AC Corrosion Tests on Materials for Electrically Heated Flowlines

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ABSTRACT

This paper presents results from AC corrosion tests on cathodically protected steel flowlines. An important factor, which has an increased focus in the industry, is to understand AC corrosion and how it can be mitigated. Tests have been carried out at 100 and 200 Hz, where no current transfer design limits exist, as well as at 50 Hz. The results show that the corrosion rate is independent of transfer current density (0-400 A/m^2) and power frequency (0-200 Hz) on steel. On the anodes, the corrosion rate increases as a function of transfer current density (0-80 A/m^2) at 50 Hz. However, the correlation is less prominent at higher frequencies (100-200 Hz).

KEY WORDS: DEH; Direct Electrical Heating; AC Corrosion; Subsea Structures; Pipeline Integrity; Experiment; Steel.

INTRODUCTION

When a hydrocarbon production flowline is shut down, it gradually cools to a temperature level where hydrates or wax may form. If hydrates and wax are to form in a flowline, they may restrict the flow and in a worst-case situation block the entire pipe. Removal of hydrates is difficult and potentially hazardous. One of several field proven methods to prevent hydrates and wax formation is Direct Electrical Heating (DEH). Since the first installation in year 2000, approximately 30 flowlines have been installed with the DEH technology.

In a DEH-system, the flowline steel conducts electrical alternating current (AC) to generate heat in the flowline. For safety and reliability reasons, the heating system is electrically connected ("earthed") to surrounding seawater through several sacrificial anodes. Typically, 40 % of the current is conducted by seawater, while the flowline steel conducts the remaining 60 %, (Nysveen et al., 2007). The electric current is transferred from the flowline steel to surrounding seawater via anodes connected to the flowline. This is indicated in Fig. 1.

When AC current transmits from metal to seawater, corrosion may occur. During the positive half-wave of the AC current, part of the current flow may be faradaic, i.e. contributing to the oxidation of solid metal to ions. In most situations, the current transfer across the metal-seawater interface is dominantly capacitive, and the faradaic component amount only to a minor part of the total current. The rate of AC corrosion depends on several parameters, including metal quality, cathodic protection level, power frequency, transfer current density (TCD), temperature,

hydrostatic column pressure etc. The governing parameter in literature is usually considered to be the TCD. For DEH, this is the current density crossing the metal-electrolyte interface between flowline steel and seawater, as well as between anodes and seawater. Existing DEH systems are designed to use maximum limits for the TCDs under which AC corrosion has been considered acceptable. The limits are decided on a project basis by the operator. The most common acceptance levels for DEH have been 20 or 40 A/m^2 for aluminum anodes and 100 or 240 A/m^2 for carbon steel, (Lervik, 2004; Nysveen, 2007).
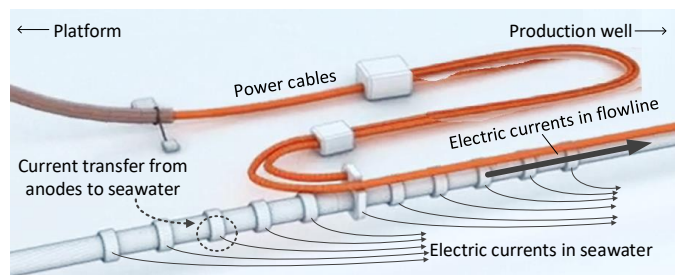

Fig. 1: Principle sketch of Direct Electrical Heating. Electrical currents are transferred from anodes on the flowline to surrounding seawater.

A 3-year development program for further development of the DEH technology was initiated in 2016. The main activity relates to an increase in the supply power frequency from 50/60 Hz up to 200 Hz, where several benefits are expected, (Lervik, 2016). One is a reduction of AC corrosion. None of the empirical corrosion studies (French, 1973; Guo, 2015) found in literature are directly applicable to DEH, but the same behavior is expected. Most of the literature investigates steel without any cathodic protection, which is not the case for DEH installations. Hence, these studies cannot be used directly for comparison. Other differences are material alloy composition, test temperature, applied current density, power source current wave form and power frequency.

