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Offshore Wind Farms Successful Corrosion Protection and Effective Quality Management

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More items for **Quality Control**

By Peter Kronborg Nielsen, FORCE Technology

Following an uncertain start, the present offshore coating systems for wind farms have shown fine durability against aggressive marine environments. In this article, positive features from the first wind farms with more than 15 years of service are described, and the importance of quality management is explained.

Constructions such as offshore wind farms are subject to aggressive environments. They are exposed to humidity with high salinity and to intensive UV-radiation. The UV-radiation occurs directly on the structures as well as from light reflections from the sea.

Additionally, an area of concern is the tidal zone, or splash zone, where the wind turbine construction is stressed both from mechanical impacts — service boat collisions and waves — and from corrosion created by shifting saline seawater with a high oxygen level. The seawater stress levels can be extensive in waters with high tidal activity, such as the Irish Sea or the English Channel.

Thus, in particular, the protection of the wind turbine foundation, the transition piece (TP), is imperative (Fig. 1). Long-term resistant coating systems with no need for future refurbishment combined with flawless application operation activities are essential, as offshore repair is costly.

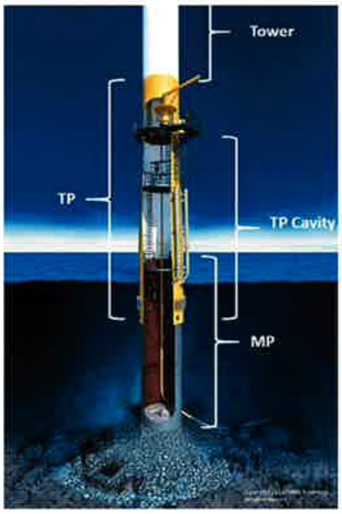

Fig. 1: Offshore wind turbine construction showing the tower, transition piece (TP), transition piece cavity and the monopile (MP) which is the underwater support of the tower and TP. *Photo courtesy of FORCE Technology*

NORTH SEA WIND FARMS — THE BEGINNING

The first wind farm in the North Sea, Horns Rev 1 (HR1), was planned in the mid-1990s. At the time, designers considered using offshore coating systems from the oil and gas industry to prevent corrosion. In particular, the Norwegian standard on coatings, NORSOK M-501[1], was studied.

However, and against all earlier studies and NORSOK M-501 systems, the previous owner of HR1 selected a two-coat, ceramic-reinforced epoxy system, applied wet-on-wet with a total dry film thickness (DFT) of 350 µm (13.7 mils) for the TP and the upper part of the monopile (MP) (-2m mean sea level [MSL] and upwards). The paint system had been approved following the testing regime of NORSOK M-501, in this case being applied as a two-coat system with drying between the coats. Such a lean system was seldom used for splash-zone areas.

As a test, the last five of the 80 TPs at HR1 were painted with a two-coat solvent-free epoxy system, at a total DFT of 1,000-to-1,100 µm (40-to-43 mils), and with drying between the coats.

The interior of the TPs and the rest of the MP were left uncoated. Sacrificial anodes were installed on the outside of the TP for corrosion protection of both the underwater part of the TP and the MP.

The railings on the TP platform were hot-dipped-galvanized steel, with a DFT of approximately 150 µm (6 mils).

The turbine tower itself was protected with a well-known epoxy/polyurethane (PU) system, primed with a thermally sprayed zinc/aluminium 85/15 coating. This system had a long and successful onshore track record and also in coastal areas.

THE FIRST EXPERIENCES

Within the first two years of service, pinpoint corrosion was observed on the TPs painted with the lean 350 µm two-coat epoxy system (Fig. 2).

The corrosion took place both in the atmospheric and splash-zone areas of the TP. A forensic investigation showed that the corrosion started as blistering on the coated surface and as the blisters ruptured from wave and tide movements, corrosion started. The cause of damage turned out to be the lean coating combined with insufficient grinding of the ceramic extenders in the paint. Microscopic analyses of pieces of paint flakes showed that the extenders had not been ground sufficiently during the production of the paint. This defect and the low DFT of the coating permitted pinpoint access of salty water to the steel surface. The surface (that is, the film) had become permeable (Fig. 3).

