Investigation of Galvanic Corrosion between Graphite Gaskets and Stainless Steel Flanges

Martin Bengtsson
Abstract

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At Forsmark, several cases of suspected galvanic corrosion have been detected and believed to be caused by an inappropriate use of graphite gaskets in brackish water. This report studies the likelihood of galvanic corrosion between the graphite gasket and stainless steels and aims to be a reference when investigating galvanic corrosion in the future. To evaluate galvanic corrosion, several electrochemical experiments were studied, such as galvanic series, polarization curves, and galvanic current measurements with a ZRA.

The electrochemical results showed that when immersing the stainless steel (254 SMO) and the graphite gasket (Novatec) into brackish water, there was a current flowing between the electrodes. However, the current was very small, which could be explained by the protection from a passive film on the stainless steel. The difference in corrosion potential between the two materials was measured and compared to results from polarization curves. It appeared that 254 SMO would be protected by a passive film at the measured potential. Galvanic current measurements also indicated the presence of a passive film under the investigated conditions.

The results indicate that galvanic corrosion itself should not have caused the corrosion attacks at Forsmark. The found corrosion is more likely due to crevice corrosion that was accelerated by the combination of a crevice, a welded flange surface, chlorides in water and possibly a graphite gasket.
Utredning om galvanisk korrosion mellan grafitpackningar och flänsar av rostfritt stål

Martin Bengtsson

Forskning och utveckling inom materialområdet resulterar i framsteg som kan vara allt ifrån att ett stål får bättre mekaniska egenskaper till att en solcell ger högre verkningsgrad och kan alstra mer ström. Skapandet av nya material kan i sin tur leda till användandet av nya materialkombinationer som i vissa fall kan vara olämpliga. Materialkombinationer som i ett visst scenario fungerar väl kan i andra fall där materialet har bearbetats annorlunda eller är i kontakt med en annan vätska, leda till oönskade problem. Ett exempel är packningsmaterial innehållande grafit, som används för att täta mellan två rördelar. Grafitpackningen fungerar väldigt bra i dricksvatten, men när vätskan byts ut mot bräckt vatten eller havsvatten så kan detta leda till korrosion genom galvaniska strömmar mellan materialen. Anledning till dessa strömmar är att den nya vätskan kan leda elektrisk ström, vilket resulterar i en så kallad galvanisk cell då de andra två komponenterna, anod och katod redan är närvarande. I detta fall agerar grafitpackningen som katod då grafit är ädlare än det rostfria stålet, som agerar som anod.

I detta arbete har flera tekniker som utvärderar och förutspår galvanisk korrosion studerats och har sammankopplats med ett korrosionsfall som upptäcktes av Forsmarks Kraftgrupp AB under revisionerna år 2010 och 2012. Det uppmärksammade korrosionsfallet påträffades på flänsar av rostfritt stål (254 SMO) i kylsystemet till hjälpkraftsdieslarna och ansågs ha uppstått på grund av grafitinnehållet i packningen (Novatec) tillsammans med det ledande bräckt vattnet (elektrolyten). Totalt har fem sorters stål och tre sorters packningar utvärderats genom flera elektrokemiska experiment i bräckt vatten i kombination med analyser i ett svepelektronmikroskop. De elektrokemiska metoderna som har använts är galvaniska serier, polarisationskurvor och galvaniska strömmätningar med en nollresistansamperemeter.

Experimenten visar att genom sammankoppling av det rostfria stålet och grafitpackningen, så kommer det att gå en ström mellan dem på grund av att en galvanisk cell uppstår. De uppmätta strömmarna var dock väldigt låga, både för experiment med och utan omrörning, och antogs ske på grund av en stabil passiv film på det rostfria stålet. Korrosionspotentialen jämfördes för den grafitinnehållande packningen (Novatec) och för det rostfria stålet (254 SMO) där skillnaden i potential var 0,3 V, vilket indikerar en risk för galvanisk korrosion. Genom att jämföra potentialen med resultatet från polarisationskurvorna framgick det dock att 254 SMO är i ett passiverat tillstånd vid den potentialen. Det vill säga, stålet är skyddat av en passiv film, vilket också strömmätningarna visade.

Med dessa resultat är det högst troligt att inte enbart galvanisk korrosion kan ha förorsakat de skador som uppmärksammades på Forsmark. Det är mer troligt att skadorna uppkom på grund av spaltkorrosion, som uppstår genom en kombination av en spalt mellan packning och fläns, en svetsad flänsytta och klorider i det bräckta vattnet.
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1. Background

With progress from research and development, new and improved materials are invented and available on the market. These improvements apply to all industries, for piping systems the improvement may be, e.g. increased corrosion resistance for a new stainless steel or a gasket with better sealing capacity. This, in turn, can lead to new and uninvestigated material combinations. These new material combinations can react with each other in an unwanted way and can for example increase the risk for galvanic corrosion.

A problem from new material combinations has been observed by Forsmarks Kraftgrupp AB. During audit work 2010 and 2012 it was recorded that several flanges in system 721 suffered from what was believed to be galvanic corrosion. System 721 is a cooling system to the backup diesels, which was built during 2005 and 2006. The corrosion was located on the flange surfaces, which in some cases weakened the sealing capacity resulting in drip-leakage. The reason for the corrosion was investigated by FTMQ who concluded that it derived from an inappropriate use of gasket material in brackish water. The used gasket was Novatec Premium II, which contains graphite and is believed to have caused corrosion by creating a galvanic cell with the stainless steel flange and the brackish water. The stainless steel flange was made out of 254 SMO that has a great corrosion resistance in seawater from its high molybdenum content [1, 2]. The flanges were, however, welded in such a way that the weld would be closest to the gasket and it could have weakened the nearby flange surface and therefore increasing the risk for corrosion.

In present time, all gaskets in the seawater systems have been changed to Dixo® 4000, which is a nonconductive gasket, in addition the flanges are casted in one piece and therefore the weld is further away from the formed crevice between the flange and gasket. After changing the flanges and gaskets no further corrosion attacks have been recorded but it is still unclear what caused the previous corrosion attacks. [3]

1.1 Main Objective

Safety is very important at Forsmarks Kraftgrupp AB and to ensure safe operation in the future, a tool to predict and avoid galvanic corrosion could prove very useful. Therefore, this work will focus on studying reasons for galvanic corrosion and different methods that predicts and evaluates it. The main objectives of this project are:

- To perform different experiments to predict and investigate galvanic corrosion between graphite containing gaskets and different stainless steels in brackish water. The results are then evaluated to act as a guide to evaluate galvanic corrosion in the future.
- To connect the electrochemical results to the corrosion observed in system 721 and state possible explanations for it.

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1 FTMQ is a section at Forsmarks Kraftgrupp AB that works with material, welds and vibration.
2. Theory

2.1 Corrosion Basics

The word corrosion comes from the Latin word “corrodere”, which means “to gnaw to pieces” [4]. Corrosion is an electrochemical reaction between a material and the surrounding environment. As a result of corrosion, the material changes its properties, mostly for worse. Common corrosion environments are aqueous (wet corrosion) and gaseous (dry corrosion). The corroding materials are in general metals and alloys, although almost all materials can corrode in some ways.

In a common corrosion process of a metal or an alloy, the corroding material will oxidize. For iron, this process is commonly referred to as rusting and it may occur when iron is exposed to oxygen and moisture. An example of rusted iron is visible in Figure 1.

![Image of rusted iron](image.png)

*Figure 1. An example of rusted iron [5].*

The overall process for the corrosion of iron can, in a simplified way, be explained with Equation 1 [6].

\[
\text{Iron + Water + Oxygen} \rightarrow \text{Rust} \quad \text{(Eq. 1)}
\]

The corrosion process of iron is, however, more complex and in reality, it is a summary of several reactions, starting with cathode and anode reactions. In this system, iron is oxidized at the anode and gives away electrons, while water and oxygen are reduced at the cathode and will consume the released electrons. Examples of anode reactions where iron gives away electrons are visible in Equation 2 and 3 while an example of a cathode reaction is given in Equation 4. [7]

\[
2\text{Fe}(s) \rightarrow 2\text{Fe}^{2+}(aq) + 4e^- \quad \text{(Eq.2)}
\]

\[
2\text{Fe}^{2+} \rightarrow 2\text{Fe}^{3+} + 2e^- \quad \text{(Eq.3)}
\]

\[
\text{O}_2(g) + 2\text{H}_2\text{O}(l) + 4e^- \rightarrow 4\text{OH}^-(aq) \quad \text{(Eq.4)}
\]

The products of the anode and cathode reactions will then react with each other, forming corrosion products of different composition depending on access to compounds such as oxygen and water. Two examples of this are given in Equation 5 and 6 where iron(II)- or iron(III) hydroxides are formed.

\[
2\text{Fe}^{2+}(aq) + 4\text{OH}^-(aq) \rightarrow 2\text{Fe(OH)}_2(s) \quad \text{(Eq.5)}
\]

\[
2\text{Fe}^{3+}(aq) + 6\text{OH}^-(aq) \rightarrow 2\text{Fe(OH)}_3(S) \quad \text{(Eq.6)}
\]
2.2 Driving Force and Rate of Corrosion

To understand the corrosion process, it is important to know what drives materials to corrode, such as thermodynamic and kinetic parts of corrosion. The thermodynamic aspect of corrosion is a good tool for calculation if a reaction can occur. This is derived from that all materials look to minimize their own energy. If the reaction will lower the energy of the system, the reaction may occur. [8,9]

In Table 1, the standard potential for pure metals are given and the values can be used as a thermodynamic guideline for corrosion. It must be considered that the standard potential is given for standard conditions\(^2\), and in most cases, alloys are used, therefore if the real potential is wanted it has to be measured for the given material combination and medium. [10]

Table 1. Standard potential for different elements, most of the elements are metals, which reaction is the following: \(Me \rightarrow Me^{n+} + ne^-\) [10].

<table>
<thead>
<tr>
<th>Element</th>
<th>Normal potential E° vs. SHE [Volt]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg/Mg(^{2+})</td>
<td>-2.40</td>
</tr>
<tr>
<td>Al/Al(^{3+})</td>
<td>-1.70</td>
</tr>
<tr>
<td>Mn/Mn(^{2+})</td>
<td>-1.70</td>
</tr>
<tr>
<td>Cr/Cr(^{3+})</td>
<td>-1.00</td>
</tr>
<tr>
<td>Zn/Zn(^{2+})</td>
<td>-0.76</td>
</tr>
<tr>
<td>Fe/Fe(^{2+})</td>
<td>-0.44</td>
</tr>
<tr>
<td>Co/Co(^{2+})</td>
<td>-0.29</td>
</tr>
<tr>
<td>Ni/Ni(^{2+})</td>
<td>-0.22</td>
</tr>
<tr>
<td>Sn/Sn(^{2+})</td>
<td>-0.14</td>
</tr>
<tr>
<td>Pb/Pb(^{2+})</td>
<td>-0.12</td>
</tr>
<tr>
<td>H(_2)/2H(^+)</td>
<td>± 0.00</td>
</tr>
<tr>
<td>Cu/Cu(^{2+})</td>
<td>+0.35</td>
</tr>
<tr>
<td>O(_2)/OH(^+)</td>
<td>+0.40</td>
</tr>
<tr>
<td>C/C(_2)</td>
<td>+0.72 (^3)</td>
</tr>
<tr>
<td>Ag/Ag(^+)</td>
<td>+0.80</td>
</tr>
<tr>
<td>Hg/Hg(^{2+})</td>
<td>+0.86</td>
</tr>
<tr>
<td>Cl(^-)/Cl(^-)</td>
<td>+1.36</td>
</tr>
<tr>
<td>Au/Au(^{3+})</td>
<td>+1.50</td>
</tr>
<tr>
<td>Pt/Pt(^{2+})</td>
<td>+1.60</td>
</tr>
</tbody>
</table>

The thermodynamic possibility of a corrosion process does not tell at what rate the corrosion process will have. It only reveals if the system can corrode and what reactions may occur. To determine the corrosion rate for the reactions given by thermodynamics, the kinetic part of corrosion should be studied.

