Field Gradient Survey of Offshore Pipeline Bundles affected by Trawling

Gro Østensen Lauvstad[1], Harald Osvoll[2], Jens Christofer Werenskiold[2], Lars Helgesen[3]

[1]FORCE Technology, Hornebergveien 1, NO-7038 Trondhem, NORWAY, grl@force.no
[2]FORCE Technology, Hornebergveien 1, NO-7038 Trondhem, NORWAY
[3]STATOIL ASA, Forusbeen 50, NO-4035 Stavanger, NORWAY

Abstract

A new field gradient (FG) tool has been developed for measurement of electric fields surrounding structures and pipelines submerged in seawater. By analysis of the FG data for structures provided with cathodic protection (CP), coating damages can be located and the current density on exposed steel determined. Also, anode current output can be assessed, enabling more accurate estimates of remaining anode life. This is particularly important for ageing structures and for structures located in areas where damage to the corrosion protection system can be expected, e.g. due to trawling.

The new FG tool has been applied for inspection of several offshore pipeline bundles (carrier pipes) located in an area with trawl activity. The original corrosion protection system for the bundles combined coating with sacrificial anodes. By visual inspection, extensive damage to coating and anodes was seen on some bundles. It was therefore decided that CP retrofit should be considered.

The basis for the retrofit CP design required further consideration, as use DNV-RP-B401 resulted in extensive retrofit requirements. Basing the CP retrofit design on visually estimated anode depletion significantly reduced the retrofit requirement. More direct measurements were however required to validate the retrofit design basis. This validation was provided by the FG measurements, reducing the cost of CP retrofit considerably.

Keywords

Cathodic Protection, Field Gradient Measurements, Offshore pipelines, Coating Damage, Retrofit

Introduction

Corrosion protection of offshore structures and pipelines is typically provided by coating combined with cathodic protection (CP) by installation of galvanic (sacrificial) anodes. As structures age, coating is anticipated to degrade, tentatively described by the coating breakdown factors (CBFs) provided by a number of CP design standards and recommended practices for various types of coating [1] [2] [3]. Also, the anodes get depleted to an extent which depends on the amount of current supplied to the structure/pipeline and to adjacent structures (CP drain), as well as the electrochemical capacity of the anode material. The CP current supplied to the structure/pipeline in turn depends on the coating breakdown and the extent of damage to the coating (if any), and on the current density on bare (uncoated) steel.

CP design according e.g. to DNV-RP-B401 [1] considers all the above factors in order to provide a corrosion protection system which is adequate for the entire design life of the structure/pipeline. When later assessing the condition of the CP system, the following is typically examined based on a conventional CP survey:

- The protection potential of steel, by stab or proximity measurements.

- The anode wastage (AW), which can be compared to predictions based on the CP design input parameters.

Based on visually estimated AW and CBF calculated e.g. based on coating breakdown constants of DNV-RP-B401, the current density on bare (uncoated) steel can be roughly estimated as an average for the period since installation. This value can then be used for estimation of remaining CP system life and need for CP retrofit.

The following uncertainties of the above analyses can be identified:

- Coating breakdown/degradation: Coating is used to limit the overall CP current demand and to ensure adequate CP current distribution. In CP design, the CBFs are deliberately selected in a conservative manner to ensure that a sufficient total final current output capacity is installed [1]. When performing back-calculations based on observed AW, the use of design CBFs will however be non-conservative.
- Amount of coating damage: The coating breakdown constants of DNV-RP-B401 do not account for significant damage to coatings during fabrication and installation [1], or during operation (e.g. due to trawling). If such damage is anticipated, the affected surface area is to be estimated and included in CP design calculations as bare metal surface. When performing back-calculations based on observed AW, the use of conservative estimates of the coating damage will tend to give non-conservative results.
- Estimated values of anode depletion (AW): In offshore surveys, AW is typically estimated visually based on photos or video footage with limited resolution from areas with limited visibility. Variations is seen in AW estimated by different operators and from AW estimated from one year to another (poor reproducibility).
- Burial: Assessment of coating damage and AW requires that the structure/pipeline is available for visual inspection. For buried structures, excavation may be required in order to obtain data.
- Electrochemical capacity of anode material: Typically, calculations are based on values provided in CP design standards and recommended practices. These are intended to be conservative, but will tend give non-conservative results when used in back-calculations based on observed AW.

