Non-destructive electrochemical techniques applied to the corrosion evaluation of the liner structures in nuclear power plants

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Abstract

The liner structure in nuclear power plants provides containment for the operation and therefore the study of its durability and integrity during its service life is an important issue. There are several causes for the deterioration of the liner, which in general involve corrosion due to its metallic nature. The present paper is aimed at describing the assessment of corrosion problems of two liners from two different nuclear power plants, which were evaluated using non-destructive electrochemical techniques. In spite of the testing difficulties arisen, from the results extracted it can be concluded that the electrochemical techniques applied are adequate for the corrosion evaluation. They provide important information about the integrity of the structure and allow for its evolution with time to be assessed.
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1. Introduction

Prestressed concrete containment structures for nuclear power plants often have a thin steel plate liner attached directly to the interior surface. Construction requirements dictate that the liner, except on the base slab, has to be cast into the concrete. That is, the liner is used as the inner form during placement [1].

The purpose of this liner is to provide an air tight seal for the containment. In addition, the liner must maintain its structural integrity under all loading and environmental conditions that can occur during the nuclear power plant service life. Since it must provide a seal, major care must be taken not only in the design phase, but also during the whole service life of the structure.

A number of publications have investigated the different loading conditions under which the liner can fail [2,3]. These loading conditions include internal pressure, thermal expansion, prestress forces, seismic action, shrinkage and creep of concrete, and wind action. But these are not the only risks that could affect the liner integrity. The present paper is focussed on the detection of corrosion problems in the liner that could affect its integrity and its sealing properties. The corrosion can be due to changes in the reinforcement concrete properties attached to it. Also changes in the pH of the concrete pore solution and in its internal humidity can cause alterations in the liner surface, which could lead to corrosion problems.

The aim of this paper is to present new non-destructive techniques that have been used recently for the corrosion liner evaluation in some nuclear power plants. These techniques are based on electrochemistry, and try to ensure the expected service life for this structure, and have been already used in other nuclear structures [6].

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2. Experimental

2.1. General description of the structure

2.1.1. Liner structures evaluated

Concrete containments are metal lined, reinforced concrete pressure-retaining structures that in some cases may be post-tensioned. The concrete vessel includes the concrete shell and shell components, shell metallic liners, and penetration liners that extend the containment liner through the surrounding shell concrete (Fig. 1) [4,5]. The reinforced concrete shell, which generally consists of a cylindrical wall with a hemispherical or ellipsoidal dome and flat base slab, provides the necessary structural support and resistance to pressure-induced forces. Leak-tightness is provided by a steel-liner fabricated from relatively thin plate material (e.g., 6-mm thick) that is anchored to the concrete shell by studs, structural steel shapes, or other steel connectors.

Although the liner is a continuous metallic plate that delimitates the whole contention building, the area evaluated in this paper is the one located under the building slab. This part is more exposed to possible contaminations due to leakage from different ducts that are located near the reinforcement slab attached to the liner (Fig. 2). In some cases, alkaline water, which comes from auxiliary ducts, has been detected under the cited slab; indeed, it triggered the corrosion presented here.

In this paper, two different liners (Liner A and Liner B) were studied by non-destructive electrochemical techniques. Measurements were made directly over the concrete slab. The slab structure is the same for the two nuclear power plants studied. The protection concrete has two carbon steel meshes embedded in both sides of the slab. The rebar diameter is 20 mm and the grid size is 30 cm. The concrete thickness varies along the slab, being constant at the lower surface, where the liner is attached, and variable

at the upper one, depending on the structure necessities. The total slab thickness goes from 0.50 m to 0.80 m. There are 10 mm-thick compressible materials and seals, with seismic properties, in all the joints between the slab and the perimetral walls (Fig. 2).

2.1.2. Measurement areas

For the water pH determinations, 12 different points were selected under the slab of Liner A. Due to the difficulties of access, these areas are different from the 14 selected for the electrochemical measurements in the two liners (8 points in Liner A and 6 points in Liner B) (Fig. 3). In the areas where corrosion was measured, the external painted covering was removed (a window of 30×30 cm in each area) for a better electrolytic contact of the electrodes with the concrete surface.

As all metal components (rebars and liner) are connected to a ground, there is an electrical conductivity among all these metal components. For this reason, when making the electrochemical measurements the reinforced mesh can interfere in the liner evaluation. The interference can be reduced if measurements are made placing the electrode over section of the concrete where the mesh was not directly below the point of measurement (avoiding the first reinforced layer). For that, before starting the electrochemical measurements a pachometer based on electromagnetic currents emission was used for the upper rebar location. As the position of deep reinforced layers are not easy to locate (due to the 50 cm of concrete thickness), some interferences coming from this mesh were detected in some cases.

