EFFECTS OF CHLORIDE CONTAMINATION ON PERFORMANCE OF TANK AND VESSEL LININGS

Howard Mitschke, Coatings Specialist

Shell EP Technology, Applications and Research Co.
Integrity Management of Assets Dept.
Houston, Texas

ABSTRACT: Nine, commercially available, ambient cured, thin-film lining systems were evaluated for their tolerance to various levels of natural and artificially applied chloride contamination on steel substrates. The linings were tested by immersion in water or hydrocarbon/water at various temperatures for a duration of 13 and 6 months respectively. The tolerances to chloride were found to vary significantly among the linings. In addition, the maximum service temperatures of the linings were progressively reduced as the chloride levels increased.

INTRODUCTION

It is common knowledge that soluble salt contamination on a steel substrate can cause deterioration and early failure of linings in immersion service. However, lining failures are still occurring, especially after replacement linings are installed in existing tanks and vessels. These failures can be the result of improper choice of coating, poor surface preparation or poor coating application. In recent years there has been a growing awareness of the impact of substrate contamination on lining performance. As a result, the industry is giving more attention to the cleanliness of the metal substrate.

The most common characteristic of lining failures due to salt contamination is osmotic blistering. No organic coating is impermeable to water. Once water permeates the lining, it begins to dissolve the salt contamination at the steel/lining interface. This salt solution then develops an osmotic force, which attempts to draw more water into the blister to equalize the salt concentration to that of the immersion liquid.

Chlorides and sulfates are the most common types of soluble salt contaminants and are the most problematic. Contamination can exist on new or used steel and can occur during transportation, storage, surface preparation, in-service exposures, hydrotesting and tank cleaning. For this reason all steel substrates should be checked for salt contamination prior to lining application.

Although the deleterious effects of salt contamination are well recognized, standards for surface cleanliness and maximum allowable chloride levels have not been agreed upon. This is because there are numerous variables that can affect the threshold level at which chlorides will begin to cause coating failures. Research reported in the literature indicates wide ranges of threshold values have been reported often without documenting the variables used.

Threshold values can vary considerably depending on the generic type of lining and its thickness. Other variables include the service temperature, the degree of cure or postcure, the type of immersion liquid, amount of salts dissolved in an aqueous immersion liquid, the anchor profile, cold wall effects and the type of soluble contaminants on the substrate. It is not surprising there is so much difficulty in attempting to set standards.

The first of three objectives of this study was to determine the chloride thresholds at various temperatures at which linings begin to fail. By determining and recommending those linings that have higher chloride thresholds, there will be a greater confidence they can perform in a particular service. This is not to say that linings with higher tolerances should be used as a substitute for decontamination. Removal of the chloride is still highly recommended.

A number of reports in the literature have discussed various test methods to determine maximum allowable chloride levels. At issue is the manner in which the chloride is applied to the test panels. The second objective was to compare two methods for applying the contamination. The methods are artificial and natural contamination.

Linings are often exposed to water and hydrocarbons. The third objective was to determine the effect on the chloride threshold levels when linings were immersed in a liquid containing both hydrocarbon and water. Answers to these questions would provide much needed insight as to the acceptable levels of chloride for epoxy linings.

EXPERIMENTAL

Artificial Contamination Method

In this method, sodium chloride solutions were applied to non-corroded, abrasive blasted steel panels. The panels were subsequently coated with one of nine different modified epoxy coatings. After cure, the panels were immersed into tap water at various temperatures to determine the chloride threshold values at which blistering begins to occur.

Surface Preparation for Panels Receiving Artificial Contamination Panels were prepared using AISI #1018 carbon steel with dimensions of 3" x 6" x 1/8" thick. All panels were solvent washed in methyl ethyl ketone prior to abrasive blasting. A total of 490 panels were abrasive blasted using a conventional outdoor blast unit with coal slag abrasive. Both sides were abraded to a near white (SSPC SP10) cleanliness and a surface profile of 2.9 – 3.0 mils.

