

## Long-Term Corrosion Behavior of Cr Alloyed Steels in Aqueous CO<sub>2</sub> Environments Containing Chlorides

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### ABSTRACT

This study evaluated the long-term corrosion behavior of 1Cr and 3Cr steels in aqueous environment containing carbon dioxide and chlorides. Tests lasting from 25 to 61 days were conducted using a 5 L glass cell with multiple steel samples, uniform hydrodynamic conditions, and controlled water chemistry. All tests were performed at 80°C, CO<sub>2</sub> partial pressure of 0.52 bar and moderate wall shear stress (~2 Pa). Both 1Cr and 3Cr steels exhibited comparable corrosion rates from 3 to 1 mm/y for up to about 25 days of exposure. However, between 25 to 35 days of exposure, a sharp decrease in corrosion rate and an abrupt increase in open circuit potential was measured for 3Cr steel samples indicating the occurrence of a pseudo passivation process. On the other hand, 1Cr steel maintained high corrosion rates between 1 and 1.5 mm/y while exposed for up to 61 days. The better long-term performance of 3Cr steel would be related to the formation of a pseudo passive protective film consisting of chromium oxy-hydroxide and spinel oxide, favored by its larger chromium content and the more uniform and compact precursor chromium hydroxide layer formed on this material.

Key words: 3Cr steel, long-term testing, pseudo passivation, controlled water chemistry

### INTRODUCTION

The demand for cost-effective alloy steels with improved corrosion resistance in oil and gas production environments has led to the development of low-chromium (Cr) alloyed steels, such as 3Cr steel.<sup>1-4</sup> Positioned between carbon steel and corrosion resistant alloys (CRAs), 3Cr steel offers enhanced corrosion resistance at a significantly lower cost than CRAs. The improved performance of these steels

is largely attributed to Cr additions, which promote the formation of more stable and protective corrosion product layers and reduces corrosion rates.

In CO<sub>2</sub> environments, the corrosion behavior of steels is strongly governed by the formation and stability of corrosion product layers. For carbon steels, iron carbonate (FeCO<sub>3</sub>) is typically the predominant corrosion product under conditions favorable for its precipitation, often forming dense, adherent layers that reduce corrosion rates.<sup>5-7</sup> In contrast, the corrosion resistance of low-Cr steels arises primarily from the rapid formation of Cr-enriched hydroxide and/or oxyhydroxide layers. These layers, which can form within minutes to hours of exposure, block anodic and cathodic active sites, limit ionic transport and reduce corrosion rates by factors of 2-5 compared to steels without Cr.<sup>8-11</sup>

Beyond these Cr-enriched layers, additional corrosion products may develop over time. It has been reported that Cr<sup>3+</sup> ions in solution can promote the nucleation and growth of inner or outer FeCO<sub>3</sub> layers<sup>9</sup>, but this has often been linked to uncontrolled water chemistry in the laboratory experiments, where Fe<sup>2+</sup> ions accumulate in excess near the steel surface and in the bulk solution. In contrast, long-term field studies have also shown the formation of chromite (FeCr<sub>2</sub>O<sub>4</sub>) spinel oxides in the corrosion product of 3Cr steel.<sup>1</sup> Such Cr-enriched spinel phases, often accompanied by amorphous or nanocrystalline oxides/hydroxides, provide a more compact, adherent, and stable barrier than FeCO<sub>3</sub> alone. These layered structures can further restrict ionic transport and enhance long-term protectiveness, even under conditions where FeCO<sub>3</sub> precipitation is thermodynamically unfavorable.<sup>12</sup>

Despite these benefits, the long-term stability of Cr-enriched films and their interaction with secondary corrosion products remain insufficiently understood. Most studies have focused on short-term layer formation, while the evolution of layered structures over extended exposures and their role in sustaining corrosion resistance has been largely overlooked.

To address this gap, the present study compares the long-term corrosion behavior of 1Cr and 3Cr steels in a controlled CO<sub>2</sub>-containing environment with chlorides where FeCO<sub>3</sub> precipitation is suppressed. This approach isolates the influence of chromium enrichment and subsequent corrosion product layer evolution, allowing a clearer evaluation of how multi-layered corrosion product layers form, stabilize, and control corrosion rates. The results aim to clarify the corrosion mechanisms of low-Cr steels in CO<sub>2</sub>-rich systems, inform alloy selection for field applications, and support the development of predictive models for long-term performance.

## EXPERIMENTAL PROCEDURE

Steel specimens were prepared from 1Cr and 3Cr steels in a rectangular shape (1.25 cm × 1.25 cm × 0.3 cm) for use in both electrochemical measurements and surface characterization. The surfaces were progressively polished with silicon carbide papers of 180, 400, and 600 grit, followed by ultrasonic cleaning in isopropyl alcohol and subsequent drying. To ensure single-sided exposure, the opposite face and lateral areas were either coated with polymer (specimens intended for surface analysis) or embedded in epoxy (specimens intended for electrochemical measurements).

Figure 1 illustrates the schematic of the experimental system. Corrosion experiments were conducted in a 5 L glass cell configured as a three-electrode electrochemical setup, with a rectangular steel specimen as the working electrode (WE), a platinum-coated titanium mesh as the counter electrode (CE), and a saturated Ag/AgCl electrode as the reference electrode (RE). The apparatus included a hot plate with temperature control, a pH probe, a sparging tube connected to a purified CO<sub>2</sub> inlet, and a condenser attached to the outlet. A total of seven ports were mounted in PEEK holders for specimens at an equal radial distance (7 cm) from the cell center. Hydrodynamic conditions were generated by a Rushton-type impeller rotating at 90 rpm, corresponding to a flow velocity of 1.5 m/s in a 0.1 m inner-diameter pipe to achieve equivalent mass transfer characteristics. The solution-to-specimen surface area ratio was

maintained at 3.36 mL/mm<sup>2</sup>. All specimens were exposed to the same hydrodynamic and mass transfer conditions.