2.2. Experimental techniques

The techniques used are in all cases of non-destructive nature and they are able to determine electrochemical parameters, which inform about the qualitative or
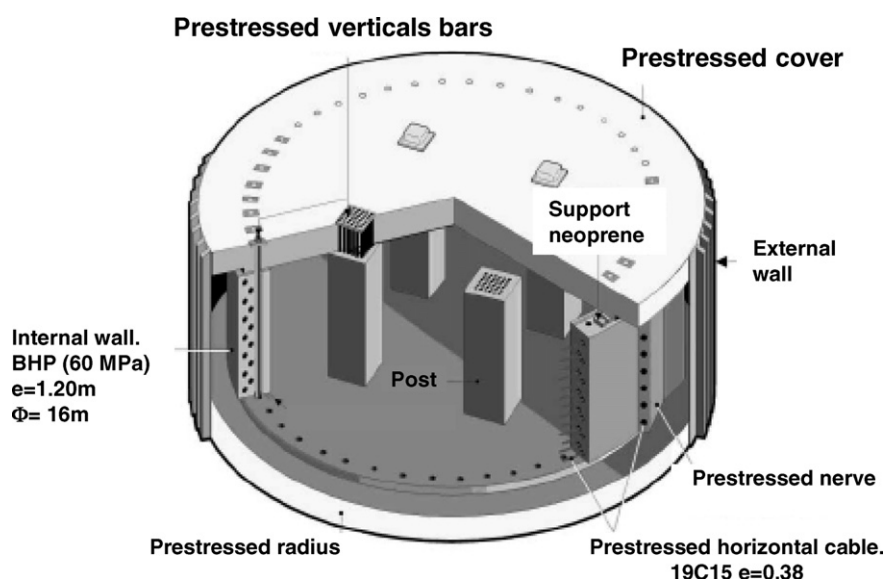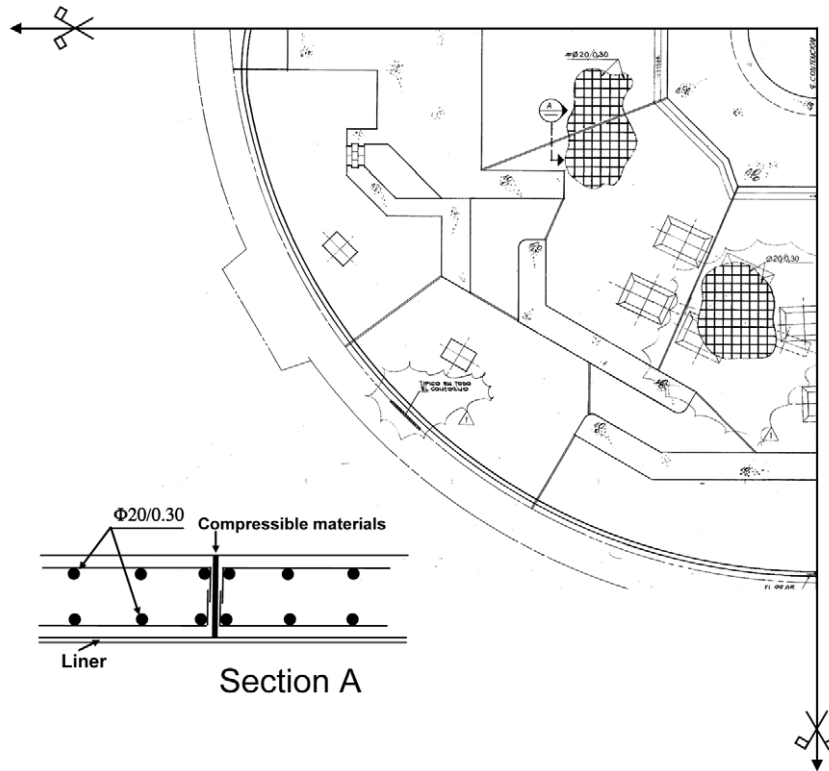

Fig. 1. General containment structure.

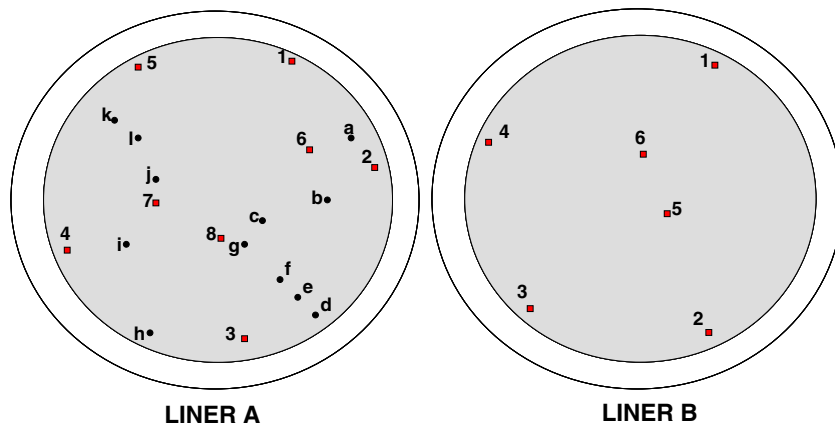Fig. 2. Slab scheme in which the liner structure is attached.

Fig. 3. Electrochemical measurement areas and water extracting points indicated in Liner A and Liner B.

quantitative corrosion of the metal components embedded into the concrete [7]. In all of them, an electrical contact with the metal (ground connection) is needed. The electrochemical parameters registered in this study have been:

- Corrosion potential (E_{corr}).
- Corrosion rate (I_{corr}).
- Concrete resistivity (ρ).
- Passivity verification technique (PVT).

The portable device used for all these electrochemical measurements was the corrosion rate meter Gecor 08 (Fig. 4). It has different measurement options and sensors

to measure the electrochemical parameters by the methods and techniques described before.

2.2.1. Corrosion potential measurement

The main objective of potential measurements on a structure is to locate areas in which metal embedded into the concrete has become depassivated and hence, is able to corrode if appropriate oxygen and moisture conditions occur.

To measure the half-cell potentials on a structure, a good electrical connection to the metal has to be made. The other input of the high impedance voltmeter must be the external reference electrode placed on a wet sponge

Fig. 4. Corrosion rate meter Gecor 8.

located on the concrete surface in order to provide a good electrolytic contact between them. The sponge should be always wetted with water.