In the following a case is presented concerning a number of offshore pipeline bundles (carrier pipes) located in an area where trawl activity has been extensive over the years.

<u>Pipe Bundles Affected by Trawling</u>

Table 1 gives an overview of the bundles.

Table 1. Bundle carrier pipe dimensions and approximate lengths

Bundle	Installed	OD [in.]	Length [km]	Start	End	Coating
A	1998	40	5.9	Platform P1	Template T1	Glas flake epoxy (450 μm)
B1	1998	34	1.7	Template T1	Template T2	
B2	1998	34	1.7	Template T2	Templates T3 and T4	
C1	2001	46	6.9	Platform P2	Towhead (TH)*	
C2	2001	46	6.9	Towhead (TH)*	Templates T5 and T6	

* With connections to Templates T7 and T8

The original CP designs were performed according to DNV-RP-B401:1993 [4] and NORSOK M-503 (which refers to DNV-RP-B401) [5]. CP design life was 20 years. The coating was regarded to be in accordance with DNV-RP-B401 Category III. CP was provided by segmented bracelet Al-Zn-In anodes attached by welding of continuity flat bars to anode pads on the bundles. Figure 1 shows examples of the type of damage observed to anodes and coating.

Figure 1. Trawl damage to bundles: (a) slightly deformed anode, otherwise intact, (b) anode ripped off and located next to bundle, (c) coating scraped off on top of bundle and (d) extensive coating removal around bundle circumference

Based on the numbers of anodes missing as defined by visual inspection, the bundles of Table 1 were categorized as extensively affected by trawling, ref. Figure 2(a), or less affected by trawling, ref. Figure 2(b). The former were characterized by relatively long sections without remaining bracelet anodes, while for the latter one or two bracelet anodes were missing at irregular intervals.

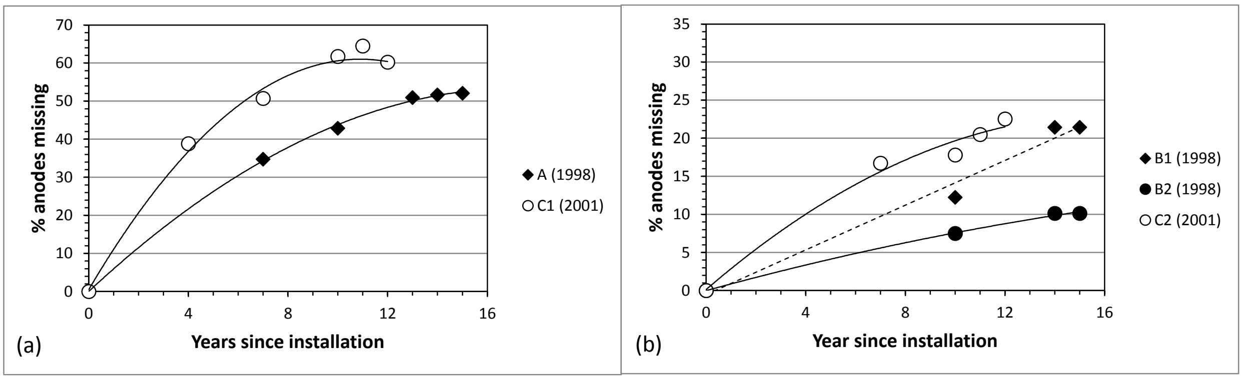

Figure 2. Percentage anodes missing: (a) extensive impact of trawling and (b) less impact of trawling

Figure 3 shows the visually estimated extent of coating damage for the two bundles most affected by trawling. The overall percentage circumference affected by trawling was 3.7% for bundle A and 4.3% for bundle C1. The corresponding figures for the bundles less affected by trawling were 1.1% (bundle B1), 0.2% (bundle B2) and 3.3% (bundle C2).

