CATHODIC PROTECTION

Prepared by:

Professor Roy Johnsen, Inst. of Engineering Design and Materials
E-mail: roy.johnsen@ntnu.no
# TABLE OF CONTENT

1  CATHODIC PROTECTION - THEORY........................................................................................................3
   1.2 Reference electrodes ..................................................................................................................7
2  DEVELOPMENT OF CALCAREOUS DEPOSITS..............................................................................8
3  DESIGN OF A CATHODIC PROTECTION SYSTEM.........................................................................8
   3.1 References ..................................................................................................................................8
   3.2 Steps in a design ..........................................................................................................................8
   3.3 Protection potential for stainless alloys ......................................................................................12
   3.4 Impressed current system ..........................................................................................................13
   3.5 Use of thermal sprayed aluminium ............................................................................................14
   3.6 Distribution of anodes ................................................................................................................14
   3.6 Protection of offshore pipelines ................................................................................................15
   3.7 Monitoring and/or Inspection of CP performance ..................................................................17
      3.7.1 Current output from sacrificial anodes .................................................................................17
      3.7.2 Potential measurements ......................................................................................................17
4  INTERNAL CATHODIC PROTECTION IN PIPES.........................................................................20
   4.1 Introduction ..................................................................................................................................20
   4.2 Potential drop for current transport inside an insulated pipe ....................................................21
   4.3 Potential drop inside a metal pipe with constant current density on the internal wall ............22
   4.4 Potential drop inside a pipe with actual polarization curves ....................................................23
ATTACHMENT – EXAMPLE .............................................................................................................24

Author: Professor Roy Johnsen, E-mail: roy.johnsen@ntnu.no
1 CATHODIC PROTECTION - THEORY

Carbon steel and stainless steel (depending on the temperature) exposed to seawater will suffer from corrosion. The following reactions will occur on the surface:

Anodic reaction: \[ \text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \]  
Cathodic reactions: \[ \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- \]  
\[ 2\text{H}^+ + 2e^- \rightarrow \text{H}_2(\text{g}) \]

These reactions can be shown schematically in an overvoltage diagram (E-logI) according to Figure 1.1.

![Overvoltage diagram (E-log I) for steel in seawater.](image)

The actual corrosion situation is defined by the crossing of the anodic reaction curve (Eq.1) and the sum curve for the cathodic reactions (Eq. 2 and 3). This corresponds to a corrosion potential of \( E_{\text{corr}} \) and a corrosion current density \( i_{\text{corr}} \) (\( i = i_{\text{corr}}/\text{Area} \)). The corrosion rate is proportional to the current density \( i_{\text{corr}} \).

The Pourbaix diagram gives the connection between electrochemical potential \( E \), solution pH and the condition of the metal (corrosion, passive, and immune) as shown in Figure 1.2 for carbon steel in water. The corrosion potential \( E_{\text{corr}} \) for carbon steel is in the order of -600 mV vs. Ag/AgCl. As can be seen from the Pourbaix diagram this indicate that carbon steel will be in the corrosion region in water with pH = 7. One way to reduce the corrosion rate is to lower the potential into the immune region of the Pourbaix diagram. According to Figure 1.1, a lowering of the potential will also reduce the current density on the anodic reaction (iron dissolution). This is called cathodic protection (CP) and is achieved by supplying an external current to the structure to be protected.
Figure 1.2 Pourbaix diagram for carbon steel in tap water with pH 7 (potential against SHE).

Figure 1.3 Overvoltage diagram for steel in seawater with protection current I_P included.
Figure 1.3 shows the E-logI curve with a cathodic current $I_p$ added. As can be seen from the figure the lowering of the potential caused by the external current, will reduce the anodic dissolution of iron according to Eq. (1) – see the yellow point in the figure.

For carbon steel in seawater the normal corrosion potential $E_{corr}$ is in the range -550 to -600 mV vs. Ag/AgCl. To achieve protection a potential $E_p \leq -800$ mV vs. Ag/AgCl is normally required for carbon steel in seawater /1/.