It is completely necessary to assure the electrical continuity of the reinforcement steel. In this case, as all the metal components (rebars and liner) are connected to the ground, the continuity is always assured for all measurements.

The interpretation of the potential readings has evolved in the last few years. According to ASTM C 876 Standard [9], a threshold potential value of −350 mV CSE was established. Lower values of potential suggest corrosion with 95% probability; if potentials are more positive than −200 mV CSE, there is over 90% probability that no reinforcement steel corrosion occurs. For those potentials between −200 mV and −350 mV, corrosion activity is uncertain.

Type of reference electrodes used. The unpolarizable reference electrodes (Calomel, Cu/CuSO$_4$ or Ag/AgCl) are more accurate than other types (carbon, for instance). Finally, temperature also influences the potential, being the unpolarizable electrodes the most reversible ones. Copper/copper sulphate electrode is the most used one for in situ potential measurement, and thus, it was used for this evaluation.

2.2.2. Concrete resistivity

The method used for on-site concrete resistivity determination is the one called 'Disc method' (Figs. 5 and 6).
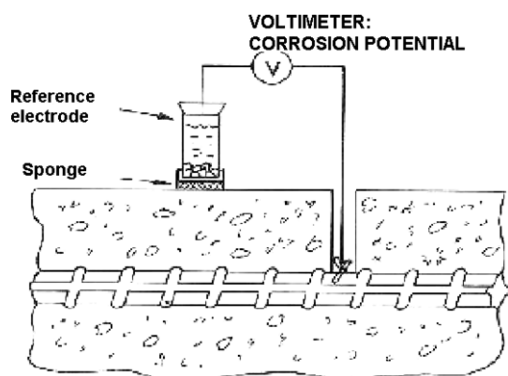

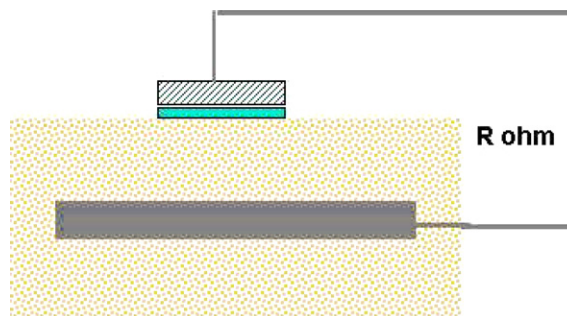Fig. 5. Potential measurement of concrete reinforcement.

Fig. 6. Disc method.

Based on Newman's [10] work, and fully developed by Feliú et al. [11], it estimates the ohmic drop from the resistance between a small disc placed at the surface of an electrolyte and a much larger counter electrode placed at infinity. It is demonstrated that electrical resistance is a function of the resistivity of the electrode, and it can be calculated from the expression:

$$\rho = 2 \cdot R_e \cdot \phi. \tag{1}$$

A conductive material disk, a galvanostat and a reference electrode compose the device. Once good contact between electrode and concrete is obtained, a galvanostatic pulse is applied and then, the ohmic drop is recorded from the instant response. Distance between disk and rebar has to be at least two times the disk diameter. Resistivity units frequently used are Ω m or kΩ cm. The range of values frequently measured in concrete and its relation with corrosion risk is presented in Table 1.

2.2.3. Corrosion rate

The measurement of the corrosion current is made by means of a reference electrode, which indicates the electrical potential, and an auxiliary electrode, which gives the current. The working electrode is the metal element that wants to be evaluated.

The most used technique to measure corrosion current is the so-called polarisation resistance, R_p, which is based in very small polarisations around the corrosion potential

$$R_p = \frac{\Delta E}{\Delta I} \quad \Delta E < 20 \text{ mV}. \tag{2}$$

The corrosion current I_{corr} is inversely proportional to R_p by means of the following relation [12]:

Table 1
Relation between concrete resistivity and corrosion rate

Resistivity (kΩ cm)	Corrosion risk
>100–200	Negligible corrosion, concrete too dry
50–100	Low corrosion rate
10–50	Moderate to high corrosion when steel is active
<10	Resistivity is not the controlling parameter of the corrosion rate

Table 2
Relation between corrosion rate and level of corrosion

Corrosion rate, I_{corr} (μm/year)	Corrosion intensity, I_{corr} (μA/cm^2)	Corrosion level
<1	<0.1	Negligible
1–5	0.1–0.5	Low
5–10	0.5–1	Moderate
>10	>1	High

$$I_{corr} = \frac{B}{R_p}, \tag{3}$$

where B is a constant, which oftenly takes the value of 26 mV [13].

So, as the B constant is given in mV, and the polarization resistance is given commonly in kΩ cm^2 (as always must be refereed to a certain steel area), the most used units for the corrosion rate are μA/cm^2.

Concerning the interpretation of the values of the corrosion current, Table 2 gives the ranges linked to the corrosion level [14].

The electrolyte resistance against the current applied, R_e must be taken into account when R_p measurement is made. The R_T calculated is the sum of the resistance associated with the actual corrosion process and the resistance associated with the electrolyte resistance (concrete) [14]

$$R_T \text{ (calculated)} = R_p \text{ (corrosion)} \\ + R_e \text{ (electrical resistance)}. \tag{4}$$

The devices to be used for on-site measurements have to be able to calculate the ohmic drop (IR) or to compensate for its influence during the recording of the R_p measurement.

