, the partially dry paint now hits as a ball of tacky paint that only partially sticks to the other paint and never spreads out into a consistent film. Issues with dry spray include a lack of cohesion to itself, a reduced thickness overall, a duller appearance and a poor anchor for any later coats of paint.

THICKNESS OF PAINT

As stated above, the standard method for measuring paint thickness is not possible with a degree of accuracy. Instead, the Tooke method was used. This is a destructive instrument that cuts through all layers of paint to the substrate. The cutting blade is set at an angle that allows observation of the paint layers via a 50 times microscope. Thus, the thickness of each layer and their total can be ascertained. Several readings were taken on both tanks at different elevations. Because the tanks were painted on their sides, readings around their circumference would be sufficient to characterize for thickness. However, to verify conditions across all areas, samples were done at elevation. The results are listed later in the report.

Significant findings include the great diversity of thickness. The thickness is certainly nonconforming to the specification and manufacturer's recommendations. Further, the

thickness is inconsistent. Nowhere was the coating uniform. The difference in Type II Gage readings and Tooke Gage readings range from 0.6 mils difference to 9 mils difference. Again this difference is due in large part to the blistering and other surface defects. Of note, the Tooke gage was not able to cut through the mill scale underneath the paint. In fact, the blade became dull because of the mill scale's hardness. Several of the cut sample sites were exposed to copper sulfide and all were verified as being mill scale rather than cleaned steel.

In the areas examined, many had layers of zinc that were underconforming to the specification to include no detectable zinc primer, as confirmed with copper sulfide. Some areas were underconforming on the top coat. Several of these areas can be visually seen as the shade of zinc showing through the thin top coat, without the aid of any tools. Because of the great variation of thickness, as well as under and overconforming thickness of both primer and top coat, it is not possible to characterize which areas need repair.

ADHESION

The most important property of any paint is its adhesion or its ability to stay on the surface. If the surface is properly prepared, we can expect similar results as the manufacturer's Data Sheet. The zinc rich primer should hold up to 585 psi pulling it away from the steel before it rips off. Pull-off gage readings were taken at Tooke gage test sites 1 through 6, see attached results. Tests 1 through 5 had the same result. The primer cohesively failed at less than 50 psi. These are catastrophic failures. Test 6 resulted in a partial cohesive failure in the top coat only at less than 50 psi. Possible reasons for these cohesive failures could be incorrect mixing of paint components or ambient conditions during application and/or curing cycle. Either cause would be under the control of the applicator. These PSI values indicate the paint will disbond, or fall off, well before the performance criteria engineered by the manufacturer. Several spots have already fallen off.

SUMMARY

The coatings industry considers the leading cause of paint failures are poor or incorrect surface preparation. That is the case here. Without a proper foundation, the coating will prematurely fail. These surface preparation failures include mill scale, high salts levels, lack of correct anchor profile and heavy debris contamination. Any one of these alone is cause for rejection of the work and will likely lead to premature system failure.

Additionally, the poor adhesion seems to be caused by a mixing or environmental issue. The primer as it exists will not hold to the surface. This alone is cause for rejection of the coating. Contamination by debris may include materials that will corrode themselves while in the coating, causing more blisters, a loss of adhesion or reduce longevity.

Any of the above issues are cause for rejection of the work in and of themselves. In combination, they are so extreme as to make the paint system unrepairable. If the intended service life is to be achieved, the entire existing system should be removed. In all issues listed, the coating violates the specification and custom and practice in the industry.

This case illustrates that multiple errors can occur from ignorance or inattention. As a result of the report, the owner included it in the request for bids to re-blast and apply a new paint system in place. Through the use of some basic chemistry, we can make determinations that explain causes and allow us to find solutions.

CASE STUDY 4 – THE CASE OF THE BAD HIGH RISE BUILDING

In downtown Chicago a new residence building was built. The steel structure was shop machine blasted and shop primed. The finishing coats of paint were applied after erection. The railings on the balconies were steel and prepared in the same manner as the structural steel. The top coats of paint were failing. The painting contractor engaged my services and an investigation was begun. The following report was issued.

On March 17, 2016, we made a site visit to observe conditions, review rust complaints, sample coatings and investigate the cause of rust through the coatings. The following areas were observed: Units PH01, 3201, 3901, 3101, 3001, 3009, 2202, 1701, 802. Additionally, the 3rd Floor balcony and the Roof were observed. The individual photographs are attached in support of this report.