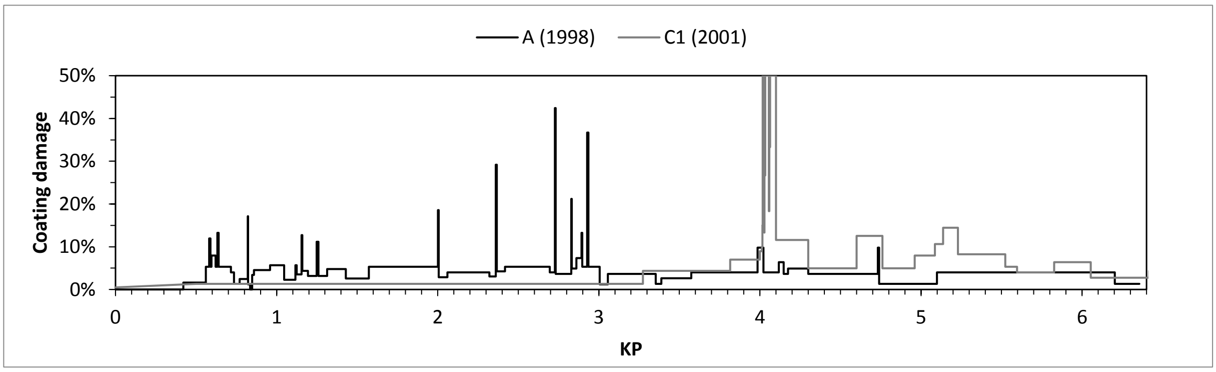

Figure 3. Coating damage as percentage of bundle circumference vs. kilometre point (KP) (2013)

Table 2 summarizes anode depletion data, confirming the uncertainty associated with visually determined AW. Also included are results from CP stab measurements, last performed in 2011. Figure 4 shows the complete potential profile for bundle C1. Here, a discrepancy can be seen between the measurements performed in 2008 and 2011 whereby the latter were more negative by approx. 50 mV. The measurements were performed on bare steel at locations of missing anodes.

Table 2. Visually estimated depletion (AW) of anodes remaining and results from CP stab measurements (vs. Ag/AgCl/seawater reference electrode)

Bundle	Installed	AW (2013)	AW (2011)	Max. potential (2011)
A	1998	100% within 0-30%	70% within 30-60%	-990 mV
B1	1998	100% within 0-30%	100% within 0-30%	-1010 mV
B2	1998	100% within 0-30%	100% within 0-30%	-1010 mV
C1	2001	100% within 0-30%	75% within 30-60%	-890 mV
C2	2001	100% within 0-30%	70% within 30-60%	-1035 mV

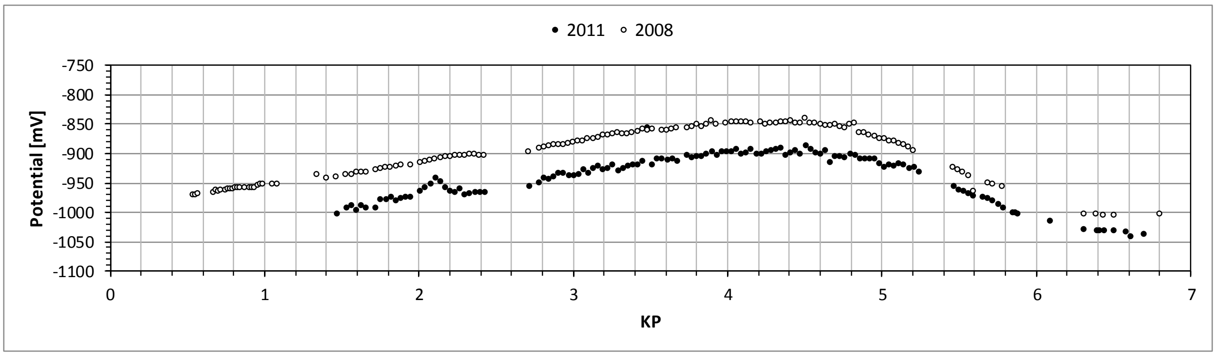

Figure 4. CP stab potential profile for bundle C1 in 2011 and 2008

As can be seen from Table 2, the bundles less affected by trawling are characterized by protection potentials negative of -1000 mV vs. Ag/AgCl/seawater reference electrode and appears to be well protected. Significantly more positive potentials were measured for the bundles most affected by trawling.