2.2.3.1. Modulated confinement of the current: guard ring method. There are several ways of accounting for a true I_{corr} value when measuring on-site, among which the most extended one (and used for present experimentation) is the use of a guard ring [15] aimed at confining the current in a particular rebar area, as Fig. 7 depicts. The measurement is made by applying a galvanostatic step (minimum of 5 μA), lasting 30–100 s, from the central counter. Then, another counter current is applied from the external ring, and this external current is modulated by means of the two reference electrodes called 'ring controllers' in order to equilibrate internal and external currents, which enables a correct confinement, and therefore, calculation of R_p. By means of this electrical delimitation to a small zone of the polarized area, any localised spot or pit can be localised.

As this parameter is measured as a current density (μA/cm^2) it is necessary to determine the metal area affected by the electrical signal applied. The confinement system concentrates the measurement area into a cylinder projected under the sensor of 10.5 cm in diameter. That is, all metallic components embedded in the concrete and situated in
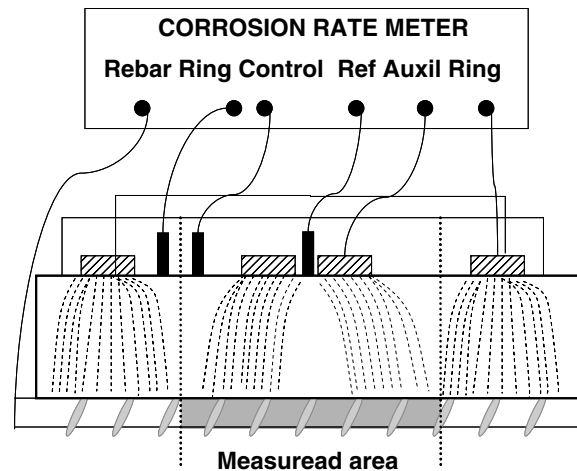

Fig. 7. Modulated confinement system.

this volume must be taken into account for the I_{corr} calculation.

The technique has been calibrated by its comparison with gravimetric tests, and good results were obtained [16].

In the cases reported in this paper, the first reinforced layer has been avoided, so, it was considered that not only the liner, but also part of the deeper reinforced layer are being measured together (total steel area considered for the corrosion rate measurements 152.6 cm^2).

2.2.4. Passivity verification technique (PVT)

This technique has been recently developed and it is used for the determination of the passive state of a metallic component embedded in concrete [17]. It is used as a qualitative technique that determines whether the metal is corroding or not when it is not possible to measure the corrosion rate by the quantitative method. It is used when external currents are affecting the metal regularly (when a cathodic protection system is connected) or eventually (due to erratic currents), causing misunderstandings in the corrosion rate results.

The technique is based on electrochemical impedance spectroscopy (EIS) in a low range of frequencies (from 100 to 0.01 Hz). The PVT technique is applied by means of the commercial portable corrosion rate meter (Gecor 8), that gives an indication on the passivity based in a percentage of protection. The mode that the PVT operates in is that it detects whether a semicircle appears or not over the range of frequencies of 0.1–0.01 Hz. If no semicircle appears, the passivity is considered (conventionally) higher than 90% and classified as WELL PROTECTED. If a semicircle appears, depending on the phase angles measured in that frequency range, the classification decided for practical purposes is MODERATELY PROTECTED or NON-PROTECTED. An external circular sensor with a current confinement system is placed on the concrete surface over the metal to be tested (rebar is located prior to positioning the electrode), assuring the electrolytic contact

Fig. 8. Arrangement used for PVT and corrosion rate measurements.

Table 3
pH measured in the water detected under the slab of Liner A

Extracting point	pH				
	Feb-05	May-05	Mar-05	Apr-05	Oct-00
a	–	–	–	–	12.6
b	–	8.46	–	–	–
c	–	–	–	–	10.16
d	–	–	12.58	–	–
e	–	–	–	12.59	
f	–	–	–	–	12.75
g	–	–	–	8.2	–
h	–	–	–	–	11.57
i	–	8.63	10.89	–	–
j	7.53	8.17	–	–	–
k	–	11.49	12.3	–	–
l	–	–	–	–	8.32

between them by a wet sponge. An electrical contact with the metal is also needed for the electrical circuit to be closed.

Both techniques, corrosion rate measurements by modulated confinement and PVT, were performed with the same arrangement, as is shown in Fig. 8.

3. Results

3.1. pH measurements

Some water samples were taken in different points under the slab of Liner A. Before starting the electrochemical liner evaluation, the pH of the water was measured in the different samples taken at different times. Results are summarized in Table 3. The values correspond to alkaline pH, and all of them were in the range 7.5–12.7, depending on the extracting point and the date of sample extraction.

3.2. Electrochemical techniques

Table 4 presents the summary of all the electrochemical measurements taken from Liner A and Liner B.

3.2.1. Corrosion potential (E_{corr})

Fig. 9 presents the corrosion potential values (vs Cu/CuSO$_4$) measured in the eight areas evaluated in Liner A. Almost all values are in the range between −250 and −350 mV. In this range, information about corrosion risk is not clear, as it was explained previously in this paper. Points 1, 2 and 3 presents a corrosion potential value more negative than −350 mV, so, these areas are the most susceptible for suffering corrosion.

