Offshore windfarms – successful corrosion protection combined with effective quality management

Article presented in The Journal of Protective Coatings & Linings, JPCL, December 2016

Following an uncertain start, the present offshore coating systems for windfarms have shown fine durability against the aggressive marine environment. Positive features from the first windfarms with more than 15 years of service are described, and the importance of quality management is explained.

Introduction

Constructions such as offshore windfarms 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 constructions as well as light reflections from the sea.

Additionally, an area of concern is the tidal zone (splash-zone), where the wind turbine construction is stressed both from mechanical impacts – service boat collisions and waves – and from corrosion strains 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, Figure 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.

North Sea Windfarms – the beginning

The first windfarm in the North Sea, Horns Rev 1 (HR1), was planned in the mid 1990’s. At the time, designers obviously 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.

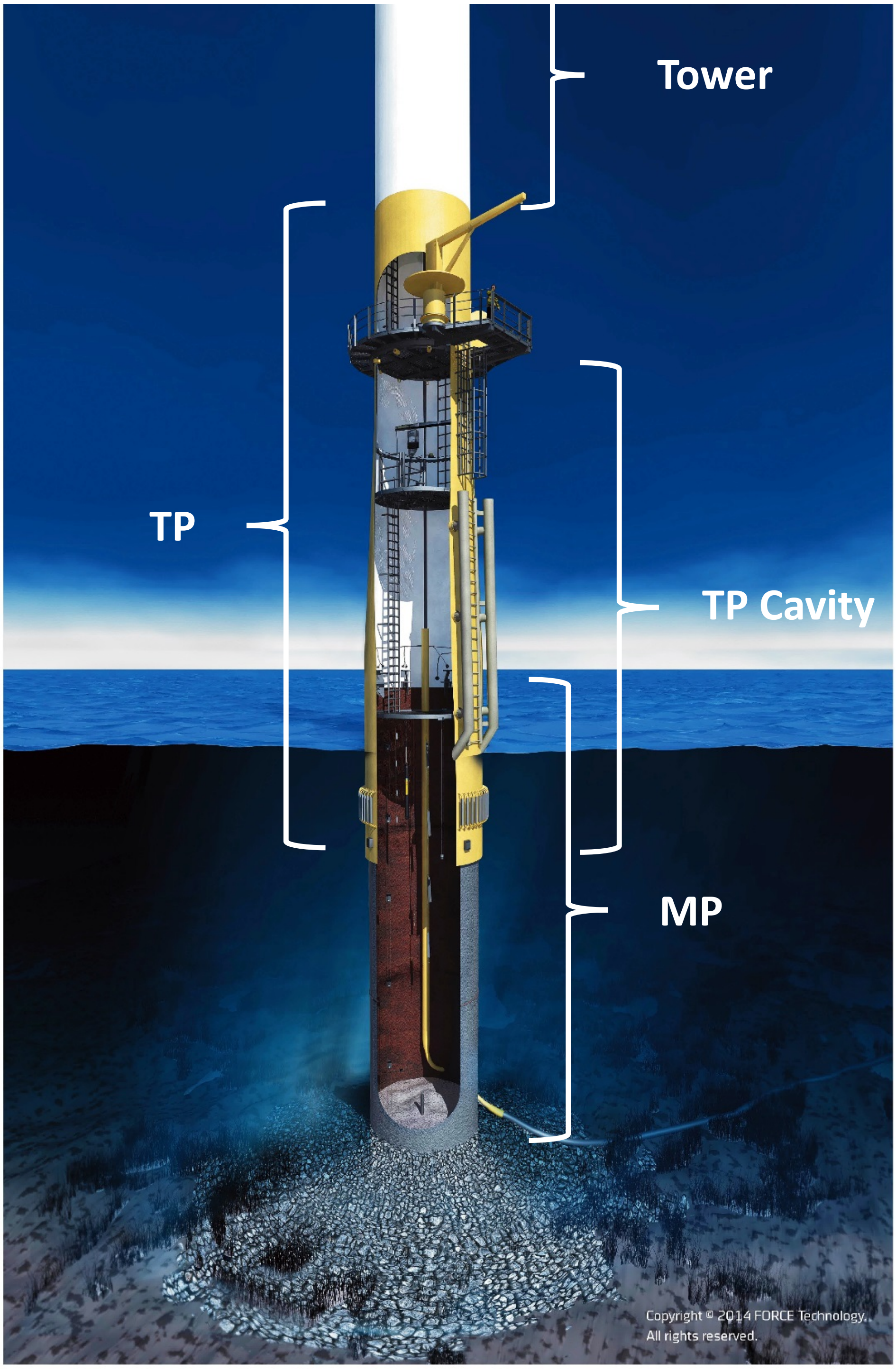

Figure 1. Offshore wind turbine construction, model: Tower, TP (Transition Piece), TP Cavity (The inner void of the TP), and MP (Monopile: The underwater support of the TP and Tower). © FORCE Technology.