CP Retrofit Requirement

Based on the original CP design, end of CP life is 2018 for bundles A, B1 and B2 and 2021 for bundles C1 and C2. For the bundles less affected by trawling, B1, B2 and B3, potential and AW data indicate that the original CP designs were adequate also when considering the impact of trawling. However, for the bundles most affected by trawling, A and C1, the shift in potential towards more positive values may indicate that the CP systems for these bundles are approaching the end their useful life due to the large number of anodes missing and the extent of accumulated coating damage.

As the operator of the offshore field wished to continue operation until 2020, the questions to be answered were:

- What extent of CP retrofit is required to extend the CP life of bundles A and C1 to 2020?
- Will the CP systems for bundles B1, B2 and C2 be adequate until 2020?

As a starting point, CP retrofit requirements were defined based on DNV-RP-B401 [1], i.e. with mean current density requirement 90 mA/m^2 (assuming that the bundles would remain adequately polarized until CP retrofit could be performed) and final current density 140 mA/m^2. Combining this mean current density with the observed loss of anodes over the years and an estimated coating breakdown (based on DNV-RP-B401 and accounting for additional coating damage due to trawling), the following AW values were estimated (2013):

- Bundles most affected by trawling, A and C1: 50-60%
- Bundles least affected by trawling, B1, B2 and C2: 30-50%.

These values appeared however to be somewhat conservative when compared to visually estimated AW.

Field Gradient Measurements

In order to investigate further the basis for the CP life/retrofit requirement assessments, FG measurements were performed using the FG tool, 'FiGS'. The tool, which is described in more detail elsewhere [6], accurately measures electric fields surrounding submerged structures and pipelines.

The FG data was analysed in combination with Finite Element Models (FEM) of the bundles, considering parameters such as bundle outer diameter (OD), anode geometry/dimensions and burial conditions, as well as distance between FG tool and bundle, vertically (vs. top of pipe) and horizontally (vs. centre of pipe).

For the FG survey, two sensors were installed on an ROV and run in parallel along the pipe bundles. The electric field signature from the ROV was subtracted from the FG raw data and turned out to be relatively constant once the ROV flies at constant speed and at constant height above the seabed. When calculating the corresponding currents, the direction of the FG vector is used to determine if currents are cathodic or anodic. Positive values define cathodic currents, negative values defines anodic currents.

Figure 5 shows an example of FG data converted from measured μV/cm to corresponding effective cathodic current per unit length of pipeline bundle. In general, the agreement between the sensors was excellent and the average over the two sensors was used in the further analyses.

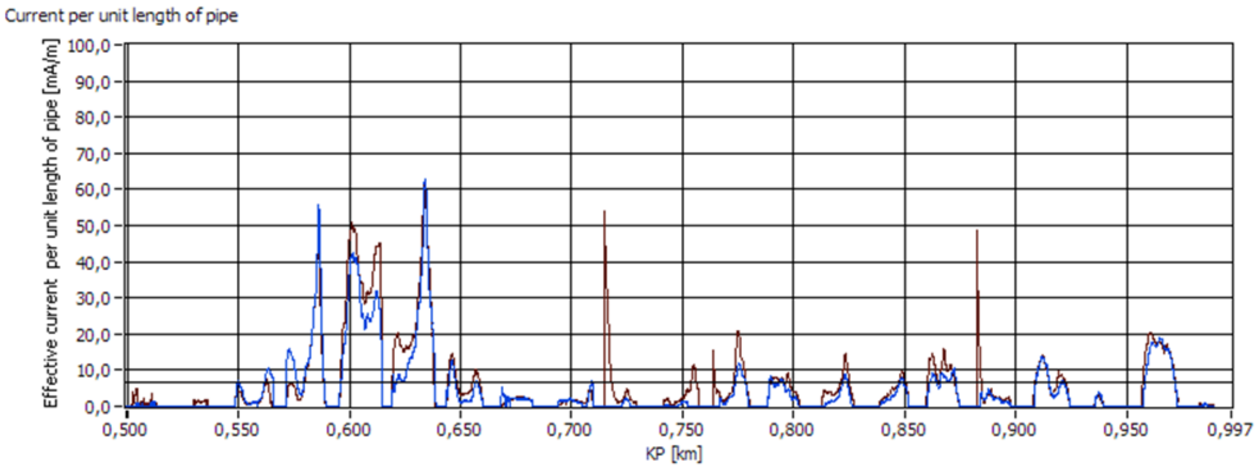

Figure 5. FG data from two sensors given as effective current per unit length of bundle