To regulate the Fe<sup>2+</sup> and Cr<sup>3+</sup> concentrations, the setup incorporated a recirculation pump and a flow-through column filled with Na-form ion-exchange resin. The resin removed Fe<sup>2+</sup> and Cr<sup>3+</sup> ions from the electrolyte while simultaneously releasing Na<sup>+</sup> to maintain charge neutrality. Further details on the configuration can be found elsewhere.<sup>13,14</sup>

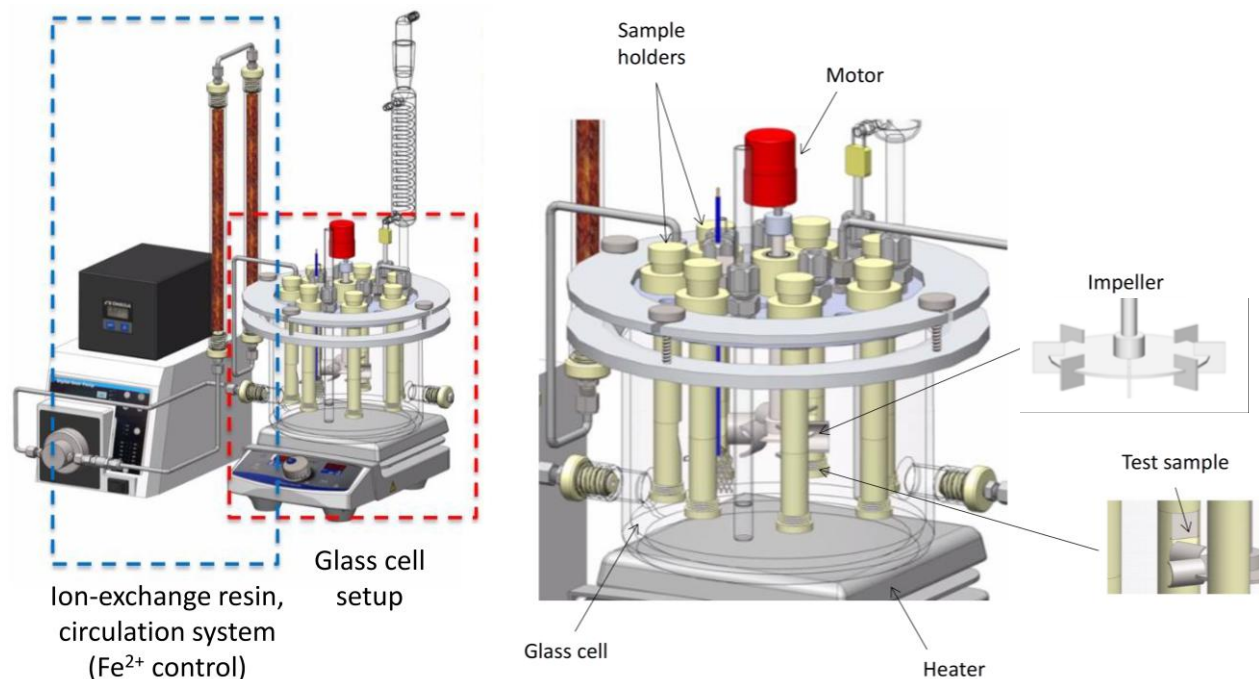


**Figure 1: Schematic of the multi-specimen glass cell with circulation system through ion-exchange resin.**

Table 1 summarizes the experimental conditions used in this study. Three independent tests were conducted under these conditions, with exposure durations of 25, 51, and 61 days for both 1Cr and 3Cr steels. For each test, the specimens were mounted in the specimen holders as follows:

- One 1Cr steel specimen for electrochemical measurement.
- One or two 1Cr steel specimens for surface analysis and weight loss measurement.
- One 3Cr steel specimen for electrochemical measurement.
- One or two 3Cr steel specimens for surface analysis and weight loss measurement.

Test solution was prepared using deionized water and analytical grade NaCl with a concentration of 40,000 mg/L. Prior to specimen immersion, the solution was purged with CO<sub>2</sub> for at least 2 h to minimize oxygen, ensuring dissolved oxygen levels remained below 5 ppb, as verified with an Orbisphere™ analyzer. The starting pH was adjusted with deoxygenated NaHCO<sub>3</sub>, and during testing, the pH was maintained at 5.5 ± 0.15 by carefully adding deaerated HCl or NaHCO<sub>3</sub>. The solution temperature was kept constant at 80°C. The Fe<sup>2+</sup> concentration was monitored once or twice daily using UV/Vis spectrophotometry. The electrolyte was circulated through a Na-form ion-exchange resin column at flow rates of up to 250 mL/min as needed to keep the concentration < 10 mg/L. This process stabilized the Fe<sup>2+</sup> level and maintained the bulk FeCO<sub>3</sub> saturation ratio ( $S_{\text{FeCO}_3}$ ) below unity.

Electrochemical evaluation of steel corrosion was carried out using open-circuit potential (OCP) monitoring and linear polarization resistance (LPR) measurements. For LPR measurement, the potential was scanned from -10 mV to +10 mV relative to the OCP at a scan rate of 0.166 mV/s. The LPR

measurements were repeated every 3 hours. The polarization resistance ( $R_p$ ,  $\Omega$ ) obtained from LPR measurement was used to calculate the corrosion current density ( $i_{corr}$ , A/m<sup>2</sup>) by using Equation (1):<sup>15</sup>

$$i_{corr} = \frac{B}{SR_p} \quad (1)$$

where  $S$  is the specimen surface area (m<sup>2</sup>). A  $B$  value of 13 mV was used in the present study which was obtained from the weight loss corrosion rate. Then, the  $i_{corr}$  was converted into corrosion rate ( $CR$ , mm/y) using Equation (2):<sup>16</sup>

$$CR = \frac{3.27 \times 10^{-11} \cdot i_{corr} \cdot EW}{\rho} \quad (2)$$

where  $EW$  is the equivalent weight (kg) and  $\rho$  is the density (kg/m<sup>3</sup>) of iron, and  $3.27 \times 10^{-11}$  is a constant factor for unit conversion to mm/y.

**Table 1: Parameters used in corrosion tests**

| Parameter                           | Description                                                   |
|-------------------------------------|---------------------------------------------------------------|
| Materials                           | 1 wt.% Cr steel<br>3 wt.% Cr steel                            |
| Partial pressure of CO <sub>2</sub> | 0.53 bar                                                      |
| Temperature                         | 80°C                                                          |
| Solution pH                         | 5.5 (adjusted by NaHCO <sub>3</sub> )                         |
| Chlorides (Cl <sup>-</sup> )        | 24,000 mg/L                                                   |
| Solution volume                     | 4.5 L                                                         |
| Flow velocity                       | Impeller 90 rpm (equivalent to 1.5 m/s in a 0.1 m ID pipe)    |
| Control of Fe <sup>2+</sup>         | Maintained < 10 mg/L with Na <sup>+</sup> ion exchange resin  |
| Control of Cr <sup>3+</sup>         | Maintained < 0.1 mg/L with Na <sup>+</sup> ion exchange resin |
| Dissolved O <sub>2</sub> content    | < 5 ppb                                                       |
| Control of solution pH              | Manual injection of deaerated HCl or NaHCO <sub>3</sub>       |

Following the corrosion tests, ex-situ characterization of the corrosion product layers was carried out using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), and Raman spectroscopy. For cross-sectional examination, specimens were embedded in epoxy resin and then prepared and analyzed.