Cathodic protection from sacrificial anodes is based on the principle of galvanic corrosion. This means that a less noble material is connected to the structure (metal) to be protected. To select the right sacrificial anode material, the galvanic series is important. Figure 1.4 shows the galvanic series for selected materials in seawater.

From this series one can see that carbon steel normally has a corrosion potential in the range -550 to -600 mV vs. SCE in seawater. To reduce the potential by installing sacrificial anodes, an anode material with a potential more negative than -600 mV vs. SCE needs to be selected. The figure indicates that zinc and aluminum alloys are well suited as sacrificial anodes when protecting carbon steel.

Figure 1.3 also shows how the hydrogen reaction is more and more dominating when the potential is lowered. This is reason why it is important to restrict the min. potential on steels that can suffer from hydrogen induced cracking.

This protection current can be supplied in two different ways, as schematically shown in Figure 1.5:

- Impressed current from an external power source
- Sacrificial anodes

See also Section 3.4.

A complete corrosion protection system for a structure or a component is normally a combination between the use of cathodic protection and a coating system (see Section 3.2).
Figure 1.4  Galvanic series for selected materials in seawater.

Figure 1.5  A schematic picture of the cathodic protection principle with a) sacrificial anodes and b) impressed current.
1.2 Reference electrodes

Different reference electrodes are used to describe the electrochemical potential on a surface exposed to an electrolyte. Table 1.1 gives an overview of the most frequent used reference electrodes and the potential difference between the different electrodes.

Table 1.1 Overview over most frequent used reference electrodes.

<table>
<thead>
<tr>
<th>Name</th>
<th>Nernst Equation</th>
<th>Potential (V vs. SHE)</th>
<th>T coefficient (mV °C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (SHE)</td>
<td>E⁰ - 0.059 pH</td>
<td>0.00</td>
<td>..</td>
</tr>
<tr>
<td>Silver chloride</td>
<td>E⁰ - 0.059 log aₐ₃Cl</td>
<td>0.2224</td>
<td>-0.6</td>
</tr>
<tr>
<td>0.1 M KCl</td>
<td></td>
<td>0.2881</td>
<td>..</td>
</tr>
<tr>
<td>1.0 M KCl</td>
<td></td>
<td>0.235</td>
<td>..</td>
</tr>
<tr>
<td>saturated (KCl)</td>
<td></td>
<td>0.199</td>
<td>..</td>
</tr>
<tr>
<td>seawater</td>
<td></td>
<td>~0.250</td>
<td>..</td>
</tr>
<tr>
<td>Calomel (SCE)</td>
<td>E⁰ - 0.059 log aₐ₃Cl</td>
<td>0.268</td>
<td>..</td>
</tr>
<tr>
<td>0.1 M KCl</td>
<td></td>
<td>0.3337</td>
<td>-0.06</td>
</tr>
<tr>
<td>1.0 M KCl</td>
<td></td>
<td>0.280</td>
<td>-0.24</td>
</tr>
<tr>
<td>(SCE) saturated (KCl)</td>
<td></td>
<td>0.241</td>
<td>-0.65</td>
</tr>
<tr>
<td>Mercurous sulfate</td>
<td>E⁰ - 0.0295 log aₐ₃Sulfate</td>
<td>0.6151</td>
<td>..</td>
</tr>
<tr>
<td>Mercuric</td>
<td>E⁰ - 0.059 pH</td>
<td>0.926</td>
<td>..</td>
</tr>
<tr>
<td>Copper sulfate</td>
<td>E⁰ + 0.0295 log aₐ₃Copper</td>
<td>0.340</td>
<td>..</td>
</tr>
<tr>
<td>saturated</td>
<td></td>
<td>0.318</td>
<td>..</td>
</tr>
</tbody>
</table>

Silver chloride = Ag/AgCl  
Saturated Calomel = SCE  
Copper Sulfate = Cu/CuSO₄

Author: Professor Roy Johnsen, E-mail: roy.johnsen@ntnu.no
2 DEVELOPMENT OF CALCAREOUS DEPOSITS

Seawater is a complex chemical solution containing several organic species in addition to carbonates and bi-carbonates. The content of CO₂-gas, manganese (Mg) and Calcium (Ca) ions has great influence on the effectiveness of cathodic protection.