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) 350 µm for the TP and the upper part of the MP (-2m 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. However, such a lean system was seldom used for splash-zone areas.

As a test, the last 5 of the 80 TPs at HR1 were painted with a two-coat solvent free epoxy system, total DFT 1000-1100 µm, 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, DFT approximately 150 µm.

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

The first experiences

Within the first two years of service, pinpoint corrosion was observed on the TP's painted with the lean 350 µm two-coat epoxy system, Figure 2.

Figure 2. Horns Rev 1. Pinpoint corrosion on TPs with the lean two-coat epoxy system after two years of service.

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, the rust attacks were activated. The cause of damages 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 film had become permeable, Figure 3.

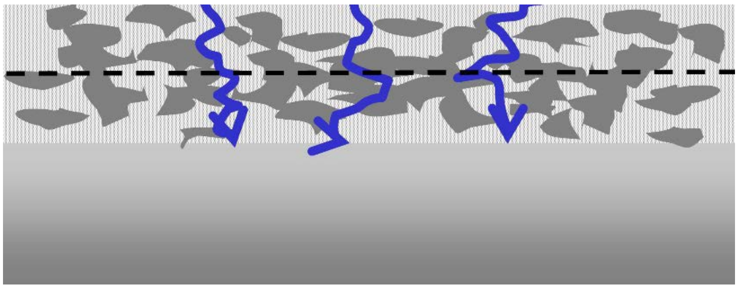

Figure 3. Model. Poorly ground ceramic extenders combined with a low DFT make the coating film permeable.

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

It should be added that the corrosion damages are not yet considered detrimental to the TPs of HR1. Due to the original conservative corrosion allowance in the structure, the integrity of the windfarm is kept. So the present owner of HR1, Vattenfall A/S, expects the farm to be in service as planned until the mid-2020’s.

It should also be mentioned that ceramic reinforced epoxy paint systems have shown relatively good protection over 15 years in the Yttre Stengrund (Sweden) decommissioned windfarm in the Baltic Sea, Figure 4.

Figure 4. Decommissioned TP from Yttre Stengrund Windfarm, Baltic Sea, Sweden, after more than 15 years of service. The splash-zone area is attacked from ice and 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.

The two-coat epoxy system with the DFT of 1000-1100 µm on the last five of the HR1 TPs has shown good and lasting resistance, apart from damages made by impacts from supply boats. The protection is 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.

Figure 5. HR 1 in 2015. TP painted with the high DFT solvent free epoxy system 1000-1100 µm after 14 years of service. The protection of the coating system is intact.

Figure 6. HR 1 in 2015. TP painted with lean and permeable coating system after 14 years of service. Compare the corrosion progress with Figure 2.

Consequently, the two-coat, solvent free coating system with the high DFT became a starting point for suitable coating systems meant for future windfarm 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].

Later and present paint systems

Jackets for substations and external TPs

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

Paint system for jackets og TPs	
Type	**NTFT, µm**
High-build epoxy primer	250
High-build epoxy intermediate coating	250
High-build epoxy intermediate coating	250
Polyurethane (PU) top coat	80
Total dry film thickness	830

Table 1

The paint system has shown excellent durability on windfarm projects in the North Sea, The Channel and the Irish Sea. The few damages observed have originated from inferior quality control during the painting process – see later – and blows from 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. This has also 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. Among these, also the cost of paint and painting. 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's testing regimes and also from good references from the offshore oil- and gas industries. Thus the paint system used in the latest UK projects is the three-coat system listed in Table 2:

Revised paint system for jackets og TPs	
Type	**NTFT, µm**
High-build epoxy primer	300
High-build epoxy intermediate coating	300
Polyurethane (PU) top coat	60
Total dry film thickness	660

Table 2

To apply three coats instead of four and to reduce the paint consumption will naturally create a cost reduction.

Meanwhile, some operators still favour the four-coat system in Table 1 to obtain a higher safety margin.