Fig. 10 presents the corrosion potential values (vs Cu/CuSO$_4$) measured in the six areas evaluated in Liner B. In this case, a comparison about the influence of the paint over the concrete surface in the corrosion potential measurement has been done. In general, slightly more negative potentials are measured when placing the reference electrode over the

Table 4
Corrosion potential, resistivity, corrosion rate and PVT results obtained in Liner A and Liner B

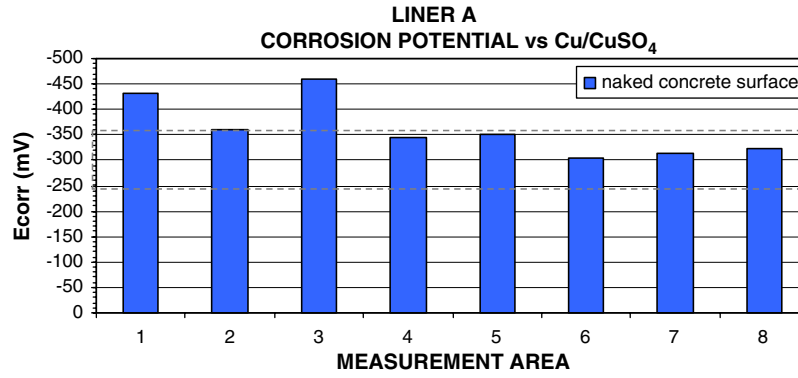| Point	Non-painted concrete surface				Painted concrete surface	
	E_{corr} (mV)	ρ (kΩ cm)	I_{corr} (µA/cm^2)	PVT	E_{corr} (mV)	ρ (kΩ cm)
Liner A						
1	-432.840	3.6	0.638	–	–	–
2	−361.726	5.0	0.185	–	–	–
3	−460.000	13.5	–	–	–	–
4	−343.943	13.0	0.031	–	–	–
5	−350.498	–	0.409	–	–	–
6	−303.178	9.0	0.415	–	–	–
7	−315.124	–	0.106	–	–	–
8	−324.143	–	0.123	–	–	–
Liner B						
1	−348.16	6.61	0.351	Well protected	−285.36	231.88
1b	-306.742	5.708	–	Moderately protected	−285.36	231.88
2	−243.01	7.01	0.119	Moderately protected	231.88	147.06
3	−214.89	9.75	0.037	Well protected	−171.18	138.40
4	−264.60	6.41	0.219	Well protected	−266.57	525.63
5	−181.29	6.09	0.080	Moderately protected	−139.86	726.75
6	−183.27	9.35	0.131	Well protected	−149.01	1244.24

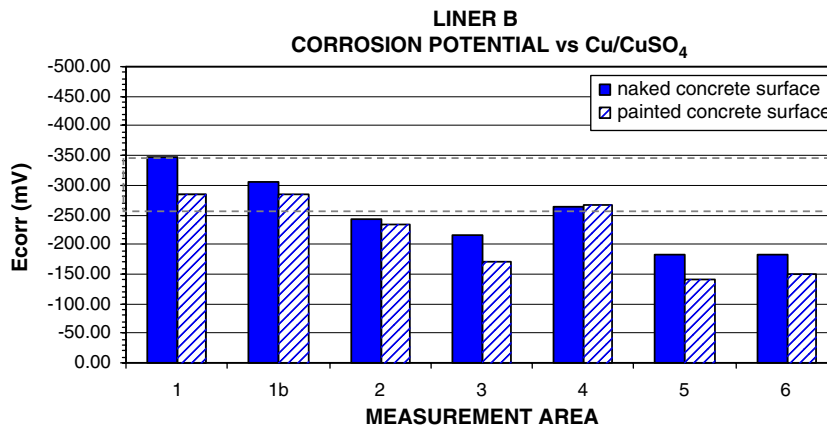Fig. 9. Liner A: corrosion potential vs Cu/CuSO₄.

Fig. 10. Liner B: corrosion potential vs Cu/CuSO₄.

non-painted concrete surface. The registered values indicate that there is not a high corrosion risk (as no values more negative than −350 mV are found) (Table 4).

3.2.2. Concrete resistivity (ρ)

Fig. 11 shows the resistivity values measured in the slab over Liner A. They are between 3.6 and 13.5 kΩ cm (under the threshold value of 100 kΩ cm) (Table 4), which

indicates that the concrete was wet when taking the measurements.

As in the previous parameter, a comparison between resistivity measurements made in the naked concrete surface and in the painted concrete surface was made in Liner B. Fig. 12 shows that when measuring through the paint, resistivity values are higher than when measuring in the naked concrete surface (it seems logical, as the paint always acts as an extra resistance layer). When measuring in areas
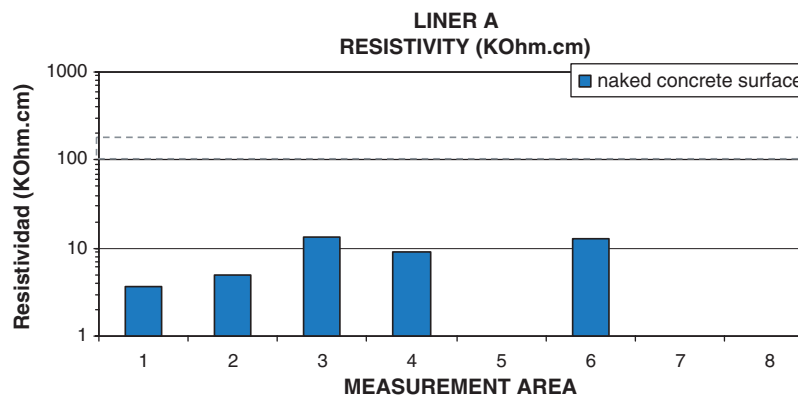