## RESULTS

Figure 2 shows the LPR corrosion rates of 1Cr and 3Cr steels as a function of exposure time, obtained from tests of different durations. Figure 3 shows the corresponding open circuit potential (OCP) values measured for all tested steels. During the 51-day test, the 1Cr steel specimens were retrieved after 34 days of exposure because the electrical connection with the potentiostat was interrupted. For 1Cr steel, the initial corrosion rates ranged from 2.5 to 3.6 mm/y, reaching maximum values between 2.9 and 5.1 mm/y within the first 5-10 days of exposure. The 3Cr steel exhibited slightly lower corrosion rates, with initial values between 2.3 and 3.3 mm/y and maximum values between 2.9 and 4.2 mm/y.

For exposure times longer than 5-10 days, corrosion rates of both steels started decreasing gradually. However, between 20 and 35 days, 3Cr showed a marked change in behavior, with corrosion rates abruptly dropping from  $\sim 2$  mm/y to  $\sim 0.3$  mm/y or lower. This sharp reduction appears to be associated with a spontaneous pseudo passivation of the 3Cr steel surface, as evidenced by a sudden increase in OCP values (20-30 mV above the preceding values, see Figure 3). It is noteworthy that this sudden increase in OCP occurred only after the corrosion rate had already decreased by more than a factor of two from its initial, gradually declining trend, which had been accompanied by a slow increase in OCP. For instance, the 3Cr specimen tested for 25 days (black squares in Figures 2b and 3b) did not reach full pseudo passivation before the end of the exposure period. The abrupt change in OCP is likely related to the formation and consolidation of a protective corrosion product layer that effectively blocks active sites on the metal surface.

Furthermore, based on the corrosion rate and OCP trends observed in the 61-day exposure test (blue triangles in Figures 2b and 3b), additional consolidation of the pseudo passive layer appeared to occur after 50-55 days, as indicated by another period of accelerated OCP increase and concurrent corrosion rate reduction. It is worth mentioning that the onset of pseudo passivation exhibited a temporal dispersion of roughly 10 days. Specifically, the reduction in corrosion rate began around 20 days in the 25-day test, whereas it was delayed until  $\sim 30$  days in the longer exposure tests. Given that the environmental conditions (e.g., temperature and solution chemistry) were maintained within relatively narrow limits, this variation could be attributed to slight differences in the Cr content among specimens. These differences may have arisen because the samples were machined from both the inner and outer walls of a seamless tubing section. Unfortunately, no compositional data were available to verify this hypothesis.

In contrast, 1Cr steel did not exhibit pseudo passivation, and its corrosion rates remained relatively high ( $\sim 1$  mm/y or greater), even after 61 days of exposure. The OCP values of 1Cr and 3Cr steels evolved similarly before pseudo passivation of 3Cr steel. However, the OCP values of 1Cr steel remained constant or showed only a slight increase for longer exposure times, while 3Cr steel OCP kept an increasing trend. Note that a maximum dispersion of about 15 mV was observed among the recorded OCP values for both 1Cr and 3Cr steels across tests of different durations. This level of variability is not uncommon in corrosion testing of carbon and low alloy steels and may arise from factors unrelated to corrosion kinetics- such as minor shift in the intrinsic potential of the reference electrode or other experimental uncertainties.