The established TCD design levels for AC corrosion on flowline steel and anodes are used for all present DEH installations, which are operated at 50 or 60 Hz. To prepare for Next Generation DEH Systems at higher frequencies, new TCD design levels must be established.

This paper presents results from small-scale AC corrosion tests with flowline steel and AlZnIn anode materials, galvanically connected. The test program considers corrosion rate at various power frequencies (50-200 Hz) and TCD levels (20-400 A/m^2).

EXPERIMENTAL METHOD

Test conditions (power frequency and TCD levels) and specimen materials were like what is commonly used in DEH installations. The steel specimens were machined from a 12" pipe joint which was manufactured in accordance to the flowline standard DNV OS F101 2007 HFW 450 PD. The anode compound was AlZnIn, machined from a bracelet anode. All specimens were ground and polished on the exposed side.

The specimens were coin shaped with a thickness of 2 mm, see Fig. 2. Exposed areas were 0.79 cm^2 and 3.84 cm^2. For bare steel, AC corrosion acceptance limits are typically referred to coating defect sizes of 1 cm^2, like in British Standard 15280. Thus, a steel specimen size close to 1 cm^2 is preferred and has been used in the tests.

Fig. 2: Polished specimens of steel (left) and aluminum (right)

The specimens were placed in special-built containers, where only one side was exposed to seawater. See Fig. 3. An insulated electrical wire was terminated to the reverse side of the specimens.
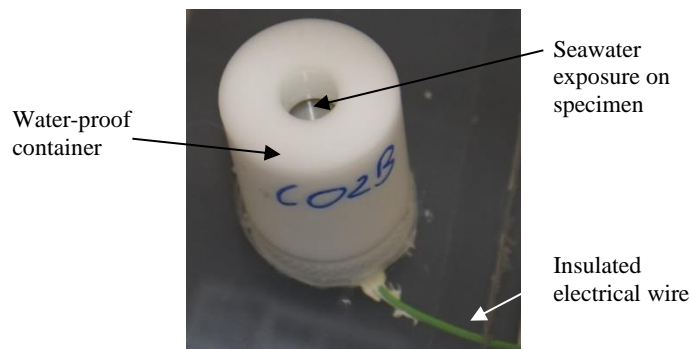

Fig. 3: Watertight container for steel specimen.

Each test consisted of five pairs of specimens located in storage boxes, filled with approximately 20 L of artificial seawater. The seawater mixture was in accordance to ASTM D1141. An AC current from a contant voltage source was forced between pairs of specimens; one steel and one aluminum. A safety transformer ensured equal amount of current flowing in all specimen pairs. Fig. 4 shows a sketch of the test set-up. The water was not stirred during the test period, only replenished as water vaporized. Ambient temperature was approx. 20℃. The pH level was measured to 8 in all test set-ups prior to and during the test periods.
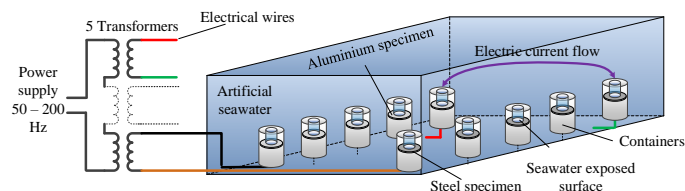

Fig. 4: AC corrosion test set-up. An AC current is forced between a steel and aluminum specimen.