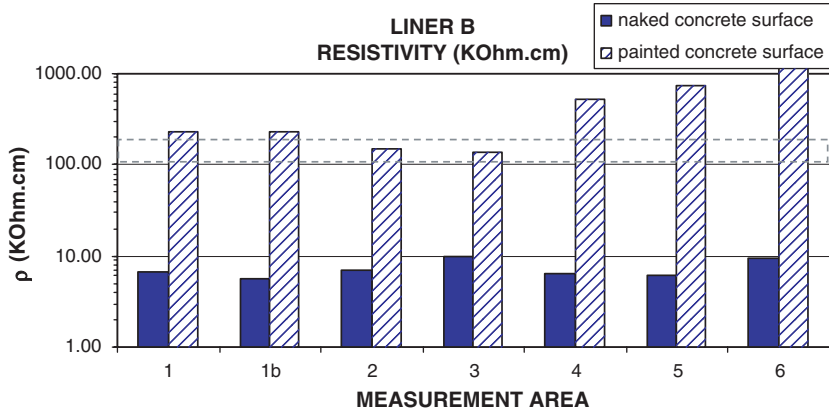Fig. 11. Liner A: concrete resistivity measurements.

Fig. 12. Liner B: concrete resistivity measurements.

without paint, resistivity values are in all cases lower than 10 kΩ cm, which indicates that, as in the previous case, the concrete attached to the liner is quite wet.

3.2.3. Corrosion rate (I_{corr})

Figs. 13 and 14 show the quantitative corrosion rate values measured in Liner A and Liner B, respectively. Following the criteria presented in Table 2, only one (measurement area number 1 in Liner A) of the 14 areas evaluated in both

Liner A and Liner B has a moderate corrosion value (between 0.5 and 1 µA/cm^2). Remaining points show negligible or low corrosion rate values.

3.2.4. Passivation verification technique (PVT)

As a complement to the rest of the electrochemical measurements already described, the passivation verification technique was also applied in some areas of Liner B. Results presented in Fig. 15 indicate that none of the six
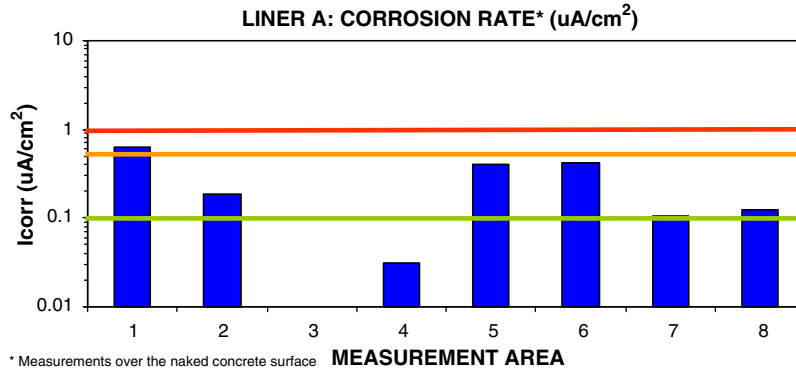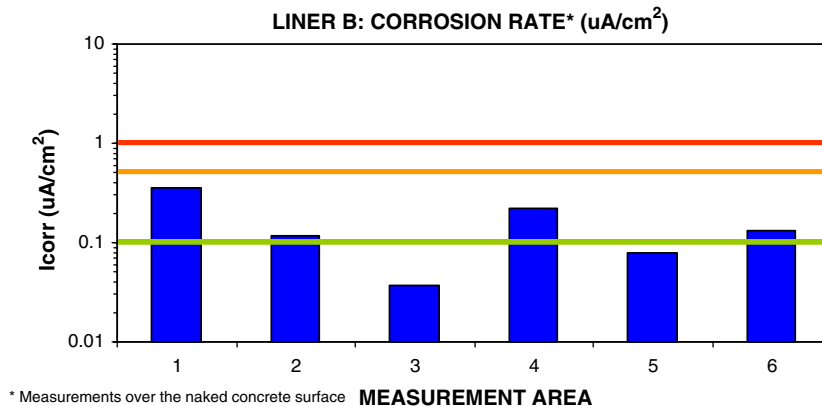

Fig. 13. Liner A: corrosion rate measurements.

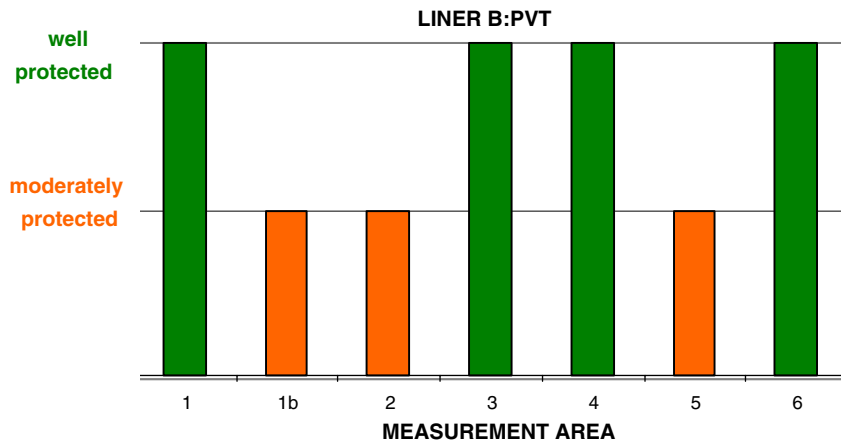Fig. 14. Liner B: corrosion rate measurements.