To study the kinetic part of aqueous corrosion (wet corrosion), an electrochemical view of corrosion is essential. Aqueous corrosion is a form of corrosion that occurs when a material (often a metal or an alloy) is in contact with an aqueous electrolyte. The electrochemical corrosion process of aqueous corrosion consists of two parts, reduction and oxidation. The anode will oxidize and the cathode will reduce the solution. The combination of an anode and a cathode in an aqueous solution corresponds to a galvanic cell, which is presented in Figure 2 and further explained in section 2.3.1. [8]

---

\(^2\) Standard Potential is determined under the following conditions:
1. Measured against standard hydrogen electrode.
2. Concentration 1 Molar.
3. Pressure 1 atmosphere.
4. Temperature 25°C.

\(^3\) Calculated values for: \(C + \frac{1}{2} O_2 \rightarrow CO + 2e^-\)
At what rate the system will corrode depends on the rate at which ions can transfer between the anode and cathode. The transfer rate is highly affected by electrode kinetics, which determines how fast the cathode and anode sites react. Usually, either the cathode or anode reactions are rate limiting [8], but it can also be coupled to the mass transport between the sites where three types of transport are possible [9]:

- Migration – Charged ions transported by a potential difference.
- Diffusion – Spontaneous scattering process of charges that depends on the concentration gradient.
- Convection – Movement caused by stirring or flowing fluid.

The corrosion rate can be measured by studying the corrosion current ($I_{Corr}$). The corrosion current is equal to the anodic current ($I_{Anode}$) and also equal to the cathodic current ($I_{Cathode}$), but with opposite sign [8]. An example of anodic and cathodic currents is visible in Figure 2. In short, $I_{Corr} = I_{Anode} = -I_{Cathode}$, where the anodic current is carried through the metal by electrons flowing from the anode to the cathode. This current is equal to the current through the electrolyte carried by ionic species as well as the cathodic current that reduces the oxygen in the solution (example for reducing of a neutral alkaline environment in Eq.4).

![Figure 2. A schematically drawn picture of a galvanic cell. In the figure, electrons flow from the anode to the cathode, which then reduces the oxygen in the solution [8].](image)

The anodic and cathodic current are as previously stated always the same but with opposite signs, while the anode and cathode area can vary greatly. This means that the current per area ($A$) can be very different from each other. Therefore the total current ($I$) might not be relevant for measurements, while the current density ($j$) is relevant (Eq.7). By studying Equation 8 it is understood that awareness of the current density and area is important. For example, a large anode area combined with a small cathode area but with a large current density can still cause a high corrosion current and therefore a high corrosion rate according to Equation 9.

$$\frac{I}{A} = j \left( \frac{A}{cm^2} \right)$$  \hspace{1cm} (Eq.7)

$$j_{Anode} * A_{Anode} = -j_{Cathode} * A_{Cathode}$$  \hspace{1cm} (Eq.8)

By using Faraday’s law (Eq.9) the corrosion current can give the corrosion rate [11].

$$\frac{m}{t} = \frac{IM}{nF}$$  \hspace{1cm} (Eq.9)
The corrosion rate per area is defined as mass of the corroded material divided by the time and area, this is expressed in Equation 10 where Equation 7 and 9 have been used to simplify the expression [11].

\[
\text{Corrosion rate} = \frac{m}{tA} = \frac{ItM}{nF} \cdot \frac{1}{tA} = \frac{jM}{nF}
\]  
(Eq.10)

Where:

\( A = \text{area (cm}^2\text{)} \)
\( I = \text{current (A)} \)
\( t = \text{exposure time (s)} \)
\( n = \text{number of electrons transferred per reaction formula} \)
\( F = \text{Faraday's constant} \left( \frac{96485 \text{ C}}{\text{mol}} \right) \)
\( M = \text{molar weight of the material} \left( \frac{g}{\text{mol}} \right) \)
\( m = \text{mass of corroded material (g)} \)

2.3 Corrosion Forms

Corrosion can take many forms and originate from several different systems and environments, this chapter will describe the relevant corrosion forms for this report. Such as, galvanic, crevice, pitting and microbiologically influenced corrosion, which all are presented in Figure 3 together with uniform corrosion. Galvanic corrosion, which is the foundation of this report will be described further with possible predicting calculation and measurements.

![Figure 3. An overview of different types of corrosion.](image)

2.3.1 Galvanic Corrosion

Galvanic corrosion (also called bimetallic corrosion) is a corrosion process that occurs when a metal/alloy, a dissimilar metal/alloy (or another electron conductive material) and an electrolyte are in contact. This system is called a galvanic cell, which is schematically drawn in Figure 2. An example of galvanic corrosion is seen in Figure 3 where two metals are present and the less noble metal is corroded in present of an electrolyte. Nobility is measured in how willing the metal/compound is to attract or give away electrons and is often measured in corrosion potential \(E_{\text{corr}}\). The material with the highest corrosion potential will act as the cathode while the material with lower corrosion potential will act as the anode and also be the subject to corrosion. A common electrolyte is seawater and the effects it has on different materials are well known. An example of this is displayed in Figure 4 where a galvanic series is measured in seawater for different materials. The figure shows that graphite is the most noble and magnesium the least noble in seawater. [8, 9, 12]
Figure 4. Galvanic series in seawater where graphite is the most noble and magnesium the least noble, this series can be used to predict galvanic corrosion [12].

There are several factors contributing to galvanic corrosion, which make it hard to predict the outcome. Some of the most important factors to consider before coupling two materials together are presented below and illustrated in Figure 5. [9]

- Connection between the two materials, welds might increase risk for galvanic corrosion and so could an inappropriate use of a gasket.
- Area quotes between the different materials, different corrosion rate depending on the limiting factor to corrosion.
- Distances between the materials, further away makes it harder for the current to travel.
- Difference in corrosion potential between the materials, larger difference leads to higher risk for galvanic corrosion.
- Access to oxygen and hydrogen and eventual pollutions in the solution.
- Temperature and flow rate of the solution.
- Properties of an eventual protective film.
- Impurities or other defects.
2.3.2 Crevice Corrosion

Crevice corrosion is a corrosion form that originates in small gaps of approximately 0.1 to 100 μm and creates a very inhospitable environment [8]. An example of crevice corrosion is visible in Figure 3 where the formed crevice is illustrated. Crevice corrosion is one of the most damaging corrosion forms and can quickly cause a lot of damage [8]. Crevice corrosion does not form as deep attacks as pitting corrosion but instead causes broader damage, which is visible on a stainless steel flange in Figure 6 [9].

![Figure 6. A 316L stainless steel flange that has suffered from crevice corrosion [9].](image)

The inhospitable environment created originates from no or very low flow rate in the crevice, in combination with a general corrosion that decreases the oxygen content by a reducing process, seen in Equation 4. With a limited amount of oxygen the stainless steels are unable to form a passive layer, protecting the surface. This causes the steel to be unprotected and extra vulnerable for corrosion. An example of an environment with a low oxygen content is visible in Figure 7. [13]
Figure 7. An example of crevice corrosion that has resulted in an electrochemical potential difference with help from the surrounding electrolyte [8].

2.3.3 Pitting Corrosion

Pitting corrosion is similar to crevice corrosion but it appears on open surface in difference to crevice corrosion, which originates in confined sites. An example of pitting corrosion is visible in Figure 3 where three different pit attacks are visible. As seen in Figure 3 the corrosion attacks are narrow but deep. The attacks are caused by small weaknesses or damages in the passive film, which results in local corrosion attacks. In Figure 8 a schematically drawn figure of pitting corrosion on a stainless steel is visible, the steel is partially protected by a passive film. In the pit iron is converted to the soluble iron(II), which then forms iron(II)hydroxide, which is the same reactions as seen in Equation 2, 4 and 5. Extra content of chlorides in the already formed pit, seen in Figure 8, accelerates the corrosion attack greatly. [8, 9, 13]

Figure 8. Pitting corrosion on a stainless steel with an oxide layer [9].
2.3.4 Microbiologically Influenced Corrosion

Microbiologically influenced corrosion is a corrosion form that occurs under the influence of microbiological bacteria or films. The corrosion form is initiated by the formation of biological films on the surface, which creates a network for different bacteria, e.g. iron oxidizing and sulfur reducing bacteria. The formed network combines bacteria that dislike oxygen (anaerobic bacteria) and bacteria that need oxygen (aerobic bacteria) by deploying anaerobic bacteria near the surface and aerobic bacteria in the outer part of the biofilm. [13]

An example of a macro network is visible in Figure 9 where the network has grown as a lump on a strut in a firewater system. The lump derives from microorganisms that attach to the surface, which eventually starts to build up a biofilm and eventually forming a visible lump and meanwhile “eats” in to the surface causing a pit. The lump grows and the corrosion of the underlying surface is accelerated. The lump can then disperse and attach to a different site to create a new colonization. [13]

![Figure 9. The first image from left is a strut from a firewater system where a lump has been formed, the second image is of the same strut where the lump has been removed and the third and fourth image shows the lump after it was removed from the strut.](image)

2.4 Predicting and Evaluating Galvanic Corrosion

The best way to predict galvanic corrosion is to immerse the material combination in the electrolyte and simulate the real condition as best as possible, this can, however, be very time consuming, which is not desirable if many materials are to be tested. Therefore it is common that new material combinations are evaluated with screening tests first in order to sort out those that are not compatible before longer simulations are made. These screening tests can vary and differ greatly in time and equipment needed and it is recommended to start with less time consuming tests. The sections below show some possible screening tests. [15, 16]

**Galvanic series** is one of the easier and fastest methods to predict galvanic corrosion. An example of a galvanic series is visible in Figure 4 and it shows the difference in corrosion potential for a certain medium, which in this case is seawater. By observing the difference in corrosion potential it is possible to predict the risk for galvanic corrosion where a big difference in potential gives a high risk for galvanic corrosion and a small difference a lower risk. [8, 9, 16]

**Polarization curves** are great tools to predict how an electrode will react with the given electrolyte. The measured curve is divided in two parts, the first part where the dominant reaction is cathodic where the electrode or the electrolyte reduces, and the second part where the dominant reaction is anodic and the electrode oxidizes. [8, 9]

**Galvanic current measurement with a Zero-resistance amperemeter.** A ZRA is an amperemeter with a very low resistance. The instrument is used to measure the current between two electrodes by short-circuit them. A schematically drawn image of how the galvanic current is measured is visible in Figure 10 where the electrodes are partially immersed in an electrolyte and short-circuited by a ZRA. The measured current combined with the area of the electrodes can give the corrosion rate by using Equation 10. [8, 9]
Figure 10. Schematically drawn figure of a ZRA where an anode and cathode are immersed in an electrolyte and coupled to a Zero-resistance amperemeter.

For ZRA experiments it is beneficial to imitate the real system as much as possible and some of the most important factors to consider are [9]:

- Area quotes and distance between the electrodes.
- Liquid flow.
- Electrolyte temperature.
- Access or absence of air (i.e. oxygen).

2.5 Material Information

The following sections give information about the different materials used in this report. Section 2.5.1 give information about stainless steels and 2.5.2 give information about gaskets. The following sections also guide how to use the different materials according to Forsmarks Kraftgrupp AB’s rules and regulations.