Ca-ions in seawater will react with H₂CO₃ and form Ca(HCO₃)₂. As soon as the solution is saturated with calcium carbonate, CaCO₃ will be precipitated on the surface. The same will occur with Mg(OH)₂ when the saturation product is exceeded.

Both CaCO₃ and Mg(OH)₂ (later called calcareous deposit) developed on a surface will act as a barrier for O₂-diffusion to the metal surface. The result is a reduction in the current density during cathodic protection as a function of the build up of the calcareous deposit. The quality of the calcareous deposit depends on parameters like:

- Protection potential
- Temperature
- Relative flow velocity
- Surface condition
- Chemical composition of the seawater

Current density requirement under cathodic protection is given in standards or recommended practices like e.g. DnV RP B401 (see Section 3.2). As can be seen from this document the current density varies depending on location, water depth, temperature and salinity.

3 DESIGN OF A CATHODIC PROTECTION SYSTEM

3.1 References

Design of a cathodic protection system for a structure shall normally be in accordance with a standard or a recommended practice. The following are the most frequently used:

/1/ DnV RP B401 “Cathodic Protection Design”, revision 1993
/2/ NORSOK M-503 “Cathodic Protection”
/3/ NACE RP0176-83: “Corrosion control of Steel Fixed Offshore Platforms Associated with Petroleum Production”

The most frequently used documents are DnV RP B401 /1/ for structures and ISO 15589 /4/ for subsea pipelines. The DnV document is up for revision during 2004, while the ISO document has recently been revised and approved for implementation.

3.2 Steps in a design

1. Preparation of the design basis
Before the design work starts a design basis shall be prepared and accepted by the customer/management before the work starts. The design basis shall include the following information:

- Which standard or recommended practice to base the design upon
- Type of protection; sacrificial anodes or impressed current
- Combined protection with coating
- Current densities to be used (if not directly in accordance with the standard)
- Protection potentials (as above)
- If coating – type of coating and degradation rate
- Deviations from actual standard/RP
- Documentation to base the design upon
- Is the structure in electrical contact with other structures permanently or from time to time?
- Documentation level for the design

2. Definition of surface area to be protected

Based on the documentation of the actual structure the total surface to be protected shall be calculated. Assuming that different parts of the structure see different temperature levels and/or different water depths, total areas for the different regions shall be specified. Which region to divide the structure into shall be specified in the “Design Basis”.

\[ A_T = \sum A_1 + A_2 + \ldots + A_n, \quad n = 1 - m \quad (3.1) \]

3. Calculation of total protection current

Total protection current \( I_T \) shall be calculated from the following equation:

\[ I_T = \sum (i_1 x A_1 + i_2 x A_2 + \ldots + i_n x A_n) \quad (3.2) \]

Where: \( i_1, \ldots, i_n \) corresponds to the current density for area \( A_1, \ldots, A_n \).

According to DnV RPB401 three different current values have to be calculated:

**Initial current, \( I_I \):**
Cathodic current that is required to give an effective polarization of the surface shortly after exposure start up.

\[ I_I = \sum (i_{I1} x A_1 + i_{I2} x A_2 + \ldots + i_{In} x A_n) \quad (3.3) \]

**Average current, \( I_A \):**
Average or maintenance current as a measure of the anticipated cathodic current once the cathodic protection system has attained its steady state protection potential.

\[ I_A = \sum (i_{A1} x A_1 + i_{A2} x A_2 + \ldots + i_{An} x A_n) \quad (3.4) \]

**Final current, \( I_F \):**
Current required at the end of the exposure period with developed calcareous deposits and marine growth. It takes into account the additional current required to re-polarize the steel surface if the calcareous layer is partly and periodically damaged, e.g. by severe storms.

\[ I_F = \sum (i_{F1} x A_1 + i_{F2} x A_2 + \ldots + i_{Fn} x A_n) \quad (3.5) \]

Initial \( (i_I) \), average \( (i_A) \) and final \( (i_F) \) current densities are given in /1/, Chapter 6.3, for the actual sub-areas.
Assuming that the protection system consists of a combination between coating and cathodic protection, the required current for protection is multiplied with:

**Coating breakdown factor, \( f_b \):** Anticipated reduction in cathodic current due to the application of an electrically insulating coating.