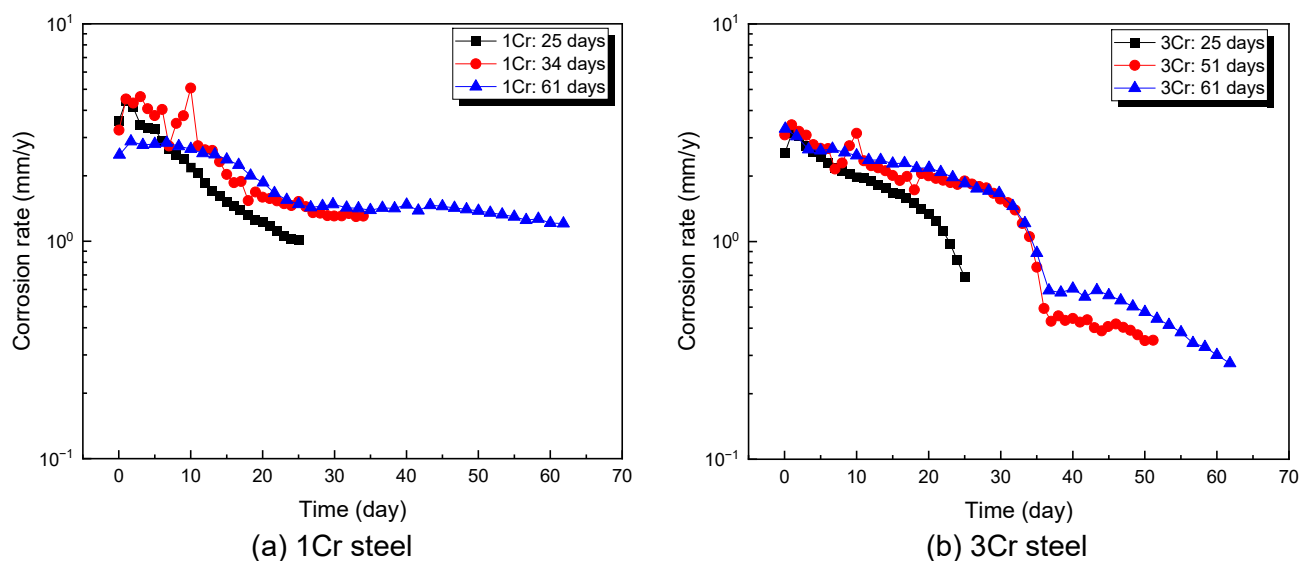


**Figure 2. LPR corrosion rates as a function of time for 1Cr and 3Cr steels.**

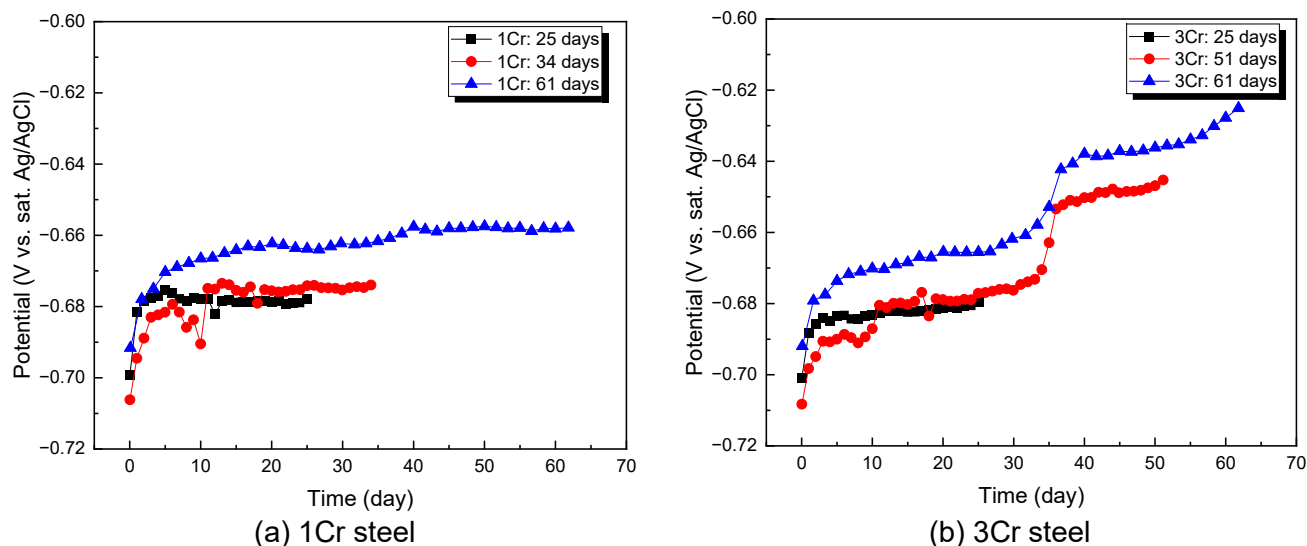


**Figure 3: OCP values of 1Cr and 3Cr steels as a function of exposure time.**

It should be noted that corrosion rates of 3Cr steel continued to decrease gradually after the onset of spontaneous pseudo passivation. This suggests that 3Cr steel could achieve stable corrosion rates of  $\sim 0.1$  mm/y or lower for exposures longer than 2 months in controlled conditions where protective  $\text{FeCO}_3$  corrosion product layers are not likely to form. Figure 4 shows examples of recorded solution pH, which was kept around the target value of 5.5 (5.35-5.7), as well as dissolved  $\text{Fe}^{2+}$  concentrations that averaged 3-5 mg/L in all tests with a few maximums of 10-13 mg/L. Dissolved  $\text{Cr}^{3+}$  concentrations were not measured; however, based on literature values<sup>17</sup>, they were assumed to be approximately one hundredth of the  $\text{Fe}^{2+}$  concentrations. The estimated maximum bulk  $\text{FeCO}_3$  saturation was  $\sim 0.065$ .

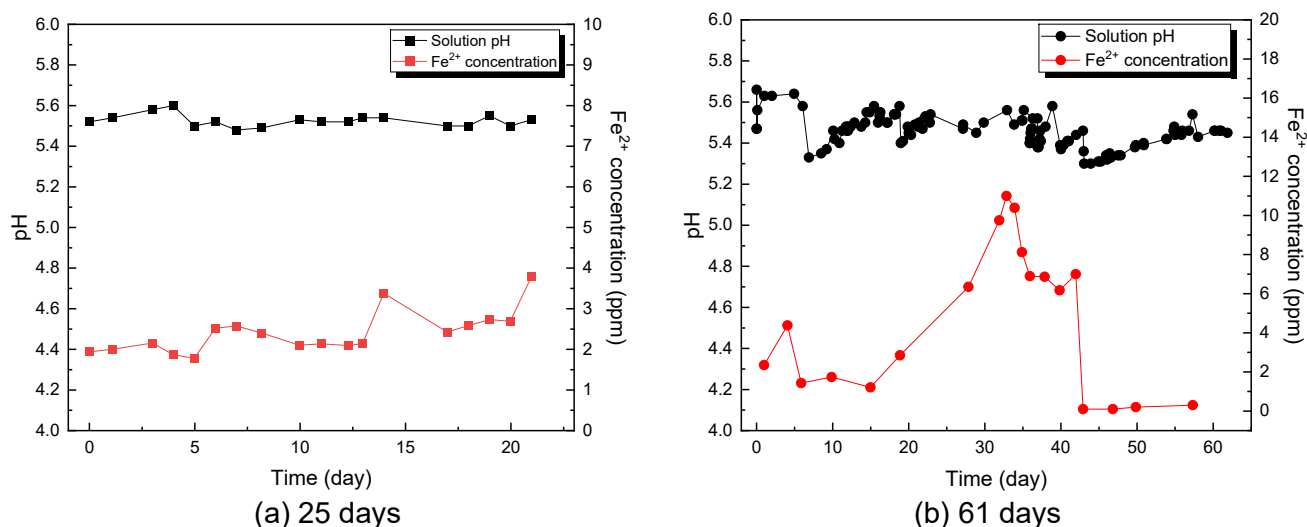


**Figure 4: Variation of solution pH and  $\text{Fe}^{2+}$  concentration as a function of exposure time.**

Figures 5 and 6 show cross-sectional SEM and EDS mapping/line scans of 1Cr steel after 61 days of exposure. It is worth mentioning that most of the cracks that are present across the corrosion product thickness and the interface between the corrosion product and the steel substrate, were most likely produced during the retrieval and further dehydration of the corroded samples. Similar dehydration cracking was observed in all the samples analyzed of both tested steels. The corrosion product layers of 1Cr steel showed a layered structure composed mainly of Fe, Cr, and O with a clearly porous interface between the outer layer of 80-100  $\mu\text{m}$  thickness richer in Cr and the thicker inner layer that also exhibited

significant porosity at some areas across its thickness. It is not known if the missing portions of the top layer on these samples were due to post-test dehydration cracking or an intrinsic spalling process produced during the immersion tests. Anyhow, the discontinuous porous morphology shown in the whole corrosion product layer suggests poor mass barrier and corrosion protection characteristics, which is consistent with the relatively high corrosion rates of 1Cr steel (Figure 2 (a)).