All specimens were chemically cleaned, dried and weighed before and after the tests. After the corrosion tests, the steel specimens were cleaned by a mixture of concentrated hydrochloric acid (HCl), antimony trioxide (Sb_2O_3) and stannous chloride ($SnCl_2$). This is according to ASTM G1. The aluminum specimens were cleaned by concentrated nitric acid (HNO_3) and chromium oxide (CrO_3). This is a variant of ASTM G1 which has proven to be good in countless in-house experiments. The cleaning mixture was proven not to corrode or influence the steel samples. The corrosion rate was calculated using the weight loss method

TEST PROGRAM

The test program examines AC corrosion of flowline steel galvanically protected by aluminum anodes at a range of frequencies (50-200 Hz), TCD levels on steel specimens (100 - 400 A/m^2) and TCD levels on aluminum specimens (20 - 80 A/m^2). In addition, there is one set of reference specimens without any imposed AC current (only cathodic protection). Table 1 shows the test program.

Table 1: DEH corrosion test program.

Test no.	Frequency [Hz]	Current density [A/m^2]		Comment
		Steel	Aluminum	
1	0	0	0	Reference
2	50	100	20	Common design level at 50/60 Hz for steel. Al also 40 A/m^2
3	50	200	40	
4	100	200	40	
5	200	200	40	
6	50	400	80	
7	100	400	80	
8	200	400	80	

All samples were submerged in seawater for 34 days. The first 7 days, they samples were acclimatized, meaning that no AC current was applied. The final 27 days, AC current was applied to the test specimens, except for the reference group.

RESULTS

Corrosion Rate on Steel Specimens

The corrosion rates on the steel specimens varied from 0.002 to 0.08 mm/year, as seen in Figs. 5 and 6. The leftmost data points are the reference specimens, with no applied AC current. There is no clear indication that the corrosion rate is dependent on TCD or power frequency. For most of the data points with applied AC current, the corrosion rate is within the span of the reference specimens (horizontal dashed lines). Visual inspection of the samples did not reveal any localized or uniform corrosion attacks.

Due to very little material loss of the specimens (range from 0.1 to 4 mg), the sources of error produce relatively large error margins. The balance has a linear deviation of +/- 0.2 mg. This corresponds to a corrosion rate deviation of +/- 0.01 mm/year for the specific material size. Another error source, which cannot be quantified, is the effectiveness of the cleaning processes,. The cleaning process was checked and found not to cause material loss on non-corroded specimens. However, there is no guarantee that all corrosion products were removed during cleaning.

A few samples deviate from the remaining, indicating higher corrosion rates. The reason for these anomalies is unknown. Equal amount of current circulated in all specimen pairs of each test. The corrosion products were of similar magnitude for all samples in each test. The DC potential was measured to approximately -1050 mV vs. Ag/AgCl prior to and after the AC test period.
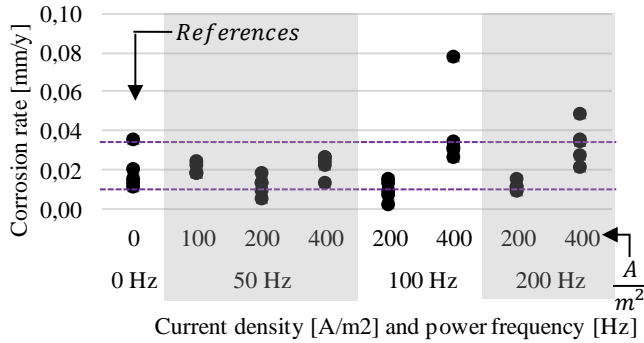

Fig. 5: AC corrosion rate of steel specimens. The leftmost results are reference measuremens with no AC current applied. The horizontal lines indicate span in corrosion rate for the reference specimens.
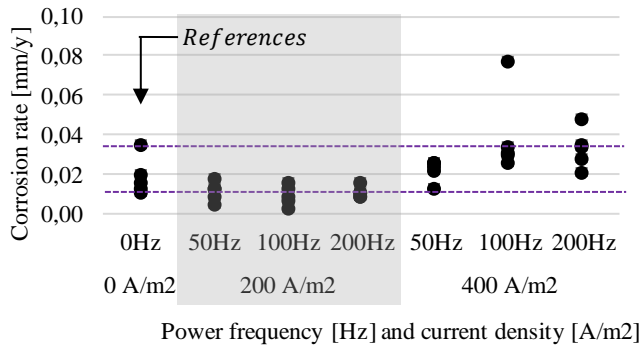

Fig. 6: AC corrosion rate of steel specimens. The leftmost results are reference measuremens with no AC current applied. The horizontal lines indicate span in corrosion rate for the reference specimens.

