Editor’s Note: This article is the third part of the authors’ report on testing coating performance on offshore wind towers. The first part, “Investigating Corrosion Protection of Offshore Wind Towers,” was published in the April 2008 JPCL (pp. 30–43) and won SSPC’s highest editorial honor, the Outstanding Paper Award, which was announced at PACE 2009. Part 1 described the rationale behind the authors’ test program. Part 2, “Results of the Site Tests,” which described fouling on the coated steel panels on the field test site as well as coating performance on the panels, was published in the April 2009 JPCL (pp. 24–34). In addition to appearing in the print edition of JPCL, Parts 1 and 2 can also be accessed in the JPCL archives on www.paintsquare.com.

Part 3 of the study discusses the results of the laboratory investigations of several coatings on offshore wind towers and compares them with site testing of the same systems.

Test Rationale

The rationale for the test program is based on the following. The location of steel structures several miles offshore is not a new situation. Oil and gas exploration and extraction platforms have performed in such areas for decades. There are, however, critical differences between platforms and towers, the most significant being that offshore wind energy towers are unmanned structures with highly restricted access. On oil and gas platforms, corrosion protection systems are generally under permanent inspection, which is not the case on offshore wind energy towers. Thus, whereas on oil and gas platforms, areas of

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Investigating Corrosion Protection of Offshore Wind Towers

Part 3: Results of the Laboratory Investigations
deteriorated coating can be recognized and repaired comparatively easily, such repairs are not feasible on offshore wind energy towers.

Laboratory Test Samples

Three types of laboratory samples were manufactured. The first type covered the specimens for the degradation tests according to ISO 20340, “Performance requirements for protective paint systems and current test scenarios.” The coated specimens were provided with two artificial scribes to simulate localized mechanical damage. The second type covered the specimens for the cathodic disbonding tests. The specimen consisted of a lower primary section and an upper, smaller secondary section, whereas the top part of the upper section remained uncoated. A hole with a controlled cross section (Ø 10 mm) was drilled through the coating down to the plain steel in the center of the specimen. The third specimen, used for EIS measurements, was a simple, coated plate 30 mm x 30 mm. More detailed descriptions of the laboratory samples and tests conducted can be found in Part 1 of this series (April 2008 JPC1, pp. 30–43).

Results of the Accelerated Ageing Tests

The coatings tested are shown in the box below. The results of the accelerated ageing tests according to ISO 20340 are shown in Table 1 (p. 40). The various coating systems responded differently to the applied stresses. As expected, the number of ageing cycles had a notable effect on the coating systems, although the actual effects depended on the particular coating system. In terms of corrosion protection performance, the tendency of a coating to blister and delaminate and, as a result of the corrosion process, the occurrence of corrosion products like white rust and red rust were taken as benchmarks for the assessment process. Chalking was considered a secondary issue of the degradation of the polymer coatings.

The upper row of photographs in Table 1 illustrates the appearance of the samples after four ageing cycles (total exposure time of 1 month). System 1 exhibited notable traces of red rust in both scribes. Blister formation occurred, starting from the edges of the horizontal scribe. Chalking could not be observed because of the PU topcoat. System 2 featured slight traces of red rust and slight chalking. In the horizontal scribe, Systems 3 and 4 showed notable white rust formation resulting from the cathodic protection of the steel from the metallization layer. System 4 had started to chalk. System 6 showed no corrosion in the scribes. System 5, the single-layer thick coating, was not part of the laboratory tests.

The visual inspection of the coating systems after 18 ageing cycles (total exposure time of 4.5 months) gave the following results. System 1 showed massive delamination at the scribes and blistering around the scribes. The substrate corrosion was severe in both scribes. System 2 exhibited severe corrosion in the scribes, combined with signs of underrusting. System 3 featured red rust, an indication that the cathodic protection capability of the metallization was starting to deteriorate. Cracks started to form at the edges of the horizontal scribe. The cracks were probably caused by the volume expansion of the corrosion products. System 4 still showed white rust, evidence that the cathodic protection from the metallization was still active. Chalking was severe for System 4. System 6 exhibited moderate corrosion only in the horizontal scribe.

