This article is the second part of a report on a nationally funded project on the performance testing of different corrosion protection methods for offshore wind towers under site and laboratory conditions. Part 1, published in the April 2008 JPCL, reported on the rationale behind, and setting up of, the test program. The present article discusses the test results.

**Background**

Testing was conducted for performance of coatings in the underwater, intermediate, and splash zones. Six coating systems were tested, although not all systems were tested in all three zones. The coatings were applied over steel blast cleaned with steel grit and in accordance with ISO 8504-2. Uncoated steel with cathodic protection was also tested. The systems tested are shown in the box on the opposite page.
Fouling assessment results may to some extent depend on the season.

The samples in this study were released in the summer season (July). Some environmental conditions applying to the test site are listed in Table 1.

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)2) (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)2) (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)2) (350 µm)</td>
<td>EP (40 µm)</td>
<td>EP (450 µm)</td>
<td>-</td>
<td>390</td>
</tr>
</tbody>
</table>

*µm=25.4=mils 1) topcoat; 2) metallization; 3) primer + pore filler; 4) particle reinforced; 5) applied in one layer; 6) (pore filler)

Therefore, results of fouling assessment may to some extent depend on the season.

The samples in this study were released in the summer season (July). Some environmental conditions applying to the test site are listed in Table 1.

Fouling can affect the corrosion of coating systems.
Coatings for Offshore Wind Towers

Table 1: Site-Specific Environmental Conditions (Ref. 3)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity</td>
<td>29 – 33 PSU</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Low – moderate</td>
</tr>
<tr>
<td>Light (PAR)</td>
<td>100 – 2,000 mol/m²•s</td>
</tr>
<tr>
<td>Wave exposure</td>
<td>Exposed</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>0.3 – 1.5 m/s</td>
</tr>
<tr>
<td>Specific wave Height</td>
<td>0.5 – 4 m</td>
</tr>
<tr>
<td>Temperature</td>
<td>2 – 20 °C</td>
</tr>
</tbody>
</table>

Table 2: Visual Appearance of Underwater (UZ) Specimens under Various Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
<th>System 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>After 5 months (total fouling)</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
</tr>
<tr>
<td>After 13 months (total fouling)</td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
</tr>
<tr>
<td>After 36 months (total fouling)</td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
</tr>
<tr>
<td>After 36 months (first cleaning)</td>
<td><img src="image16" alt="Image" /></td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td><img src="image19" alt="Image" /></td>
<td><img src="image20" alt="Image" /></td>
</tr>
<tr>
<td>After 36 months (final cleaning for assessment)</td>
<td><img src="image21" alt="Image" /></td>
<td><img src="image22" alt="Image" /></td>
<td><img src="image23" alt="Image" /></td>
<td><img src="image24" alt="Image" /></td>
<td><img src="image25" alt="Image" /></td>
</tr>
</tbody>
</table>

1) Lower section of the specimen is System 5 (red, respectively gray)

Steel in several ways: creation of areas of trapped water; oxygen concentration cells; sites for aerobic bacteria; removal of metal. It is, however, not clear if fouling and marine growth can affect the performance of protective coatings.

Fouling in the Underwater Zone (UZ)
All UZ samples were heavily fouled (as shown in the upper three rows of Table 2). Species found on the test specimens included brown algae (*Laminaria*) with large brown leaves up to 2 m long. They appeared predominantly in the upper region of the UZ. Further on, green algae (*Ulva*) were found, as were at least three species of red algae, which were not classified (Fig. 1). Moreover, the following types of species were identified: sponges, mussels (common mussel, oyster-type mussel), anemones, bryozoan (very striking was the species *Bugula neritina*) and sea firs. One special kind of barnacle (*Balanus crenatus*) could be found in the UZ only. This species features a calcareous basal plate, which could not be dislodged completely, even when the barnacles were removed from the specimens (Table 2). This species was reported to likely occur in the UZ of wind towers in the North Sea. Vagile (mobile) species were detected as well, among them worms, some crabs (Fig. 2), and small fish (up to 20 cm long). The settling of numerous species of crabs and fish at submerged wind tower sections in the North Sea was also reported. Algae could not be detected at the rear side of the sample plates because of lack of sunlight in that area.