Application of Artificially Contaminated Chloride Various concentrations of sodium chloride were prepared in solutions of ethanol and water (80%v/20%v). Each solution was applied as uniformly as possible onto the panels using a volume of 500 microliters (µl) per panel. The chloride applications ranged from 0 - 30 micrograms (µg) chloride/cm^2 (see Table 3 for actual levels for each lining). For each panel, both sides were contaminated at the same level and tested. There were ten chloride levels for each coating system at each temperature. The tests were conducted at five or seven immersion temperatures ranging from 75 – 190°F.

Prior to application of the salt solutions, the panels were warmed to 130°F. Then 500 µl of the salt solution was applied and immediately spread evenly over the entire panel with a 3/8 inch O.D. glass rod. The glass rod was continuously wiped (but not rotated) over the panel to keep the solution uniformly distributed until the liquid dried. Then a gentle stream of dry, compressed air was blown over the panel to remove any residues of moisture.

Uniformity of Chloride Application To test the uniformity of salt application over the entire panel, three panels were contaminated, as described above, on one side only, at a nominal level of 33.5µg/cm^2. Each panel was then cut into 18 one-inch squares with a band saw. Each square was extracted with 10 ml of deionized water for several hours at 130°F. The chloride concentrations in the extracts were quantified by chloride specific electrode and the dimensions of each square measured with a micrometer. Based on the area of the squares and the amount of chloride in the extract, the chloride levels in µg/cm^2 were determined for each square.

Coating Application Nine commercially available coating systems noted in Table 1 were applied to the artificially contaminated panels, in two coats using a conventional sprayer, as recommended by the manufacturer. The immersion tests were initiated after a minimum of two weeks cure time at room temperature.

Natural Contamination Method

Although these panels are still prepared in the laboratory, it is called the "natural method" to reflect the fact the panels are corroded and pitted. As a result, this method gives a better simulation of the real manner in which chloride is distributed on the surface and within the pits.

In this method, panels were corroded in various levels of salt solution in a salt fog cabinet. The panels were then grit blasted and coated with six coating systems. After cure, the panels were immersed into tap water at various temperatures to determine the chloride threshold values.

Surface Preparation for Panels that were Naturally Contaminated Panels in this test were also ANSI #1018 carbon steel with dimensions of 3" x 6" x 1/8" thick. They were initially grit blasted with fine grit to remove the mill scale. A total of 175 panels were placed into salt fog chambers for 2 weeks to develop various levels of contamination on pitted and corroded panels. Five different concentrations of sodium chloride in water were used for the salt fog exposures: 0.25, 0.5, 1.0, 2.5 and 5%. After two weeks exposure to the salt fog, the wet panels were placed into plastic bags and allowed to continue corroding at room temperature under moist conditions for an additional two weeks. The panels were then dried and stored until needed.

Before the coating application, these panels were abrasive blasted, outdoors, as noted above for the artificially applied set. Immediately after grit blasting, the panels were placed into containers along with silica gel, moisture absorbent. However, the panels still developed flash rust and this required a second brush blasting in a blast cabinet prior to the coating application to bring the cleanliness back to a near white. To minimize further flash rusting in the 1 – 2 hour interval before coating application, the panels were placed into plastic bags and filled with dry air.

Five randomly selected grit blasted panels from each of the five salt fog exposures were extracted to quantify the chloride levels for each set. The extractions were performed in boiling deionized water for one hour and quantified by ion exchange chromatography. The average chloride contamination for each set was determined as follows:

Salt Fog Level (% NaCl in water)	0	0.25	0.5	1.0	2.5	5.0
Avg chloride level on panel (µg/cm^2)	<0.2	0.6	5.3	3.9	7.6	1.4
Standard Deviation ± (µg/cm^2)		0.1	1.1	2.1	2.8	0.4

The chloride levels for the 0.5 and 5% exposures did not correlate well to other sets. There was a greater level of chloride for the 0.5% exposure than for the 5% exposure. In an attempt to bring the panels back to a near white cleanliness, it is believed the panels from the 5% exposure received a greater degree of abrasive blasting than for the other sets and the 0.5% exposure a lesser degree of cleaning. This is because of the different degrees of flash rust that had developed on each set. Keep in mind that all panels were abrasive blasted twice. The flash rust was removed on the second blast.