Values for the coating breakdown factor \( f_b \) is given in /1/, Chapter 6.4. Total initial, average and final current shall be adjusted with the initial, mean and final coating breakdown factor, \( f_{bI} \), \( f_{bA} \) and \( f_{bF} \) respectively.

Total *initial* current:  
\[
I_{TI} = \sum (i_{1}A_{1}x_{f_{b1}} + i_{2}A_{2}x_{f_{b2}} + \ldots + i_{n}A_{n}x_{f_{b1n}}) \quad (3.6)
\]

Total *average* current:  
\[
I_{TA} = \sum (i_{1}A_{1}x_{f_{bA1}} + i_{2}A_{2}x_{f_{bA2}} + \ldots + i_{n}A_{n}x_{f_{bAn}}) \quad (3.7)
\]

Total *final* current:  
\[
I_{TF} = \sum (i_{1}A_{1}x_{f_{bF1}} + i_{2}A_{2}x_{f_{bF2}} + \ldots + i_{n}A_{n}x_{f_{bFn}}) \quad (3.8)
\]

**Situation with no coating** on the surface:

Required protection current for the actual lifetime \( I_P = \text{Max} \ (I_i, I_A, I_F) \quad (3.9) \)

**Situation with a combination between coating and cathodic protection:**

Required protection current for the actual lifetime \( I_P = \text{Max} \ (I_{TI}, I_{TA}, I_{TF}) \quad (3.10) \)

If *sacrificial anodes* are the preferred solution then execute point 4 – 9 in the following. If *impressed current system* is selected, required protection current \( I_P \) shall be delivered from the system, see Section 3.4.

### 4. Calculation of total anode weight

Total required anode weight \( m_{TA} \) (or mass) based on the average total current \( I_{TA} \) is calculated according to the following equation:

\[
m_{TA} = \frac{(I_{TA} \times t \times 8670)/(U \times C)} \quad (3.11)
\]

where:
- \( t \) = Lifetime (years)
- \( U \) = Utilization factor for the anode
- \( C \) = Anode capacity (Ah/year)
- 8670 = # hours / year

### 5. Selection of anode type and size

Anode size and shape shall be selected. The most frequent used sacrificial anode types and shapes are shown in Figure 3.1.
Figure 3.1 Anode types a) Stand off, b) Flush mounted, c) Bracelet (Jotun Cathodic Protection – today Skarpenord Corrosion)

Anodes should be selected in standard size according to information from an accepted anode supplier. As soon as the actual anode type, material and size is selected anode parameters like:

- Utilization factor $U$
- Anode capacity $C$
- Anode resistance $R_a$

can be defined from the supplier documentation and/or calculations.

6. Anode resistance calculation

The anode resistance $R_a$ shall be calculated according to the formulas given in Table 3.1.

Table 3.1 Anode resistance formulas

<table>
<thead>
<tr>
<th>ANODE TYPE</th>
<th>RESISTANCE FORMULA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long slender stand-off anode; $L \geq 4r$</td>
<td>$R_a = \frac{\rho}{(2\pi L)}(\ln(4L/r)-1)$</td>
</tr>
<tr>
<td>Short slender stand-off anode; $L &lt; 4r$</td>
<td>$R_a = \frac{\rho}{(2\pi L)}(\ln[2L/r(1+\sqrt{1+(r/2L)^2})] +r/2L - \sqrt{1+(r/2L)^2})$</td>
</tr>
<tr>
<td>Long flush mounted $L \geq 4x$ with and thickness</td>
<td>$R_a = \frac{\rho}{(2S)}$</td>
</tr>
<tr>
<td>Short flush mounted, bracelet and other flush mounted shapes</td>
<td>$R_a = 0.315\frac{\rho}{\sqrt{A}}$</td>
</tr>
</tbody>
</table>

With:

