Effect of Porosity on Resistance of Epoxy Coatings to Cold-Wall Blistering

J.R. Kosek, J.N. DuPont, and A.R. Marder*

ABSTRACT

Six epoxy-based coating systems were tested for their resistance to degradation in the form of "cold-wall" blistering. The coatings were applied to type 1010 steel (UNS G10100) substrates and exposed to heated water for up to 10 months in Atlas test cells as a modified version of NACE Standard TM0174. The performance of the coatings was measured by the exposure time for the coatings to start blistering, the time for the corrosion potential (Ecorr) of the coating substrates to shift toward active values, and the delamination (or blistering) rate of the coatings. Good cold-wall blistering resistance was observed for two polyamine-cured epoxy coating systems with porosity levels < 1 vol%. These two coating systems exhibited longer lifetimes than the other coating systems under four different test conditions that varied coating thicknesses and exposure temperatures. Intermediate performance was observed for a polyamine-cured epoxy with an average porosity level > 1 vol%. Poor cold-wall blistering resistance was shown by a polyamide epoxy system, an amine adduct epoxy system, and an amido-amine epoxy system, all of which had porosity levels > 1 vol%. Most of the coating samples exhibited linear blistering rates, which indicated that the kinetics of cold-wall blistering were diffusion controlled. The two coating systems that showed the best resistance to cold-wall blistering also showed the lowest blistering rates, indicating that these coatings may have had lower permeabilities and/or better adherences than the poorer performing coatings, probably as a result of their lower porosity levels and similar compositions.

KEY WORDS: blistering, coatings, corrosion potential, diffusion, disbondment, epoxy coatings, immersion testing, organic coatings, polymer coatings, porosity, thermo-osmosis, utilities

INTRODUCTION

Electric utilities use polymer coatings for corrosion protection in a variety of locations, such as cooling towers, water boxes, and tubesheets. In some cases, these coatings are vulnerable to failure in areas where a temperature gradient exists between a cold substrate and relatively warm fluid (i.e., "cold-wall" blistering). The temperature gradient accelerates the rate of water permeation through the coating (toward the cooler substrate), which promotes coating delamination and subsequent substrate corrosion.

In general, all polymeric materials absorb some amount of water when immersed in an aqueous solution or exposed to high humidity conditions.1 In addition, all polymers are semipermeable to water, oxygen, ions, and other species. Water can migrate through polymer coatings by a number of different means. For example, individual water molecules can take a random walk through holes in the polymer network, or through channels, capillaries, or pores in the coating.2 Potential pathways for water also exist in pigmented coatings at the interface of pigments and fillers with the polymer matrix.2 In fact, water permeation rates have been found to be higher in coatings with pigment aggregates than in coatings in which the pigment was finely dispersed.3

For polymer coatings on metal substrates, directional water transport through polymer coatings to
the coating/metal interface is the result of diffusion under a concentration gradient. Perera and Heertjes showed that organic coatings are sensitive to osmotic pressure differences and that water can diffuse through the coating under an osmotic pressure gradient. In cold-wall blistering, a temperature gradient across the coating causes the transport of heat and mass through the coating toward the cooler side (i.e., the side in contact with the substrate). This process is known as thermo-osmosis, and thermal gradients are believed to be an efficient mechanism for water condensation at the metal/coating interface. Aqueous phase water can nucleate and accumulate at small disbonded regions or defects at the coating/metal interface, and the accumulation of water in localized regions of the interface can cause local deformation of the coating in the form of blisters. The formation and growth of blisters stops if the amount of water leaving the coating by osmosis equals or exceeds the amount entering the coating under the influence of the temperature gradient. The termination of blister formation and growth also can result from attaining an equilibrium between osmotic and hydrostatic pressure.

Some of the different factors that affect blistering resistance and coating disbondment in general are:

- The nature and the substrate surface,
- The coating’s composition, and
- The exposure temperature.

Improved adhesion and blister resistance have been observed for blasted steel surfaces over unroughened surfaces, and the application of primers such as silanes has been shown to increase coating adhesion and blister resistance. Alternatively, the presence of hydrophilic solvents, salts, or contaminants on the steel surface has been shown to decrease the adhesion and blister resistance of organic coatings.