Uniformity of Chloride Application Three grit blasted panels from the 5% NaCl salt fog exposure were tested for uniformity of chloride distribution as described previously for the artificial set. These panels were abrasive blasted only once then cut into 18 one-inch squares, extracted and the chloride content quantified by chloride specific electrode.

Due to constraints on time and materials, only six coating systems were used to evaluate the natural contamination method.

Panel Preparation for Testing in Water/Gasoline

This test was performed to determine the effects on the chloride threshold when a hydrocarbon was added to the water. Panels were cleaned and abrasive blasted as noted above for the artificial contamination method. Several levels of chloride were applied to the panels using the artificial application method. Four coating systems were tested.

Immersion Testing

Tap water immersions: After a two-week cure time at ambient temperatures, the artificially and naturally contaminated panels were immersed into tap water ranging from 75 to 190°F (see Tables 3 and 5). The conductivity of the tap water was about 550 microsiemens. Only one test panel was used for each chloride level at each temperature. The panels were observed weekly for blistering and cracking for the first six months, then at 1 – 3 month intervals from 6 – 13 months. The duration of the immersion test was 13 months.

Tap water/gasoline immersions: These panels were also cured for two weeks at ambient temperatures. This test also used one panel per chloride level. The panels were immersed upright with the top half of the panel in the gasoline phase and the bottom half in water. The gasoline contained 10% methyl tertiary butyl ether. The test temperature was 130°F and the test duration was six months.

RESULTS AND DISCUSSION

Uniformity of Chloride Application

It is important to obtain an even distribution of chloride across the panel. If the distribution is very uneven, then there could be areas containing chloride levels that are significantly greater than the nominally applied values. If blistering occurs in these regions, it may not be representative for the nominal values being tested.

It was felt an acceptable level of deviation from the nominal value was about ±10%. For the naturally contaminated panels, 7 out of 18 squares, or 39% of the area, exceeded the maximum deviation level.

For the artificial application of chloride, only 3 out of 18 squares for each panel contained levels that exceeded the maximum deviation. Three squares amount to about 20% of the total area on one side of a panel. This variability of the chloride levels within panels receiving the artificial application, may be a result of very slight warpage of the panel during abrasive blasting. Depending on how the panel is warped, there may be more or less salt deposited in the center compared to the edges. It is possible this variability can be lowered by using thicker panels, i.e. 3/16" or ¼" which would be less susceptible to warpage.

This demonstrates that artificially contaminated panels have a more uniform distribution of chloride and should be the method of choice for studying the effects of salt contamination on coatings.

From the tests with the artificially contaminated panels, it seems reasonable to disregard any blistering up to 20% of the area of the panel. Any blistering that exceeds 20% of the area should then be a result of the nominally applied value. Consequently, coating failure for the artificial application method was defined as blistering that was greater than 20% of the area on any one of the two sides tested. Linings were also considered failed if there were greater than 5 blisters or cracks scattered over the face of the panel. Cracks and blisters along the edges were not counted.

With the greater variability of the naturally contaminated panels, it was felt that failure should be defined as blistering that is greater than 40% of the area on either of the two sides of a panel.

Coating Application

The average coating thicknesses for each coating system are listed in Table 1. All of the average thicknesses were within or very close to the desired dry film thickness.

Threshold Limits for Artificially Contaminated Panels

The results are shown in Tables 2 & 3 and Figure 1. In this study the threshold level was defined as the maximum chloride level at a given temperature for which the coating was still considered passing. The chloride threshold levels for all but one coating system decrease with increasing temperatures. Lining # 4 did not follow this trend, since the thresholds increased in the temperature range of 110 to 170°F. One possible explanation is that this lining developed a higher degree of "postcuring" at the higher immersion temperatures than at the lower temperatures. This greater postcuring could impart greater water resistance and better wet adhesion for the lining resulting in a higher chloride tolerance.