The interior of TPs, and the exterior and interior 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 in the inner cavity (see Figure 1) would be deprived of oxygen after a short time, and that inside tidal movements would be insignificant. Thus, no corrosion should be possible. However, experience showed otherwise as older windfarms have shown substantial corrosion in the interior 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 CP retrofit solutions due to under-protection of the structures (e.g. 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 2-coat epoxy system, such as recommended in NORSOK M-501 (System 7B, 350+ µm). The epoxy coating must be resistant to cathodic disbondment.

Railings

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

Appurtenances

Accessories such as outer ladders, platforms and fenders are protected with the system in Table 2. Over the years, the appurtenances have received various treatments on the individual windfarms, but Table 2’s epoxy/PU system has shown the best resistance – in particular because the chosen 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 windfarms

An important control issue of all projects has been, and is, 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.

As regards respect for control of the corrosion protection and surface treatment, the attitudes of some owners of initial windfarm projects were somewhat reserved. Checks of painting operations were infrequent. Fortunately, the approach to painting quality control, third party QC in particular, is now positive, and all projects are now checked. The main QC-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

Some faults that do appear have been and are:

Paint errors

Apart from the previously mentioned poor grinding, poor paint rheology has 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 top coat has been seen. The remedial measure here has been to choose a whitish/yellowish-coloured 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, such as seen in Figure 7.

Mounting of new accessories

Frequently, accessories such as lamps, clamps and alike 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 constructions, cf. Figure 7.

Figure 7. Offshore transformer station. Two typical faults in the surface treatment process that initiate corrosion attacks: Red circles: Lack of rounding of edges (chamfering) on part of the steel bar. Blue circle: Poorly mounted and painted light accessory after installment of the station. See also the intact ventilation duct on the left hand side, which has been mounted correctly during the manufacture of the station.

Flaking

Epoxy and PU paints have a recoating window. If the maximum recoating interval has been infringed, the subsequent coat may have adhesion setbacks. Similarly, a greasy or dusty surface may deter adhesion of the following coat. The result is flaking, Figure 8. A more detailed description is found in [3].