Fig. 15. PVT measurements taken during the inspection.

areas evaluated with this technique have high corrosion activity, because all are 'well protected' or 'moderately protected'.

4. Discussion

4.1. Considerations about pH

The pH is an important parameter to determine whether the metals in contact with the aqueous solution are at corrosion risk or not. This information can be obtained from Pourbaix diagrams [8]. These diagrams represents pH of the electrolyte vs the corrosion potential of the metal at a certain temperature. Even when these are thermodynamic diagrams, they allow for different areas in which the metal is in a corrosion, passivity or immunity state to be identified.

As water sampling to measure the pH and the E_{corr} measurements have been taken at different points and, in some cases, also at different times, the values of pH and E_{corr} have been correlated taking care of a proximity criterion. Thus, for the sake of analysis, the pairs of E_{corr} pH values has been assigned by proximity between the point of taking of water sample and the corrosion measurement point. Fig. 16 shows the Pourbaix diagram of Fe at 25 °C, in which the experimental results for Liner A are presented.

The corrosion potential values measured are all between −300 and −450 mV (Table 4), and the pH values went from 7.5 to 12.8 (Table 3). As shown in Fig. 16, for the corrosion potential range measured in Liner A, Fe will be corroded if pH is below 8. For more alkaline pH, Fe will remain passivated unless the corrosion potential reaches values of around −600 mV or more negative. Then, it is expected that the liner is passive except at the points where the pH has decreased below 8. However, that point shows a corrosion rate of 0.11 µA/cm^2, which although is above the threshold of passivity (Table 2), it is not the highest value measured. This is not an unexpected consideration, because the E_{corr} is only giving qualitative indications and the oxides formed and their aging plays an important role in its
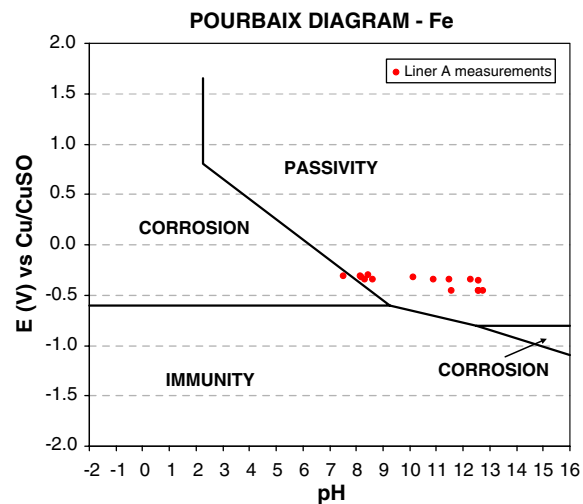

Fig. 16. Pourbaix diagram for Fe at 25 °C.

value, and therefore, the E_{corr} value gives some indication on the risk, but does not quantify the actual situation.

Regarding the pH value, it has to be added that additional ions also play an important role. Thus, whether there are carbonates, sulphates or nitrates, for the same pH the activity/passivity state can change. Then, Pourbaix diagrams are helpful to show certain trends, but the results cannot be taken as conclusive.

4.2. Electrochemical parameters

Fig. 17 shows the plotting of the E_{corr} and I_{corr} values measured in the 14 points selected. Then, both parameters are taken in the same place.

In this figure, the criteria given in [9] are shown with dotted lines, which indicate that the corrosion rate values are 'negligible' when corrosion potential are less negative than −250 mV(vs Cu/CuSO$_4$), and are 'moderated' when the corrosion potentials are more negative than −350 mV. In the range between −250 and −350 mV negligible, low and moderate corrosion rate values are expected.
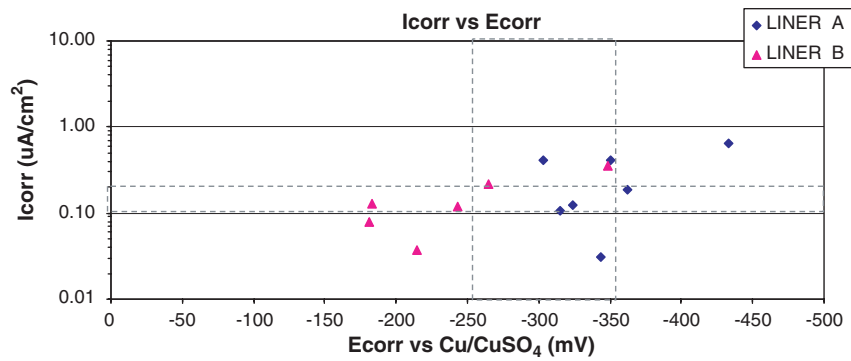
Fig. 17. I_{corr} vs E_{corr}.

So, there are some points showing I_{corr} values <0.1 μA/cm^2, while the E_{corr} is more cathodic than −250 mV. Thus, even when measured at the same point, the E_{corr} is not a suitable parameter to distinguish between activity and passivity. Only the I_{corr} provides a quantitative indication.

4.2.1. Relation between resistivity (ρ) and I_{corr}

In order to compare both parameters, let us start by presenting some considerations on their meaning. The *electrical resistivity* of concrete is one of the most influencing material parameters concerning to corrosion intensity. The resistivity of a given structure provides information about how wet is the concrete and therefore on the risk of corrosion damage. There is a linear relationship between corrosion rate and electrolytic conductivity, that is, low resistivity is correlated to high corrosion rate (Table 1). However, it is necessary to point out that corrosion rate is only controlled by concrete resistivity, when there is an active corrosion process. If the metal is at a passive state, the resistivity (water content of concrete) does not influence the value of corrosion rate.