Cathodic disbondment of the coating system may also have contributed to the generation of blisters in the splash zone.

It should be added that at present, the corrosion damage is not considered to be detrimental to the TPs of HR1. Due to the original conservative corrosion allowance in the structure, the integrity of the wind farm is intact and therefore, the present owner of HR1, Vattenfall A/S, expects the farm to be in service as planned until the mid-2020s.

It should also be mentioned that ceramic-reinforced epoxy paint systems have shown relatively good protection over 15 years in the Swedish Yttre Stengrund decommissioned wind farm in the Baltic Sea (Fig. 4).

The two-coat epoxy system at 1,000-1,100 µm DFT on the last five of the HR1 TPs has shown good and lasting resistance, apart from damage caused by impact from supply boats, and the protection remains intact today, as shown in Figure 5. As a comparison, Figure 6 shows the corrosion attacks in 2015 on TPs coated with the lean 350 µm permeable coating system. Consequently, the two-coat solvent-free coating system with the high DFT became a starting point for suitable coating systems meant for future wind farm projects.

Later inspections at HR1 and other wind farms have shown that the interior of the TPs and MPs had to be better protected.[2,3]

Fig. 2: At the Horns Rev 1 (HR1) facility, pinpoint corrosion is noted on TPs painted with the lean two-coat epoxy system. *Photos, Figures 2-4, courtesy of FORCE Technology*

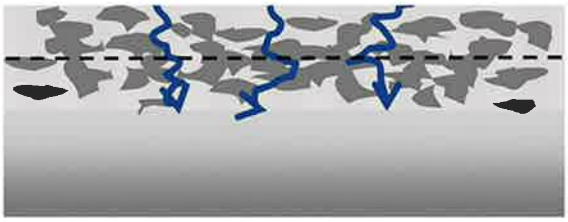

Fig. 3: Poorly ground ceramic extenders combined with a low DFT render a coating film permeable.

Fig. 4: This image shows a decommissioned TP from Yttre Stengrund Wind Farm, Baltic Sea, Sweden, after more than 15 years of service. The splash zone area has been attacked by ice, other impacts and general wear. The area above the splash zone is in fairly good condition. The brackish, low-saline water and the cold climate of the Baltic Sea may have contributed to the lesser corrosion.

Fig. 5 (left): The two-coat epoxy system at 1,000-1,100 µm DFT on the last five of the HR1 TPs has shown good and lasting resistance, apart from damage caused by impact from supply boats, and the protection remains intact today. Fig. 6 (right): This photo shows the corrosion attacks in 2015 on TPs coated with the lean 350 µm permeable coating system. *Photos courtesy of Morten Mortensen, Hempel A/S*

LATER AND PRESENT PAINT SYSTEMS

Jackets for Substations and External TPs

Following the experiences from HR 1, new coating systems were introduced. The new paint system on the exterior of jackets and TPs is seen in Table 1.

TABLE 1: Paint System for Jackets on TPs

Type	TFT, µm
High-build epoxy primer	250
High-build epoxy intermediate coating	250
High-build epoxy intermediate coating	250
Polyurethane (PU) topcoat	80
Total dry film thickness	830

TABLE 2: Revised Paint System for Jackets on TPs

Type	TFT, µm
High-build epoxy primer	300
High-build epoxy intermediate coating	300
Polyurethane (PU) topcoat	60
Total dry film thickness	660

The paint system has shown excellent durability on projects in the North Sea, the English Channel and the Irish Sea. The few damages observed originated from inferior quality control during the painting process described later, and from blows during installation activities and collisions. The protective ability of the paint system in marine environments is confirmed.