Integrating the cathodic current curves, the average effective current density for sections of the pipe bundles was determined by dividing the effective cathodic current per unit length of pipe by the bundle circumference (π·OD), see Figure 6 for bundle C1. The agreement between the effective current density and the visually observed coating damage appears to be reasonable, considering that these parameters have been derived by averaging over different sections of the bundle.

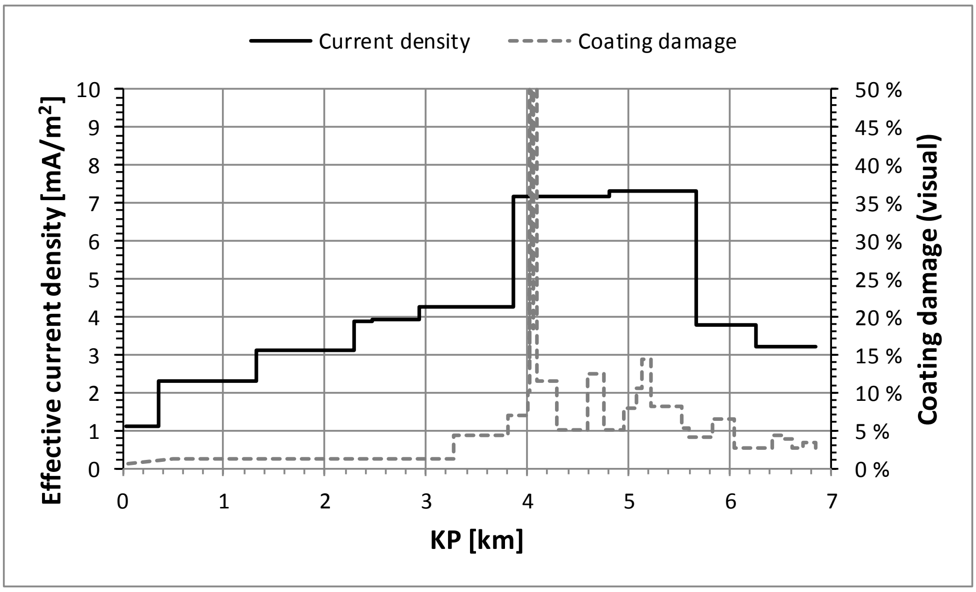

Figure 6. Effective cathodic current density and visually determined coating damage for bundle C1

It should be noted that the effective current density equals the current density for bare (uncoated) steel times the CBF and/or the coating damage ratio. Examining specific areas on bundle C1 where 50% of the coating appeared to be damaged, the current density on bare steel was estimated to 43 mA/m^2 (assuming CBF=0 for remaining coating) or 38 mA/m^2 (assuming CBF according to DNV-RP-B401 Coating Category III for remaining coating). Considering the effective current averaged over the length of the bundle, the current density of bare (uncoated) steel was below 30 mA/m^2 (CBF according to DNV-RP-B401 Coating Category III for remaining coating). For bundle A, the maximum and average effective current densities corresponded to current densities of bare (uncoated) steel of 46 and 27 mA/m^2, respectively (CBF according to DNV-RP-B401 Coating Category III for remaining coating). Consequently, a current density of 50 mA/m^2 on bare (uncoated) steel appears to be reasonable for the bundles most affected by trawling.

Performing similar analyses for the other bundles, less affected by trawling, only the maximum effective current density on each bundle was considered. The resulting current densities on bare (uncoated) steel were below 30 mA/m^2 for all bundles, which appears to confirm a previously noted conservatism of the CP design standard current densities [7].