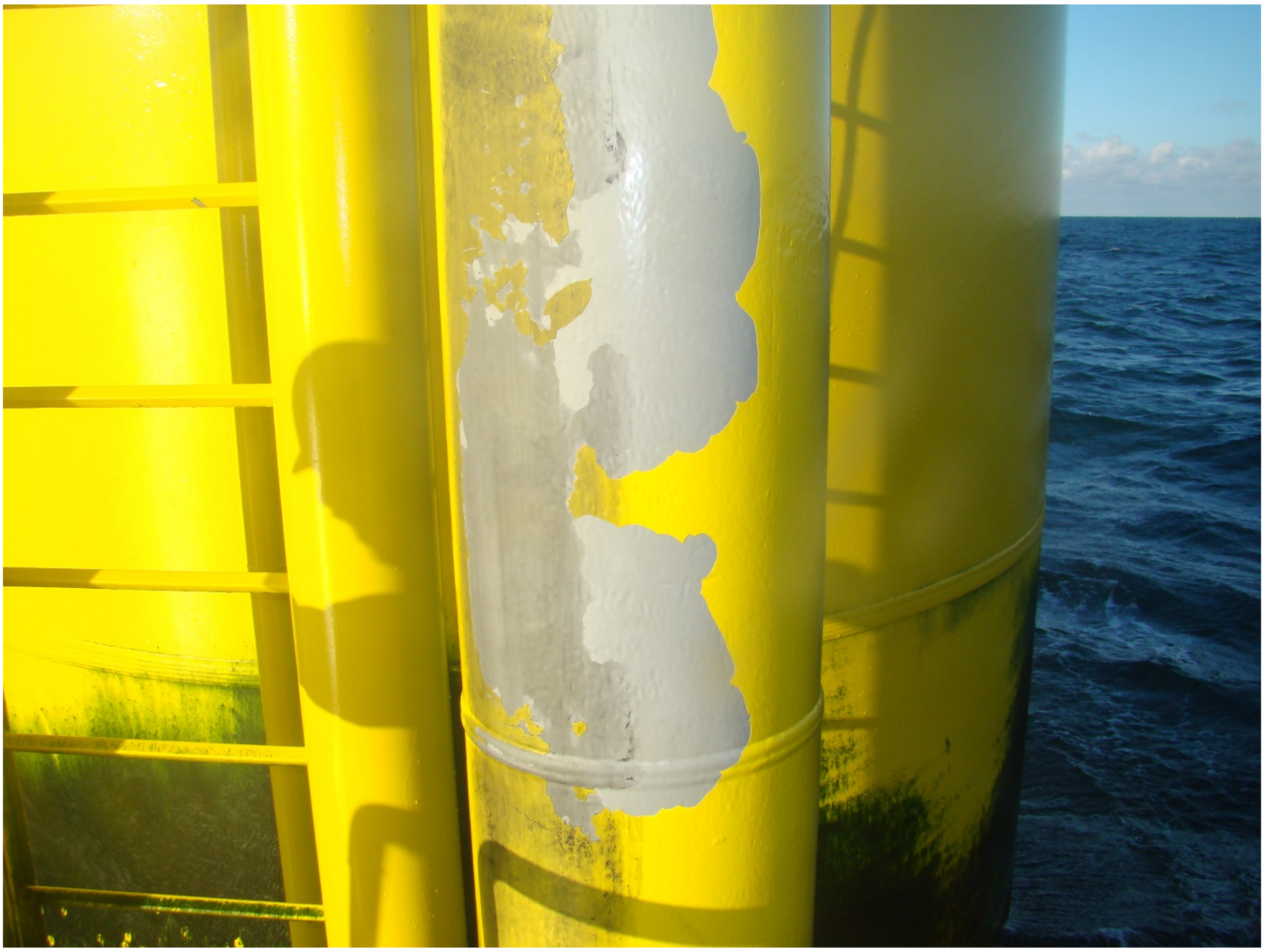

Figure 8. Flaking of topcoat and penultimate intermediate coat on a boat landing. The flaking was caused by aluminium dust, originating from adjacent thermal spray application during construction, and from exceeding recoating intervals.

Occasionally, flaking has also been observed on hot-dipped galvanized structures. The primer has detached due to improper preparation of the HDG-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 may settle on adjacent freshly painted surfaces and soon turn rusty. The result is freckled discolouration 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 cosmetic nature, as the underlying epoxy coats prevent further intrusion. The spotted surfaces are repaired by abrasive grinding of the top coat and repainting.

Cracking

When painting the boat landing constructions, occasionally too high DFTs are registered on weld assemblies and corners. Total dry film thicknesses of more than 2000 µm 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 subsequent corrosion attacks, Figure 9. A careful check of the DFTs is mandatory, especially in these areas.

Figure 9. Cracks in a coating film caused by inner tensions in the coating film from excessive DFT.

Dry film thickness measurements

In general, control of the DFTs is one if not the most important operation in QC. Too lean DFTs cause permeation of moisture and salts and may also create pores in the coating system, and too high DFTs may generate cracks, cf. Figure 9. Solvent-containing paints have the greatest tendency to crack due to the risk of solvent entrapment in the paint film during curing.

The DFT-verifications are carried out as single measurements with magnetic gauges, and frequently the number of readings surpasses the recommendations listed in ISO 19840. The criteria of acceptance/rejection of the minimum DFT is the so-called 80/20-rule of ISO 19840 – see text box points 1-3:

DFT measurements acceptance criteria:

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

Source: ISO 19840.

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, cf. [1.].

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

Control of painting operations

Additional to the DFT-checks, proper QC-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 the paint application. Final check after drying also involves possible continuity checks and visual appearance. Windfarms projects for German waters are also statutorily checked for proper colour (yellow, RAL 1023) by colour measuring equipment.

All observations are registered in daily logs and reports, later to be submitted to classification societies.

Summary

Offshore windfarms are today protected with paint systems, which are corrosion resistant after more than 15 years of service. With high probability, the protection will remain effective during the designed 25 – 30 years' 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. Such good protection will only be possible with proper quality control, carried out by well-educated painting inspectors, e.g. FROSIO- or ICorr-certified inspectors, and with proper documentation of the whole painting operation processes from the bare steel to the finished construction.

Acknowledgements

The author wishes to thank *Ove Thomsen*, Vattenfall A/S, *Anders R Black*, DONG Energy A/S, and *Claus E Weinell*, FORCE Technology, for valuable comments and suggestions to this paper. *Morten Mortensen*, HEMPEL A/S, has kindly supplied the photos Figures 5 and 6.

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[1] NORSOK M-501, “Surface Preparation and Protective Coating”, Ed. 6, NORSOK, Standards Norway, 2012

[2] *Corrosion Risks and Mitigation Strategies for Offshore Wind Turbine Foundations*, page 18-21, Materials’ Performance, December 2015.

[3] *Corrosion protection of offshore windfarm structures – present understanding and future challenges*, A. R. Black and P. K. Nielsen, Eurocorr 2011, Stockholm.