The system declared by the building owner's representative and the field painting contractor show a surface tolerant epoxy primer and a UV resistant top coat. This is a typical system for this type of service environment. The owner claimed that the fabricator wheel abraded the steel and applied the primer. Based on the manufacturer's data and experience, the system should not have signs of corrosion so soon in its life cycle. Corrosion observed has disbonded the coating at the primer substrate interface. The result of this corrosion has been blistering and a loss of coatings. There was some general corrosion found on some handrails on the outer face of balconies as well. Coating thickness measurements were taken with a Type 2 electromagnetic gage to determine approximate thicknesses. Further testing was done with a "Tooke" gage. The Type 2 DFT readings allowed the selection of settings for the "Tooke" gage. Typical thickness, per the coating manufacturer, is 5 mils minimum for the primer and 3 mils minimum for the topcoat. The coating manufacturer allows the primer, when used as a shop primer, to be as thin as 3 mils minimum.

Spot readings (defined in SSPC PA2) were found sufficient in the overall thickness of paint. "Tooke" gage readings found the minimum thickness of both the primer (assuming a minimum of 3 mils) and top coat to be sufficient. One area in two of the units have a disbonding of the

topcoat and primer, discussed later in the conclusions of this report. Thus, thickness of the coatings could be ruled out as a cause of the corrosion issues.

During the above observations, the substrate under the coatings were exposed. Because ferrous oxides (rust) were present, these areas stood out because they were black in color, not rust colored. Rust as it is called in common parlance is iron oxide. This oxide is a product of corrosion in the presence of oxygen. A black color indicates it could be corrosion products without oxygen present or mill scale. Since it was exposed to the air, it would have likely turned to rust. Application of a copper sulfate solution to the substrate will turn steel to a copper color. Application of the solution to mill scale will result in no color change. Below are photographs showing that these areas all identify as mill scale. The last two photographs were from a control test of the solution on a known substrate of steel. This sample was on the roof and was prepared by using a hand file to file away coatings and mill scale to expose shiny steel.

SUMMARY

Since all such tests at different locations show mill scale under the coatings, it is likely that all surfaces have mill scale. In time, it is likely that all the coatings applied over these surfaces will fail. Without third-party inspection of the shop process it is not possible to ensure compliance with the manufacturer's recommendations. Wheel abrator blasting depends on the size and hardness of the abrasive and the speed at which the steel passes through the "hot spot". Without the correct speed and abrasive, one can pass the steel through multiple times and still not remove the mill scale. Mill scale is cathodic to carbon steel, thus the carbon steel will sacrifice in favor of the mill scale. The result is corrosion of the steel. As the steel corrodes iron oxide is formed which expands up to 7 times the volume of the steel and pushes the paint off. This is likely the disbonding seen during the site visit. No matter what coating is applied, the corrosion process will likely repeat itself until the mill scale is removed. This is why the manufacturer recommends the complete removal of mill scale to a Commercial Blast, SSPC SP6.

Regarding the disbonding between the top coat and the primer referenced earlier in the report, another mechanism was at work. In unit 3001, on an area of the balcony railing and directly below that in unit 3101, the top coat disbonded from the primer. This is consistent with, from my past experiences, water damage to the top coat of paint while still uncured. Inspection of the units above and below were not possible because those units were occupied.

This case illustrates yet again the importance of verifying the removal of mill scale. The consequences of this case will result in astronomical cost. The entire steel skeleton of the 38 floor building is covered with mill scale. To repair the damage would require the disassembly and reconstruction of the entire building. Had proper inspection been used for the project the cost would likely have been 4/100th of one percent of the cost to build the high rise once.

CASE STUDY 5 – THE CASE OF THE STINKY RUST

The case illustrates non-visible and perhaps not easily recognized agents of accelerated corrosion. As part of an underground sewage system 100 meters below ground a vault room containing valves and pumps held a surprise for engineers. One year had past since a pre-job assessment and when construction would begin. The vault had laid fallow during that time. The question was whether the conditions had changed significantly between the two meetings. The following report discusses the problems.

On 13 and 14 July, 2015, on site walk-arounds were made of the work area. Several observations were made. First, significant corrosion had occurred since the pre-bid walk-around. Below are photos of a fire hose rack. Observe the greatly deteriorated condition in the later photo.

Steel loss was measured at approximately one-eighth inch or 125 mils (317.5 mm). Normally, one can expect steel loss to corrosion, without protective coatings, of approximately 3 mils (76 microns) per year. The above fire hose rack DID have protective coatings on it. The material loss shows corrosion of over 40 years within a one year period. The primary change in conditions is the ground water infiltrating the vault.