Figure 7 shows the current output from remaining anodes on bundle C1 as determined by analysing anodic FG peaks. Anodes identified as damaged by trawling are indicated. For this bundle, the FG sensors identified 111 anodes, of which 8 were seen to be damaged but still in electrical contact with the bundle, ref. Figure 1(a). For comparison, the last visual survey identified 109 anodes remaining on the bundle. Hence, the FG tool provided a more accurate method of positively identifying anodes not affected by trawling.

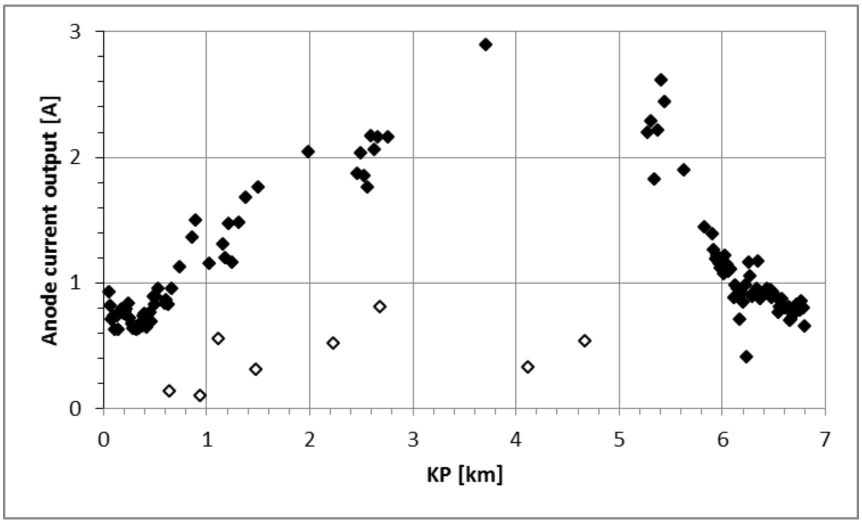

Figure 7. Current output from remaining bracelet anodes on bundle C1: Intact anodes (closed symbols) and damaged anodes (open symbols)

As can be seen from Figure 7, the current output from the single anode remaining at KP 3.7 is fairly high, approx. 3 A, while for the anodes remaining at each end of the bundle, where impact of trawling has been more limited, is approx. 0.8 A. By assuming a linear increase in CP current requirement with time since installation and an electrochemical capacity of 2000 Ah/kg [1], the corresponding AW is order of 100% for the anode at KP 3.7 and 30-40% for the anodes located towards the end of bundle C1. This appears to be in reasonable agreement with visually determined AW.

Table 3 summarizes the current balance for each bundle. As can be seen, the anodes generally supply more current than required by the bundles themselves. Part of this difference may be due to assumptions made during the analyses of the FG data, but may also be taken to indicate significant CP current drain to adjacent structures (platforms and templates with wells, ref. Table 1).

Table 3. Summary of FG measurements – current balance

Bundle	Current [A]			Comment
	Anodic	Cathodic	Difference	
A	132	94	38	Platform P1 to Template T1
B1	34	9	25	Template T1 to Template T2
B2	31	8	24	Template T2 to Templates T3/T4
C1	130	117	13	Platform P2 to TH/Templates T7/T8
C2	122	52	70	TH/Templates T7/T8 to Templates T5/T6

When looking at the current balance in more detail, the following is seen:

- For the mid-section of bundle A, anodic and cathodic currents balance. Between KP 0 and KP 1.3, the excess current supplied by the bundle anodes (e.g. to platform P1) is approx. 26 A, while between KP 5.5 and KP end, the excess current supplied by the bundle anodes (e.g. to adjacent template wells) is approx. 12 A.
- For bundle C1, anodes between KP 0 and KP 0.4 supply an excess current of approx. 13 A (e.g. to platform P2). For the remainder of the bundle, the anodic and cathodic currents more or less balance.

- For bundle C2, anodes located between KP 0 and KP 5 supply an excess current of approx. 26 A, e.g. to adjacent towheads (with connections to templates with wells) and possibly also to the trawl-affected bundle C1. Between KP 5 and KP end, the excess current is approx. 38 A, supplied e.g. to adjacent templates with wells.
- For the shorter bundles B1 and B2, the CP drain to adjacent structures appears to be rather evenly supplied by all the remaining bracelet anodes.

