

Causes of Coating Failures

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Abstract:

Industrial and marine protective coating systems are most commonly applied without incident, and perform as expected over their anticipated service life. However, occasionally, a coating system will fail prematurely, for unexpected reasons, and with expensive consequences. This paper addresses those unexpected failures, and provides reasons and remedies for such occurrences.

The paper addresses in brief the following topics:

Coating deficiencies attributed to:

1. Coating manufacturing
2. Specifications
3. Surface preparation and application
4. Service environment excursions

Additionally, normal environmental deteriorating effects on a coating are briefly discussed. These topics include:

5. Internal stresses-coating drying and curing.
6. External stresses-Vibration, flexing, mechanical damage.
7. Solar energy.
8. Heat.
9. Permeation (water, chemicals, oxygen).

Unfortunately, each of these deficiencies may occur in combinations with each other, and any or all may aggravate a coating system. One or more of these deficiencies or deteriorating effects are often sufficient to cause a coating system that otherwise would be protective and long lasting to break down prematurely months or years after the original application.

Too often the cost to remediate and repair or replace a coating system that has failed prematurely is greater than the cost of the original coating installation, especially when down time of the structure is considered.

Introduction:

According to the National Paint and Coatings Association, the total amount of industrial coatings sold in the United States in 2006 was 385 million gallons valued at \$6 billion. The value of field applied industrial maintenance coatings was an additional \$1.18 billion, and field applied marine maintenance coatings was \$252 million¹. At an average cost of \$30/gal for the industrial and marine maintenance coatings, approximately 47.7 million gallons of these coatings were manufactured in 2006. The overwhelming

majority of these 433,000,000 gallons of industrial and marine corrosion protective coatings applied each year provide the intended corrosion protection envisioned by the specifier.

However, a very small percentage of these coatings after application will fail prematurely for one reason or another. This paper categorizes the technical reasons for such coating failures, and discusses ways to prevent those failures.

There are always contractual relationships between parties involving a coating problem or failure, but these are not considered herein. Such contract items are within the realm of legalists, and usually become major issues in settling or litigating coating failures.

Categorization of coating deficiencies:

While coating failures may occur for number of reasons, they can generally be categorized into four main groupings:

1. Coating manufacturer related or caused
2. Owner/specifier related or caused
3. Coating applicator related or caused
4. Environmental service related or caused.

1. Coating manufacturer related or caused coating deficiencies:

Industrial and marine coating manufacturers have done a wonderful job of formulating and manufacturing coatings suitable for service in a given environment from various resins, pigments, additives and solvents (or water). Coating failures attributed in any form to the coating manufacturer are rare. However, such failures can occur for a number of reasons. Those reasons include the following:

1. An errant product recommendation by the coating manufacturer, or their sales representative. Such erroneous recommendations are difficult to detect by an owner or specifier. In fact, often than specifiers rely on coating manufacturer's recommendations and written literature's representative, or salesperson to select a coating system.
2. Errant information listed on the coating material product data sheet (PDS).
3. A bad batch of coating material.
4. Formulation of a coating not suitable for the intended service
 - a. Substitution of less expensive resins, pigments or solvents for cost control purposes
 - b. Substitution of different solvents, pigments and/or resins to comply with government regulations regarding VOCs; hazardous material; OSHA or EPA regulations.

The gaffes by a coating manufacturer are extremely hard to detect by an owner or specifier. In fact, the owner/specifier relies on the coating manufacturer for his recommendations with regard to suitable coatings for a given service environment. Often, the coating manufacturer prepares guideline specifications for use by specifiers. As a rule, only when the coating fails, and there is a technical investigation regarding the cause of failure will coating manufacturers' errors be discovered. Even then, proof is

often difficult, and expensive to obtain-and usually expensive laboratory analysis and testing is necessary in order to conclusively determine coating manufacturer error.