14 July, samples were taken of water on steel surfaces in situ and by Bresle extraction. Both were tested with a conductivity meter and the results showed high conductivity of the samples. The sample was retained for testing with a CSN kit and listed below.

We have to understand that corrosion is an electrochemical reaction. An anode and cathode connected by a metallic pathway needs only an electrolyte (such as water) to form a corrosion cell. Steel has anodic and cathodic areas that form in its manufacture; they exist within the metallic pathway. The only thing missing for corrosion is the electrolyte or water. Since all coatings will eventually be breached by water, it is only a matter of time before corrosion takes place. If soluble salts are present, they can increase the effectiveness of the conductivity of the water. These salts are Chlorides, Nitrates and Sulfides. They of interest because when mixed with water, they become Hydrochloric acid, Nitric acid and sulfuric acid. When this happens, corrosion can accelerate by 30 times. What we see in the vault is the water bringing in these salts. The sample from water sitting on the steel was further tested with a CSN kit which measures each of the above contaminants through a series of chemical tests. The results are as follows:

Sampled Tested	Recommended Levels by Manufacturer
>25 micrograms/cm ² of Chlorides	<3 micrograms/cm ²
25-50 micrograms/cm ² of Nitrates	<5 micrograms/cm ²
160 micrograms/cm ² of Sulfides	<10 micrograms/cm ²

Since these salts are being brought in by the water infiltration, the water must be stopped before conditions can be brought into a range that will allow the coatings to be applied.

The problem is continuing if the water is just diverted as the moisture in the air will still carry the salts. Because a significant portion of the infiltration is coming into the vault as water falls, the contaminants are becoming aerosolized and carried throughout the vault. On average, dehumidifying equipment can reduce the relative humidity by about 35%. If the water continues to flow into the vault, more than one waterfall is present, there is little hope for DH equipment (of the size that can be lowered into the vault) will be able to keep up.

Further issues remain that the water infiltration has caused. Samples were taken of a black slime. This later confirmed to be Manganese. This element is a food source certain types of bacteria that induce corrosion, called MIC. MIC is present in nearly all situations that Manganese has been identified. MIC further accelerates corrosion. Again, creating an urgent need to have the water controlled.

The increased water infiltration has deposited minerals on the concrete floor. This layer prevents soundings to determine solid concrete from areas that need to be removed and patched or repaired. The photos below show calcium deposits greatly added since the pre-bid walk-around.

Further, the floor is wet and has flowing water. Not only must this condition be abated, but additional time must be given, as much as 30 days and perhaps longer, until conditions are such that the vapor transmission rate is low enough to allow application of coatings.

Cracks are another issue. Active cracks are those which continue to propagate or grow. Static cracks can be filled; active will continue expand regardless of filler materials. Because of the greatly increased hydraulic activity, tests need to be conducted to determine if cracks have become static or continued to grow. A comparison of photos pre-bid shows many new cracks and thus cause for concern. One might never finish filling cracks if they keep growing and new ones continue to develop. Tests take as long as 72 hour to perform.

For the above reasons, the greatly changed conditions within the vault make compliance with current contracts and schedules impossible. Additional time, scope of work and cost will be substantial.

Some failures occur before the painting project even begins. We often hear about environmental conditions during surface preparation and application. But the conditions before work ever begins can have just as a significant impact on the project. Of note was that the vault had a cracked pipe that filled the vault some 4 meters deep with raw sewage. The pipe had been repaired and vault pumped out, but the area was not washed down. The residue contributed to the acidic conditions. In this case, these problems had to be addressed prior to work or the coatings were destined to fail.

CASE STUDY 6 – THE CASE OF THE HIGH AND LOWS OF LEAD ABATEMENT

This case illustrates that knowledge of various painting techniques, even old ones, can make or break the project. In the spring of 2016, a painting contractor was removing lead containing paint from a cast iron dome above the U.S. Capital. The paint had been undisturbed for 150 years. The specification required the paint to be removed by chemical stripping, but a specific

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toxic chemical could not be used. That toxic chemical was the only stripper that might have removed the 150 year old, 90 plus mil (2286 micron) lead paint. The less aggressive chemicals were not able to remove the paint. The owner's representative agreed to allow sponge blasting to remove the paint. Daily air samples were taken from the blasters and assistants who were doing the work with personnel air sample pumps. The government's industrial hygienists monitored the daily results of the air samples. Regulations require lead levels to be below 50 micrograms per cubic meter of air. The workers wore air supplied respirators rated for 1000

times the 50 micrograms level. However, the sample results varied widely and although the upper limit was not exceeded, because of the inconsistent readings, the government shut the project down. I was engaged as both a coatings consultant and industrial hygiene/safety consultant. The following was explained to the government.