2.5.1 Stainless Steel

A stainless steel is steel with minimum of 10.5% Cr, despite its name it is not immune to corrosion, but has an increased protection since the Cr in the steel forms a 1-3 nm protective passive film [13, 17]. The passive film is formed in contact with oxygen and consists mainly of iron oxide, chromium oxide and chromium hydroxide. The passive film is formed on the stainless steel, often in a combination with a nickel enriched transition layer, see Figure 11 [13]. The passive film is spontaneously formed and small injuries in the film will be mended if the steel is in contact with air or aerated water. For corrosion to occur the passive film needs to be partially or fully removed under conditions that do not facilitate spontaneous repassivation [13].
Stainless steels are almost always alloyed with other elements than chromium, which all give the steel different properties and microstructure. Some elements will promote ferrite structure and some austenite structure. The ferrite stabilizing effect is measured in chromium equivalents and austenite stabilizing effect in nickel equivalents. [13]

Different amounts of alloying elements yield different corrosion prevention properties and in general the steel has a greater resistance against corrosion if it is highly alloyed [2]. For a low alloy stainless steel there is a high risk for crevice and pitting corrosion in seawater and to prevent them it is recommended to use a stainless steel with a pitting resistance equivalent number (PREN) over 40. PREN is defined in Equation 11 and depends on the chromium, molybdenum and nitrogen weight percentages. Stainless steels with PREN over 40 are referred to as super duplex or super austenitic stainless steel depending on the microstructure. [18]

\[
PREN = \%Cr + 3.3 \times \%Mo + 16 \times \%N
\]  
(Eq.11)

Other techniques to determine the resistance in seawater is the use of a so called “Engineering diagram” or galvanic series (example in Figure 4). An “Engineering diagram” is presented in Figure 12 where temperature is plotted against chloride content to show critical pitting and crevice conditions [13].
Figure 12. Engineering diagram showing the maximum temperature and chloride content for pitting (p) and crevice (c) corrosion. In the diagram 254 SMO has the highest crevice/pitting corrosion resistance and 4404 has the lowest [13].

2.5.1.1 Stainless Steel for Seawater Systems at Forsmarks Kraftgrupp AB
The Swedish Nuclear power companies Ringhals AB, Forsmarks Kraftgrupp AB and Oskarshamns Kraftgrupp AB have together published a document, Technical determinations for mechanical equipment (TBM) [19]. In TBM requirements for materials in seawater is presented and special requirements for stainless steel in those systems are:

- Austenite stainless steel must at least have 6% molybdenum
- Ferrite – austenitic (duplex) stainless steel must at least have 3% molybdenum

2.5.2 Gaskets
A gasket is a mechanical seal used in many different systems and components, often to prevent piping systems and flanges from leaking. A schematically drawn picture of the gasket addressed in this report is visible in the left image in Figure 13, the right image is an image from a sealing in system 721.

Figure 13. The left image is a schematically drawn picture of a gasket sealed in between two flanges and the right image is from a sealing in operation [20].

In an ideal condition, the two flanges would seal in the gasket with a contact pressure sufficiently high to seal in the liquid in the system without it entering between the gasket and flange. This would prove as an excellent prevention of crevice corrosion. But in practice it would require pressures high enough to permanently damage either the flange or gasket combined with a perfect geometry of the components [21].
A gasket can be very good for a type of flange in a nonconductive medium but while in saltwater or another conductive medium it would be inappropriate and may lead to corrosion of the materials surrounding the gasket. In the gasket industry the corrosion forms are divided in three types [10]:

- Contact corrosion
- Galvanic corrosion (see 2.3.1).
- Crevice corrosion (see 2.3.2).

The three types of corrosion often cooperate, e.g. contact corrosion can lead to crevice corrosion and crevice corrosion could enhance galvanic corrosion. Therefore it is often hard to determine the exact corrosion process that has occurred.

**Contact corrosion** can originate from substances in the gasket that provokes a chemical reaction between itself and the surrounding material. Three common provoking substances in gaskets are chloride, fluoride and sulfide.

1. High chloride content in the gasket increase the risk for pitting corrosion and some manufactures and ASM advises that the chloride content should not exceed 100 ppm on parts exposed to stainless steel [22, 23]. Leachable chloride also increases the risk for stress corrosion cracking on the surrounding stainless steel, but this risk is decreased with higher content of Ni in the stainless steel. Leakage of hydrogen chloride often comes from certain coatings or impregnations and often at high temperatures. [23]
2. Fluoride is able to provoke chemical reactions with the nearby material and can for example be released from gaskets of PTFE if the gasket is exposed to high temperatures (over 300 °C) [10].
3. Leachable sulfides from the gasket may promote corrosion processes on flanges made of stainless steel, and for flexible graphite gaskets the sulfide content should not exceed 500 ppm, although power plants often demand content less than 200 ppm to minimize the enhanced aggressiveness of the media [10].

2.5.2.1 Gaskets for Forsmarks Kraftgrupp AB

At FKA the choice of gasket for respective media and flange is a highly addressed problem. The reason for this is earlier inappropriate use of gaskets that is believed to have initiated or assisted in different types of corrosion attacks such as galvanic and crevice corrosion.

In TBM, rules for the use of gaskets are presented. The relevant rules for this report are the following [19]:

- Gaskets of expanded graphite are not allowed to be used in systems that may be in contact with seawater, the reason is the increased risk of galvanic corrosion on the nearby equipment.
- Rubber bound fiber gaskets may be used if consulted with the manufacturer.

FKA has also given out an own report/standard for the use of gaskets [24]. The report strives to narrow down the amount of used gaskets to three, Grafex® EX, DIXO® 4000 and Specmaflex® FSP4, but other gaskets may still be used. The three gaskets have different application areas. Grafex® EX is a universal gasket used for almost all medium, except seawater and strongly oxidizing acids in high temperatures. DIXO® 4000 is used in seawater systems and with gases. Specmaflex® FSP4 is used in systems with high pressure or temperature, but not in seawater.

In this report some experiments are made on a gasket named Novatec Premium II, which is not mentioned in FKA’s standard [24], but has been frequently used in the power plant and will probably be used for many years to come [25]. The gaskets (except Specmaflex® FSP4) are visible in Table 2.

---

4 A corrosion induced by substances in the gasket.
5 PTFE stands for polytetrafluoroethylene but is commonly known as Teflon.
Table 2. Gasket description including content and chloride content [24, 26].

<table>
<thead>
<tr>
<th>Name</th>
<th>Content</th>
<th>Chloride content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novatec Premium II</td>
<td>Graphite blended with aramid fiber and NBR-rubber coated in a non-stick coating</td>
<td>≤ 50 ppm</td>
</tr>
<tr>
<td>Grafex® EX</td>
<td>SS 316L covered with 100% graphite</td>
<td>≤ 50 ppm</td>
</tr>
<tr>
<td>Dixo® 4000</td>
<td>Aramid fibers and nitrile rubber</td>
<td>&lt; 50 ppm</td>
</tr>
</tbody>
</table>

6 A universal gasket used for most applications, however, not saltwater systems
7 Combination of 316L and carbon steel, the gasket is not used for experiments in this report and is therefore not explained further.
8 Chloride content is not given although it is expressed as very low in comparison to the other gaskets.
3. Experimental Setup

3.1 Materials

For these experiments and evaluations eight different materials are used, see Table 3.

Table 3. The different materials used for experiments.

<table>
<thead>
<tr>
<th>#</th>
<th>Material</th>
<th>Comment</th>
<th>PREN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>304L</td>
<td>Standard</td>
<td>18.1</td>
</tr>
<tr>
<td>2</td>
<td>304L</td>
<td>High Nickel</td>
<td>18.2</td>
</tr>
<tr>
<td>3</td>
<td>316L</td>
<td>Standard</td>
<td>24.0</td>
</tr>
<tr>
<td>4</td>
<td>316L</td>
<td>High Molybdenum</td>
<td>26.4</td>
</tr>
<tr>
<td>5</td>
<td>254 SMO</td>
<td>Standard</td>
<td>43.5</td>
</tr>
<tr>
<td>6</td>
<td>Novatec Premium II</td>
<td>With and without non-stick coating</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Grafex® EX</td>
<td>Standard</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Dixo® 4000</td>
<td>Standard</td>
<td>-</td>
</tr>
</tbody>
</table>

Some of the samples were cast in epoxy to make it possible to calculate the respective area of the different materials. This was done with a cold casting technique where Epofix resin and hardener were mixed and drained into casting molds together with the samples by using an Epovac (see Figure 14). The samples were then left to set for about 8 hours. When the Epofix had set, the sample was removed from the casting mold and polished with sandpaper of different grit until the electrodes were visible and polished.

Figure 14. Epofix Resin, Hardener and the used Epovac.

3.2 Electrochemical Experiments

3.2.1 Galvanic Series / Corrosion Potential Measurement

The galvanic series are executed in brackish water from Forsmark and the series are measured by using a multimeter, a reference electrode and working electrodes. Two different methods are used, where the first measures the potential between a working electrode and a reference electrode and the second measures the difference in potential between two working electrodes. Both setups are visible schematically drawn in Figure 15.
3.2.1.1 Setup 1
In these experiments an Ag/AgCl (sat.) reference electrode was used to measure the galvanic potential of sample 1 to 7 from Table 3. The working electrodes was measured one by one and was connected to high input and reference electrode to the low input on the multimeter, which measured the potential difference between them. The potential measurement was executed over different temperatures to illustrate the temperature dependence.

The experimental setup is visible in Figure 15 where the container is placed on a heater with a magnetic stirrer. The measurement started at 20 °C and potential values were noted every 5 °C to 70 °C and was done on sample 1 to 7 visible in Table 3.

The measured potential is given in potential vs. the reference electrode, to give the potential relative to the standard hydrogen electrode (SHE) the potential for the reference electrode relative to the SHE is subtracted. The reference electrode potential is calculated with Equation 12 and displayed in Table 4. [27]

\[ E_0(V) = 0.23735 - 5.3783T \times 10^{-4} - 2.3728T^2 \times 10^{-6} - 2.2671(T + 273) \times 10^{-9} \] (Eq.12)

Where \( T = \text{temperature in °C in the span from 25°C < T < 275°C} \)

<table>
<thead>
<tr>
<th>T [°C]</th>
<th>E [V vs SHE]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20(^9)</td>
<td>0.22564</td>
</tr>
<tr>
<td>25</td>
<td>0.22242</td>
</tr>
<tr>
<td>30</td>
<td>0.21908</td>
</tr>
<tr>
<td>35</td>
<td>0.21562</td>
</tr>
<tr>
<td>40</td>
<td>0.21204</td>
</tr>
<tr>
<td>45</td>
<td>0.20834</td>
</tr>
<tr>
<td>50</td>
<td>0.20453</td>
</tr>
<tr>
<td>55</td>
<td>0.20059</td>
</tr>
</tbody>
</table>

\(^9\) The Equation is used for a temperature which it does not apply to but the error is considered too small to make a difference in this case
### 3.2.1.2 Setup 2

For these experiments two working electrodes are connected to a multimeter and then put into the electrolyte. The value given on the multimeter is the difference in potential between the two electrodes. This experiment was also conducted under increasing temperature to show the difference in potential depending on temperature.

The result is plotted in potential difference between the electrodes and also compared to the values calculated from the measurements against the Ag/AgCl reference electrode.

#### 3.2.2 Polarization Curves

For measurement of polarization curves an Autolab potentiostat/galvanostat is used. The experimental setup is seen in Figure 16 where the red cable is connected to the substrate (working electrode), the black cable is connected to the counter electrode consisting of platinum and the blue is connected to a reference electrode of silver/silver chloride. The working electrode area is set to 0.2 cm² by using a rubber gasket to conceal the rest of the substrate.

The measurement will start with a pretreatment with a constant potential at a predetermined time, after pretreatment the measurement started at the selected potential and stepped up to the end potential. For every potential the current is measured and plotted, usually in logarithmic scale.

![Figure 16. The left image show the experimental setup for polarization curve measurement. The right image is a schematic image of the experimental setup [28]. CE – Counter electrode, Ref – Reference electrode and WE – Working electrode.](image)

The different materials examined are presented in Table 3. A picture of the five stainless steels and the gasket that was measured are visible in Figure 17. Two different settings for measurements are used and those are visible in Table 5. The first measurement setting is a scan with a high scan rate and a large potential range and the second measurement setting gives a narrower scan and ten times slower scan rate. The first measurement setting is supposed to give an overview spectrum for the material, which would show the properties of the steel. The second measurement setting is used to plot a so called Tafel plot, which will indicate where the total current changes from being cathodic to anodic.
Figure 17. Picture of sample 1 to 6 from Table 3, which was measured.

Table 5. Two settings used for measurement of polarization curves in an Autolab potentiostat.