The second row in Table 1 illustrates the appearance of the coating systems after 25 ageing cycles (a total exposure time of 6.25 months). System 1 was severely deteriorated. It showed notable substrate corrosion in both

Coating Systems Tested (Composition and dft)*

<table>
<thead>
<tr>
<th>System</th>
<th>Primer</th>
<th>2. Layer</th>
<th>3. Layer</th>
<th>4. Layer</th>
<th>Total dft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zn-EP  (80 µm)</td>
<td>EP (300 µm)</td>
<td>EP (300 µm)</td>
<td>PUR  (70 µm)</td>
<td>750</td>
</tr>
<tr>
<td>2</td>
<td>Zn-EP  (80 µm)</td>
<td>EP (450 µm)</td>
<td>EP (450 µm)</td>
<td>-</td>
<td>980</td>
</tr>
<tr>
<td>3</td>
<td>Zn/Al  (85/15) (100 µm)</td>
<td>EP  (20 µm)</td>
<td>EP (450 µm)</td>
<td>EP (450 µm)</td>
<td>1,020</td>
</tr>
<tr>
<td>4</td>
<td>Zn/Al  (85/15) (100 µm)</td>
<td>EP  (20 µm)</td>
<td>EP (450 µm)</td>
<td>EP (450 µm)</td>
<td>1,020</td>
</tr>
<tr>
<td>5</td>
<td>EP    (1,000 µm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1,000</td>
</tr>
<tr>
<td>6</td>
<td>Al/Mg  (95/05) (350 µm)</td>
<td>EP    (40 µm)</td>
<td>-</td>
<td>-</td>
<td>390</td>
</tr>
</tbody>
</table>

*µm÷25.4=mils ¹topcoat; ²metallization; ³primer + pore filler; ⁴particle reinforced; ⁵applied in one layer (not part of laboratory tests); ⁶(pore filler)
The results were interpreted in terms of an “Anticorrosive Effect” (AE) as suggested by reference 3:

\[ AE = \frac{(A+B+2C)}{4} \]

Here, AE is the anticorrosive effect. A is a term related to the blister degree (according to ASTM designation); B is a term related to scribe delamination; and C is a term related to rust degree (according to SSPC designation). A value of AE=100 characterizes best performance. The parameters A to C must be estimated according to a matrix procedure.3 The estimated AE values are listed in Table 1.

Based on the above procedure, the ranking of the systems after the ageing test according to ISO 20340 is as follows (from best to worst): 6, 4, 3, 2, 1. The ranking corresponds very well with the ranking obtained from the results of the site tests.1 Another result worth mentioning is that the damage to the coatings was much more severe after the artificial ageing procedure compared to the ageing under site conditions.

### Results of the Cathodic Compatibility Tests

Figures 1 and 2 (p. 43) show the results of the compatibility tests. The graphs show two lines for most systems because two samples were investigated for each system (except for System 6). The current consumption is a criterion for assessing the compatibility of the systems with cathodic protection. If cathodic disbonding occurs and part of the steel substrate

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### Table 1: Visual Appearance and AE Values of the Coating Systems after Accelerated Ageing per ISO 20340

<table>
<thead>
<tr>
<th>Number of Ageing Cycles</th>
<th>Coating System</th>
<th>AE Value* (After 25 Cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Cycles (1 Month)</td>
<td>1: 41</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>2: 43</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>3: 38</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>4: 39</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>6: 45</td>
<td>100</td>
</tr>
<tr>
<td>25 Cycles (6.25 Months)</td>
<td>1: 41</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>2: 43</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>3: 38</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>4: 39</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>6: 45</td>
<td>100</td>
</tr>
</tbody>
</table>

*See Eq. (1)
is exposed, the consumption of current increases to try to protect the substrate. Figure 1 shows the results of the compatibility test according to ASTM G8. (See Part 1 of the paper for the testing conditions.) It can be seen that the current consumption for Systems 1 to 4 stayed at a stable level over the entire testing period of 30 days. No disbonding was noted during a visual examination after the tests. Thus, these systems were compatible with cathodic protection. System 6 consumed a high amount of current immediately after the test started, and coating delamination was noted during a visual assessment of the specimens after the test. The cause for these phenomena was assumed to be metal dissolution rather than cathodic disbonding. The potential of -1.450 mV_{SCE} applied during the test, was below the potential that dissolution of the metal occurs.

Figure 2 shows results of the compatibility tests according to ISO 15711-2. (See Part 1 of the paper for the testing conditions.) Differences in the scale of the current consumption (compare to Fig. 1) are due to the different applied polarization potential and the electrolyte. In the first period of polarization, the current decreased due to the precipitation of less soluble salts (Mg, Ca salts) on the metal surface as a result of cathodic polarization. No delamination of the coating could be noted, either by increase of the current consumption or by visual examination after the test. Hence, all systems passed the test and were compatible with cathodic protection.