The measurement of the *corrosion current* gives the quantity of metal that goes into oxides by unit of reinforcement surface and time. The amount of oxides generated is directly linked with the cracking of concrete cover and the loss in steel/concrete bond, while the decrease in steel cross-area in addition significantly affects the load-bearing capacity of the structure. The rate of corrosion is therefore an

indication of the rate of the structural load-carrying capacity decrease. The main consequences of reinforcement corrosion are:

- The loss of section of steel.
- The loss of ductility of the steel.
- The loss in bond between steel and concrete.

Apart from the calculation of the loss in rebar cross-section, the corrosion current may be used to identify corroding zones in the same manner as potential mapping.

Considering that concrete resistivity (measured at the nude concrete surface) is in all cases between 3 and 13 kΩ cm, the possibility of a certain corrosion risk is high as the concrete seems to be very wet. To confirm whether this wet condition is or is not inducing corrosion, a graphic correlation of both parameters is given in Fig. 18. This plot indicates that the threshold in corrosion current of 0.1 μA/cm^2 is related to resistivity values of 9–10 kΩ cm^2, one order of magnitude smaller than the measured in normal concrete structures [18]. This non-usual behaviour can be due to the fact that here the metal is a plate and not only a longitudinal bar, and therefore the normal ranges of correlation can be different due to the different geometry of the liner with respect to reinforced concrete with bars.

4.2.1.1. Calculations of loss of metal section from I_{corr} values. The simple comparison of the corrosion rate, I_{corr},
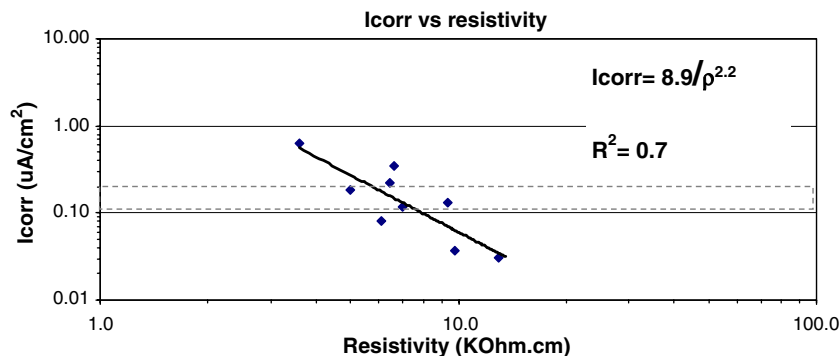
Fig. 18. I_{corr} vs resistivity.

values with the ranges in Table 2 helps to classify the corrosion risk in levels [14]. However, the accumulated corrosion or the attack penetration P_x can be calculated from the expression:

$$P_x = 0.0115 \cdot I_{corr}^{REP} \cdot t_p, \qquad (5)$$

being I_{corr}^{REP} the representative value of I_{corr} during the period t_p; t_p = the time in years after corrosion started and 0.0115 a conversion factor of μA/cm² into mm/year (for the steel). This expression implies the need to know when the corrosion has started in order to account for t_p.

When the corrosion is localised, the maximum pit depth can be calculated by multiplying expression (5) by a factor named α, which usually takes a value of 10 [19]. Hence expression (5) above becomes

$$P_{pit} = 0.0115 \cdot I_{corr}^{REP} \cdot t_p \cdot \alpha = 0.115 \cdot I_{corr}^{REP} \cdot t_p. \qquad (6)$$

Then, taking into consideration the life of the structure, the maximum instantaneous value measured in the liner evaluation, if considered as a representative corrosion rate value, will produce a maximum penetration attack of 6.6 μm/year (following expression (5)). Applying the α factor = 10 for the calculation of the maximum pit depth (6), the P_{pit} calculated could reach 66 μm/year for this maximum experimental value measured. Considering the initial liner thickness (6 mm), and applying the previous calculations, it will be necessary more than 90 years (since the initiation of the corrosion process) for a total loss of the liner in a certain point due to a corrosion pitting problem.

That is, some areas of the liner are actively corroding, however, the corrosion rate detected even if it is localised, will not drill the liner in the 30–60 years of assumed life of the power plant.

5. Conclusions

In spite of the differences with normal reinforced concrete, non-destructive electrochemical techniques here applied seems to be an appropriate tool for the evaluation of this sort of structures, where visual inspection is not an easy task. Even when corrosion potential and resistivity parameters provides fast and important information about the corrosion probability, the only parameter capable of quantifying the speed of the metal being transformed into oxide is the corrosion rate, I_{corr}. Corrosion rate measurements provide a tool to determine when the liners could lose their integrity.

The most relevant conclusions extracted from the electrochemical measurements made in the two liners evaluated are:

- pH measurements in the water that wets the concrete, indicates if a metal in contact with this electrolyte could be at a corrosion risk situation (introducing experimental data into the Fe-Pourbaix diagram).
- The resistivity values indicate how wet is the concrete. It seems that it has a high moisture content in both liners, enabling a relatively high corrosion risk for the metals embedded in the concrete.
- From the corrosion rate values registered, it can be concluded that some areas were corroding at the moment when measurements were taken. The maximum corrosion rate value measured was 0.6 μA/cm², which can be translated as an expected metal loss in that area of 66 μm/year. Considering the initial metal thickness (6 mm), this estimated loss would not cause a failure in the liner integrity during its service life.

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