There were significant differences among the threshold values of the linings at a given temperature. The values ranged from approximately 4 to 20 $\mu g/cm^2$ at 75°F. (Some of the values for 90 & 75°F in Table 2 were determined by extrapolation.) This demonstrates that even within the same generic coating type, there are considerable differences in tolerance to chloride contamination.

Another way to view these results is to look at the effect of increasing levels of contamination on the maximum service temperatures of a lining. As noted in Figure 1, even levels of 1 μg/cm^2 can affect the lining's performance. On the average, each additional microgram lowered the maximum service temperature of the lining by about 10°F.

Shell Oil Co. currently sets the maximum allowable chloride level at 5 μg/cm^2 for ambient temperature immersion service. Three of the nine coating systems evaluated here would possibly have failed if the steel substrate were contaminated at the maximum allowable level of 5 μg/cm^2.

A draft ISO document[1] reported the maximum acceptable chloride levels from 11 coating manufacturers for immersion service. The levels ranged from 1 to 10 μg/cm^2 with an average of 5 μg/cm^2. The work described in this report also tends to support a maximum allowable chloride criteria of about 4 - 5 μg/cm^2 for ambient temperature service when no other critical factors are involved. As service temperatures are increased, this criteria should be progressively lowered.

As noted in Tables 3 and 5, the linings with the highest chloride levels at a given temperature generally failed first. This was followed by progressively longer failure times for the lower chloride levels. The longest failure time for a given temperature occurred just above the threshold value. Nevertheless, these failure times (just above the threshold value) still ranged from 2 – 43 weeks and surprisingly did not depend on temperature. There were short failure times at low temperatures as well as at high temperatures.

Another observation is the degree of blistering above and at the threshold levels. Almost all of the samples at the threshold had no blistering. A few ranged from 0 – 20% of the area and the average was 2%. At the first chloride level above the threshold, the samples had a significant increase in the amount of blistered area. The average percentage of area for these samples was 46%. So there was a definite transition at the chloride threshold level that was easy to identify.

After ten months immersion, the panels containing chloride levels at the threshold level were tested for the degree of adhesion. Observations were also made for the degree of corrosion on the steel under the coating. In 38 out of 40 samples, the steel was still a gray to dark gray color. The adhesion values were all good.

In previous unreported work performed by Shell on a similar study, linings with salt levels below the threshold have shown no significant deterioration after 23 months immersion. Therefore, it appears that linings do not have significant long-term deterioration for chloride levels at or below the threshold. As a result, an immersion test duration of ten months should be sufficient to determine threshold values for most thin film linings.

Threshold Limits for Naturally Contaminated Panels

The chloride threshold values were determined for six lining systems at five levels of chloride contamination and at five temperatures (see Table 5). These values were then compared to the values obtained for artificially contaminated test panels (see Table 4).

The purpose for the comparison was to determine how similar the threshold values are for the two contamination methods. In the artificial contamination method, a known amount of chloride is uniformly applied onto the panels prior to coating application. The advantages of this method are relative ease of preparation, known levels of contamination and a more uniform distribution over the panel.

The natural method is more realistic because the panels are first corroded in a salt fog cabinet. This method is a better simulation of the real nature of corroded steel because it includes micropits and ferrous/ferric types of chloride salts. However, it is much more difficult to make the naturally corroded panels and to quantify the chloride levels on them. There is also greater variability of the chloride levels in these panels. One reason for the high degree of variation in these panels is the difficulty in providing uniform grit blasting of the corroded panels, both within the panel and from panel to panel.

If the thresholds are similar for the two methods, then this justifies the sole use of the artificial method for determining the salt tolerance of a lining.

Threshold values could not be determined for linings 1 & 4 because the thresholds at all temperatures were above the highest contaminant level on the test panels. For the four other linings, the trends followed those for the artificially contaminated panels. As the temperature increased, the threshold values decreased.