Generalizations about coating composition on disbondment and blister resistance are difficult to make because of the wide range of polymers and additives used in commercial coating systems. However, coating compositions that combine the properties of good adherence and low permeability (or vapor transmission rate) are desirable. Amine-cured epoxies, polyamide epoxies, and variations of these types of epoxies have good water resistance and can be used at temperatures up to ~93°C (200°F). Commercial epoxy coating systems used for corrosion protection usually consist of two or more coats and usually contain an array of pigment or extender particles that are added to inhibit corrosion of the substrate metal, to strengthen the coating, and to decrease the coating’s permeability to water and oxygen by creating longer paths for diffusion of these species. The objective of the present work was to evaluate a series of epoxy-based coating systems for their resistance to cold-wall blistering.

### EXPERIMENTAL

Six epoxy-based coating systems were applied to 6 in. by 6 in. square, 0.25 in.-thick (152 mm by 152 mm square, 6.4 mm-thick) panels of type 1010 carbon steel (UNS G10100) that had been grit-blasted to about a 3-mil (0.08 mm) finish. All of the coatings were solvent-based and were brushed onto the substrates. Generic compositions of the six coating systems are shown in Table 1, along with a summary of the test matrix where each testing condition is identified by its coating thickness and test solution temperature. The reported coating thickness represented the average of five thickness measurements taken per ASTM G 12 with a magnetic coating thickness tester.

The testing of the coated steel panels involved the use of Atlas test cells in a modified version of NACE Standard TM0174. This standard is used for the evaluation of protective coatings used as lining materials in immersion service, and a schematic of the test cells used in the experiment is shown as Figure 1.

Each test cell was constructed of glass and fitted at both ends with coated panels. The panel of the left side of the cell shown in Figure 1 was coated on one side (i.e., the side facing the interior of the cell) to achieve a water-to-air heat-transfer condition. A stream of air was forced onto the bare side of this panel to prevent the development of thermal boundary layers. The panel on the right side of the cell shown in Figure 1 was coated on both sides and positioned between the test cell and a water jacket to achieve a water-to-water heat-transfer condition. Tap water was circulated continuously through the cooling jackets to maintain a constant water-to-water temperature gradient. The test solution used in the cells was 500 kΩ-cm (197 kΩ-in.) distilled water, and the cells were kept filled to three-fourths capacity with the solution to achieve water and vapor conditions within the cells. Two solution temperatures, 43°C (110°F) and 63°C (145°F), were used. The two test solution temperatures induced water-to-air temperature gradients of 19°C (35°F) and 39°C (70°F) and water-to-water temperature gradients of 12°C (22°F) and 32°C (57°F), respectively.

Each of the coating samples was inspected daily for the appearance of blisters. When blisters first were noticed on each coating, the test cell containing that coating was dismantled, and a detailed evaluation of the two coating samples from that cell was

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(1) UNS numbers are listed in Metals and Alloys in the Unified Numbering System, published by the Society of Automotive Engineers (SAE) and cosponsored by ASTM.
### TABLE 1

**Generic Composition of Coating Binders and the Test Matrix for Evaluation of the Resistance of Polymer Coatings to Cold-Wall Blistering**

<table>
<thead>
<tr>
<th>Coating</th>
<th>Coating Binder Generic Composition</th>
<th>Coating Layer</th>
<th>Test Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>43°C, Thin (mils)</td>
</tr>
<tr>
<td>A</td>
<td>Epoxy cured with a polyamine</td>
<td>Base, top</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>B</td>
<td>Modified epoxy cured with a polyamide</td>
<td>Base, middle, and top</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>C</td>
<td>Modified multifunctional epoxy cured with a polyamine</td>
<td>Base, middle, and top</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>D</td>
<td>Modified epoxy cured with a modified polyamine</td>
<td>Base, top</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>E</td>
<td>Epoxy cured with a multifunctional amine adduct</td>
<td>Base, top</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>F</td>
<td>Epoxy cured with a modified amido-amine</td>
<td>Base, middle, and top</td>
<td>NT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(A) The four test conditions are indicated as combinations of the two cell solution temperatures and the thin and thick coating variations. The actual thicknesses of the coating samples used in each test condition are noted. NT indicates the coating was not tested in that condition.