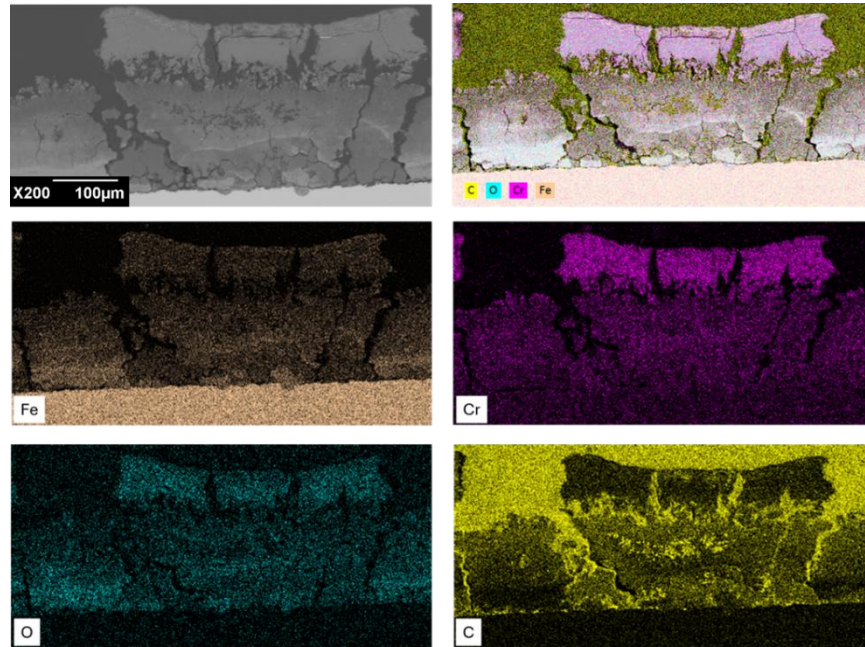


**Figure 5: EDS mapping of the chemical composition of the corrosion product layer on 1Cr steel after 61 days of exposure.**

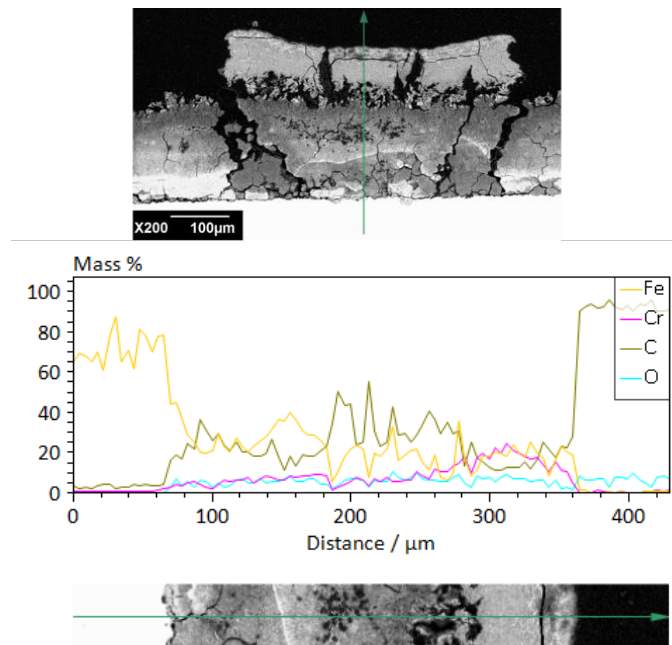


**Figure 6: EDS line scan of the chemical composition of the corrosion product layer on 1Cr steel after 61 days of exposure.**

Figure 7 shows cross-sectional SEM-BSE images of 3Cr steel after 25 and 51 days of exposure, corresponding to just before (A) and ~15 days after pseudo passivation (B). The corrosion product

thickness after 51 days was only about 45  $\mu\text{m}$  thicker (~40 %) than that measured after 25 days, consistent with the reduced corrosion rates recorded after pseudo passivation. The gray-scale contrast in Figure 7B revealed a duplex corrosion product structure, comprising a denser inner layer of irregular thickness (30-70  $\mu\text{m}$ ) and a lighter outer layer resembling the uniform single layer seen in Figure 7A for shorter exposure. Note that the corrosion product layers on 3Cr steel were compact and did not show significantly porous or spongy areas like those seen in the 1Cr steel corrosion product layers (Figure 5 and 6).

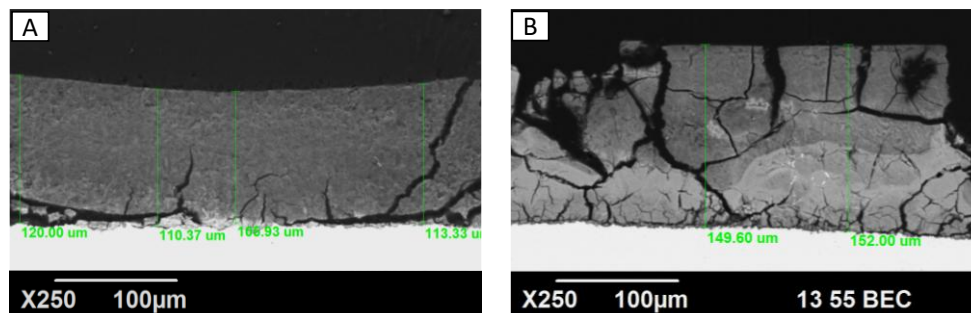


**Figure 7: Cross-sectional SEM images of 3Cr steel exposed in the multi-specimen glass cell for: (A) 25 days and (B) 51 days.**

EDS mapping and line scans (Figures 8 – 11) indicated that both corrosion product layers were Cr-rich (average ~30 wt.%). However, pseudo passivated samples displayed distinct compositional gradients, with lower Cr and higher Fe contents in the dense inner layer. By contrast, non-passivated layers showed more uniform distributions, with only slight decreases in Cr and increases in Fe near the metal surface.