Stripe-coating on welds and edges between every coat of paint has always been specified and the structures have benefitted from the positive results.

As with all industrial enterprises, all parties involved in wind farm projects are constantly searching for ways to reduce construction costs, the cost of paint and painting among these. Based on the positive experience with the epoxy/PU system and due to new developments of these types of paints within the last five years, the paint manufacturers have proposed that the system listed in Table 1 be modified from a four- to a three-coat system. The paint manufacturers' recommendation is justified from pre-qualifications in the NORSOK M-501 and ISO 20340 testing regimes and also from positive references from the offshore oil and gas industries. Thus, the paint system used in the latest U.K. projects is the three-coat system listed in Table 2.

To apply three coats instead of four and to reduce the paint consumption will naturally create a cost reduction, but some operators still favor the four-coat system in Table 1 to obtain a higher safety margin.

The Interiors of TPs and Interiors and Exteriors of MPs

Throughout the first wind farm projects, owners and consultants had assumed that the interior part of the foundations did not need any corrosion protection. It was anticipated that the air inside the inner cavity would be deprived of oxygen after a short time, and that the internal tidal movements would be insignificant and thus, no corrosion should be possible. However, history demonstrated otherwise as older wind farms have experienced substantial corrosion in the interiors of TPs and MPs.[2] Consequently, these inner areas are now being coated in newer projects.

The outside of the uncoated, submerged MPs was relatively protected by anodes. But to reduce anode consumption and to avoid costly corrosion protection retrofit solutions due to under-protection of the structures (for example, the installation of remote anode sleds), owners and contractors soon agreed to partly coat the outside of the MPs.

The specified coating system for the inner and outer MPs is a traditional two-coat epoxy system, such as recommended in NORSOK M-501 (System 7B, 350+ µm). It is essential that the epoxy coating be resistant to cathodic disbondment.

The Railings

The railings and balusters on the outdoor platform on TPs are now thermally sprayed and then coated with epoxy/PU systems. Some projects have also used stainless steel such as EN 1.4404 or aluminium such as the EN AW 5000-series for railings and balusters.

The Appurtenances

Accessories such as outer ladders, platforms and fenders are protected with the system shown in Table 2. Over the years, the appurtenances have received various treatments on the individual wind farms, but Table 2's epoxy/PU system has shown the best resistance — in particular because the selected epoxies have been the impact-resistant ones ("icebreaker epoxies"). On some projects, non-immersed parts have been primed with thermally sprayed zinc/aluminium (85/15) prior to painting.

QUALITY CONTROL OF STEEL AND SURFACE TREATMENT ON WIND FARMS

An important control issue on all projects has been, and remains, nondestructive testing (NDT) checks of all welds and joints. All parties involved have realized the importance of systematic control and it is a statutory requirement from the classification societies.

Regarding respect for control of the corrosion protection and surface treatment, the attitudes of some owners of initial wind farm projects were somewhat reserved. Quality checks of painting operations were infrequent. Fortunately, the approach to painting quality control — third-party quality control in particular — is now positive, and all projects are now checked. The main quality control guidelines have been NORSOK M-501, Annex D, or ISO 12944-8, and all contractors' daily logs are supplemented with third-party painting inspection activities. Thus, damages and corrosion attacks originating from poor painting operations have been drastically reduced.

DEFECTS

Paint Errors

Apart from the previously mentioned poor grinding, poor paint rheology has also been observed on a few projects. The result has been sagging and improper coating continuity. Formulation modification and proper paint control have reduced these defects. The contractors have also introduced more skilled master painters for the jobs.

Poor opacity of the yellow topcoat has also been seen. The remedial measure here has been to choose a whitish/yellowish-colored intermediate coat. Additionally, the topcoat paint formulation has also been modified by introducing better and more opaque yellow pigments.

Insufficient Pre-Treatment of Welds and Edges

Treatment (grinding) of weld spatter, weld slag, undercuts and weld porosity must be carried out prior to abrasive blasting. Likewise, all edges must be rounded. If not, the areas could be starting points for corrosion attacks.