Conducted. This evaluation included photographic documentation of the coating samples to show the blistered region and determination of the degree of blistering by quantitative image analysis (QIA). Upon completion of an evaluation, the test cell containing the two coating samples was reassembled with the addition of new test solution. After the initial evaluation conducted on each coating sample, additional evaluations were conducted at intervals of 3 weeks to 8 weeks, depending on the increase in blistered area, as determined by daily visual inspections.

The data for each coating’s blistered area, as determined by QIA, at each of the evaluations was plotted vs exposure time to determine the delamination or blistering rate exhibited by each sample.

Electrochemical potentials of the steel substrates of the coated panels were monitored daily throughout the length of exposure. A programmable electrometer was used in conjunction with a saturated calomel electrode (SCE) to measure corrosion potentials ($E_{corr}$) of the coated steel substrates. $E_{corr}$ of one of the steel substrates corroding in the test solution would be in the range of $-660 \text{mV}_{\text{SCE}}$. Therefore, when the potential of a coated substrate began to decline or suddenly dropped toward active values (i.e., $-400 \text{mV}_{\text{SCE}}$ to $-700 \text{mV}_{\text{SCE}}$ from an original potential of $\approx -50 \text{mV}_{\text{SCE}}$ to $-100 \text{mV}_{\text{SCE}}$), it was assumed that substrate corrosion had initiated. When a coating sample’s potential remained in the active range for long periods of time, it was assumed that active corrosion was occurring on the substrate beneath the coating.

Cross-sectional samples of all of the coatings were prepared by cutting samples from the exposed and unexposed areas of each of the coated panels after they were removed from test cells for the final evaluation. The samples were prepared by standard metallographic techniques, and the polished cross-sectional samples then were used for porosity measurements.

The volume percents (vol%) of porosity in each of the coatings were characterized using QIA. Four samples of each coating, representing exposed and unexposed areas were used for the measurements. The vol% porosity values obtained for the coatings represented the average of the measured porosity from 15 random fields of view on each of the four samples for each coating.

The porosity measurements represented the average porosity throughout the entire coating system. Some of the coating systems had two layers (i.e., base and top coat) and others had three layers (base, middle, and top coat). The thicknesses of these layers varied in proportion to one another along the length of each cross-sectional sample and from sample to sample. In addition, the distribution of pores throughout the three layers appeared to be random, as some fields of view had no porosity in any layers while other fields showed pores in all the layers. Therefore, the porosity data used to evaluate the coatings were representative of the entire coating cross-sections (i.e., there was no distinction made between the porosity or physical characteristics of the different layers).
RESULTS AND DISCUSSIONS

Performance Summary for the Six Coating Systems

Coating lifetimes as measured by the time to blister and the time to active E$_{corr}$ (i.e., substrate corrosion) under the four different test conditions are shown in Figures 2 and 3, respectively. The four test conditions involved the two coating thicknesses and the two cell temperatures (43°C and 63°C). Under this experimental condition, blistering occurred almost entirely within the coating area in contact with the liquid phase. Assuming the data followed Arrhenius-type behavior, Figures 2(a) and (b) are plots of time to blister on a log scale (normalized for sample thickness) vs the inverse of the exposure temperature difference for the water-to-air and water-to-water heat-transfer conditions, respectively. Similarly, Figures 3(a) and (b) plot the time for the shift in E$_{corr}$ toward active values (normalized for sample thickness) vs the inverse of the exposure temperature difference in the water-to-air and water-to-water heat-transfer conditions, respectively. All data for the time to blister and time for active E$_{corr}$ were divided by the sample thickness to normalize the data for comparison. This was justified because coating permeability has been found to vary linearly with the inverse of coating thickness.$^{19}$

Figures 2(a) and (b) show a consistent ranking of the coatings’ performance based on the time for the coating samples to start blistering. For example, in all of the test conditions, the samples of Coating C took longer to blister than all of the other coatings, followed by samples of Coatings D and A. The samples of Coatings B, E, and F failed relatively quickly in all of the test conditions. Figures 2(a) and (b) also show Coatings C, D, and A to some extent showed much larger gains in lifetime than Coatings B, E, and F as the temperature gradients were reduced. The dashed lines and the arrows on the datapoints for Coating C at the low-temperature gradients on Figures 2(a) and (b) indicated these samples did not blister by the end of the test exposure. Therefore, datapoints for these samples were approximated by dividing the entire length of the exposure time (over which they did not blister) by the coating samples’ thicknesses. This provided a lower limit of the lifetime of these samples.