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>First conditioning potential (V)</td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>Duration (s)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Equilibration time (s)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potentials</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin potential (V)</td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>End potential (V)</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Step potential (mV)</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Scan rate (mV/s)</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

3.2.3 Galvanic Current Measurement with a Zero-Resistance Amperemeter

For experiments galvanic current measurements with zero-resistance amperemeter the ratio between anode and cathode is important, both to show current densities and to determine the rate limiting effect. To receive a reliable area quote the electrodes was cast into epoxy by using an Epovac. An example of a cast sample is schematically drawn in Figure 18 where the Epofix surround the electrodes and only exposing the bottom of the electrodes to the electrolyte. In this example the two electrodes consist of a gasket and a stainless steel, which are isolated from each other with thin plastic that will insure that the current travels through the ZRA.

Figure 18. An example setup for ZRA testing where the two electrodes consist of the noble gasket and the less noble stainless steel, which are connected by an electrolyte.

Two identical electrodes can be very different on short-term tests but identical on long-term tests when the electrodes have stabilized [29]. So to get good results from zero-resistance amperemeter experiments the
electrodes has to be immersed and short-circuited for a long time to let it stabilize. This stabilization may take up to 1000 hours (i.e. 41 days and 16 hours) and only after stabilizing the corrosion current at steady state can be measured [16].

### 3.3 Gasket Evaluation

EDS-analysis was performed on three different gaskets. Dixo® 4000, Novatec Premium II and Grafex® EX, information of the gasket is given under section 2.5.2.1. Samples were created by cutting out pieces with a scissor and then placed on an SEM stage, the samples are visible in Figure 19. To evaluate Novatec the non-stick coating was partly removed to reveal the underlying material but the other gaskets where evaluated intact.

For SEM images a secondary electron detector was used and for EDS an EDX-detector. Area and Mapping EDS was mainly used to examine the gaskets.

![Figure 19. The gasket pieces examined in SEM and EDS. The different gaskets are from left to right Dixo, Grafex and Novatec.](image)

### 3.4 Long-Term Simulations

Long-term experiments are intended to simulate what the result will be if the chosen material combination is exposed to the given electrolyte for a period of time. The tests are performed on 5 different stainless steels (visible in Table 3) combined with Novatec and exposed in brackish water from Forsmark. The samples are prepared by pressing the stainless steel and gasket together and cast them into Epofix. After the casting the samples are cut to fit in an SEM stage and polished with sandpaper. The 5 different samples are presented in Table 6 and the prepared samples are visible in Figure 20

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material combination</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>304L cast together with Novatec</td>
<td>38</td>
</tr>
<tr>
<td>2</td>
<td>304L (high Ni) cast together with Novatec</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>316L cast together with Novatec</td>
<td>38</td>
</tr>
<tr>
<td>4</td>
<td>316L (high Mo) cast together with Novatec</td>
<td>38</td>
</tr>
<tr>
<td>5</td>
<td>254 SMO cast together with Novatec</td>
<td>38</td>
</tr>
</tbody>
</table>
The results from Area EDS measurements are compared to the chemical composition in weight percent from Table 7 where the values for 304L (standard and high Ni) are typical chemical composition and 316L (standard and high Mo) and 254 SMO are chemical composition given from the manufacturer.

Table 7. The five different stainless steel, the two 304L is based on typical chemical composition in weight percent and the rest of measured chemical composition for the individual samples received from manufacturer [13].

<table>
<thead>
<tr>
<th>SS</th>
<th>304L</th>
<th>304L (high Ni)</th>
<th>316L</th>
<th>316L (high Mo)</th>
<th>254 SMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREN</td>
<td>18.1</td>
<td>18.2</td>
<td>24.0</td>
<td>26.4</td>
<td>43.5</td>
</tr>
<tr>
<td>Cr</td>
<td>18.1</td>
<td>18.2</td>
<td>16.614</td>
<td>17.02</td>
<td>20.08</td>
</tr>
<tr>
<td>Ni</td>
<td>8.1</td>
<td>10.1</td>
<td>10.006</td>
<td>12.78</td>
<td>17.88</td>
</tr>
<tr>
<td>Mo</td>
<td>-</td>
<td>-</td>
<td>2.044</td>
<td>2.51</td>
<td>6.04</td>
</tr>
<tr>
<td>N</td>
<td>-</td>
<td>-</td>
<td>0.037</td>
<td>0.066</td>
<td>0.22</td>
</tr>
<tr>
<td>Mn</td>
<td>-</td>
<td>-</td>
<td>1.284</td>
<td>1.46</td>
<td>0.62</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>-</td>
<td>0.367</td>
<td>0.29</td>
<td>0.038</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>-</td>
<td>0.034</td>
<td>0.039</td>
<td>0.018</td>
</tr>
<tr>
<td>C</td>
<td>0.02</td>
<td>0.02</td>
<td>0.026</td>
<td>0.018</td>
<td>0.01</td>
</tr>
<tr>
<td>S</td>
<td>-</td>
<td>-</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.71</td>
</tr>
</tbody>
</table>

10 Calculated with Equation 11
4. Results and Discussion

4.1 Electrochemical Experiments

4.1.1 Galvanic Series / Corrosion Potential Measurement

4.1.1.1 Results
The corrosion potential is measured against an Ag/AgCl(Sat.) reference electrode for seven different samples. The results are shown in Figure 21 where the measured potentials are plotted against a Standard hydrogen electrode by compensating with the values from Table 4. All materials are plotted together, for individual plots where stainless steels and gaskets are separated see appendix section 10.1.

From Figure 21 the following are visible:

- The graphite containing gasket Novatec is higher in potential at all temperatures measured but the potential decreases with increasing temperature.
- Grafex, which is the second highest in potential of the samples is similar to stainless steel at low temperatures and more similar to Novatec (graphite) at higher temperatures.
- The stainless steels are relatively similar to each other in potential and behavior at all temperatures.

![Figure 21](image-url)

*Figure 21. The seven different samples, which all are measured against an Ag/AgCl (Sat.) and compensated according to Table 4.*

The results from the measurement where two electrodes are measured against each other are shown in Figure 22 and Figure 23. From Figure 22 it is visible that Novatec is higher in potential than 254 SMO at all temperatures. The measured potential difference is -0.3±0.025 V at temperatures between 5°C and 70°C.
In Figure 23 the measured difference in potential between 254 SMO and Grafex. From the figure the following information is given:

- Grafex is higher in potential than 254 SMO at all temperatures.
- The difference in potential is low at room temperature but increases with higher temperatures.

Experiments with stainless steels in combination with Novatec were performed to show what stainless steel would be the most appropriate in the combination regarding galvanic corrosion. The results are given in potential difference between the gasket and the stainless steels where larger difference indicates higher risk for galvanic corrosion. The stainless steels are 316L and 254 SMO and the results (Figure 24) shows that the potential difference for the 254 SMO combination is twice as high compared to that for 316L.
4.1.1.2 Discussion

Measurements against an Ag/AgCl (Sat.) reference electrode showed that Novatec, which is containing graphite is the most noble, this is consistent with the results in Figure 4. The graphite potential is from 0.2 to 0.4 V and for stainless steel 316 from -0.1 to 0 V, which is similar to values in room temperature (20°C) from Figure 21. The potential is, however, larger than the values from this galvanic series. This can derive from that brackish water is not as saline as seawater, which would make the materials appear nobler in this electrolyte.

The material, which is the second noblest material is Grafex, which nobility was increased with increased temperature. The potential vs. SHE was similar to stainless steel in room temperature and similar to the graphite containing gasket Novatec at 70°C. This could derive from that the gasket contains both pure graphite and pure 316L stainless steel, and could therefore be a sign of that the activity of the graphite coating is more dominant at higher temperatures while the stainless steel is more dominant at lower.

The stainless steels are according to these results similar in appearance with potential values from -0.25 to +0.75 V vs. SHE. The five stainless steels are, however, different from each other regarding alloys and concentration of alloys, which gives them different susceptibility for corrosion in seawater. This is, however, not visible in this galvanic series, which could reduce the confidence for this method while investigating, which stainless steel is more appropriate for a certain material combination. An experiment was performed, which is presented in Figure 24, the test shows what stainless steel would be the most appropriate in combination to Novatec. The results show that the potential difference between 316L and Novatec is half of the difference between 254 SMO and Novatec, which indicates that the risk for galvanic corrosion is lower for the 316L combination than the one with 254 SMO. This could, however, be a result from that the two measurements are conducted with the same gasket where 254 SMO was measured first and then 316L. 316L should, however, be more susceptible for pitting and crevice corrosion than 254 SMO according to their PREN values, 24 vs. 43.5 (values from Table 7).

The potential difference between 316L and 254 SMO from Figure 21 and Figure 24 could derive from the high content of Mo in 254 SMO. This indication is also visible for 316L in comparison to 316L (high Mo), which could indicate that additional Mo in the stainless steel will reduce the corrosion potential and could potentially increase the risk for galvanic corrosion.

Figure 24. Two different stainless steels are measured against Novatec to show what would be the most appropriate combination.
4.1.2 Polarization Curves

4.1.2.1 Results
This section gives the results from two different types of potentiodynamic measurements. The two measurements are both line scans where the first test is over a larger potential difference with a higher scan rate and the second is with a narrower potential difference but with a slower scan rate.

Potentiodynamic line scans

Line scans from –0.5 V to +1.1 V has been made for six different materials, five of them are stainless steels and one is a graphite containing gasket. The stainless steels and the graphite containing gasket, Novatec, are presented in Table 3 and the settings for the scans are presented in Table 5.

Line scans performed on stainless steels show five important regions, in Figure 25 these regions are marked for 254 SMO:

I. **Cathodic region** – the cathodic current is much larger than the anodic current. This results in a reducing reaction on the electrode or in the electrolyte.

II. **Corrosion potential** – the cathodic current is equal to the anodic current. At potentials lower than the $E_{\text{corr}}$ the dominating current is cathodic and at higher potentials the dominating current is anodic.

III. **Passive region** – the dominating current is anodic and the stainless steel surface is protected by its passive film.

IV. **Transpassive region** – The passive film is dissolving by oxidation of chromium (III) to chromium (VI).

V. **Second passive region** – The passive film is reformed and iron oxidizes to Fe (III), forming an iron-rich passive film. The passive film decreases the diffusion rate from the surface and creates a steady state.

![Figure 25. Line scan for 254 SMO, which is separated in five regions (I, II, III, IV and V).](image-url)
The results for the scans are presented in Figure 26 where all six curves are plotted. For the line scans plotted individually see appendix (10.2.1).

In Figure 26 it is possible to see that the four stainless steels, 304L (standard and high Ni) and 316L (standard and high Ni) have similar polarization curves with a noise-like appearance when entering the transpassive region after approximately 0.4 V vs. Ag/AgCl (Sat.). 254 SMO did not show this appearance and was noise free under the transpassive and second passive region.

![Figure 26. Polarization curves for six different materials. The materials are SS 304L, SS 304L (high Ni), SS 316L, SS 316L (High Mo), 254 SMO and Novatec without its non-stick coating. The polarization curves are measured according to Table 5 with the current density (logarithmic scale) plotted against potential vs. Ag/AgCl (sat.) in the same figure.](image)

Tafel plots

The Tafel plots are measured with a 10 times lower scan rate than the plots in Figure 26 but with a narrower range (-0.4 to +0.1), settings are visible in Table 5. By staying longer on each potential, the stainless steel is given time to let its passive film closer to the steady state for the given temperature and potential. This leads to lower currents and a more detailed value for the corrosion potential. The results from the line scans are visible in Figure 27 where one scan from each of the five different stainless steels and the one gasket are plotted together, in appendix section 10.2.2 each material are plotted individually with one or two curves. The stainless steels curves exhibit much noise as they pass the corrosion potential, this will be addressed in the discussion.
Figure 27. Tafel plots for 5 different stainless steels (304L, 304L (high Ni), 316L, 316L (high Mo) and 254 SMO) and one gasket (Novatec). Each curve is plotted individually in appendix section 10.2.2.

The Tafel plot for Novatec is plotted in Figure 28 with Tafel lines for the cathodic and anodic current. In the figure the corrosion current density and corrosion potential (E_{corr}) are marked. By adding Tafel lines to the rest of the curves visible in Figure 27 and in appendix (10.2.2) the corrosion current density and corrosion potential are given for the different materials (Table 8).