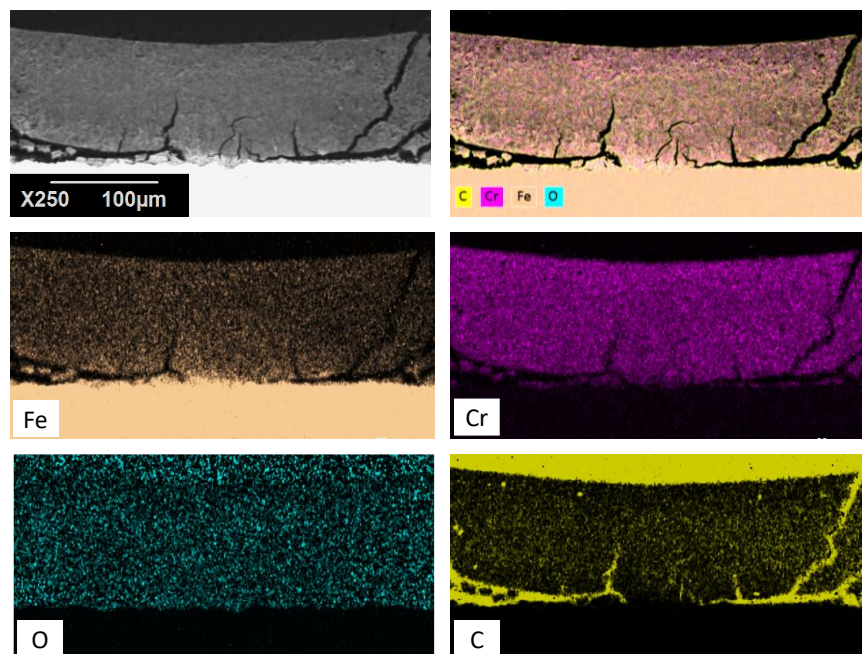


**Figure 8: EDS mapping of the chemical composition of the corrosion product layer on 3Cr steel after 25 days of exposure.**

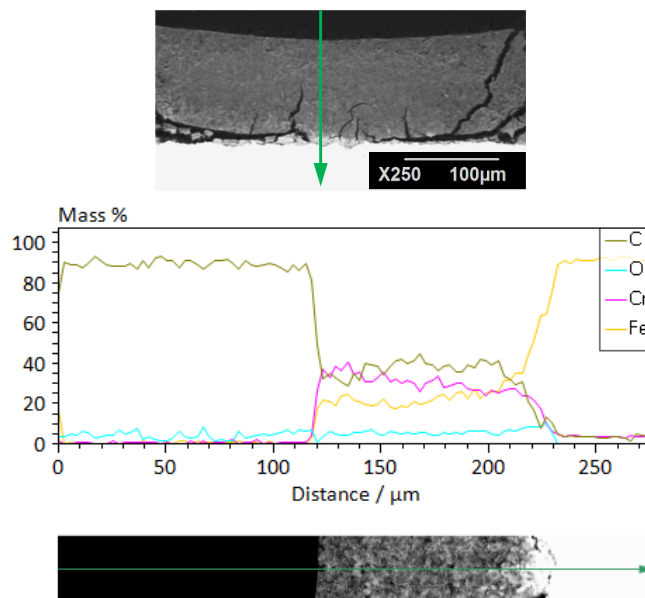


**Figure 9: EDS line scan of the chemical composition of the corrosion product layer on 3Cr steel after 25 days of exposure.**

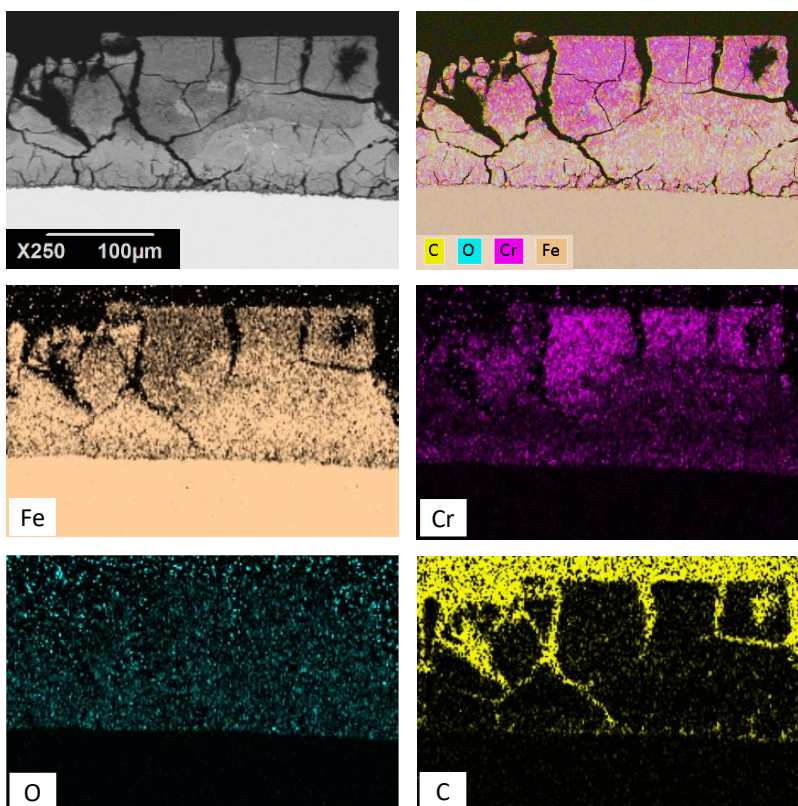


**Figure 10: EDS mapping of the chemical composition of the corrosion product layer on 3Cr steel after 51 days of exposure.**