2. Specifier related or caused coating deficiencies:

Coating failures caused by a specifier are also rare, and occur only infrequently. This does not mean to say that all coating specifications are good, and quite the contrary, many coating specifications are very poor, and sometimes nonexistent, stating only "apply in accordance with the manufacturer's instructions." However, some coating failures can be attributed to the specification, such as:

1. A specification requiring the wrong coating for the intended service environment; or specifying an inexpensive paint to economize; or specifying a lesser degree of surface preparation than required for the system.

2. A "bad spec" that does not use standards written by a standards organization such as SSPC, NACE, ASTM, ISO and others for describing surface preparation requirements, measurement of coating thickness, and other coating operations.

3. A specification that does not provide provisions for owner or specifier oversight, or inspection.

A knowledgeable professional painting contractor may question some of the provisions in the specification if they are not standardized, or are contrary to his experience.

Sometimes a contractor will recognize a poor specification, and after being awarded the job, will point out those deficiencies during the course of work, and attempt to get extra reimbursement for any additional work (because the necessary work was not addressed by the poor specification). A third-party inspector (if one is used), should recognize specification deficiencies, and the inspector, or his company should be able to point out deficiencies prior to commencement of work. Pre-job meetings are essential, and will for the most part, enable the owner, contractor, specifier, inspector and any other stakeholder to understand the specification requirements, the work schedule, prevailing working conditions and the communication procedure to be used in the event of a work problem, or specification deviation.

3. Coating application related or caused coating deficiencies:

Since surface preparation and coating application are by far the most expensive and difficult portions of any coating work, it is logical to surmise that they as well, would be the source of most coating failures. Some examples of coating failures that can be attributed to deficient surface preparation or coating application are as follows:

- A. Inadequate surface preparation -- a degree of cleaning less than that specified, or coating over dust, dirt, soluble salts and/or debris on the surface after surface preparation. Poor or deficient surface preparation is probably the number one cause of coating failures.

- B. Deficient coating thickness -- this is perhaps the second most common cause of coating failures.

- C. Inadequate mixing or mis-mixing -- prior to application, coating material should be mixed properly and for sufficient duration to ensure that the pigment and resin are blended to a homogeneous consistency. Some heavily pigmented coatings (such as zinc riches) will require an in-pot agitator in order to maintain mixing homogeneity.

D. Inadequate or deficient curing -- to release solvents, or for water evaporation, followed by setting and curing of a cross-linked coating film all must occur at proper ambient humidity, and temperatures, and for a sufficient duration. These conditions should be spelled out, either in the specification, or in the coating manufacturer's product data sheet for a specific coating material. It is essential that this information be followed for optimum performance of the coating material.

E. Application of the coating material under incorrect ambient conditions (temperature, humidity, dew point).

F. Lack of protection from precipitation, or extreme heat or cold after application and before the coating has cured.

G. Use of improper surface preparation or application equipment, and/or failing to adjust the equipment properly during the course of work.

H. If the coating work is to be shipped, failure to adequately protect the coating from shipping and handling damage.

While all the above aggregate to become the most common reasons for coating failure either prior to placing the coated product in service, or after it has been in service, these defects are also the most easy to detect and to remedy. Conscientious professional contractors take pride in their work and are aware of the importance of each of these items and its role in preventing premature coating failure. Good contractors often advocate for owner or third party coating inspection services for verification that they have done the work properly. Low bid, or less reputable contractors whose work is verified by inspection may also have fewer surface preparation and coating application deficiencies than would otherwise occur without inspection.

4. Service environment related or caused coating deficiencies:

After the coating work has been properly completed, the coated item is subjected to environmental exposure. If all other factors have been done correctly, including the selection of the proper coating material and its surface preparation, application, curing, shipping and handling, and erection, premature failure still may occur. Some of the reasons for such failures are listed below:

A. Exposure to excessive moisture (such as ponding water), or temperatures (hot and cold) than anticipated.

B. Exposure to different or more concentrated chemicals than anticipated.

C. Exposure to abrasion, impact or mechanical damage.

D. Combinations of the above.

Such exposure excursions -- unanticipated exposure conditions -- may stress the coating system beyond its ability to perform in a given environment. If these exposure excursions are transient, and occur unknowingly, it may be very difficult to trace the cause of the coating failure. Even if exposure excursions are known by the owner, records may be hard to find, or alternately, may not be available to the coating failure investigator.