In general, there were two differences between results for the two methods. The natural contamination method gave thresholds that were slightly higher than for the artificial method. But this occurred only in the 110 - 150°F range (see Table 4). Because the differences in threshold values were minor, the two methods may be considered as giving similar results. The second difference was the times to failure for the naturally contaminated panels. They were longer in the 110 – 170°F range than for corresponding panels prepared with the artificial method (compare Tables 3 & 5).

Because the artificial method gives slightly lower thresholds for linings, it can be thought of as slightly more "conservative" compared to the natural contamination method. This is actually desirable. In the real world there are a number of other factors (not included in this test) that tend to lower the chloride threshold values. Examples are: less than optimum abrasive blasting cleanliness and profile, cold wall effects, insufficient cure, etc.

Also, when quantifying chloride on steel, most tests extract only about 50% of the chloride, so there is an underestimation of the chloride on the steel. Therefore, it is desirable to use the artificial method which gives more conservative results.

Knowing there is a wide range of performance with regard to chloride tolerance of linings, it would be appropriate for owners to set performance criteria for lining products. Linings, for example, could be specified to withstand particular chloride levels for a given service.

It is recommended that the artificial contamination method be used to compare the chloride tolerance levels of commercially available linings. The use of this test is highly recommended for services at higher temperatures where contaminated steel is likely.

A combination of proper surface cleaning and the use of linings with greater tolerance to chlorides, should result in a longer lifetime for the lining system. At 130°F, five of the nine linings tested would fail if a metal substrate had 5 µg chloride/cm^2 on the surface. So the tolerance of the lining to chloride contamination should be a factor in the choice of a lining.

Threshold Limits for Linings Immersed in Gasoline/Water

The addition of an organic or hydrocarbon phase such as gasoline appears to lower the chloride threshold for linings compared to immersion in water only. For three out of four coatings tested at 130°F for a 6 month duration, there was a decrease in the threshold values as follows:

Lining	Threshold at 130°F	
	Water only*	Gasoline/Water*
1	>20	15
2	5	2-3
6	4	1
9	4	4-5

* The duration of the gasoline/water immersion was 6 months. For purposes of direct comparison, the results for the water immersions are also at the 6 month immersion times.

These reductions in thresholds ranged from 0 to about 75%. For the samples immersed in gasoline/water, the failures in all cases occurred in the lower half of the panels that were exposed to the water phase.

CONCLUSION

These results demonstrate that chloride threshold levels varied considerably (about 4-20 µg/cm^2 at 75°F) for nine different modified epoxy linings. For elevated service temperatures, even 1 µg/cm^2 has an effect that lowers the maximum service temperature of the lining by about 10°F. Also, there does not appear to be a significant long-term deterioration for chloride levels at or below the threshold level.

Both methods for applying salt contamination (artificial and natural) give a similar trend: as immersion temperatures increase, there is a decrease in chloride tolerance. The natural contamination method was found to have slightly higher tolerances for chloride in the 110 - 150°F range and longer times to failure than for the artificial method. However, the use of the artificial method is a more acceptable method for comparing salt tolerances of linings. It gives a slightly more conservative evaluation of performance, is easier to prepare and has a more uniform distribution of chloride over the panel.

Most, but not all the linings used in the gasoline/water immersions were found to have lower thresholds for chloride than for immersions in water only. For linings exposed to hydrocarbons and water, it is recommended that owners make a careful evaluation of the service conditions to determine acceptable levels of chloride. In many cases, especially at elevated temperatures, the maximum allowable amounts could be non-detectable levels.

REFERENCES

1. ISO Draft # 15235, British Standards Institution, Preparation of Steel Substrates Before Application of Paints and Related Products, Nov 12, 1999.