Fouling in the Intermediate Zone (IZ)
All IZ samples were heavily fouled (see the upper two rows of Table 3). Species detected included green algae (*Enteromorpha*) and brown algae (among others, *Ventricaria ventricosa*). Algae could not be detected at the rear side of the sample plates because of lack of sunlight in that area. Two species of barna-
Coating Performance in the Underwater Zone

Performance after 5 and 13 Months

The samples were assessed after 5 months and after 13 months. Results of these surveys are reported elsewhere. The results obtained after 13 months are briefly recapitulated here. A striking, and rather unexpected, feature was heavy fouling on the underwater samples (upper two rows, Table 2). The fouling consisted of small barnacles and a dark biofilm (algae, sponges). The severity of the fouling differed notably. The sample with System 6 showed the most severe fouling; it was almost completely covered with barnacles. System 5 exhibited the least severe coverage with barnacles but was covered extensively with biofilms. The coating performance could not be assessed in detail. At a few small areas, the fouling was carefully removed, and the coatings were visually inspected. No signs of deterioration were detected.

Performance after 36 Months

The samples were mechanically cleaned with a wood scraper and subsequent high-pressure water washing to visually assess the conditions of the coatings (Table 2).

System 3 showed slight delamination at the front after cleaning, perhaps due to mechanical damage and subsequent deterioration. The steel/primer interface exhibited initial delamination. System 4 did not show any damage to the surface. Slight initial delamination at the steel/primer interface was noted.
Table 4: Assessment of Bond between Steel (Weld Seam) and Applied Coating Systems, Based on Polished Cross Sections

<table>
<thead>
<tr>
<th>System</th>
<th>Image</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No image available</td>
<td>Excellent bond over the entire length.</td>
</tr>
<tr>
<td>2</td>
<td>Excellent bond over the entire length. Reduction in DFT at the right weld section.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Excellent bond over the entire length.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Excellent bond over the entire length. Reduction in DFT at the right weld section.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Excellent bond over the entire length. Coating partly broken due to cutting.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Coating failed.</td>
<td></td>
</tr>
</tbody>
</table>

Systems 1 and 2 performed the same as System 4.

System 6 exhibited large-scale blistering and severe coating delamination. This sample could not be cleaned properly because high-pressure washing would have removed the deteriorated coating. The sample showed white corrosion products, which were identified as the corrosion product of the metallization. The total system could be removed by scratching it slightly with a fingernail (Fig. 3). Because metallization with adequate sealers (at least Al/Zn metallization) is usually an effective and proven method for protecting offshore steel structures,10,11,12 the result was surprising. No conclusive explanation can be delivered at the moment, and this issue will be the topic of a subsequent study. It is not clear whether fouling effects contributed to that failure. The compatibility of this coating system with cathodic protection under laboratory conditions was good (See Part 3 of this series, to be published in an upcoming issue).

Table 5: Assessment Scheme for Underwater Zone (UZ) Specimens after 36 Months of Exposure

<table>
<thead>
<tr>
<th>System</th>
<th>Coating general (blisters, defects)</th>
<th>Coating at weld seam</th>
<th>Delamination steel / primer</th>
<th>Delamination primer / topcoat</th>
<th>Adhesion (pull-off test)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>4.18 MPa Steel/primer interface: very preliminary delamination</td>
<td>Transition to single coat: no delamination No damage to surface</td>
</tr>
<tr>
<td>2b</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>7.41 MPa Steel/primer interface: slight initial delamination</td>
<td>Transition to single coat: no delamination No damage to surface</td>
</tr>
<tr>
<td>3a</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>6.31 MPa Delamination at the front surface after cleaning (maybe due to mechanical damage with subsequent corrosion and delamination)</td>
<td>Steel/primer interface: initial delamination Transition to single coat: no delamination</td>
</tr>
<tr>
<td>4b</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>9.41 MPa Steel/primer interface: no delamination</td>
<td>Transition to single coat: no delamination No damage to surface</td>
</tr>
<tr>
<td>5</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>Does not apply</td>
<td>Does not apply Steel/coating interface: slight initial delamination</td>
<td>No damage to surface</td>
</tr>
<tr>
<td>6</td>
<td>––</td>
<td>––</td>
<td>––</td>
<td>––</td>
<td>Not measured Assessment was performed at fixing points only Large-scale blistering and coating delamination</td>
<td></td>
</tr>
</tbody>
</table>