The dome was first painted, and for several more overcoat projects over the century, "white" lead pigment was used. 150 years ago there were no spray guns nor powered mixers. The lead paint came in a paste. The paste was scooped out by hand and set in a large tub. Linseed oil was used as a binder and was kneaded by hand like dough in the tub. Then tinting was added. After the mixture was thoroughly mixed it was thinned with turpentine. Small buckets were dipped into the tub and the buckets carried to the work. The paint was applied by brush.

As soon as the mixing was over, the heavier lead pigments would begin to settle in the bottom of the buckets. Perhaps the top fifth of the bucket was painted on at the correct mixture of ingredients. The next three-fifths of the bucket contained less and less lead as the lead was sinking to the bottom of the bucket. The bottom fifth of each bucket had high concentrations of lead. This resulted in varying densities of lead pigments. When abrasive blasted a century later,

any given area blasted might have low or high lead content, thus the air sampling during blasting would have a wide range of readings.

Now that the government understood the older technology was effecting the current work methods, they were confident the painting contractor was following the correct methods. The eight days of delay in the project this caused cost the contractor over 800,000.00 USD. This case shows that full knowledge of the industry, past and present, is important to the project and costs.

CASE STUDY 7 – THE CASE OF BASIC MATH

This case illustrates that basic math and logic in coatings work can determine liability. In November of 2002, an older petrol storage tank was being repaired. The tank was covered with lead containing paint. The external walls had been encapsulated in additional coatings, but the external roof had not. Some of the roof surface had rusted from the coating being worn away. The paint contractor was hired to remove the remaining roof coatings using hand tools only by scraping. Not all of the coating could be removed by this method.

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The owner's representative chose an alternate method of chemical stripper. For small areas, chemical strippers come on poly-cloth material impregnated with chemical. Simply place it on the surface and a certain time later pull it off and the paint comes with it. For large industrial projects, the poly-cloth backing comes in large rolls and the chemical in 208 liter barrels. The industrial kit was ordered. The foreman had to check on another job and told a worker to collect the kit from the warehouse and begin the removal of the remaining coating. The worker was not as knowledgeable as the foreman. He applied the chemical to the coating, but did not know the poly-cloth material was at the warehouse. Instead he used a sheet of 1 mm plastic sheet. Because the sheet was not compatible with the chemical stripper, it did not adhere. This left a congealed soup of lead paint. The worker continued to repeat the process in the hope that the next time it would work. Eventually, all the remaining paint was congealed and setting on the top of the tank.

The worker decided to use a pressure washer to wash the lead soup off the tank roof. The congealed lead paint ran down the sides of the tank. We must understand that decades of lead paint chip were all around the tank before any of this work had begun. But because the sides of the tank was streaked with lead material, the owner's engineers claimed all the lead was released into the ground by the painting contractor. The laws in that state required that any release into the environment above 1 pound of Lead must be reported to the authorities. Additionally, the engineers demanded that the soil surrounding the tank be dug out until testing showed no Lead and replaced with clean soil. In essence, they tried to use this event to force the contractor to clean their long contaminated soil.

Because the initial removal method was scraping, the paint chip had been collected and place in a large rubbish bin. I was able to retrieve a full thickness paint chip. Using a micrometer I could determine the thickness of the paint. Given the square meters of remaining paint that the chemical was applied to I was able to calculate the volume of paint on the roof prior to the chemical being applied. Taking the laboratory analysis of the lead content of the paint I could calculate the volume of Lead. Knowing the specific gravity of Lead, I was able to calculate the weight of the Lead. The result was less than one pound, therefore the reporting level was not reached and we were not in violation of environmental laws. Further testing showed that nearly all of the Lead had stuck to the sides of the tank. Because of these calculations, there was no basis for the claim to clean the soil by the paint contractor. The oil company was required to clean their own property.

This case shows that with simple knowledge of the processes and basic math, regulatory and liability issues can be applied to the correct party.