Figure 28. A Tafel Plot for Novatec where Tafel lines have been added to show the cathodic and anodic lines., which give \( I_{cd} \) (corrosion current density) and \( E_{corr} \) (Corrosion potential).
Table 8. Current corrosion density and the corrosion potential for the six different materials where the data is mean values from the figures in appendix section 10.2.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>$I_{cd}$ [A/cm$^2$]</th>
<th>$E_{corr}$ [mV vs. Ag/AgCl (sat.)]</th>
<th>$E_{corr}$ [mV vs. SHE]</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L</td>
<td>$7.2 \times 10^{-9}$</td>
<td>-90</td>
<td>136</td>
</tr>
<tr>
<td>304L (high Ni)</td>
<td>$9.8 \times 10^{-9}$</td>
<td>-120</td>
<td>106</td>
</tr>
<tr>
<td>316L</td>
<td>$1.4 \times 10^{-8}$</td>
<td>-125</td>
<td>101</td>
</tr>
<tr>
<td>316L (high Mo)</td>
<td>$8.8 \times 10^{-9}$</td>
<td>-135</td>
<td>91</td>
</tr>
<tr>
<td>254 SMO</td>
<td>$2.5 \times 10^{-9}$</td>
<td>-100</td>
<td>126</td>
</tr>
<tr>
<td>Novatec</td>
<td>$2.1 \times 10^{-6}$</td>
<td>-4</td>
<td>222</td>
</tr>
</tbody>
</table>

In Figure 27 and in Table 8 it is visible that the corrosion current density and open circuit potential for Novatec is much higher than for the 5 stainless steels. The lowest corrosion current density is recorded for 254 SMO and the lowest corrosion potential is recorded for 316L (high Mo).

4.1.2.2 Discussion

The results from the full range scans show that the five stainless steels are similar to each other in region I, II and III, but when entering region IV (transpassive) 304L, 304L (high Ni), 316L and 316L (high Mo) stainless steels experienced a noise-like appearance and the measured current increased significantly. During region IV the oxidation of chromium makes the steel more vulnerable and the noise-like appearance is coupled to pitting corrosion on the surfaces.

254 SMO had one of the lowest corrosion potentials, both seen in galvanic series and from polarization curves (Figure 21, Figure 26 and Figure 27) and this would make the stainless steel less resistant to corrosion (e.g. galvanic) compared to the other steels. However, the polarization curves showed that 254 SMO did experience low currents even at high potentials and had a passive region much larger than the other stainless steels. From the results it is shown that the resistance to corrosion (e.g. pitting and galvanic corrosion) is much higher for 254 SMO than for the other stainless steels, which is consistent to the PREN-values seen in Table 7.

By observing the difference between the two different scans (Figure 26 and Figure 27) it is visible that the stainless steels exhibited a much greater amount of noise in the Tafel plots. This is coupled to the significantly decreased current, which is obtained with the ten times slower scan rate in combination with the use of a logarithmic scale and therefore the noise is more pronounced.

The graphite containing gasket did not exhibit much noise, most likely due to the much high currents. The higher current arose from several surface group reactions on the graphite surface. Both in the full range plot and in the Tafel plot the graphite gasket experienced the highest corrosion current density and to receive lower currents the scan rate would have to be considerably lower. Due to the numerous possible reactions that can occur on the graphite surface it is hard to draw any other conclusions from the curves than that the current is very high.

The obtained results for the stainless steels are comparable to the results from [16] (Table 9) where two of the stainless steels examined in this report was measured in brackish water at the same scan rate as the curves in Figure 26. The results from the Tafel plots show that 254 SMO experience the lowest corrosion current, which indicates that 254 SMO forms a tighter passive film that better protects the underlying metal.
Table 9. Corrosion current and potential from experiments in brackish water [16].

<table>
<thead>
<tr>
<th>Material</th>
<th>$I_d$ [A/cm$^2$]</th>
<th>$E_{corr}$ [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L</td>
<td>$1.3 \times 10^{-7}$</td>
<td>160</td>
</tr>
<tr>
<td>316L</td>
<td>$2.5 \times 10^{-7}$</td>
<td>150</td>
</tr>
</tbody>
</table>

4.1.3 Galvanic Current Measurement with a Zero-Resistance Amperemeter

4.1.3.1 Results

Three different samples containing stainless steels and gaskets were cast together in epoxy and exposed to brackish water. During the exposure the electrodes were short-circuited by a zero-resistance amperemeter, which measured the current traveling between the electrodes.

Due to problem with the zero-resistance amperemeter only three of the cast samples were measured. The three samples were different combinations of 254 SMO together with Novatec cast in epoxy. The three samples are visible in Table 10 where the composition and areas of the stainless steels and gaskets are given and one of the cast samples is visible in Figure 24.

Table 10. Three different combinations of 254 SMO and Novatec, which was cast in epoxy for ZRA experiments. The electrodes are all separated with a thin plastic as seen in Figure 16.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Abbreviation</th>
<th>SS area</th>
<th>Gasket area</th>
</tr>
</thead>
<tbody>
<tr>
<td>254 SMO – Novatec</td>
<td>SMO-N</td>
<td>3 cm$^2$</td>
<td>0.375 cm$^2$</td>
</tr>
<tr>
<td>254 SMO – Novatec – 254 SMO</td>
<td>SMO-N-SMO</td>
<td>6 cm$^2$</td>
<td>0.375 cm$^2$</td>
</tr>
<tr>
<td>Novatec – 254 SMO – Novatec</td>
<td>N-SMO-N</td>
<td>3 cm$^2$</td>
<td>0.75 cm$^2$</td>
</tr>
</tbody>
</table>

Figure 29. One of the samples used for ZRA testing. The light grey parts are 254 SMO and the dark grey is Novatec. The electrodes are separated with a thin plastic and cast in epoxy.

The measurements on the three samples are visible in Figure 30 where the current densities of the stainless steel are plotted against time. One of the samples was removed after 26h (1560 min). The two other samples were measured 21 days (30240 min) and were considered to be stabilized with a current below 10 nA. The results show that the N-SMO-N combination gave the highest initial current (550 nA) but after 26 h (1560 min) the SMO-N-SMO combination had the largest current (136 nA).
The two remaining samples were considered as stabilized and the samples were examined regarding the strong inhibition of the current. This was done with two different experiments where the sample consisting of N-S-N was removed and a 2 cm scratch was drawn on the surface before exposing it to the electrolyte again. The result is visible in Table 11 where the current rose to 600 nA, which is above the initial current value from Figure 30 (550 nA). However, the current decreased fast and after 10 minutes the current was 5 nA and appeared to be stabilized again.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Current [nA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

The second inhibition experiment the sample consisting of SMO – N – SMO (red curve Figure 30) was exposed to a magnetic stirrer. The stirrer increased the current density on the stainless steel from $1.6 \frac{\text{nA}}{\text{cm}^2}$ to approximately $41.6 \frac{\text{nA}}{\text{cm}^2}$, which gives the corrosion density rate $365 \left( \frac{\mu \text{g}}{\text{cm}^2 \cdot \text{year}} \right)$ with use of Equation 9. The sample, which exposed 6 cm² of stainless steel to the brackish water would experience $4.6 \times 10^{-4} \text{ (mm)}$ corrosion every year assuming that it is uniform on the surface and the mass corroded would be $2.2 \left( \frac{\mu \text{g}}{\text{year}} \right)$.

4.1.3.2 Discussion
Experiments showed that by immersing 254 SMO and Novatec into brackish water a current travels between the materials. Initially the current was high but it decreased fast and eventually was too low to be measured with the used equipment. The decreasing current corresponds to the stabilization of the electrodes [16]. The strong stabilization effect is most likely a result of that one of the electrodes is able to inhibit the current, for example by a passive film reaching steady state.

By measuring three different combinations of 254 SMO and Novatec it was seen that the highest initial current was observed for the N-SMO-N combination while SMO-N and SMO-N-SMO had almost the same initial current. However, the current decreased faster for the samples with less stainless steel, which
indicates that the gasket is limiting initially but after a period of time the stainless steel would be the limiting factor, which increases the beliefs that the stainless steel forms a protective passive film, which acts as a current inhibitor.

The suspicion of a passive film was tested with two tests, the first test the surface was scratched and the results strengthen the belief that it was the stainless steel, which inhibited the current and not the graphite gasket. By scratching the surface the passive film was temporarily removed and the current increased to values equal to the initial values for the sample. This caused the limiting factor to no longer be from the stainless steel but instead from the graphite gasket. However, when the passive layer was reformed the limiting factor would once again be the stainless steel.

In the second test a magnetic stirrer was applied, the current density on the stainless steel rose to 26 times to the previously value and when the stirrer was removed it returned to the stabilized current value. The increased current could be a result of increased mass transport by convection. This would help removing metallic ions from the stainless steel surface and also increase the access to oxygen.

The results from 4.1.2.1 showed that the current density was 1000 times higher for Novatec than the value for 254 SMO. During the ZRA-tests the stainless steel surface was 5-20 times larger than the Novatec surface, which still would lead to 50-200 times higher current density for the gasket in comparison to the stainless steel. With that information the stainless steel should be the limiting factor to the current rate for all experiments above. This does not add up with the results for the three samples and it draws suspicions that the three samples could differ in more ways than anticipated. The difference could for example origin from the sample preparation, including the grinding with sandpaper, which could have created different conditions for the different samples. This would mean that more samples of the same composition needs to be evaluated to draw any concluding results.

4.2 Gasket Evaluation

4.2.1 Manual Evaluation

4.2.1.1 Results

The three gaskets Novatec, Grafex and Dixo were evaluated manually considering the conduction of the gaskets. The evaluation was performed with a multimeter, which measured the resistance through the different gaskets. Grafex and Dixo were new and undamaged but the Novatec gasket, which had been used in the system had small visible scratches on some parts of the surface.

**Dixo (Aramid fibers and nitrile rubber)**

No conduction was measured anywhere on the surface and the resistance was too high to be measured.

**Grafex (SS 316L covered with graphite)**

Measurements with 1-5 cm between the test leads gave conduction on all parts of the gasket with a resistance of 0.5-1 Ω.

**Novatec (graphite blended with aramid fiber and NBR-rubber coated with a non-stick coating)**

The parts with intact non-stick coating gave no conduction and the resistance was too high to be measured, but the damaged parts, which revealed the graphite blend underneath the coating were conductive as well as the sides of the gasket. The following resistance was measured:
• Edge to edge (Inside to outside) gave approximately 90 Ω
• Edge to a nearby scratch (distance ~1 cm) gave approximately 70 Ω
• Scratches from different sides of the surface gave approximately 100 Ω

4.2.1.2 Discussion
The gasket evaluation showed that Dixo was nonconductive on all parts of the gasket, which was expected since the gasket is made of nonconductive materials (aramid fiber and nitrile rubber).

All the spots measured on Grafex were conductive and the resistance was very low, which most likely derives from good conduction between the stainless steel and graphite.

The evaluation of Novatec showed that the scratches from operation went through the non-stick coating and exposed the conductive graphite blend. The resistance was, however, much higher than for Grafex, which could derive from that the blend contains less conductive materials.

4.2.2 SEM and EDS Evaluation
SEM and EDS analysis was performed on the same three gaskets (Dixo, Grafex, and Novatec). The most relevant measurements are presented in this chapter and the rest of results can be found in Appendix.

4.2.2.1 Results

Dixo® 4000

An SEM image of Dixo is presented in Figure 31 where Area and Mapping EDS were used. The figure shows the two regions where the analyses were performed and the result from Area EDS is shown in Table 12 and EDS mapping is presented in Figure 32. The result show that the gasket mainly consists of carbon, oxygen, silicone, zinc and sulfur.