Conditions: –bad; +acceptable; ++good; +++very good 1) See Table 4; 2) Average of three measurements (ISO 4624); 3) See Fig. 3

Table 5 lists results of pull-off tests. The pull-off strength values were between 4.18 MPa and 9.41 MPa. With the exception of System 1, the values are still well above the value of 6.0 MPa, which is recommended in ISO 20340 for newly applied coatings for immersion service.13 On the other hand, only System 1 showed fractures in the coating system alone, not in the steel-primer interface.

The internal areas, originally filled with seawater, were inspected as well. They showed signs of oxidation, but, in general, the corrosion was not severe, and pitting was not detected. Signs of more severe oxidation were recognized along a stripe that ran exactly along the weld seam (see image for System 4, Table 4). This feature was interesting because the weld seam was attached only to the external surface. Metallurgical changes in the steel, originating from the welding process, might have caused this phenomenon.

The results of the assessment procedure are listed in Table 5, which shows that they did not allow for a reliable ranking of the systems in terms of coating performance (except for
Notable effects were found for Systems 1 and 2. The scribe delamination was about 2 mm for sample 1a and about 1 mm for sample 1b. The sample 1a exhibited severe corrosion at the scribe (Table 7). Scribe delamination was about 2 mm for sample 2a and about 3 mm for sample 2b. Both samples for System 2 showed limited corrosion at the artificial scribe. Sample 1a exhibited blistering up to a distance of 10 mm from the scribe.

As shown in Table 6, values for pull-off strength varied between 2.35 MPa and 11.9 MPa. With the exception of System 4a, the values were higher than the values estimated for the UZ specimens (Table 5), and are well above the value of 4 MPa, which is recommended in ISO 20340 for newly applied coating systems in C5-M service. Typical fracture types were fractures in the paint system and in the glue. These fractures are in contrast to the observations of the UZ specimens, where the fracture was primarily adhesive.

According to the results of the assessment, summarized in Table 6, coating performance among the systems could be ranked as follows: 3, 4, 2, 1.

### Table 6: Assessment Scheme for Intermediate Zone (IZ) Specimens after 36 Months of Exposure

<table>
<thead>
<tr>
<th>System</th>
<th>Coating general</th>
<th>Scribe: corrosion</th>
<th>Scribe: delamination</th>
<th>Adhesion (pull-off test)</th>
<th>Remarks 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>++</td>
<td>–</td>
<td>–</td>
<td>9.78 MPa B/C, C, C/Y</td>
<td>Neither delamination nor blistering at the area. Notable corrosion and delamination at the scribe and blistering (up to 10 mm away from the scribe).</td>
</tr>
<tr>
<td>1b</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>6.70 MPa A/B 20% B 80%</td>
<td>Neither delamination nor blistering at the area. Notable corrosion and delamination (ca. 1 mm) at the scribe.</td>
</tr>
<tr>
<td>2a</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>11.9 MPa B 30% C/Y 70%</td>
<td>Neither delamination nor blistering at the area. Limited corrosion and delamination (ca. 2 mm) at the scribe.</td>
</tr>
<tr>
<td>2b</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>Not measured</td>
<td>Limited corrosion and notable delamination (ca. 3 mm) at the scribe.</td>
</tr>
<tr>
<td>3a</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>8.99 MPa B/C 80% B/Y 20%</td>
<td>Neither delamination nor blistering at all.</td>
</tr>
<tr>
<td>3b</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>11.6 MPa B/C 10% B/Y 90%</td>
<td>Neither delamination nor blistering at all.</td>
</tr>
<tr>
<td>4a</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>2.35 MPa B/C 100%</td>
<td>Neither delamination nor blistering at all. Compared to SZ, no chalking and less metallic appearance.</td>
</tr>
<tr>
<td>4b</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>Not measured</td>
<td>Neither delamination nor blistering at all.</td>
</tr>
</tbody>
</table>

Conditions: – bad; + acceptable; ++ good; +++ very good 1) See Table 7; Average of three measurements (ISO 4624)

System 6).