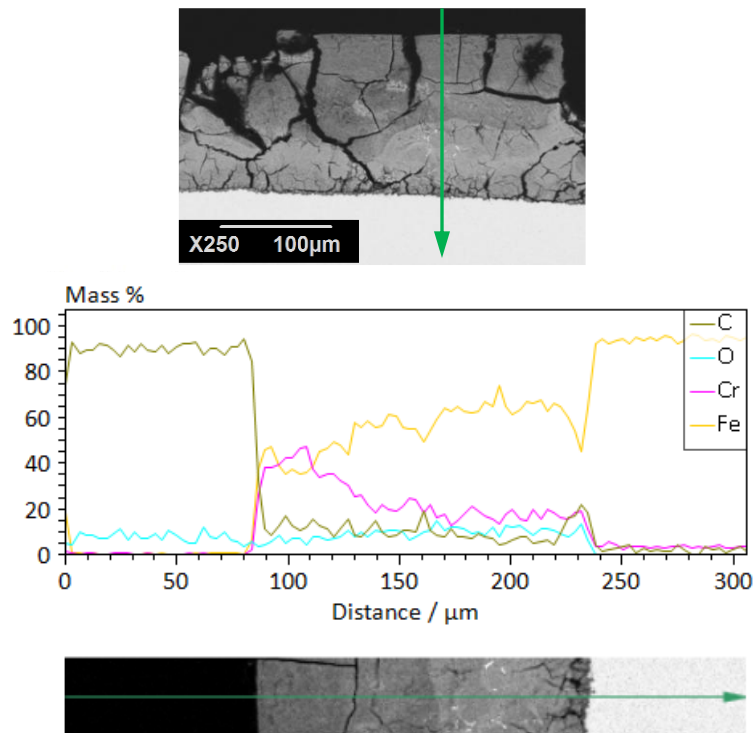


**Figure 11: EDS line scan of the chemical composition of the corrosion product layer on 3Cr steel after 51 days of exposure.**

XRD and Raman analyses identified chromium hydroxide ( $\text{Cr}(\text{OH})_3$ ) and iron and chromium carbides ( $\text{Fe}_3\text{C}$ , and  $\text{Cr}_3\text{C}_2$ ) in the corrosion product layers of 3Cr steel after 25 days, suggesting that early corrosion layers were relatively permeable and provided limited protection. In contrast,  $\text{FeCr}_2\text{O}_4$  and oxy-hydroxide ( $\text{CrO}(\text{OH})$ ) were detected in 3Cr steel exposed for 51 days, indicating the development of more protective phases. For 1Cr steel, XRD and Raman analyses mainly detected iron and chromium carbides, oxy-hydroxide, and evidence of spinel oxide, but it was not associated with  $\text{FeCr}_2\text{O}_4$ . After corrosion product removal, all steels showed only shallow pits with low penetration rates, confirming that corrosion was predominantly uniform.

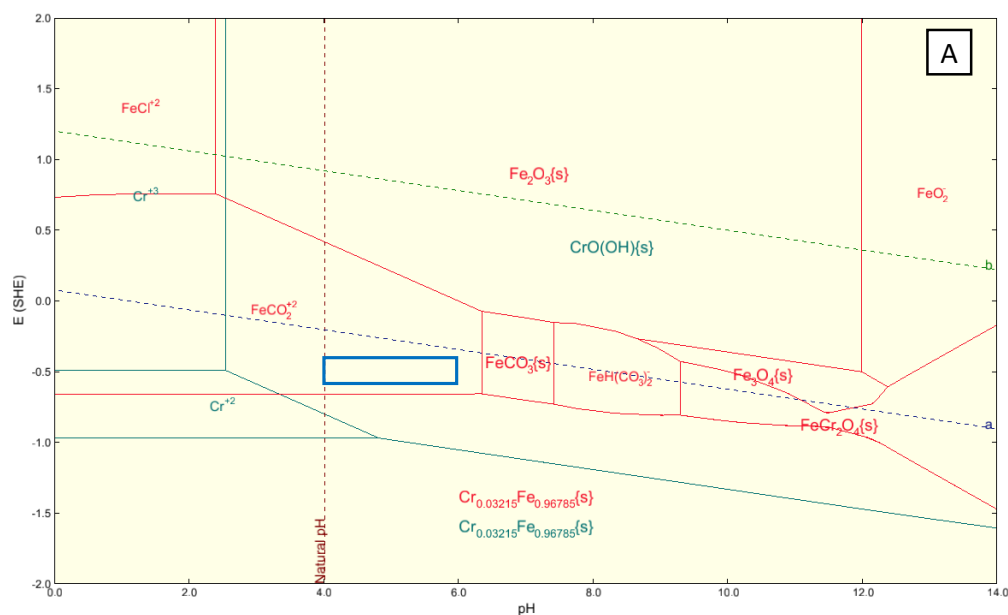
For longer exposures, 3Cr steel progressively developed less permeable corrosion product layers, which acted as mass transfer barriers particularly impeding Fe dissolution and outward diffusion. This process contributed to the substantial reduction of corrosion rates to  $\sim 0.1$  mm/y and was associated with pseudo passivation. In contrast, 1Cr steel showed no evidence of pseudo passivation under the same conditions, even after 60+ days.

It is important to mention that no crystalline or amorphous  $\text{FeCO}_3$  was detected by SEM, EDS, XRD, or Raman analyses in the corrosion products of both tested steels, as expected since the solution chemistry was maintained at very low  $\text{FeCO}_3$  saturation values. Thus, it is assumed that the observed pseudo passivation of 3Cr steel was not related to the precipitation of  $\text{FeCO}_3$ . Instead, pseudo passivation appears to be primarily linked to the formation of  $\text{FeCr}_2\text{O}_4$ , which is thermodynamically favored in  $\text{CO}_2$  containing environments across wide potential-pH ranges as shown in the Pourbaix diagrams (Figure 12).

The thermodynamic assessment of the 3Cr steel- $\text{CO}_2$ -water system indicates that, in the absence of near-surface buildup of  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$ ,  $\text{FeCr}_2\text{O}_4$  is not stable at the relevant potentials ( $-0.4$  to  $-0.6$  V vs. SHE) and bulk pH values (4-6; Figure 12, blue rectangle). Under such conditions,  $\text{Cr}(\text{OH})_3$  or its dehydrated form,  $\text{CrO}(\text{OH})$ , are the most stable phases. This aligns with experimental observations where the initial corrosion product on 3Cr steel was a continuous  $\text{Cr}(\text{OH})_3$  layer. With time, these  $\text{Cr}(\text{OH})_3$

layers grow thicker and more compact, progressively hindering species diffusion. Although this does not significantly reduce corrosion rates, it promotes important accumulation of  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$  at the steel surface. For example, assuming  $\text{Fe}^{2+}$  diffusion in water at  $80^\circ\text{C}$  (diffusion coefficient  $\approx 2.1 \times 10^{-9} \text{ m}^2/\text{s}$ ) and a flux equivalent to a corrosion rate of 1 mm/y,  $\text{Fe}^{2+}$  accumulation at the steel surface can reach  $\sim 1.1 \text{ mg/L}$  per  $10 \text{ }\mu\text{m}$  of fully permeable layer. Accounting for porosity,  $\text{Fe}^{2+}$  accumulation per  $10 \text{ }\mu\text{m}$  of layer thickness could reach  $\sim 3.3$ ,  $\sim 7$ , and  $\sim 12.9 \text{ mg/L}$  for porosities of 50%, 30%, and 20%, respectively. Therefore, considerable buildup of  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$  is expected during the growth of the  $\text{Cr}(\text{OH})_3$  layer.