![Figure 31. SEM image of Dixo gasket. Two rectangles show the regions in which area and mapping EDS analysis was performed.](image)

![Table 12. Detailed element information from Area function in EDS.](table)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Zn</th>
<th>S</th>
<th>Mg</th>
<th>Ca</th>
<th>W</th>
<th>K</th>
<th>Os</th>
<th>Na</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt.%</td>
<td>39.84</td>
<td>38.70</td>
<td>12.45</td>
<td>3.10</td>
<td>1.93</td>
<td>0.88</td>
<td>0.66</td>
<td>0.63</td>
<td>0.62</td>
<td>0.60</td>
<td>0.59</td>
<td>100.00</td>
</tr>
</tbody>
</table>
Figure 32. Five different elements recorded in the mapping site on Figure 31.

**Grafex® EX**

Area and Mapping EDS was performed on the gasket. The results from the Area spectrum showed that the surface consists mainly of carbon (97.97%) and the mapping result showed that it was uniformly covering on the surface. An SEM image of the sample is showed in Figure 33 while EDS spectrum and mapping can be found in appendix.

![SEM image of the Grafex gasket](image)

Figure 33. An SEM image of the Grafex gasket.

**Novatec Premium II**

The Novatec gasket had been used in the system before analysis and it had many small damages on the non-stick coating. The surface of the gasket is presented in Figure 34, where the left image shows an overview of the gaskets surface and the right image shows the largest scratch in the surface. Area analysis was performed on three different sites, which are marked with rectangles in Figure 34. Element composition in Table 11 shows that the light area from the SEM image (site 1) varies greatly from the dark areas (site 2 and 3), which contained much more carbon. Site 2 and 3 have the same chemical composition and contain mostly carbon (74.7%) while site 1 has much lower carbon content and higher content of oxygen, calcium, silicone, sulfur, bromine and potassium. Site 1 also contains some elements, which are not present on site 2 and 3, e.g. barium and fluoride.
Figure 34. Two EDS images where three different spectrum sites are visible. The result from the chemical composition is visible in Table 13.

Table 13. Chemical composition of the three sites from Figure 34.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>O</th>
<th>Ba</th>
<th>Ca</th>
<th>F</th>
<th>Si</th>
<th>S</th>
<th>Br</th>
<th>Mg</th>
<th>Ti</th>
<th>Cu</th>
<th>K</th>
<th>Na</th>
<th>Fe</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>28.2</td>
<td>25.5</td>
<td>17.9</td>
<td>7.3</td>
<td>6.0</td>
<td>4.9</td>
<td>4.1</td>
<td>1.8</td>
<td>1.5</td>
<td>1.0</td>
<td>0.9</td>
<td>0.7</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Site 2</td>
<td>74.7</td>
<td>13.2</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
<td>8.5</td>
<td>0.3</td>
<td>1.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
<td>-</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Site 3</td>
<td>74.7</td>
<td>13.2</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
<td>8.5</td>
<td>0.3</td>
<td>1.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
<td>-</td>
<td>0.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

EDS mapping was used on the large scratch from the right image in Figure 34, the mapping site is visible in Figure 35 and the eight recorded elements are visible in Figure 36. The mapping result shows the same as Figure 35, that the carbon content is much higher and the silicone content is a little bit higher in the scratched surface than in the non-scratched surface. From the figure the scratch appears to be approximately 125 μm wide.

Figure 35. Mapping site on a large scratch in the non-stick coating.
Figure 36. The recorded elements from mapping site three, which is visible in Figure 35.

EDS mapping was used to examine the transition site between the non-stick coating and the manually removed non-stick coating. The evaluation was performed in order to confirm the hypothesis that the scratches on the surface go through the non-stick coating. The mapping site is visible in Figure 37 and the recorded elements are visible in Figure 38. The result shows that the carbon and silicone content is higher in the area where the non-stick coating is removed while oxygen, magnesium, sulfur, fluoride, calcium and barium concentration is higher in the coated area.

Figure 37. Mapping site on the gasket Novatec where the light area is the non-stick coating and the darker area where the non-stick coating has been removed manually.
4.2.2.2 Discussion

Dixo was uniformly coated with a coating mainly consisting of carbon, oxygen, silicone, zinc and sulfur. The non-stick coating appears to be of another material than for Novatec by observing the chemical composition where elements as barium and fluoride are present in the Novatec coating in difference from Dixo.

The gasket Grafex was uniformly coated with a coating consisting of 97.97% carbon, which is near to the “100% expanded nature graphite” that the manufacturer claims it consists. SEM and EDS analysis show that the whole surface is unharmed and the surface is uniformly coated.

The Novatec gasket that had been used in the system was full with small scratches, which were examined with SEM and EDS. The hypothesis that the scratches go through the non-stick coating was confirmed by Area and Mapping EDS. Area EDS (Figure 34 & Table 13) showed that the concentration of carbon and silicon was higher in the darker areas (scratches) in combination with a lower concentration of oxygen, magnesium, sulfur, fluoride, calcium and barium compared to the light area. The same trend was observed with EDS mapping on one of the scratches (Figure 36) where the darker area was higher in carbon and silicone content and lower in the remaining elements. Result from EDS mapping on the scratch (Figure 36) was compared to the result from the mapping on the manually removed coating (Figure 38), which gave the same result. This result proves that the small scratches on the surface go through the non-stick coating and reveals the carbon blend underneath.

4.3 Long-Term Simulations

Five different stainless steels samples combined with Novatec Premium II were exposed to brackish water for 38 days. The samples were examined with SEM and EDS before and after the exposure in order to evaluate the changes in chemical composition on the surface. The results from the difference in chemical composition before and after are visible in Table 14, which show if the chemical composition of each element was increased or decreased from the exposure.
Table 14. Difference in element composition before and after exposure to brackish water, is based on result from Table 15 – Table 19, where “+” represent that the composition was increased from exposure, – represents that it was decreased and blank means that the quantity is almost the same as before exposure.

<table>
<thead>
<tr>
<th></th>
<th>304L</th>
<th>304L (high Ni)</th>
<th>316L</th>
<th>316L (high Mo)</th>
<th>254 SMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cr</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ni</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mo</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mn</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>C</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Br</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
</tbody>
</table>

By optical visual inspection of the surfaces it was observed that a rust colored circular coating was visible on the border between the gasket and the stainless steel on sample 1 but otherwise no deviations were seen.

4.3.1 SEM and EDS Results

4.3.1.1 Sample 1 – 304L cast with Novatec Premium II

304L stainless steel was cast in epoxy together with Novatec Premium II and examined with SEM and EDS before and after exposure to the brackish water. Area EDS was performed to measure the chemical composition for the two sites in Figure 39 where site 1 is before exposure and site 2 is after. The results from the spectrum sites are visible in Table 15 where the chemical composition is compared to the standard element composition.

Figure 39. Both images are taken in EDS where the left image is before exposure to the brackish water and the right image is after exposure. Element composition from site 1 and 2 are visible in Table 15.

In Table 15 it is seen that the measured C wt.% from site 1 is much larger than for the standard element composition. After exposure the rate of Fe, Cr, Ni and Mn is decreased and the C, Mo and O rate is increased.

Table 15. Element composition from the two sites in Figure 39 where site 1 is before exposure to brackish water and site 2 is after. Standard element composition is taken from Table 7.

<table>
<thead>
<tr>
<th>Element</th>
<th>Standard</th>
<th>Wt.% site 1</th>
<th>Wt.% site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Balance</td>
<td>68.09</td>
<td>62.27</td>
</tr>
<tr>
<td>Cr</td>
<td>18.1</td>
<td>18.51</td>
<td>17.35</td>
</tr>
<tr>
<td>Ni</td>
<td>8.1</td>
<td>7.70</td>
<td>6.55</td>
</tr>
</tbody>
</table>
The observed circular coating from the optical visual inspection was examined with EDS mapping at the site visible in Figure 40 and the result is presented in Figure 41 where the coating appears to be consisting of iron, chromium, oxygen, sodium and chloride.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Mo</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>0.02</td>
<td>1.95</td>
<td>1.09</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Weight</td>
<td>2.67</td>
<td>1.81</td>
<td>1.09</td>
<td>0.50</td>
<td>2.19</td>
</tr>
</tbody>
</table>

*Figure 40. Mapping site on the surface after exposure to brackish water.*
4.3.1.2 Sample 2 – 304L (high Ni) cast with Novatec Premium II

304L (high Ni) was cast together with Novatec Premium II and exposed to brackish water for 38 days. In Figure 42 two EDS images are visible, the left one is before exposure and the right one is after the exposure. The surface was examined with Area EDS to give element composition of the stainless steel (Table 16).

Compared to standard element composition the C rate is much higher from site 1 and also Mn, Si and Mo is measured. The high carbon rate is, however, not visible in site 2 after exposure to brackish water and the Mo signal is removed while a sulfur signal is added.
Table 16. Element composition from Table 7 compared to the two sites from Figure 42.

<table>
<thead>
<tr>
<th>Element</th>
<th>Standard</th>
<th>Wt.% site 1</th>
<th>Wt.% site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Balance</td>
<td>67.67</td>
<td>69.35</td>
</tr>
<tr>
<td>Cr</td>
<td>18.2</td>
<td>18.55</td>
<td>18.83</td>
</tr>
<tr>
<td>Ni</td>
<td>10.1</td>
<td>9.48</td>
<td>10.03</td>
</tr>
<tr>
<td>C</td>
<td>0.02</td>
<td>2.25</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>0.93</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>0.65</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>0.48</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>-</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>

Figure 43 shows no injuries on the surface but the gasket seemed to have a thin coating that had been formed during the exposure. The coating was examined with EDS mapping (Figure 44), which showed that it consist mainly of chloride and sodium.

Figure 43. Mapping site where the partially covering coating is visible on the gasket darker area.

Figure 44. EDS mapping of the rectangular area in Figure 43.
4.3.1.3 Sample 3 – 316L cast with Novatec Premium II

Stainless steel 316L was cast together with Novatec Premium II and exposed to brackish water for 38 days. In Figure 45 two SEM images are presented, the left one is before exposure and the right one is after exposure. Three different sites were examined with Area EDS in order to obtain chemical composition and the result is presented in Table 17 together with material information from the manufacturer.

![Figure 45. Stainless steel 316L cast together with Novatec Premium II. The left image is before exposure and the right image is after 38 days of exposure to brackish water. The rectangulars marked as 1, 2 and 3 are analysed with Area EDS and the result is visible in Table 17.](image)

In Table 17 it is seen that the Fe, Mo and Ni contents are lower and the Cr, Si and S rate is higher in site 1 compared to the manufacturer information and N, C and P are not detected in any of the sites. Between site 1 and 2 the major difference is less Fe and more Mo signal. In site 3 more sulfur is detected in combination with O, Na and Cl.

Table 17. Chemical composition of the three sites from Figure 45 compared to data from manufacturer (Table 7).

<table>
<thead>
<tr>
<th>Element</th>
<th>From manufacturer Wt.%</th>
<th>Wt.% site 1</th>
<th>Wt.% site 2</th>
<th>Wt.% site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>69.57</td>
<td>68.51</td>
<td>67.56</td>
<td>65.24</td>
</tr>
<tr>
<td>Cr</td>
<td>16.61</td>
<td>17.94</td>
<td>18.12</td>
<td>17.44</td>
</tr>
<tr>
<td>Ni</td>
<td>10.20</td>
<td>9.99</td>
<td>9.81</td>
<td>9.47</td>
</tr>
<tr>
<td>Mo</td>
<td>2.04</td>
<td>1.45</td>
<td>2.36</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>1.28</td>
<td>1.27</td>
<td>1.36</td>
<td>1.20</td>
</tr>
<tr>
<td>Si</td>
<td>0.37</td>
<td>0.70</td>
<td>0.79</td>
<td>0.81</td>
</tr>
<tr>
<td>N</td>
<td>0.037</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>0.002</td>
<td>0.14</td>
<td>-</td>
<td>0.68</td>
</tr>
<tr>
<td>C</td>
<td>0.026</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>0.034</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>O</td>
<td>-</td>
<td>-</td>
<td>3.63</td>
<td>-</td>
</tr>
<tr>
<td>Na</td>
<td>-</td>
<td>-</td>
<td>1.21</td>
<td>-</td>
</tr>
<tr>
<td>Cl</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The right image from Figure 45 was examined with EDS mapping at the site visible in Figure 46 and the mapping result is presented in Figure 47. The mapping result showed that the flake (marked #1) to the right in the picture was mainly consisting of carbon and oxygen. The larger damage (marked #2) shows that stainless steel surface has increased content of carbon and oxygen in difference to site 3 in Table 17 where oxygen, sodium and chloride contents are increased. The result also shows that epoxy has been cast in between the steel and gasket during sample preparation.
Figure 46. Mapping site over two damages near the border to the gasket.