Unless there is physical evidence of coating degradation that may be traced to an exposure excursion (such as high heat, chemical attack or physical damage), the cause of failure may be difficult to discern.

A brief discussion of normal environmental effects on coating deterioration:²

Normal environmental effects that cause or contribute to coating deterioration are discussed below:

5. Internal stresses-coating drying and curing.
6. External stresses-Vibration, flexing, mechanical damage.
7. Solar energy.
8. Heat.
9. Permeation (water, chemicals, oxygen).

5. Internal Stress-coating drying and curing:

Internal coating stresses build up during drying, curing and upon aging. Curing stresses are caused by solvent (or water, if a water-based coating) evaporation causing a volume loss, and cross-linking resin polymerization, which shrinks the coating film.

Drying of a coating (unless it is 100% solids with no volatile solvents or materials) results in a volume decrease as the water or solvent evaporates into the atmosphere. As the coating initially gels, but remains soft after initial drying, stress is minimal because the resin is still deformable. However, as the coating dries further, and commences to cross-link, stress increases as the resin becomes harder and less deformable. Low molecular weight plasticizers added to keep the resin soft and relatively flexible may in time volatilize causing embrittlement, and stress. Thick, highly cross-linked resins (such as polyester and vinyl ester resins) have greater stresses than less cross-linked resins, or thinner coating systems. Over time, cross-linking and solvent evaporation and plasticizer migration and volatilization continues, further embrittling and stressing the coating film. In extreme cases, disbonding and/or cracking and splitting of the coating may occur, usually initiated at stress points such as edges or damage to the coating. Internal stresses can be relieved by proper pigmentation, and pigment distribution throughout the coating film. Good cleaning and surface profiles can also help to mitigate that effect of the stresses on the adhesion of the system. When applying additional coats to an existing system, if the old coating has insufficient adhesion, stresses from the new coating will disbond the existing material.

6. External Stress-vibration, flexing, substrate expansion/contraction:

External stresses on a coating usually affect an applied coating to a greater extent than internal stresses, although the combination is cumulative. Significant stress results when solar heating/cooling occurs and the substrate, often a metal, expands when heated, and contracts when cooled. Depending upon formulation, pigmentation and thickness, the coating usually does not expand or contract at the same rate, in which may cause cohesive splitting of the coating or adhesive disbonding from the substrate or between coats.

Similarly, flexing of a coating system as a result of wind and snow loads on a structure, vibration of machinery or imposition of weight loads (such as traffic on a bridge or the filling/emptying of a water storage tank) can provide further stress. Such cyclical stresses can be destructive particularly when combined with the other stresses and deteriorating effects mentioned above.

Impact, abrasion and mechanical damage are other types of external stresses to a coating system. These influences are most usually sudden, localized and abrupt relative to the other stresses and influences previously described. Impact of a coating from dropped tools, stones or other types of mechanical damage may chip and break the coating film. Such damage is greatest when the coating is brittle or is below the glass transition temperature T_g .

Abrasion results from scraping, scuffing and erosion due to moving particulate such as sand, or slurries. The coating is worn down by continued abrasion, and wear-through may occur. Hard brittle coatings are more susceptible to abrasion damage than softer more rubbery coatings. Abrasion resistant pigments such as aluminum oxide, sand, quartz garnet and other hard materials may be added to a coating to increase abrasion resistance. Rubber linings or thick abrasion resistant coatings, or installation of wear plates (metallic plates installed at areas of impact or extreme abrasion) will reduce the effects of impact and abrasion stress.