Corrosion Rate on Aluminum Specimens

The AC corrosion rate of aluminum specimens varied between 0.1 and 4.1 mm/year, as shown in Fig. 7. This corresponds to a material loss from 8 to 315 mg, excluding the single negative corrosion value. The dashed lines indicate the trend of the data. At 50 Hz, there is a clear trend that the corrosion rate increases at increased TCD. A corrosion rate rise by a factor 10 is seen when increasing from a TCD level of 20 to 80 A/m^2. For 100 Hz and 200 Hz, the corrosion rate is fairly unaffected by TCD increase within the tested range.

For TCD of 40 A/m^2, the average corrosion rate is similar for 50 and 100 Hz, see Fig. 8. At 200 Hz, the rate is reduced by a factor 2-3. At a TCD of 80 A/m^2, the corrosion rate is reduced to 1/5th at 100 Hz compared to what is observed at 50 Hz. At 200 Hz, the corrosion rate is half what is observed at 100 Hz. This is seen in the rightmost section of Fig. 8.
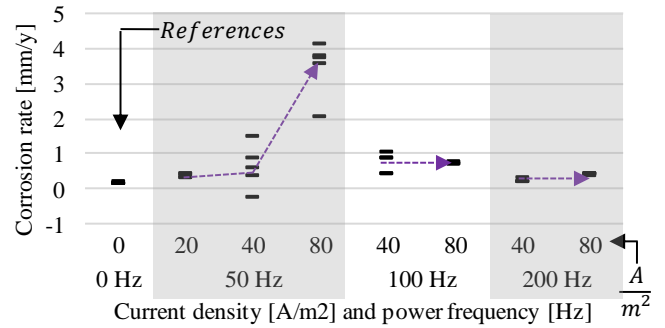

Fig. 7: AC corrosion rate of aluminum specimens. The leftmost results are reference measuremens with no AC current applied.
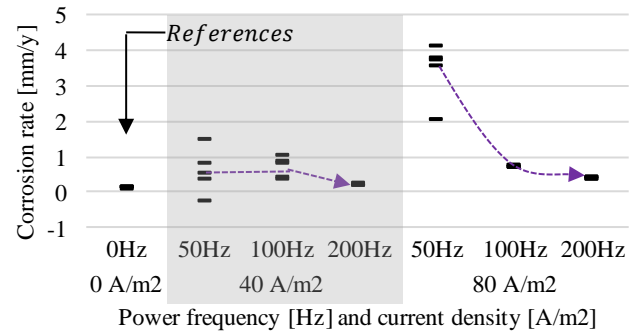

Fig. 8: AC corrosion rate of aluminum specimens. The leftmost results are reference measuremens with no AC current applied.

The data point scatter is more significant at 50 Hz, compared to 100 and 200 Hz. It seems that the corrosion mechanism is more even at higher frequencies. For one sample at 50 Hz, negative corrosion was measured. The negative corrosion rate on this specimen exceeds the expected balance error margin and cleaning process error.

Deposits

Deposits formed on both the steel and aluminum specimens. The deposits were more dominating at higher TCDs and lower frequencies.