TABLE 1
THICKNESSES FOR LININGS EVALUATED IN THIS STUDY

Coating #	Type Coating	Avg Actual DFT
1	EN	12.6
2	EP	7.6
3	EP	9.4
4	EN	10.3
5	EP	10.1
6	EP	10.1
7	E	10.8
8	EP	10.7
9	EP	18.4

Type coating: E: epoxy, EN: epoxy novalac, EP: epoxy phenolic

TABLE 2
SUMMARY OF THRESHOLD LIMITS FOR ARTIFICIALLY CONTAMINATED PANELS AFTER 13 MONTHS IMMERSION IN TAPWATER
(μg chloride/cm²)

Coating	190°F	170°F	150°F	130°F	110°F	90°F	75°F
1	7.5	7.5	15	>20	>20	(>20)*	(>20)*
2	F at 0	F at 0	4	5	7.5	10	10
3	F at 0	F at 0	F at 0	F at 0	2	(3)	(4)
4	F at 0	>20	10	10	7.5	(6)	(4)
5	F at 0	F at 0	F at 0	2	3	(3)	(4)
6	F at 0	F at 0	3	4	5	5	5
7	F at 0	1	1	3	5	(6)	(7)
8	17.5	15	20	17.5	22.5	<20	20
9	F at 0	F at 0	0	2	5	5	7.5

*Threshold limits in parenthesis in the 90 and 75°F columns are extrapolated values.
F at 0 means that the lining failed even though no salt contamination was applied, in other words, the maximum service temperature of the lining was exceeded.

TABLE 3

Time to Failure by Blistering for Coatings Applied on Artificially Contaminated Panels

Applied Salt Level (μg/cm²)	Time to Blistering (weeks) At Various Temp. (°F)						
	190	170	150	130	110	90	75
Coating # 1							
0	>56	>56	>56	>56	>56	---	---
1	>56	>56	>56	>56	>56	---	---
2	>56	>56	>56	>56	>56	---	---
3	>56	>56	>56	>56	>56	---	---
4	>56	>56	>56	>56	>56	---	---
5	>56	>56	>56	>56	>56	---	---
7.5	>56	>56	>56	>56	>56	---	---
10	4	7	>56	>56	>56	---	---
15	1.5	6	>56	>56	>56	---	---
20	1.5	1.5	26	>56	>56	---	---
Coating # 2							
0	16	26	>56	>56	>56	---	---
1	26-36	26-36	>56	>56	>56	---	---
2	18	26-36	>56	>56	>56	---	---
3	16	26	>56	>56	>56	---	---
4	4	26	>56	>56	>56	---	---
5	5	9	26	>56	>56	---	---
7.5	1.5	1.5	1.5	11	>56	---	---
10	1.5	1.5	1.5	3	1.5	>56	>56
15	1.5	1.5	1.5	1.5	1.5	4	4
20	1.5	1.5	1.5	1.5	1.5	2	2
Coating # 3							
0	6	11	8	36-43	>56	---	---
1	3	7	8	13	>56	---	---
2	3	4	7	36-43	>56	---	---
3	3	3	6	20	3	---	---
4	1.5	1.5	5	5	1.5	---	---
5	1.5	1.5	4	1.5	1.5	---	---
7.5	1.5	1.5	1.5	1.5	1.5	---	---
10	1.5	1.5	1.5	1.5	1.5	---	---
15	1.5	1.5	1.5	1.5	1.5	---	---
20	1.5	1.5	1.5	1.5	1.5	---	---
Coating # 4							
0	43-56	>56	>56	>56	>56	---	---
1	43-56	>56	>56	>56	>56	---	---
2	43-56	>56	>56	>56	>56	---	---
3	43-56	>56	>56	>56	>56	---	---
4	43-56	>56	>56	>56	>56	---	---
5	43-56	>56	>56	>56	>56	---	---
7.5	43-56	>56	>56	>56	>56	---	---
10	43-56	>56	>56	>56	7	---	---
15	43-56	>56	2	7	1.5	---	---
20	43-56	>56	1.5	1.5	1.5	---	---
Coating # 5							
0	2	1.5	3	>56	>56	---	---
1	1.5	1.5	5	>56	>56	---	---
2	1.5	1.5	3	>56	>56	---	---
3	1.5	1.5	3	7	>56	---	---
4	1.5	1.5	1.5	10	4	---	---
5	1.5	1.5	1.5	6	0.5	---	---
7.5	1.5	1.5	1.5	1.5	1.5	---	---
10	1.5	1.5	1	3	0.5	---	---
15	1.5	1.5	1	3	0.5	---	---
20	1.5	1.5	1	1.5	0.5	---	---