Figures 3(a) and (b) show the same trends established in Figures 2(a) and (b). Coatings C, D, and A showed large improvements in lifetime, as measured by the time for substrate corrosion to begin as the temperature gradient was lowered. However, Coatings B, E, and F had very limited lifetimes at the high- and low-temperature gradients.

Coatings B, E and F failed almost as quickly at the low-temperature gradients as they did at the high-temperature gradients. This suggested that these coatings had poor barrier characteristics. Under any exposure temperature gradient, water and oxygen permeated through these coatings and caused coating disbondment and substrate corrosion. Coatings C, D, and A to some extent showed large gains in lifetime as the temperature gradients were lowered. This provided evidence of the effective barrier characteristics of these coatings. As the tem-
Temperature gradients were lowered, the driving force (i.e., the thermo-osmotic force) for water transport through the coatings decreased. Therefore, these coatings were more effective at blocking the transport of water and oxygen and at retaining adherence to the substrate. In fact, some samples of the better performing coatings (i.e., Coatings C, D, and A) did not blister at all under the low-temperature gradient conditions after almost 300 days of exposure. This suggested that the better performing coatings might have exhibited a critical solution temperature below which no blistering occurred.

A ranking of the performance of the six coating systems (Table 2) was made based on the lifetime measurements. Coatings C and D, both polyamine-cured epoxies, were more resistant to cold-wall blistering than Coating B (a polyamide epoxy), Coating E (an amine adduct epoxy), and Coating F (an amido-amide epoxy system). Coating A, a polyamine epoxy, usually failed after less exposure than Coatings C and D, but Coating A showed better blister resistance than Coatings B, E, and F.

**Porosity Measurements of Coating Systems**

Photomicrographs of the cross section of each of the six coating systems used in this study are shown in Figures 4(a) through (f). These photomicrographs were taken using dark field illumination; therefore, the steel substrates (noted on the photographs) appear dark. Figure 4(a) shows Coating A consisted of a base and top coat with various amounts of filler particles and porosity distributed throughout both coats. An interfacial pore, such as the one marked by the arrow on Figure 4(a), possibly acted as a blister

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**FIGURE 2.** Plots of the epoxy coatings’ time to blister (normalized for coating thickness) vs the inverse of exposure temperature difference for the (a) water-to-air and (b) water-to-water heat-transfer conditions.

**FIGURE 3.** Plots of the epoxy coatings’ time for active $E_{corr}$ (normalized for coating thickness) vs the inverse of exposure temperature difference for the (a) water-to-air and (b) water-to-water heat-transfer conditions.
initiation site since it represented a nonbonded area of the coating where water could accumulate. Similar cross-sectional samples of the five other coating systems are shown in Figures 4(b) through (f). All of these coating systems consisted of either two or three coats, and each contained varying amounts of filler particles and porosity. The cause for variations in porosity levels among the coatings was not investigated, but it may have been due to variations in coating viscosity during application.

The average values of porosity obtained for each coating system as the result of measurements from 15 random fields on four samples of each coating are shown in Table 3. As discussed earlier, the porosity data used to evaluate the coatings were representative of the entire coating cross sections (i.e., no distinction was made between the porosity or physical characteristics of the different layers). Coatings E and A showed the largest amounts of porosity on average, and Coatings B and F had intermediate measured porosities. The lowest measured porosity contents were for Coatings C and D.

**Effect of Porosity on Coating Performance**

The two measures of coating lifetime used in this experiment, the time to blister and the time for active \( E_{\text{corr}} \), were plotted against the average measured vol\% porosity for the six coating systems (Figures 5 and 6).
As previously noted, all data for the time to blister and time for active $E_{\text{corr}}$ were divided by the sample thickness to normalize the data for comparison since coating permeability has been found to vary linearly with the inverse of coating thickness.\textsuperscript{19} In addition, Figure 7 shows that the measured porosity in the coatings was relatively independent of the average coating thickness.