CP Retrofit Design

Based on the measured potentials profiles (ref. e.g. Figure 4) and the current density for bare (uncoated) steel estimated based from FG measurements, the following was concluded:

- Bundle A: Retrofit performed as soon as possible to relieve remaining bundle anodes and limit the extent of retrofit.
- Bundle C1: Retrofit as soon as possible to avoid under-protection.
- Bundles B1, B2 and C2: Adequately protected until end of original CP design life (2021), no CP retrofit required.

Based on the CP drain evaluations, the following safety factors (SF) were considered:

- Bundle A: SF=2 on first 1500 m towards platform P1 (vs. SF=2 on first/last 1000 m according to ISO 15589-2:2012 [2]) and 10 A drain to template at KP end.
- Bundle C1: SF=2 on first 1500 m towards platform P2 and on final 500 m towards towhead at KP end.

A CP retrofit concept with sleds with 3×2 anodes and total net mass 888 kg was selected. The anode sleds were assumed to be located such that they would remain seawater exposed throughout the retrofit design life (5 years). The final current requirement turned out to govern the numbers of anode sleds required and Table 4 summarizes results based on final current density 140 mA/m^2 (DNV-RP-B401), 75 mA/m^2 (FG data including a safety factor of 1.5) and 50 mA/m^2 (FG data).

Table 4. Summary of retrofit CP design

Bundle	**No. of 3×2 anode sleds sleds**		
	140 mA/m^2	**75 mA/m^2**	**50 mA/m^2**
A	63	19	12
C1	74	33	22

It should be noted that no detail CP retrofit design was actually performed based on the CP current densities of DNV-RP-B401, results included are for comparison only. For this case, the original bundle anodes remaining were seen to contribute to the overall CP of the bundles to a very limited extent only. The number of anode sleds required then depended on the protection length of each anode sled, which was estimated in accordance with the methodology of NORSOK M-503 [3]. Reducing the current density requirement based on the FG measurements, the remaining bundle anodes could be included in the CP retrofit design to a more significant extent. This reduced the number of retrofit anode sleds considerably, particularly on bundle sections with relatively many of the original bracelet anodes remaining.

When estimating the cost of CP retrofit, the following has been considered:

- Cost per anode sled: 0.123 MNOK
- Cost for anode installation:
    - 6 sleds installed per day
    - Vessel day rate: 1.5 MNOK

Going from a CP retrofit design based on DNV-RP-B401 to a design based on results from FG measurements, the number of anode sleds is reduced from 137 (140 mA/m^2) to 52 (75 mA/m^2). Hence, the cost of anodes is reduced by approx. 60%, or by approx. 11 MNOK. The reduced installation time (tentatively from 23 to 7 days), corresponds to a cost reduction of approx. 24 MNOK. Hence, for the offshore pipe bundles considered, a significant reduction in overall cost is seen when performing CP retrofit design based on results from FG measurements.

Conclusions

The FG sensor 'FiGS' has proven to be an excellent tool for assessing the condition of several bundle carrier pipes located in an area with trawl activity and for assessing current densities to be used in CP retrofit design. In addition, FG data confirmed sections with excessive coating damage (previously estimated from visual surveys) and identified a number of anodes which appeared to be intact in previous visual surveys but were actually damaged and with limited electrical contact with the pipeline.

A CP retrofit design was performed for the two bundles most affected by trawling. Final current density for bare (uncoated) steel considered was 50 mA/m^2 (based on FG results), 75 mA/m^2 (FG results with safety factor 1.5) or 140 mA/m^2 (DNV-RP-B401). For the remainder of the bundles, the current protection level and the rather limited current density for bare (uncoated) steel below 30 mA/m^2 implied that CP retrofit would not be required. The FG measurements appear to confirm the conservatism of the CP design current densities, in particular seen for structures that have been adequately protected by CP for a number of years.

Performing a tentative CP retrofit design based on DNV-RP-B401 (140 mA/m^2) resulted in extensive CP retrofit being required. Decreasing the current density requirement to 75 mA/m^2 (FG results with safety factor) reduced the total number of anode sleds required by approx. 60%. Hence, the FG survey had significant impact on the cost of CP retrofit for the offshore pipeline bundles considered.

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