As shown in Figure 12B,  $\text{FeCr}_2\text{O}_4$  becomes the dominant stable phase within the operational potential-pH range once  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$  accumulate near the surface ( $\text{Fe}^{2+}=30 \text{ mg/L}$  and  $\text{Cr}^{3+}=0.3 \text{ mg/L}$  are considered in this case). Note that local surface pH may deviate substantially from bulk values due to (i) acidification from  $\text{Cr}^{3+}$  hydrolysis, which has been reported as a major driver of near-surface acidification from 3Cr steel,<sup>18-20</sup> (ii) alkalization from  $\text{Fe}^{2+}$  accumulation, which can shift surface pH upward, and (iii) alkalization due to proton consumption. However, regardless of any significant local pH deviation above or below bulk solution pH, formation of  $\text{FeCr}_2\text{O}_4$  is feasible. It is worth mentioning that in the case of 1Cr steel, a thermodynamically favorable scenario for the formation of  $\text{FeCr}_2\text{O}_4$  might not have occurred due to a combination of factors such as a more permeable corrosion product layer that did not allow significant  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$  buildup and lower activity of  $\text{Cr}^{3+}$  ions due to the lower intrinsic content of Cr in the steel.<sup>14</sup>



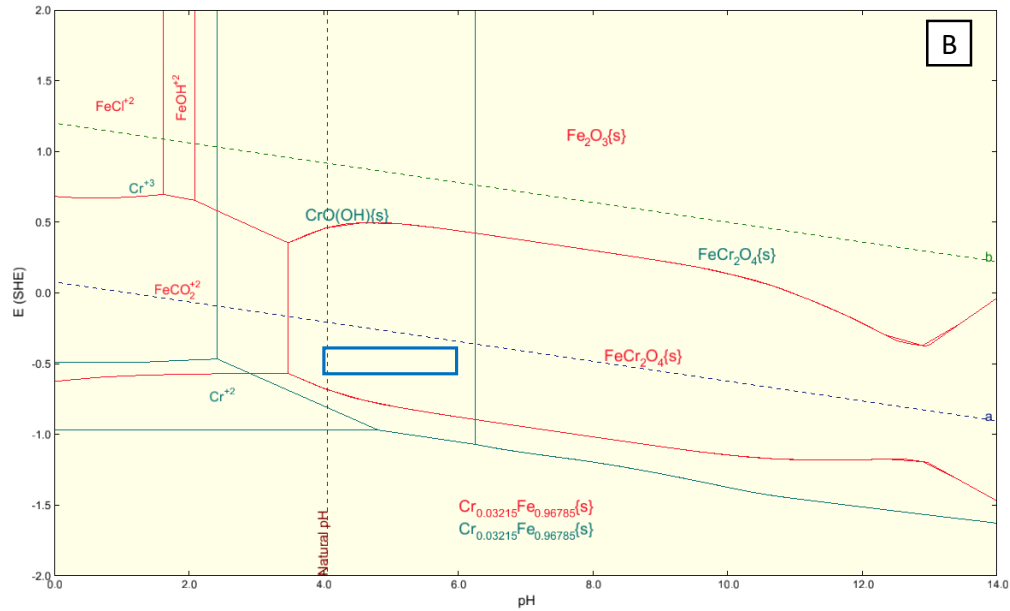
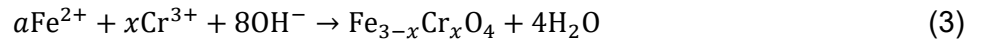


**Figure 12: Pourbaix diagrams for 3Cr steel in contact with an aqueous solution at 80°C,  $p\text{CO}_2 = 1$  bar, and 5 wt.% NaCl: (A) Condition with negligible  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$  concentrations and (B) Condition with  $\text{Fe}^{2+} = 30$  mg/L and  $\text{Cr}^{3+} = 0.3$  mg/L.**

The precipitation of  $\text{FeCr}_2\text{O}_4$  is expected to follow:



where  $a=1$  and  $x=2$  for stoichiometric  $\text{FeCr}_2\text{O}_4$ . This reaction is favored at higher pH, consistent with the thermodynamic diagram. The kinetics are thus expected to accelerate under alkaline conditions. Temperature can also enhance both the stability field of  $\text{FeCr}_2\text{O}_4$  and the kinetics of its precipitation. Furthermore, elevated  $\text{Fe}^{2+}$  and  $\text{Cr}^{3+}$  concentrations facilitate  $\text{FeCr}_2\text{O}_4$  nucleation, stabilize it across a wider potential-pH range, and promote its persistence. Once formed,  $\text{FeCr}_2\text{O}_4$  is very stable, exhibiting negligible solubility even in acidic aqueous environments at elevated temperatures.

## CONCLUSIONS

Based on the long-term corrosion tests conducted under the experimental conditions of this study, the following conclusion can be drawn:

- 3Cr steel exposed for relatively short periods (~25 days) developed permeable Cr-rich corrosion product layers with low or moderate protective properties. The corrosion rates were generally comparable to, or slightly lower than, those of 1Cr steel.
- For longer exposures (> 30 days), 3Cr steel showed a drastic reduction in corrosion rate to values as low as 0.1 mm/y. This behavior is attributed to the formation of less permeable corrosion product layers that act as effective diffusion barriers, producing a pseudo passivation effect on the surface of 3Cr steel.
- The development of protective pseudo passive layers is likely linked to the precipitation of  $\text{FeCr}_2\text{O}_4$  spinel oxide within the compact  $\text{Cr}(\text{OH})_3$  layer initially formed on 3Cr steel. In contrast, 1Cr steel did not exhibit pseudo passivation under the same conditions, and its corrosion rates remained relatively high.
- No evidence of localized attack was observed on either 1Cr or 3Cr steels under any of the test conditions.

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