Figures 5(a) and (b) show that, for all of the coatings in both water-to-air and water-to-water heat-transfer conditions, the time to blister was lower at the high-temperature gradients compared to the low-temperature gradients. More importantly, Figures 5(a) and (b) show a trend toward an increased coating lifetime for coatings with porosities $<\sim 1\ \text{vol}\%$ (i.e., Coatings C and D). This increase in time to blister for Coatings C and D, which had porosities $< 1\ \text{vol}\%$, was more evident at the lower temperature gradients. Similarly, Figures 6(a) and (b) show plots of the time for active $E_{\text{corr}}$ (normalized for sample thickness) against vol\% porosity for the water-to-air and water-to-water heat-transfer conditions, respectively. Aside from the datapoint for Coating A in Figure 6(b), the data show the same trend toward increased coating lifetime for Coatings C and D, which had porosity values $< 1\ \text{vol}\%$.

Since the lifetime measurements were normalized for coating thickness, presumably the only major
interfacial porosity that could initiate blisters. It has been shown that the existence of pores in the coating, either at the coating/metal interface or in the form of pathways through the coating, accelerates the rate of delamination of a coating. Visual inspection of the coating cross sections via light optical microscopy (Figure 4) showed that all of the coating systems had some degree of porosity, which appeared to be distributed randomly throughout their layers. However, Table 3 showed that two of the coatings, Coatings C and D, had average porosity values $< \sim 0.7$ vol%, while the rest of the coatings (Coatings A, B, E, and F) all had average porosity values $> \sim 2.4\%$. This difference in porosity appeared to have a significant effect on the extended lifetimes, as measured by time to blister and time for shift in $E_{corr}$, of the samples of Coatings C and D over the other coatings. The slightly better performance of Coatings A and E at porosity levels higher than Coatings B and F may have been attributable to differences in mechanical properties of the coatings which, as previously noted, were not investigated in this study. Further work would be required to unequivocally determine the relations between porosity, mechanical properties, and resultant coating performance.

**Blistering Kinetics**

Various sources have indicated that a delaminated area tends to increase linearly with exposure time once blistering starts. For example, a study by Murray and Hack on epoxy-coated steel immersed in aerated artificial seawater showed linear delamination or blistering rates of the coatings. In addition, Catino showed that the delaminated area of polybutadiene coatings on steel exposed to alkali metal chloride solutions under cathodic polarization increased linearly with time.

Blistering rates of the coating samples used in this experiment were determined by applying best-fit linear functions to each sample’s blistered area vs time data. The experimental blistering rate data is shown in Figures 8 and 9, which are plots of total differences between the six coating types were their compositions, adhesion characteristics, and porosity levels.

The permeability of epoxy coatings can be affected by the composition of the coating resin, by the degree of cross-linking of the resin, and by the dispersion and wetting characteristics of the pigments in the coating. In addition, the protective properties of the coating are affected by the degree of adhesion of the primer coat to the substrate. Although other influential factors such as mechanical properties (ultimate tensile strength, yield strength, and wet adhesion strength) and permeability properties of the coatings were not investigated in this study, based on the data shown in Figures 5 and 6, it appeared that the amount of porosity in a coating had a significant effect, with the best results obtained at porosity levels $< \sim 1$ vol%.

Larger amounts of porosity in a coating could lead to shorter diffusional pathways, larger water uptakes, (and, therefore, lower dielectric strength and resistance) and statistically greater chances of interfacial porosity that could initiate blisters. It has been shown that the existence of pores in the coating, either at the coating/metal interface or in the form of pathways through the coating, accelerates the rate of delamination of a coating. Visual inspection of the coating cross sections via light optical microscopy (Figure 4) showed that all of the coating systems had some degree of porosity, which appeared to be distributed randomly throughout their layers. However, Table 3 showed that two of the coatings, Coatings C and D, had average porosity values $< \sim 0.7$ vol%, while the rest of the coatings (Coatings A, B, E, and F) all had average porosity values $> \sim 2.4\%$. This difference in porosity appeared to have a significant effect on the extended lifetimes, as measured by time to blister and time for shift in $E_{corr}$, of the samples of Coatings C and D over the other coatings. The slightly better performance of Coatings A and E at porosity levels higher than Coatings B and F may have been attributable to differences in mechanical properties of the coatings which, as previously noted, were not investigated in this study. Further work would be required to unequivocally determine the relations between porosity, mechanical properties, and resultant coating performance.