CASE STUDY 8 – THE CASE OF THE EXPLORING HOME

In suburban New York State, USA, a family home was occupied by a mother, son and the mother's father (Grandfather). This home had piped in water and natural gas for cooking, hot water and other uses. Unbeknownst to them, years prior, the city work crews had been digging in their yard and broke the gas pipe. The City workers repaired the line. They saw that there was an old mastic shop applied coating on the old pipe. They purchased tape wrap coatings and wrapped them around the repaired pipe. These were not painters and they did a poor job of applying the tape. If application had been done correctly, such a coating is a viable coating. Additionally, when the line was reburied, the soil was not properly compacted and was loose.

Over the years that followed, the vibration of the pipe and surrounding soil formed a channel in the dirt around the pipe. The wrap was breached in multiple places. The corrosion patterns would suggest rust formed soon after application. One specific location rusted through the pipe and allowed a breach through which natural gas escaped. The gas followed the path of least resistance and flowed into the channel along side the pipe. The gas flowed into the house's subfloor. Gas accumulated until a flammable concentration built up and contacted a pilot flame. The house blew up.

The house was reduced to rubble, but the three family members survived. The young son was covered by flaming debris. The mother stood in the flames uncovering piles of debris trying to find her son while being burned. The Grandfather was thrown clear, but saw his daughter being burned and rushed in to save her. He carried his daughter free of the fires. He then ran back into the debris to search for his grandson. Both child and Grandfather died in the debris. The mother was left scared, inside and out.

The mechanisms of the event and corrosion causation was the result of the crime laboratory of the USA FBI who investigated the incident. This case shows us the profound effect that any failing in design, selection, preparation, application and inspection can have.

This case is pending in private litigation and thus duplicate laboratory results and photos are not available at present. However, the conclusions herein are those the FBI Laboratory.

CASE STUDY 9 – THE CASE OF THE SPOTTED AUTOS

In the summer of 2003, a power plant was undergoing a large expansion. Multiple contractors were on site with several hundred employees working day and night shifts. Three painting contractors were working on the site. My employer was painting the new exhaust stack that was 320 meters high. A 33 meter band of the stack had to be painted to protect the concrete from the older shorter exhaust stack. Our company was using a grey color epoxy paint applied with rollers. The other two painting contractors were spraying white paints. Employees of the owner and various contractors noticed that their cars had white paint specs on their autos, over 300 autos.

The general contractor demanded that we clean all the cars because we were painting at elevation. We were told that if we objected or did not start to clean the cars we would be barred from the plant and our contract cancelled without payment.

The autos ranged from older work autos to high end expensive luxury autos. All had white paint specs on them. Many auto owners demanded that their autos be stripped and repainted. Some demanded their relative's auto shops to the work. Some wanted over 5000 USD in compensation. The priority was to clean those autos of employees who were satisfied with a good cleaning. A cleaner was hired who invented the clay bar system of removing overspray paint from autos. In this system a bar of clay is used to gently scrap the paint specs from the finish. However, for glass and chrome surfaces, a razor blade is used to slice off the paint specs. This is a time consuming and tedious process, but the results are very satisfactory. I had the cleaners save the paint specs they cut off with razors. After about 100 autos I had 35 grams of the paint, enough for laboratory analysis.

Paint samples were collected from the other contractors by removing brushes and used cans from their rubbish bins. All samples and the paint specs collected by the cleaners to an independent laboratory. The results were the painters working on the general contractor's payroll had over sprayed all the autos. We were reimbursed the 30,000 USD we had spent cleaning autos and the responsible contractor had to pay for the remaining autos. The use of Gas Liquid Chromatography and Fourier Transform Infrared Spectrophotometers can pinpoint the profile of the components of paints. With a known profile, we can determine the generic type or even the exact formulation. The same equipment we see on detective movies can aid our investigations as well.

CONCLUSION

Key to any failures investigation is to form a hypothesis of the cause of the failure. Then a null hypothesis is formed. The null hypothesis is a scenario that would be mutually exclusive of the proposed hypothesis. We then gather data to prove the null hypothesis. If we can prove it, our proposed one cannot be possible and is thus disproved. If we cannot prove the null, then our proposed one is likely true. Science does not prove to a level of 100%. Science can disprove theories to a level of 100%. It is the constant challenging of what we know that us to advance our body of knowledge. Using data gathering instrument (those taught in coating inspection courses) we can disapprove cause of failure and thereby determine the likely cause.

There is also no substitute to "in process" inspection of a coating system. The documentation of this inspection can quickly rule out potential cause and make failure analysis a quicker process. Please use these lessons from these cases as a guide to what is possible in this field.

Respectfully Submitted,

Pete Engelbert

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