Applied Salt Level (μg/cm²)	Time to Blistering (weeks) At Various Temp. (°F)						
	190	170	150	130	110	90	75
Coating # 6							
0	36-43	43-56	>56	>56	>56	---	---
1	36-43	43-56	>56	>56	>56	---	---
2	3	43-56	>56	>56	>56	---	---
3	1.5	1.5	>56	>56	>56	---	---
4	1.5	1.5	7	>56	>56	---	---
5	1.5	1.5	4	13	>56	>56	>56
7.5	1.5	1.5	1.5	1.5	8	1	2
10	1.5	1.5	1.5	1.5	1.5	1	1
15	1.5	1.5	1.5	1.5	1.5	1	1
20	1.5	1.5	1.5	1.5	1.5	1	1
Coating # 7							
0	2	>56	>56	>56	>56	---	---
1	2	>56	>56	>56	>56	---	---
2	2	2	5	>56	>56	---	---
3	2	1.5	3	>56	>56	---	---
4	2	1.5	3	6	>56	---	---
5	2	1.5	3	10	>56	---	---
7.5	2	1.5	1.5	1.5	4	---	---
10	2	0.5	1.5	1.5	2	---	---
15	2	1.5	1.5	1.5	1.5	---	---
20	2	0.5	1.5	1.5	1.5	---	---
Coating # 8							
0	>56	>56	>56	>56	>56	---	---
7.5	>56	>56	>56	>56	>56	---	---
10	>56	>56	>56	>56	>56	---	---
12.5	>56	>56	>56	>56	>56	---	---
15	>56	>56	>56	>56	>56	---	---
17.5	>56	26-36	>56	>56	>56	---	---
20	1.5	1.5	>56	36-43	>56	3	>56
22.5	1.5	1.5	3	20	>56	6	25
25	1.5	1.5	1.5	36-43	26	5	25
27.5	1.5	1.5	1.5	1.5	1.5	5	23
30	1.5	1.5	1.5	1.5	1.5	4	7
Coating # 9							
0	11	26	>56	>56	>56	---	---
1	13	26	36-43	>56	>56	---	---
2	13	23	20	>56	>56	---	---
3	11	21	9	36-43	>56	---	---
4	6	3	4	26	>56	---	>56
5	4	5	3	5	>56	>56	>56
7.5	1.5	1.5	1.5	3	3	7	>56
10	1.5	1.5	1.5	1.5	1.5	3	12
15	1.5	1.5	1.5	1.5	1.5	2	5
20	1.5	1.5	1.5	1.5	1.5	---	2

Shaded cells indicate coating failure

TABLE 4

COMPARISON OF CHLORIDE THRESHOLD VALUES FOR NATURALLY AND ARTIFICIALLY CONTAMINATED PANELS

(µg chloride/cm²)

NATURALLY CONTAMINATED PANELS*

Coating	190°F	170°F	150°F	130°F	110°F
2	F at 0	F at 0	5	5	>7
3	F at 0	F at 0	F at 0	5	5
5	F at 0	0	0	>7	>7
6	F at 0	1	5	>7	>7