**Results of the Electrochemical Impedance Tests**

From EIS spectra, ohmic and capacitive properties of the organic coating can be obtained by applying model-like equivalent circuits. (For a discussion on the interpretation of EIS spectra obtained from organic coatings, see Ref. 4.) The ohmic resistance of a non-defect coating is interpreted as barrier resistance, which is considered one of the corrosion protective properties of a coating. Parameters to be interpreted include impedance and phase angle. As an example, these two parameters are plotted against the frequency of the impressed voltage in Figs. 3 (p. 44) and 4 (p. 45) for System 4, in terms of a Bode plot. Figure 3 shows impedance against frequency for different time periods. The almost linear relationship for t=0 days characterizes an intact virgin coating. The graph is not completely linear (see lower frequencies), indicating that the response of the coating is not plainly capacitive. The coating had probably already absorbed some water.

After 7 days, the shape of the graph changed, whereby the values for low frequencies decreased. This decrease was due to a decrease in the coating resistance, which resulted from the water uptake of the coating. These effects became stronger with extended immersion time. This interpretation holds for the situation in Fig. 4, where the phase angle is plotted against the frequency. For a plain capacitive response, the phase angle should be -90° over the entire frequency range for t=0 days. This was not the case for the lower frequencies. For the longer immersion periods, the phase angle was no longer constant with frequency, and the value was 90° only at high frequencies. The Bode plots for the other coating systems showed equal qualitative trends.

Table 2 gives the results of the tests performed in the present study in terms of system ranking. The results obtained during the accelerated cyclic tests agree with those of the long-term site tests for samples in the intermediate zone (IZ). The results from the EIS investigations, however, show an opposite trend. Coating
credibility, noun: capable of being believed; worthy of confidence; trustworthy
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Fig. 1: Current consumption of coated and pre-damaged specimens, estimated as per ASTM G8

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systems that performed well during accelerated testing and site testing did not show good results in terms of resistance (EIS). This surprising result is indicative in a way that a good barrier resistance, measured under constant climatic conditions (stable temperature, stable electrolyte composition, no wet-dry cycles), does not necessarily guarantee a good protective performance of the coatings under cyclic load conditions (changes in temperature and electrolyte composition, dry-wet cycles). One explanation for this phenomenon can be the pigmentation of some of the investigated systems. Investigations described in Ref. 13 suggest that certain pigments affect the water balance in an organic coating, especially in case of sudden changes in climatic conditions. This effect could be caused by condensation nuclei formed at the pigment particles. Therefore, good protection performance from such a system under cyclic conditions would not be a result of a superior barrier resistance in the first place, but rather due to the avoidance of "microfogging," which is the generation of excess water caverns.

Fig. 2: Current consumption of coated and pre-damaged specimens, estimated as per ISO 15711-2

Fig. 1: Current consumption of coated and pre-damaged specimens, estimated as per ISO 15711-2
in the coating by condensation of molecular dispersed water in the coating due to temperature changes. This phenomenon will be the topic for further investigations.

Another striking result was the behavior of the Al/Mg metallization (System 6). This system performed best during the accelerated cyclic tests (ISO 20340), but failed during the site tests in the underwater zone (UZ). The most notable differences between the accelerated and site test scenarios were the formation of fouling at the site test and the cathodic protection applied to the site test samples. Further investigations are planned to explore this phenomenon.

Summary

• Offshore wind towers are subjected to complex environmental stresses. An approach was made to reproduce the stresses through accelerated laboratory tests with defined stress conditions and through site tests with real stress conditions.

• A particular protection system needs to pass all laboratory tests, in which individual properties, such as durability under cyclic environmental load and cathodic compatibility, are estimated.

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Because each individual test allows a ranking of the systems, a “protection performance profile” (PPP) of any individual coating system can be derived at the end of the investigation. Based on the PPP, the best system can then be selected.

- Site samples and samples after accelerated ageing tests (ISO 20340) could be equally ranked. However, after 25 ageing cycles, the deterioration of the coatings of the laboratory samples was notably more severe than that of the site samples.

- EIS is a promising method for a quick and reliable assessment of the barrier resistance of protective coating systems. However, high barrier resistance does not necessarily guarantee a good protective performance of the coatings under cyclic load conditions. The EIS helps in understanding the detailed protection principles of coatings and can, therefore, deliver fundamental information for coating optimization procedures.

- The results of the cathodic disbonding test as per ASTM G8 show that limits exist for an artificial acceleration of corrosion protection tests. Acceleration is useful only if the general corrosion process is not altered due to acceleration effects.

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**Fig. 4: Bode-plot for System 4. Phase angle versus frequency**
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