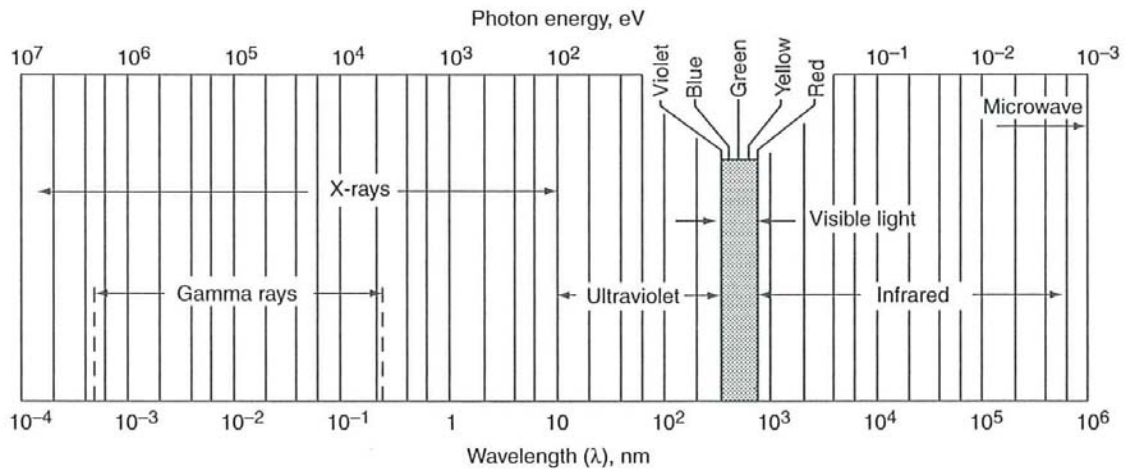
7. Solar energy:

Emitted energy from the sun is approximately 9% in the ultraviolet region, 45% in the visible range and remaining 46% in the infrared range.³

The ultraviolet light range (10 to 400 nm wavelength) has the shortest wavelength, and is most destructive to polymeric materials such as coatings. Light has sufficient energy to disrupt and break covalent bonds in organic molecules. There is sufficient radiation and penetration of ultraviolet (UV) as low as 280 nm to cause deterioration of paint. UV radiation below 280 nm is not considered detrimental because it is absorbed by water vapor and other small molecules in the atmosphere. Frequencies of radiation energy most harmful to polymeric systems are those from the violet and blue part of the visible light spectrum. The visible light spectrum ranges from 400 to 780 nm. Longer wavelengths much above 400 nm are not as detrimental to polymers. Ultraviolet energy may break covalent bonds and form free radicals in the polymer, which results in a shortening of its molecular chain length. Glass allows visible light to pass without any absorption. Glass is opaque to the shorter wavelengths of UV light, and reduces the transmission of UV light of longer wavelengths. Accordingly, materials exposed behind glass retain color and last longer than those exposed without glass protection.

Higher altitudes have higher levels of UV light. Additionally, higher altitudes may also be drier, and accordingly there may be less radiation absorption by moisture in the atmosphere. Similarly, an arid environment with clear skies may result in more intense UV light, and greater polymeric degradation. Conversely, combinations of water vapor, smog and chemical contamination from industrial environments may reduce UV damage due to UV absorption. However, the synergistic effect of these atmospheric contaminants on a polymer such as a coating may be much greater than that of UV alone. UV radiation, in combination with water on the surface (which concentrates the radiation) and chemical contamination provides the greatest potential for UV-polymeric coating degradation.

Figure 1 depicts the electromagnetic spectrum and energy of radiation⁴



Certain resins, notably aliphatic polyesters, acrylics, and polyurethanes are mostly transparent to ultraviolet light and allow UV energy to pass through them with no molecular absorption. Accordingly, there is no deterioration to these resins when they are exposed to UV light. Additionally, pigments in a paint, particularly inorganic pigments, will absorb and dissipate UV light, scatter it, or both, thereby lessening its deteriorating effect. Plate-like pigments such as leafing aluminum are particularly good reflectors and are opaque to visible and ultraviolet light. Zinc and zinc oxides are particularly good UV absorbers, with the UV energy dissipated as heat within the coating with little if any detrimental effect. Titanium dioxide is a good UV absorber, but in combination with water on its surface, and in the presence of atmospheric oxygen may accelerate UV deterioration of a coating resin.