Figure 47. The mapping result from the mapping site visible in Figure 46.

4.3.1.4 Sample 4 – 316L (high Mo) cast with Novatec Premium II
Stainless steel 316L with high molybdenum rate was cast together with Novatec and exposed to brackish water for 38 days. Figure 48 shows an SEM image of stainless steel and Novatec gasket before and after water exposure. In between the two materials a thin layer of epoxy is present. Area EDS were performed on
the stainless steel surface before and after exposure and the measured result were compared to information from the manufacturer (Table 18).

Figure 48. Stainless steel 316L (high Mo) cast together with Novatec Premium II. The left image is before exposure and the right image is after 38 days of exposure to brackish water.

In Table 18 the difference between the manufacturer information and site 1 is large, the Fe, Cr and Si signals are higher and Ni, C, P, N and S are lower in site 1 compared to the manufacturer data. In different from site 1 a Br and C signal is detected in site 2, in combination with less of the other elements (except Mn).

Table 18. Element composition from the two sites in Figure 48 combined with manufacturer data from Table 7.

<table>
<thead>
<tr>
<th>Element</th>
<th>From manufacturer</th>
<th>Wt.% site 1</th>
<th>Wt.% site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>65.816</td>
<td>67.16</td>
<td>63.04</td>
</tr>
<tr>
<td>Cr</td>
<td>17.02</td>
<td>17.63</td>
<td>16.58</td>
</tr>
<tr>
<td>Ni</td>
<td>12.78</td>
<td>10.54</td>
<td>9.90</td>
</tr>
<tr>
<td>Mo</td>
<td>2.51</td>
<td>2.57</td>
<td>2.47</td>
</tr>
<tr>
<td>Mn</td>
<td>1.46</td>
<td>1.47</td>
<td>1.68</td>
</tr>
<tr>
<td>Si</td>
<td>0.29</td>
<td>0.63</td>
<td>0.58</td>
</tr>
<tr>
<td>C</td>
<td>0.018</td>
<td>-</td>
<td>3.24</td>
</tr>
<tr>
<td>P</td>
<td>0.039</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>0.066</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Br</td>
<td>-</td>
<td>-</td>
<td>2.52</td>
</tr>
</tbody>
</table>

EDS mapping was performed before and after exposure on the sites visible in Figure 49 to evaluate the light coating visible on the gasket surface (extra visible in appendix, Figure 84 and Figure 86). The results from the two mapping sites are presented in Figure 50 and in Figure 51. The number of elements recorded before exposure were seven and after exposure were eleven. The new elements were chloride, oxygen, sodium, sulfur, and magnesium. The residue visible in mapping site 2 (Figure 49) consists mainly of silicone and oxygen.
Figure 49. Sites examined with mapping where the left image is before exposure and the right image is after 38 days of exposure to brackish water.

Figure 50. Result from the mapping performed on the right mapping site in Figure 49 and seven different elements are visible.
4.3.1.5 Sample 5 – 254 SMO cast with Novatec Premium II

254 SMO was cast with Novatec and exposed to brackish water for 38 days. Figure 52 shows an SEM image of stainless steel and Novatec gasket before and after water exposure. The chemical composition results from the two sites are presented in Table 19 where they are compared to the data given by the manufacturer.
In Table 19 the manufacturer data and data from site 1 is similar except the absence of the low C, S, P, N and Cu signals. By comparing site 1 and 2 (before and after exposure) it is seen that the C, O, Br and Cu rate is increased in combination with less signal from the other materials.

Table 19. Element composition from the two sites presented in Figure 52 compared to the material data from Table 7.

<table>
<thead>
<tr>
<th>Element</th>
<th>From manufacturer</th>
<th>Wt.% site 1</th>
<th>Wt.% site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>54.38</td>
<td>54.65</td>
<td>49.92</td>
</tr>
<tr>
<td>Cr</td>
<td>20.08</td>
<td>20.72</td>
<td>19.34</td>
</tr>
<tr>
<td>Ni</td>
<td>17.88</td>
<td>17.64</td>
<td>16.12</td>
</tr>
<tr>
<td>Mo</td>
<td>6.04</td>
<td>5.97</td>
<td>5.18</td>
</tr>
<tr>
<td>Mn</td>
<td>0.62</td>
<td>0.57</td>
<td>0.43</td>
</tr>
<tr>
<td>Si</td>
<td>0.038</td>
<td>0.45</td>
<td>0.41</td>
</tr>
<tr>
<td>C</td>
<td>0.01</td>
<td>-</td>
<td>4.54</td>
</tr>
<tr>
<td>S</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>0.018</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>O</td>
<td>-</td>
<td>-</td>
<td>1.55</td>
</tr>
<tr>
<td>Br</td>
<td>-</td>
<td>-</td>
<td>1.93</td>
</tr>
<tr>
<td>Cu</td>
<td>0.71</td>
<td>-</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Residues from the exposure were seen both on the stainless steel and the gasket (Figure 53). EDS mapping was used to evaluate the surface and the result is presented in Figure 54. The result shows that the residue on the stainless steel mainly consists of silicone and oxygen while the residue on the gasket appears to be of sodium, chloride and molybdenum.

Figure 53. The mapping site examining a small residue from the exposure.
4.3.2 Discussion

Five different stainless steels were combined with Novatec gasket and exposed to brackish water for 38 days. SEM and EDS measurements showed that residues were present on the gasket surfaces after the exposure. SEM images showed that a coating was present on most parts of the gasket, with EDS mapping (e.g. Figure 47 & Figure 51) the coating appeared to be consisting of chloride and sodium (and Mo in Figure 54). This coating could be a result of a biological film, see section 2.3.4, which had been formed by bacteria in the brackish water. This is, however, unclear and a more detailed evaluation on the gasket surface is needed to draw any conclusions.

Residues were also visible on the stainless steels, for example stainless steel 304L, 316L (standard and high Mo) and 254 SMO. From appearance the residues seemed to be spread from the gasket surface, especially for 316L high Mo (Figure 49). The residues on the stainless steel were examined with EDS mapping, which showed that they were mainly consisting of oxygen, silicone and carbon but not chloride and sodium, which were present on the gasket surface. Residues most probably originate from SiC abrasive paper, which was used to polish samples prior to exposure.

Out of five sample combinations that were exposed to brackish water only two showed any types of injuries on the stainless steel surface. The steels were 304L and 316L, both standard compositions, while 304L (high Ni), 316L (high Mo) and 254 SMO did not show any signs of injuries on the surface.

Stainless steel 304L has corroded in one of the corners next to the gasket, see Figure 39 and Figure 78. The EDS mapping showed that the deposit on steel contained higher amounts of oxygen, sodium and chloride then the site without deposit. The deposit was spread to the gasket and the site with deposit contained higher amounts of oxygen, iron, chromium, sodium and chloride then the site without deposit. The results indicate that corrosion products in form of iron oxide/hydroxide (i.e. rust) have been formed on the surface adjacent to the 304L steel and Novatec gasket.

The small injury on the surface of stainless steel 316L (site 3 in Figure 45) showed less content of iron, chromium and nickel but increased content of sulfur, oxygen, sodium and chloride than the site that was not injured (site 2 in Figure 45). Only around 30% of site 3 in Figure 45 contains an injury, which could indicate that the increased content of sulfur, oxygen, sodium and chloride in the injured area is larger than what is given in Table 17. The increased amount of sulfur could be a result of sulfate reducing bacteria (SBR) on the surface, i.e. that the corrosion could be microbiologically influenced.
Table 14 shows the element composition changes after exposure, however, it does not show any clear pattern for the studied samples. For most stainless steels the iron, chromium and nickel contents have decreased after exposure mainly due to increased content of elements such as oxygen, carbon and bromine on the surface. The increased content of carbon and oxygen is believed to come from the brackish water and the bromine could originate from the gasket. However, the spectrum sites are small and it is not guaranteed that the results are representative for the whole sample as the element composition may differ on different sites of the surface.
5. Discussion

5.1 Corrosion between Novatec Premium II and 254 SMO in Brackish Water

Electrochemical tests and evaluations with SEM and EDS have given new information about the case, which came to attention at system 721 during audit 2010 and 2012. It was believed that corrosion was caused by an inappropriate use of graphite gaskets (Novatec) combined with stainless steel in brackish water. If the corrosion was a result of galvanic corrosion the gasket would have to be conductive to fulfill a galvanic cell with the stainless steel (254 SMO) and the brackish water. The gasket would also have to be nobler than the stainless steel since the corrosion took place on the stainless steel, which indicated that it would have acted as the anode while the gasket would have acted as the cathode.

The Novatec gasket was coated with a non-stick coating, which by a manual evaluation (see 4.2.1) was concluded to be nonconductive. Therefore, the coating acts as insulation between the flanges and the gasket. However, the edges of the gasket were not coated, which means that small defects on the edge could lead to conduction. Further investigation showed that scratches were present in the non-stick coating, they were probably formed when the gasket was mounted in between the flanges. These scratches revealed the bulk material, which in difference to the coating was conductive. Therefore both the edges and the surfaces of the gasket were conductive to some extent. The coating and the bulk material were evaluated with SEM and EDS and the results showed that the widest of the scratches was ~125 μm wide and that the scratch revealed the material underneath the coating, which was high in carbon content, i.e. the graphite blend. The graphite blend was studied with EDS, it contained 74.7 wt.% carbon, which indicates that the material was not consisted of pure graphite. Information from the manufacturer revealed that the blend in Novatec gasket contained aramid fibers and NBR-rubber, which could also explain more than 100 times higher resistance for the Novatec gasket than for the pure graphite gasket Grafex.

Because of scratches present on the surface and lack of coating in the edges the Novatec gasket was found to be conductive. Therefore, the nobility of the gasket and stainless steels were of interest. In order to measure the nobility of the gasket in combination with the stainless steels, a galvanic series in brackish water was recorded (see 4.1). The series measured with an Ag/AgCl (sat.) reference electrode showed that the Novatec gasket was the noblest of the studied samples, even nobler than the pure graphite coated gasket Grafex. The series showed that at room temperature (20 °C) the gasket was 0.3 V higher in potential than 254 SMO (see Figure 22). In harsh environments, such as brackish water the difference between two dissimilar materials should be kept under 0.3 V to minimize the corrosion risk [30]. This indicates that 254 SMO coupled with Novatec gives a potential risk for galvanic corrosion in brackish water. However, the polarization curve for 254 SMO showed that the stainless steel is in the passive region (III in Figure 25) at this potential and although the current is anodic the stainless steel is protected by a passive film.

By assuming that the gasket and flanges were in electric contact during operation, experiments with a zero-resistance amperemeter were executed. By insulating the gasket from the stainless steel and using the experimental setup in Figure 18 the current could only pass through the ZRA. To evaluate if the stainless steel or the gasket would be the rate limiting factor three samples with different area ratio were made. It was shown that for long-term experiments in still water the stainless steel would be rate limiting, most likely due to the formation of a passive film.

This could indicate that in a piping system where 254 SMO and Novatec gasket are in contact in standstill brackish water there is very low galvanic corrosion risk due to the protective passive film. Interestingly, long-term tests in still brackish water (4.3) resulted in a coating of Na and Cl on the gasket surface and
residues of C, Si, Br and O on some parts of the stainless steels. These residues and coatings might be signs of biological films, which often are present in still seawater [13].

The piping system at Forsmark was regularly flushed and therefore a magnetic stirrer was used in the electrochemical experiments with a Novatec gasket in contact with two stainless steels, seen in 4.1.3.1. This was done in order to evaluate the effect of convection in the electrolyte and stirring increased the current density 26 times in comparison to the still water value, which was 41.6 $\frac{\mu A}{cm^2}$. Even with the increased current densities due to convection, the current values are very low, resulting in a low corrosion rate ($365 \frac{\mu A}{cm^2}$ each year).