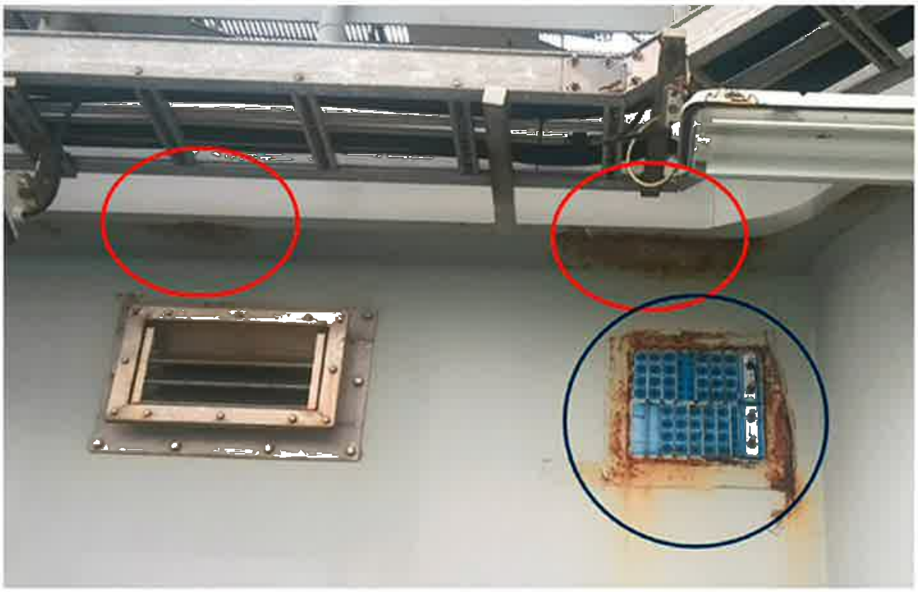

Fig. 7: This image shows an offshore transformer station. Two typical faults in the surface treatment process that initiate corrosion attacks are noted. The red circles show the lack of rounding of edges (chamfering) on part of the steel bar. The blue circle shows a poorly mounted and painted light accessory after installation of the station. The intact ventilation duct on the left side of the photo has been mounted correctly during the manufacture of the station. *Photo courtesy of Dong Energy*

Mounting of New Accessories

Frequently, accessories such as lamps, clamps and the like have to be attached to the finished structures. Sometimes these activities happen offshore. As the mountings are often performed by non-painters and out of the hand of the main contractor, early corrosion attacks may happen on the structures (Fig. 7).

Fig. 8: The flaking of the topcoat and the penultimate intermediate coat on this boat landing was caused by aluminum dust originating from an adjacent thermal spray application during construction and from exceeding recoating intervals. *Photo courtesy of FORCE Technology*

Flaking

Epoxy and PU paints have a recoat window. If the maximum recoating interval has been infringed upon, the subsequent coat may have adhesion problems. Similarly, a greasy or dusty surface may deter adhesion of the following coat and can result in flaking[3] (Fig. 8).

Occasionally, flaking has also been observed on hot-dipped-galvanized structures. The primer has detached due to improper preparation of the hot-dipped-galvanized surface prior to application.

Grinding Sparks

When the painted TP is being fitted with appurtenances, hot sparks may be generated by grinding and cutting operations. These tiny hot steel grits can settle on adjacent freshly painted surfaces and soon turn rusty. The result is a freckled discoloration of the surface.

Investigation has revealed that the flying grinding particles are often embedded in the topcoats only, and that possible damages are mainly of a cosmetic nature, as the underlying epoxy coats prevent further intrusion. The spotted surfaces can be repaired by abrasive grinding of the topcoat and repainting.