**Coating Performance in the Intermediate Zone (IZ)**

**Performance after 5 and 13 Months**
The samples were assessed after 5 months and after 13 months. Results of these surveys are reported elsewhere. The results obtained after 13 months are briefly recapitulated here. Similar to the UZ samples, the samples exposed to alternate immersion showed strong deposition of, and fouling with, biological species such as algae, barnacles, and other species (first row, Table 3). The intensity and kind of species differed notably, depending on the coating system and the immersion period. Explanations for the latter effect are the influence of the season in which the specimens were assessed and the individual life and growth cycles of the species. The coating performance could not be assessed in detail. At a few small areas, the fouling was carefully removed, and the coatings were visually inspected. No signs of deterioration were detected.

**Performance after 36 Months**
The samples were mechanically cleaned with a wood scraper and subsequent high-pressure water washing to visually assess the conditions of the coatings. Table 6 lists the results of the assessment procedure. Generally, the coated areas of the specimens were in good condition, with no signs of severe corrosion, degradation, or delamination. Corrosion and degradation effects were observed only in the sections around the artificial scribes. The delamination from the artificial scribe was measured with high-resolution optical microscope images, taken from polished cross-sections (e.g., lower images, Table 7). Notable effects were found for Systems 1 and 2. The scribe delamination was about 2 mm for sample 1a and about 1 mm for sample 1b. The sample 1a exhibited severe corrosion at the scribe (Table 7). Scribe delamination was about 2 mm for sample 2a and about 3 mm for sample 2b. Both samples for System 2 showed limited corrosion at the artificial scribe. Sample 1a exhibited blistering up to a distance of 10 mm from the scribe.

As shown in Table 6, values for pull-off strength varied between 2.35 MPa and 11.9 MPa. With the exception of System 4a, the values were higher than the values estimated for the UZ specimens (Table 5), and are well above the value of 4 MPa, which is recommended in ISO 20340 for newly applied coating systems in C5-M service.13 Typical fracture types were fractures in the paint system and in the glue. These fractures are in contrast to the observations of the UZ specimens, where the fracture was primarily adhesive.

According to the results of the assessment, summarized in Table 6, coating performance among the systems could be ranked as follows: 3, 4, 2, 1.

**Coating Performance in the Splash Zone (SZ)**

**Performance after 5 and 13 Months**
After 13 months of immersion, the splash zone samples were in good condition in terms of degradation and corrosion (second row, Table 8). The front of the metallized surface of the flanges appeared grayish due to the development of a protective oxide layer, typical for zinc. Generally, the metallization at the rear section of the flanges was in good condition. No negative interaction with the high-alloyed screws was observed. Also, the angled steel panels did not contribute to any
Table 7: Corrosion (upper image) in, and Paint Delamination (lower image; cross section view) at, the Artificial Scribe at the IZ Specimens

Table 8: Visual Appearance of Splash Zone (SZ) Specimens under Various Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>System 3</th>
<th>System 4</th>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3a</td>
<td>3b</td>
<td>4a</td>
<td>4b</td>
</tr>
<tr>
<td>After 5 months</td>
<td><img src="3a_after_5_months.png" alt="Image" /></td>
<td><img src="3b_after_5_months.png" alt="Image" /></td>
<td><img src="4a_after_5_months.png" alt="Image" /></td>
<td><img src="4b_after_5_months.png" alt="Image" /></td>
</tr>
<tr>
<td>After 13 months</td>
<td><img src="3a_after_13_months.png" alt="Image" /></td>
<td><img src="3b_after_13_months.png" alt="Image" /></td>
<td><img src="4a_after_13_months.png" alt="Image" /></td>
<td><img src="4b_after_13_months.png" alt="Image" /></td>
</tr>
<tr>
<td>After 36 months</td>
<td><img src="3a_after_36_months.png" alt="Image" /></td>
<td><img src="3b_after_36_months.png" alt="Image" /></td>
<td><img src="4a_after_36_months.png" alt="Image" /></td>
<td><img src="4b_after_36_months.png" alt="Image" /></td>
</tr>
<tr>
<td>Flanges rear section (lower part)</td>
<td><img src="3a_flanges.png" alt="Image" /></td>
<td><img src="3b_flanges.png" alt="Image" /></td>
<td><img src="4a_flanges.png" alt="Image" /></td>
<td><img src="4b_flanges.png" alt="Image" /></td>
</tr>
</tbody>
</table>

notable negative effects.