The low current values indicate that the corrosion attacks in system 721 are probably not caused by galvanic corrosion itself. The reason for the corrosion attack is most likely related to other forms of corrosion, e.g. crevice corrosion, which will be discussed below.

The geometry between the gasket and flange creates a small crevice between the flange surface and the gasket. The crevice was exposed to a liquid, which contains chlorides, in this case brackish water from Forsmark, which has a chloride concentration of 5000 ppm (± 2000 ppm) [31]. Compared to the engineering diagram in Figure 12 where the critical crevice condition for 254 SMO in 20 °C is approximately 20000 ppm the risk for crevice corrosion should be low. However, chlorides present in the gasket ($\leq 50$ ppm) could leach and increase the chloride concentration in the crevice.

The higher chloride content itself should not be enough to cause crevice corrosion on an unharmed 254 SMO stainless steel. However, the main reason to believe that the corrosion is caused by crevice corrosion is that it could derive from the sensitized stainless steel surrounding the weld. The weld was welded with the filler material Avesta P12, which is a nickel based alloy, which is suitable for welding steels such as 254 SMO. The geometry for the weld is seen in Figure 55 where the weld is on the flange surface, next to the gasket. Welding exposes the flange to very high temperatures and according to the manufacturer if 254 SMO is exposed to temperatures between 600 to 1000 °C for a period of time the steel can form intermetallic phases, which consists of micro segregated elements such as chromium, nickel and molybdenum [32, 33]. This would decrease the corrosion resistance greatly in comparison to the base metal as Cr and Ni are important for the formation of a stable passive layer and Mo is important for resistance towards crevice corrosion [33].

![Figure 55. A flange, which has suffered from corrosion in system 721.](image)

The combination of the flange material being sensitized by welding and the corrosive and oxygen-depleted environment that forms in the crevice may prevent even 254 SMO from maintaining passivity. Without a
passive film, the metal would be in its active state in the crevice, which would result in much higher corrosion currents. The presence of a galvanic cell between 254 SMO and graphite may increase the corrosion currents even further, thus accelerating the corrosion.

### 5.2 Techniques to Evaluate Galvanic Corrosion

The evaluated screening tests were galvanic series, polarization curves and galvanic current measurement with a ZRA, described in section 2.4. These techniques have been used for experiments in this report with a detailed explanation of how the techniques were used under section 3.2 and advantages and disadvantages of each method (together with simulations) are presented in Table 20.

**Table 20. Advantages and disadvantages of four different techniques for evaluating galvanic corrosion.**

<table>
<thead>
<tr>
<th>Galvanic series / Corrosion potential measurement</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Instant results</td>
<td>- Does not give corrosion rate</td>
</tr>
<tr>
<td>+ Low sample cost</td>
<td>- Does not tell exact risk for galvanic corrosion</td>
</tr>
<tr>
<td>+ Few or no pretreatments</td>
<td>- Deceptive for passivating materials</td>
</tr>
<tr>
<td>+ Equipment cost is low, only a multimeter and a reference electrode</td>
<td></td>
</tr>
<tr>
<td>+ Show corrosion potential in the chosen electrolyte</td>
<td></td>
</tr>
<tr>
<td>+ Easy to interpret results</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polarization curves</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Low sample cost</td>
<td>- Equipment cost is high (potentiostat, reference- and counter electrode and a computer coupled to the potentiostat)</td>
</tr>
<tr>
<td>+ Few or no pretreatments</td>
<td>- Hard to interpret the results</td>
</tr>
<tr>
<td>+ Show sensitivity for e.g. pitting corrosion</td>
<td></td>
</tr>
<tr>
<td>+ Show corrosion current density and corrosion potential in the chosen electrolyte</td>
<td></td>
</tr>
<tr>
<td>+ Can do fast or slow scans depending on settings</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Galvanic current measurement with a ZRA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Measures galvanic current, which can be transferred to corrosion rate</td>
<td>- Up to 1000 hours stabilization time</td>
</tr>
<tr>
<td>+ Excellent to determine risk for galvanic corrosion</td>
<td>- Could be very complicated experimental setup and expensive samples</td>
</tr>
<tr>
<td>+ Depending on similarity to the real system very exact results can be given for the chosen environment and sample combination</td>
<td>- Needs a nano-/picoamperemeter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Depending on similarity to the real system very exact results can be given for the chosen environment and sample combination</td>
<td>- High cost depending on similarity to the real system</td>
</tr>
<tr>
<td>+ Might take several months to years</td>
<td></td>
</tr>
</tbody>
</table>

At Forsmark it is now possible to perform galvanic series / corrosion potential measurements, but as showed in Table 20, the technique does not give the exact risk for galvanic corrosion. The measurements can indicate if the risk for galvanic corrosion is high or low depending on the corrosion potential difference between materials, however, it can be deceptive for passivating materials. By combining corrosion potential measurements with polarization curves it is possible to obtain a better estimate regarding galvanic corrosion.
6. Conclusions

Several electrochemical experiments have been performed on different stainless steels and gaskets. The experimental setups and results can work as a reference to predict and evaluate galvanic corrosion in the future. An experimental setup for corrosion potential measurements is now available at Forsmark with instruction from the experimental setup seen in 3.2.1.

The graphite gasket (Novatec), which was believed to cause galvanic corrosion, was examined. The gasket was coated with a nonstick coating, which was shown to be nonconductive. However, the gasket had scratches on the surface, most likely from mounting in between the flanges, which revealed a conductive graphite blend underneath the coating. The Novatec gasket resistance was compared to the resistance of a gasket coated with pure graphite. The resistance for the Novatec gasket was found to be 100 times higher than for pure graphite gasket.

Galvanic current measurements with a zero resistance amperemeter (ZRA) showed that a current would pass between the graphite gasket (Novatec) and the stainless steel (254 SMO) when the materials were immersed in brackish water. However, the current density was very low, both for still and flowing electrolyte. The limiting factor for the current was determined to be the stainless steel and it is probably due to the protective passive film on the stainless steel.

Corrosion potential measurements showed that the Novatec gasket was nobler than 254 SMO (and the other stainless steels), with a potential difference of 0.3 V, which according to [30] would give a potential risk for galvanic corrosion. However, results from polarization curves showed that the 254 SMO would be in a passive region for the measured potential difference and therefore be protected by a passive film.

The polarization curves showed a clear difference between 254 SMO and the other stainless steels, 304L (standard and high Ni) and 316L (standard and high Mo). The biggest difference was stability (i.e. corrosion resistance) at higher potentials. It was concluded that 254 SMO is less susceptible to e.g. pitting corrosion than the other stainless steels and this is consistent with the pitting resistance equivalent number (PREN) for the stainless steels.

It was concluded that galvanic corrosion itself should not have caused the corrosion attacks in system 721. Due to the presence of a crevice in between gasket and flange, poor placement of a weld and chlorides in water there was a risk for crevice corrosion in the system. The galvanic currents could have assisted crevice corrosion and a synergy effect could have led to serious corrosion damage.

7. Future Work

- Long-term tests with different stainless steels in combination with gaskets and compare the current density to results from galvanic series and polarization curves.
- Potentiodynamic polarization scans with reverse scan over Tafel-region to show the properties of the passive film more clearly.
- Evaluate welded 254 SMO regarding extra sensitivity for corrosion (e.g. galvanic and crevice corrosion) by performing experiments such as:
  - Galvanic series, which would show any difference in potential, which would tell if the weld could be more or less sensitive to galvanic corrosion in the chosen electrolyte.
  - Polarization curves would show if the weld is more susceptible to corrosion (e.g. pitting corrosion) by observing the forming and dissolving of the passive film.
  - ZRA-tests to evaluate if the welded surface increase or decrease galvanic currents traveling between the electrodes.
  - Study crevice corrosion on welded and non-welded surface in brackish water.
- SEM and EDS evaluation on a weld (e.g. Area analysis and Mapping) to show the distribution of elements.

8. Acknowledgements

I would like to express my gratitude to my supervisors at Forsmarks Kraftgrupp AB, Katarzyna Ciosek Högström and Jonas Högström who have helped me during this project and been very valuable when interpreting results and writing this report.

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Additional thanks to:

- Sara Munktell who helped me during my experiments at Uppsala University and shared her knowledge in electrochemical experiments.
- Madis Roots who instructed me how to use different equipment at Forsmark, such as Hirox microscope and SEM.
- Andreas Andersson from maintenance department who gave me and my supervisors a tour in system 721 and answered all our questions.
- All people at FTM for all the help along the way.
- Tor Svensson, cFTMQ who gave me the opportunity to do this project.
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10. Appendix

10.1 Galvanic Series

Figure 56. Galvanic series for 5 different stainless steels.

Figure 57. Galvanic series for two different gasket materials.
10.2 Polarization Curves

10.2.1 Potentiodynamic line scan

Figure 58. Potentiodynamic line scan from -0.5 to +1.1 V vs. Ag/AgCl (sat.) for 304L stainless steel.

Figure 59. Potentiodynamic line scan from -0.5 to +1.1 V vs. Ag/AgCl (sat.) for 304L (high Ni) stainless steel.
Figure 60. Potentiodynamic line scan from -0.5 to +1.1 V vs. Ag/AgCl (sat.) for 316L stainless steel.

Figure 61. Potentiodynamic line scan from -0.5 to +1.1 V vs. Ag/AgCl (sat.) for 316L (high Mo) stainless steel.
Figure 62. Potentiodynamic line scan from -0.5 to +1.1 V vs. Ag/AgCl (sat.) for 254 SMO.

Figure 63. Potentiodynamic line scan from -0.5 to +1.1 V vs. Ag/AgCl (sat.) for Novatec Premium II.
10.2.2 Tafel Plots

**Figure 64.** Two measurements for 304L.

**Figure 65.** Two measurements for 304L (high Ni).
Figure 66. Two measurements for 316L.

Figure 67. Two measurements for 316L (high Mo).
Figure 68. Two measurements for 254 SMO.

Figure 69. One measurement for Novatec Premium II.
10.3 SEM and EDS Images

10.3.1 Gaskets

10.3.1.1 Grafex EX

Figure 70. Grafex EX.

Figure 71. Mapping site Grafex EX.
Figure 72. Mapping results from Grafex EX

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>97.97</td>
</tr>
<tr>
<td>O</td>
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10.3.1.2 Dixo 4000

Figure 73. Dixo 4000.
Figure 74. Novatec Premium II.

Figure 75. Novatec Premium II with coating manually removed.
10.3.2 Long-Term Tests

10.3.2.1 304L-Novatec Premium II

Figure 76. 304L and Novatec Premium II before exposure to brackish water.

Figure 77. 304L and Novatec Premium II after exposure to brackish water.
10.3.2.2 304L (high Ni) – Novatec Premium II

Figure 78. 304L and Novatec Premium II after exposure to brackish water.

Figure 79. 304L (high Ni) with Novatec Premium II before exposure to brackish water.
10.3.2.3 316L – Novatec Premium II

Figure 80. 304L (high Ni) with Novatec Premium II after exposure to brackish water.

Figure 81. 316L with Novatec Premium II before exposure to brackish water.
Figure 82. 316L with Novatec Premium II after exposure to brackish water.

Figure 83. 316L with Novatec Premium II after exposure to brackish water.
10.3.2.4 316L (high Mo) – Novatec Premium II

Figure 84. 316L (high Mo) with Novatec Premium II before exposure to brackish water.

Figure 85. 316L (high Mo) with Novatec Premium II after exposure to brackish water.
10.3.2.5 254 SMO – Novatec Premium II

Figure 86. 316L (high Mo) with Novatec Premium II after exposure to brackish water.

Figure 87. 254 SMO with Novatec Premium II before exposure to brackish water.
Figure 88. 254 SMO with Novatec Premium II after exposure to brackish water.

Figure 89. 254 SMO with Novatec Premium II after exposure to brackish water.