On the steel specimens, a white and hard deposit attached, as seen in Fig. 9. This is believed to be calcareous deposits formed because of cathodic protection. A softer deposit was seen on the aluminum specimens (aluminum oxide), as seen in Fig. 10. It is a trend that the thickness of the deposit increases for higher TCD and decreases at higher power frequencies. This is expected since formation rate of the deposit is analogue to corrosion rate of aluminum the specimens. Deposits were observed for the reference specimen, but less than for the other specimens.
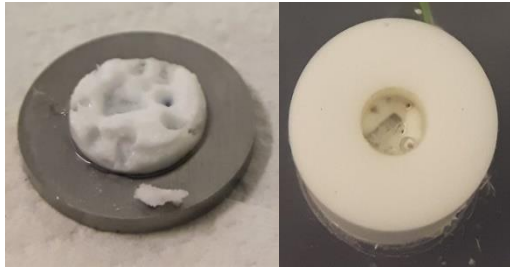
Fig. 9: Deposits on steel specimen at TCD of 200 A/m² at 50 Hz.

Fig. 10: Deposits on aluminum specimen at TCD of 80 A/mm² at 50 Hz (left) and TCD of 40 A/mm2 at 200 Hz (right).

Corrosion Morphology

Visual inspection did not identify any corrosion or dissimilarity between the steel specimens, only some discoloration. In microscopy, the reference specimen topography was even on the entire object. On the surface of the 400 A/mm² specimens at 50, 100 and 200 Hz, some unevenness was vaguely seen. However, the difference between the three frequencies were unnoticeable. See Fig. 11.
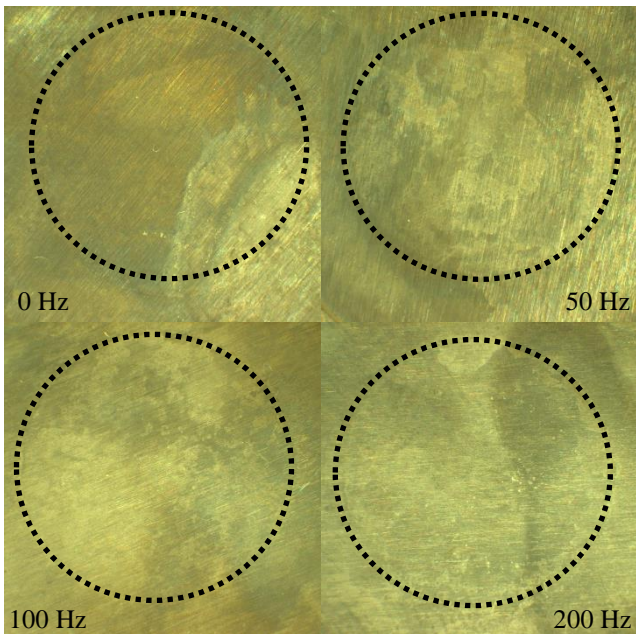

Fig. 11: Corrosion on steel specimens at 0-200 Hz. TCD was 400 A/m² on the 50, 100 and 200 Hz specimens. The exposed surfaces are indicated by black markers.