**Performance after 36 Months**

Table 8 lists the results of the visual assessment. All coating systems were generally in good condition. Chalking was observed on almost all samples, with the exception of System 1, which featured a PU-based topcoat. Chalking was most pronounced for System 4. Yellowing of the topcoat was observed for two samples. Sample 1a showed some gloss loss.

No severe corrosion or degradation effects could be detected. Delamination was not observed in the organic coating or in the transition zone between organic coating and sprayed metal. Only some slight white rust formation on the metal-sprayed layer was observed. As the results of the assessment for the coatings in Table 9 show, the systems could not be distinguished in terms of a clear ranking.

The rear sides of the metallized flange sections exhibited corrosion (Table 8). The way the flanges were affixed to the structure promoted crevice corrosion.

Fig. 4: Current consumption of cathodic protection of UZ samples
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The corrosion was mainly characterized by the formation of white rust, but the formation of red rust on the substrate was also observed at places. It could be shown that the amount of corrosion depended on the location on the flanges and on the system. Critical areas were the slits between the individual flange sections, across from the weld seams, where the most severe corrosion was observed at all specimens. Again, crevice corrosion might have caused this phenomenon. Corrosion was always more severe at the lower part of the flange, where thick, loose layers of white rust as well as partial red rust developed (Table 8, lowest row). The two abutting faces with inserted nuts did not show severe corrosion. Slight white rust formation was observed at places.

The AISI 304 steel screws showed good compatibility with the metal-sprayed layers. The boreholes for the screws were usually in good condition, although white rust formation occurred at a few locations. Grommets and screw nuts were in good condition.

**Cathodic Protection of Uncoated Sections**

Figure 4 shows results from the cathodic protection measurements. During the first months, the sample remained unprotected for technical reasons. The current had rather high values, which may have been caused by initial corrosion of the unprotected samples. After the cathodic protection was introduced, the value for the current dropped, and it seemed to be constant for the entire exposure phase. Coverage by fouling and the precipitate of alkaline earth salts are two probable reasons for the continuously low values for the protective current. Unfortunately, part of the cathodic protection device was destroyed due to heavy wave load after 17 months, and it did not work properly. Therefore, the cathodic protection failed, and the uncoated sections of the specimens started to corrode.

The uncoated sections featured two layers of corrosion products (Fig. 5). The layer next to the steel was a black, loosely adherent layer, which was identified as Fe-oxide, more specifically, Fe-hydroxide with a low oxidation number. The top layer was the typical red rust, also loosely adherent. Figure 6 provides an SEM image and an EDX spectrum taken from the external corroded wall of UZ specimen 2 after 36 months exposure.
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The classification of the biological fouling
of offshore structures, the coatings showed accelerated corrosion in the SZ systems. In contrast to plain steel, which on the performance of the coating • The corrosion zones showed no effect protection against corrosion.

• In the SZ, the flange connection was a critical structural part in terms of corrosion. Notable crevice corrosion was observed at places. Therefore, a suitable sealant between abutting faces may be considered for additional protection against corrosion.

• The corrosion zones showed no effect on the performance of the coating systems. In contrast to plain steel, which showed accelerated corrosion in the SZ of offshore structures, the coatings performed equally well, as long as the undamaged areas of the samples were considered.

• Mechanical damage to the coating initiates paint delamination and corrosion. A recommended coating system, therefore, should be either very resistant to impact or able to compensate for corrosion of the steel.

• Cathodic protection of uncoated sections in the UZ is an interesting alternative to passive coating systems.

Acknowledgement
The classification of the biological fouling was performed by Dr. Maja Wiegemann, Alfred-Wegner Institute for Polar and Marine Research, Bremerhaven, Germany.

References

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