*This is a summary of data taken from Table 5

ARTIFICIALLY CONTAMINATED PANELS*

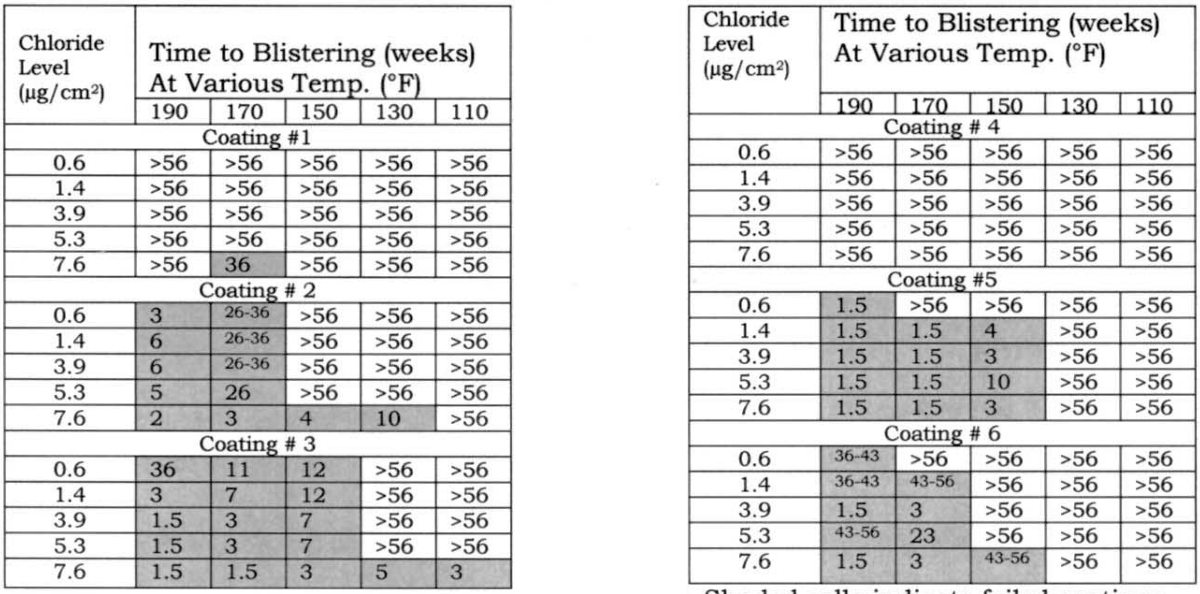
Coating	190°F	170°F	150°F	130°F	110°F
2	F at 0	F at 0	4	5	7.5
3	F at 0	F at 0	F at 0	F at 0	2
5	F at 0	F at 0	F at 0	2	3
6	F at 0	F at 0	3	4	5

* This is a summary of data taken from Table 3

F at 0 means that the lining failed even though no salt contamination was applied, in other words, the maximum service temperature of the lining was exceeded.

TABLE 5

Time to Failure by Blistering for Coatings Applied on Naturally Contaminated Panels



Chloride Level (µg/cm²)	Time to Blistering (weeks) At Various Temp. (°F)				
	190	170	150	130	110
Coating #1					
0.6	>56	>56	>56	>56	>56
1.4	>56	>56	>56	>56	>56
3.9	>56	>56	>56	>56	>56
5.3	>56	>56	>56	>56	>56
7.6	>56	36	>56	>56	>56
Coating # 2					
0.6	3	26-36	>56	>56	>56
1.4	6	26-36	>56	>56	>56
3.9	6	26-36	>56	>56	>56
5.3	5	26	>56	>56	>56
7.6	2	3	4	10	>56
Coating # 3					
0.6	36	11	12	>56	>56
1.4	3	7	12	>56	>56
3.9	1.5	3	7	>56	>56
5.3	1.5	3	7	>56	>56
7.6	1.5	1.5	3	5	3

Chloride Level (µg/cm²)	Time to Blistering (weeks) At Various Temp. (°F)				
	190	170	150	130	110
Coating # 4					
0.6	>56	>56	>56	>56	>56
1.4	>56	>56	>56	>56	>56
3.9	>56	>56	>56	>56	>56
5.3	>56	>56	>56	>56	>56
7.6	>56	>56	>56	>56	>56
Coating #5					
0.6	1.5	>56	>56	>56	>56
1.4	1.5	1.5	4	>56	>56
3.9	1.5	1.5	3	>56	>56
5.3	1.5	1.5	10	>56	>56
7.6	1.5	1.5	3	>56	>56
Coating # 6					
0.6	36-43	>56	>56	>56	>56
1.4	36-43	43-56	>56	>56	>56
3.9	1.5	3	>56	>56	>56
5.3	43-56	23	>56	>56	>56
7.6	1.5	3	43-56	>56	>56

Shaded cells indicate failed coatings

FIGURE 1. THRESHOLD LIMITS VS. TEMPERATURE