On the aluminum surface, several regions of pitting corrosion were observed. This means that the corrosion rate in the pits were larger than the average calculated by the weight loss method. This is normally not a problem for anodes, but may increase the probability for non-faradic material loss, i.e. material pieces that detach from the anodes. Fig. 12 shows images of aluminum specimens after the corrosion tests and cleaning process. The figure includes a reference specimen (no AC current applied), together with specimens at 50, 100 and 200 Hz at 80 A/m². The white substance on the 50 Hz specimen could not be removed even by extended cleaning, and is therefore believed to be porous aluminum. Minor areas of white substance can also be observed on the 100 and 200 Hz specimens. Note that a TCD of 80 A/m² greatly exceeds the current design limit at 50 Hz, meaning that such corrosion rates are not relevant for DEH installations at 50 Hz.
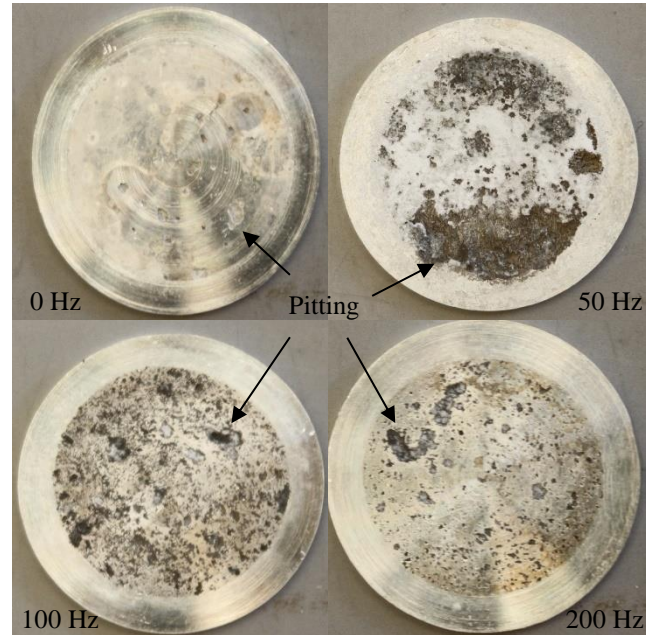

Fig. 12: Corrosion on aluminum specimens at 0-200 Hz. TCD was 80 A/m² on 50, 100 and 200 Hz specimens. This greatly exceeds design limits at 50 Hz. Thus, such corrosion rates are not relevant for DEH installations at 50 Hz.

DISCUSSIONS

TCD Threshold Levels

In the DEH qualification work for 50 and 60 Hz systems, the TCD threshold levels were set to 240 A/m² for steel and 40 A/m² for aluminum. During the field development, the acceptance criteria has, for reasons unknown to the authors, been reduced to 100 A/m² for aluminum and 20 A/m² for steel by some operators.

The corrosion rate observed during testing of all steel specimens was low. This is regardless of TCD and frequency. The corrosion rate is in the same range regardless of AC current. This could suggest that the tested conditions are below the true threshold AC current density. Testing with higher TCDs would be beneficial to reveal differences between power frequencies better.

Allowing a higher TCD design limit on the steel will simplify design of the current transfer zone (CTZ) and shorten the unheated length for future DEH installations by a reduction of required sacrificial anodes.

The CTZ may be simplified and reduced even more by allowing higher TCD on the anodes. At higher frequencies this may be possible without

increasing consumption rate.

Unsurprisingly, and in accordance with other studies, (Hesjevik, 2006), the general corrosion rates on the aluminum samples are greater than on the steel samples. The corrosion dependency on TCD and frequency are much more prominent for aluminum than steel within the range tested.

Frequency Dependency

A frequency dependence of the corrosion rate is expected if modelling the metal-electrolyte interface layer using the Randles circuit, given in Fig. 13. The double layer capacitance C is frequency dependent, in difference to the resistance R. The capacitance term is often written in the form given in Eq. 1, visualizing the frequency component.

$$Z_c = (j \cdot \pi \cdot f \cdot C)^{-n} \tag{1}$$

The formula consists of electrical impedance (Z_c), the imaginary unit (j), power frequency (f), double layer capacitance (C) and an empirical constant (n). The empirical constant (n) is between 0 and 1.
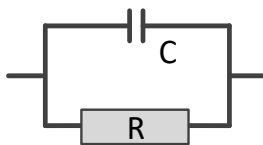

Fig. 13. Randles circuit of metal/electrolyte interface, indicating double layer capacitance (C) and resistance (R).

Only the currents flowing through the resistor represent electrochemical reactions, as the capacitor represents accumulation (charging) and dissipation (discharging) of charged particles. As the frequency increases, a larger share of the current is capacitive, reducing the current conducted through the resistance, and hence lessening the electrochemical reactions.