Cracking

When painting the boat-landing constructions, occasionally unacceptably high DFTs are registered on weld assemblies and corners. Total DFTs of more than 2,000 μm (79 mils) have been observed, if the master painter has been inattentive. The high thickness values create inner tensions in the paint film after drying, which may lead to cracking of the coating film down to the steel surface and then to subsequent corrosion attacks (Fig. 9). A careful check of the DFTs is mandatory, especially in these areas.

Fig. 9: The flaking of the topcoat and the penultimate intermediate coat on this boat landing was caused by aluminum dust originating from an adjacent thermal spray application during construction and from exceeding recoating intervals. *Photo courtesy of FORCE Technology*

DRY FILM THICKNESS MEASUREMENTS

In general, control of the DFTs is one of, if not the most important operation in quality control. DFTs that are too lean can cause permeation of moisture and salts and may also create pores in the coating system, and DFTs that are too high may generate cracks. Solvent-containing paints have the greatest tendency to crack due to the risk of solvent entrapment in the paint film during curing.

DFT verifications are carried out as single measurements with magnetic gages, and frequently the number of readings surpasses the recommendations listed in ISO 19840, "Paints and varnishes — Corrosion protection of steel structures by protective paint systems — Measurement of, and acceptance criteria for, the thickness of dry films on rough surfaces." The criteria of acceptance and rejection of the minimum DFT is the often called the 80/20-rule of ISO 19840 (points 1 through 3).

If the acceptance criteria are used on the specifications in Table 2, the lowest acceptable DFT is 660 µm x 0.80 = 528 µm. Such a DFT is still found sufficient for splash zone environments.

Some painting contractors and contracts have modified the standard to a 90/10-rule, whereby the lowest acceptable DFT becomes 660 µm x 0.90 = 594 µm.

1. The arithmetic mean of all the individual DFTs shall be equal or greater than the nominal DFTs.
2. All individual DFTs shall be equal to or above 80 percent of the nominal DFT.
3. Individual DFTs between 80 percent of the nominal DFT and the nominal DFT are acceptable provided that the number of these measurements is less than 20 percent of the total number of individual measurements taken.
4. All individual DFT values shall be less than or equal to the specified maximum dry film thickness. If it is not specified, see ISO 12944-5.[4]

CONTROL OF PAINTING OPERATIONS

Additional to the DFT checks, proper quality control guidelines encompass checks of the steel surface after abrasive blasting and prior to painting: steel cleanliness, steel and weld conditions and blasting profile. Later in the process, the wet-film thickness and film coherence are checked during paint application. A final check after drying also involves possible continuity checks and visual appearance. Wind farm projects for German waters are also statutorily checked for proper color (RAL 1023, Traffic Yellow) by color measuring equipment. All observations are registered in daily logs and reports to be submitted later to classification societies.

SUMMARY

Offshore wind farms are protected today with paint systems that are corrosion-resistant after more than 15 years of service. With high probability, the protection will remain effective during the designed 25-to-30-year lifetime of the farm. A three-coat epoxy-polyurethane system with a DFT of 660 µm is the system used on the most vulnerable area, the TP. Effective protection will only be possible with proper quality control, carried out by well-educated painting inspectors, for example FROSIO- or ICorr-certified, and with proper documentation of the entire painting operation processes from the bare steel to the finished construction. JPCL

ABOUT THE AUTHOR

Peter Kronborg Nielsen has gained a unique expertise within the coating and corrosion protection area during his more than 40 years in the industry. He began his career as a research and development chemist and later was a laboratory and marketing manager for major coating manufacturers such as Hempel and AkzoNobel. Kronborg then continued into the consultancy service as an advisor on surface treatment and corrosion protection.

Kronborg is currently managing all FORCE Technology issues on coatings for the protection of steel structures with an emphasis on offshore wind turbine farms operations in Northern Europe and Great Britain. He holds a Bachelor of Science degree in chemistry and is a FROSIO-certified inspector Level III. Kronborg is member of the Institute of Corrosion (ICorr) and former president of the Federation of Danish Paint and Lacquer Chemists.

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