8. Heat energy:

The addition of heat to material increases the vibration of atoms comprising a resin polymer. Heat energy is more uniform throughout a polymer than solar radiation, which concentrates on the outer surface. If sufficient heat is applied, molecular vibration within a polymer may increase to such a degree that chemical bonds break. When that happens, free radicals are formed, and the molecular weight of the polymer is shortened. Free radicals may further react with portions of the molecular chain, shortening it. The effect is essentially the opposite of cross-linking, and free radical scission, or bond breaking, results in a lesser ability of the polymeric resin to resist moisture and chemical permeation. If even more heat is applied, charring may occur whereby the polymeric material darkens, and ultimately may become friable with a total loss of physical properties.

9. Permeation (water, chemical and oxygen):

Permeation of a coating by moisture and chemicals in a service environment is a major factor in the deterioration of the coating. Coatings are specifically formulated and tested

to resist certain environments in immersion or in the atmosphere. Pigments and resins are carefully chosen for their resistance to a given set of environmental conditions.

Water, in liquid or vapor form is present in almost all exterior environments. Water is a very small molecule consisting of two hydrogen atoms and one oxygen atom.

Electronegative displacement of the shared electron pairs in the attractive covalent bonds between the oxygen and hydrogen atoms render a slight negative charge to the oxygen, and a slight positive charge to the hydrogens. This electrical charge to the water oxygen atom attracts other hydrogen atoms from adjacent water molecules, and from any other adjacent hydrogen atoms attached to other molecules. This attraction, called polarity, gives water its surface tension, and enables it to more readily dissolve other polar materials. Coatings often contain polar groups such as ester, ether and carbonyl groups that will attract water. Similarly, polar solvents, such as oxygenated solvents (ketones, acetates and others) will also attract water if they are retained in a coating film. Once water enters the coating film, it may force resin covalent bonds further apart, and adhesive bonds to the substrate may be swelled and/or broken. The volume of the coating may increase as much as 20-50% when in contact with water.⁵ Water swelling of a coating occurs with virtually all coating materials except those that are tightly cross-linked with a high cross-linking density (such as phenolics, phenolic-epoxies, novolacs and fluoropolymers).

Chemicals may also permeate a coating with water. Acids and alkalis dissolved from anhydrides by water will permeate a coating film. , The strength of the acid is a function of the excess of hydrogen ions (H^+) over the hydroxyl ion. , An alkali's strength is a function of the hydroxyl ion excess (OH^-) over that of the hydrogen ion. . Acid and alkali attack of coatings is a well known phenomenon, and can be avoided by careful choice of tightly cross-linked resins and resistant pigments in the coating. However, permeation of water, salts and solvents, all of which are of neutral pH (not acidic or alkaline) are also destructive.

Oxygen permeation through a film, or at a corrosion site is much slower than that of water due to the larger size of the oxygen molecule than the water molecule. O_2 (oxygen) has two oxygen atoms per molecule. The oxygen molecule is larger in diameter, and weighs much more than a water molecule (water = 18 grams/mol, and $O_2 = 32$ grams/mol).

Accordingly, its slower rate of permeation often controls the rate of corrosion (the cathodic reaction of a corrosion cell in a near-neutral environment is dependent upon oxygen permeation). If oxygen permeation is slow, the rate of corrosion is equally slow.

Unfortunately, each of these environmental stresses may occur in combination with each other, and any or all may aggravate a coating system that is compromised by deficiencies in coating manufacturing, the coating specification, or surface preparation and coating application. Sometimes all the things that can go wrong do go wrong. When that happens, the coating failure occurs quickly, and can be corrected as a work-in-progress. Usually, however, only one or two things go wrong, but those deficiencies are often sufficient to cause a coating system that otherwise would be protective and long lasting to break down prematurely months or years after the original application. Too often the cost to remediate and repair or replace a coating system that has failed prematurely is

greater than the cost of the original coating installation, especially when down time of the structure is considered.

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