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A linear delamination rate is indicative of a diffusion-controlled process, because under diffusional control, the linear diffusing front would increase with the square root of time. The delamination area of the coating increases with the square of the linear diffusing front, so the delaminated area follows a linear increase with time. It is not known whether the diffusion of water or oxygen is the rate-determining factor. However, it has been shown that the water permeability through organic coatings may be high enough to sustain corrosion rates as high as if the coating was not there, but the permeability of oxygen is usually below the range of oxygen consumption of steel corroding under various exposure conditions.

Blistering rates of the coating samples used in this experiment were determined by applying best-fit linear functions to each sample’s blistered area vs time data. The experimental blistering rate data is shown in Figures 8 and 9, which are plots of total
blistered area vs exposure time for the thin coating samples exposed to the high- and low-temperature gradients, respectively. Most of the coatings displayed linear blistering rates, as the straight lines fitted to the experimental data all had correlation coefficients > 0.9.

One coating sample had a blistering rate that varied from linearity and appeared to be exponential in form. The thin sample of Coating B exposed to the low water-to-air temperature gradient (Figure 9[a]) initially showed a large linear increase in delaminated area with time, but the delamination rate eventually declined, producing an exponential-like relationship. Intracoat cracking of the base and midcoats was observed to be associated with the blistering of the Coating B sample (Figure 10), and this may have contributed to the exponential-like delamination rate shown by the sample of this coating. A cross-sectional sample from a blistered area of Coating B (Figure 10) showed that the coating initially may have lost adherence from the substrate and started to blister, but rather than continuing to disbond in the form of a growing blister, the coating cracked in the lateral direction. The effect of this cracking would have been to relieve the stresses associated with the blister that normally would have been relieved by additional disbondment at the coating/metal interface. This would have resulted in the decrease of the observed blistering rates, or exponential shape of the blistered area vs time curve.
FIGURE 10. Light optical micrograph of a polished cross sections of a blistered region of Coating B where the coating initially lost adherence from the substrate and then cracked in the lateral direction.

The data for the thin coating samples that exhibited linear blistering rates are plotted vs the inverse of the water-to-air and water-to-water exposure temperature differences in Figures 11(a) and (b), respectively. These figures show that Coatings C and D had the lowest blistering rates of all of the coatings under both temperature gradients for both heat-transfer conditions. Plots of blistering rate vs temperature gradients were not constructed for the thick coating samples because of the limited data on blistering rates of these samples at the lower temperature gradients. For example, no blistering rates were established for the thick Coatings C and D at the low-temperature gradients because Coating C did not blister at all and Coating D had just started to blister near the end of the test exposure.

In general, most coating samples exhibited linear delamination rates, which indicated that the kinetics of cold-wall blistering were diffusion-controlled. Therefore, the coatings that showed the lowest blistering rates (i.e., Coatings C and D) must have had lower diffusional transports (or permeabilities) for water and/or oxygen. These reduced diffusion rates explained the longer lifetimes exhibited by the samples of Coatings C and D over the other coatings. The diffusion rates, in turn, were affected by coating porosity, with reduced coating porosity resulting in lower diffusion rates.

CONCLUSIONS

- Lowering a coating’s porosity level < ~ 1 vol% had a significant effect on increasing the coating’s useful lifetime. Existence of porosity, especially at the coating/metal interface and as pathways through the coating, accelerated the rate of coating delamination.
- Cold-wall blistering of the epoxy coatings appeared to follow diffusion-controlled kinetics. Most of the coating samples showed linear delamination (blistering) rates, which were indicative of a diffusion-controlled process. A nonlinear delamination rate was observed for a coating sample that formed lateral cracks after blistering initiated. The exposure times to start blistering and the linear blistering rates displayed by Coatings C and D were lower than all of the other coatings, which indicated that these two coatings may have had lower permeabilities than the other coatings. These lower permeabilities were attributed to the lower porosities and similar compositions of Coatings C and D.
- The better performing coatings (i.e., Coatings C, D, and A to some extent) showed large gains in lifetime as the temperature gradients were lowered. The poorer coatings (Coatings B, E, and F) had very lim-
limited lifetimes at both the high- and low-temperature gradients. This may have been attributable to the effective barrier properties of the better coatings.

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