During testing, gas evolution (H_2) was observed on the steel specimens exposed to AC current. A calcareous layer ($CaCO_3$) formed on all steel specimens. Both these effects seemed to increase with TCD and to decrease at higher frequencies. The formation of a calcareous layer is generally attributed to the presence of hydroxyl (OH-) ions adjacent to the metal surface, causing a pH increase favoring the precipitation of a calcareous deposit. The formation of thicker calcareous deposits at higher TCD in the tests is expected to be related to increased hydroxyl production; the observation of a surge in gas evolution at higher TCD also supports this, suggesting that hydrogen is formed by reduction of water:

$$2H_2O + 2e^- \rightarrow H_2\,(g) + 2OH^- \tag{1}$$
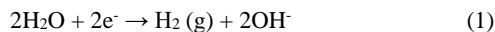
The increased rate of this reaction is a direct result of the impressed AC, since the electrode potential during parts of the AC cycle is polarized to a more negative value. Therefore, hydrogen induced stress (HISC) in the flowlines has been a topic in DEH projects. However, no issues related to HISC have emerged during laboratory tests and years of field experience, indicating that the HISC problem is purely theoretical.

CONCLUSIONS

A test program has been carried out with the purpose of studying AC corrosion on cathodically protected steel flowlines. The small-scale tests cover the power frequencies and current density levels relevant for flowlines with DEH. However, the results are valid also for other subsea steel structures which are cathodically protected.

For reference steel specimens (without AC current), an average corrosion rate of 0.02 mm/year was measured. The corrosion rate is in the same range also when impressing AC currents. Impressed TCD ranged from 100 to 400 A/m^2 at 50 to 200 Hz.

The correlation between corrosion rate, power frequency and TCD were more prominent for the aluminum specimens. At the highest TCD (80 A/m^2), the corrosion rate was clearly dependent on power frequency. For lower TCDs (40 A/m^2) the correlation was less prominent. At 200 Hz, the corrosion rate was similar for TCDs of 40 and 80 A/m^2. At 50 Hz, the rate increased by a factor 5.

The findings suggest that increasing the power frequency on DEH installations from 50 Hz to 100 or 200 Hz may allow larger AC current loads on each anode without significantly increasing consumption rate. This leads to fewer required anodes and a simpler and cheaper system with a smaller seabed footprint and lower installation costs.

ACKNOWLEDGEMENT

REFERENCES

French, W H (1973), "Alternating current corrosion of aluminum", *IEEE Transactions Power Apparatus and Systems*, Vol. 92, p. 2053-2062.

Gcuo, Y-B, Lui, C, Wang, D-G, Liu, S-H (2015). "Effects of Alternating Current Interference on Corrosion of X60 Flowline Steel, "*Petroleum Science*", Volume 12, 316-324.

Hesjevik, SM, Olsen, S (2006). "Direct Electric Heating on Subsea Pipelines a Challenge to Corrosion Protection," *NACE – International Corrosion Conference Series*, Orlando, United States, 061781-0617813.

Lervik, JK, Børnes, AH, Kulbotten, H, Nysveen A (2004). "Design of Anode Corrosion Protection System on Electrically Heated Pipeline, "*The Fourteenth International Offshore and Polar Engineering Conference*, Toulon, France, Volume 2, 26-31.

Lervik, JK, Iversen, Ø, Solheim K T (2016). "High frequency heating of subsea oil production pipelines," *26th Annual International Ocean and Polar Engineering Conference,* ISOPE, Rhodes, Vol. 2, 398-402.

Nysveen, A, Kulbotten, H, Lervik, JK (2017). "Direct electrical heating of subsea pipelines – Technology development and operating experience," *IEEE Transactions on Industry Applications*, Volume 43, 118-129.

Pagano, M, Lalvani, S (1994). "Corrosion of Mild Steel Subjected to Alternating Voltages in Seawater", *Corrosion Science*, Vol. 36, No.1, 134.