- $\rho =$ Seawater resistivity ($\Omega m$)
- $L =$ Length of anode (m)
- $r =$ Anode radius (m)
- $S =$ Arithmetic mean of anode length and with
- $A =$ exposed anode surface area ($m^2$)

To calculate the initial anode resistance $R_{ai}$ use the initial anode dimensions. The final anode resistance shall be calculated according the rules described in DnV RPB401, Section 6.7.
7. **Calculation of number of anodes**

Based on the selected anode type with weight $m_a$, the required number of anodes, $N_T$, shall be calculated based on the following equation:

$$N_T = \frac{M_T}{m_a}$$  \hspace{1cm} (3.12)

8. **Calculation of current output from each anode**

For the selected anode type, the number of anodes to deliver the total current shall be calculated for initial current $I_{TI}$ and total current $I_{TF}$.

Current output from the anode – **initial** condition:

$$I_{ai} = \frac{|E_P - E_a|}{R_{al}}$$  \hspace{1cm} (3.13)

Current output from the anode – **final** condition:

$$I_{af} = \frac{|E_P - E_a|}{R_{af}}$$  \hspace{1cm} (3.14)

Where:

- $E_P$ = Protection potential (mV vs. Ag/AgCl)
- $E_a$ = Anode potential (mV vs. Ag/AgCl)
- $R_{al}$ = Anode resistance for initial anode size ($\Omega m$)
- $R_{af}$ = Anode resistance for final anode size ($\Omega m$)

9. **Calculation of number of anodes**

Number of anodes $N_i$ based on **initial** conditions:

$$N_i = \frac{I_{TI}}{I_{ai}}$$  \hspace{1cm} (3.15)

Number of anodes $N_f$ based on **final** conditions:

$$N_f = \frac{I_{FI}}{I_{af}}$$  \hspace{1cm} (3.16)

Select the final number $N$ of anodes from:

$$N = \text{Max} (N_i, N_f, N_T)$$  \hspace{1cm} (3.17)

### 3.3 Protection potential for stainless alloys

Up to recently, -800 mV Ag/AgCl has been used as protection potential both for carbon steel and stainless steel. Testing has shown that a more positive potential can be used. See Figure 3.2 where the anodic curve for dissolution of carbon steel and stainless steel is drawn. As can be seen the max. potential ($E_{prot}$) is higher on SS than on CS.

Table 3.2 that is copied from /4/ shows potential limits for carbon steel and stainless steel alloys.
3.4 Impressed current system

An impressed current system consists of the following components:

- Rectifier (current supply)
- Counter electrode
- Reference electrode
3.5 Use of thermal sprayed aluminium

Thermal sprayed aluminum (TSA) can be used as protective coating to carbon steel exposed to seawater. This is a metallic coating that will act as an anode and protect exposed steel locally. However, Surfaces covered with TSA will normally be connected to sacrificial anodes to achieve a better long term protection of the structure. According to DnV RPB401 current requirement for TSA is 10 mA/m².

3.6 Distribution of anodes

Anodes shall be distributed in a way that secure as even current- and potential distribution on the structure as possible. The following general rules can be given:

1. Secure an even distribution of anodes on a symmetrical structure (pipe)
2. Install more anodes close to a region with concentrated surface areas (node point)
3. Always install anodes under sea level

Experience will learn where to install anodes in the most optimum position. Computer modeling can also be used to secure optimal anode distribution. See www.force.dk/forcetechnology.no. Figure 3.4 shows as an example computer modeling of the CP system of a part of an offshore structure.
3.6 Protection of offshore pipelines

/4/ shall be used as guideline for corrosion protection of pipelines. The most important with this standard compared to the other available standards or recommended practices are:

- Specifically developed for subsea pipelines.
- Based on historical information from all the major oil companies.
- Specify current density requirement as a function of seawater temperature.
- Define different protection regions (max. and min. values) for carbon steel and stainless steel.
- Specify values for coating breakdown values more in line with historical information for the different coating systems.

Another advantageous with the new ISO standard /4/ is that it does not specify any max. distance between the anodes. Instead it requires calculation of max. potential midway between two anodes based on the current density used and the actual coating breakdown factor in the end of the lifetime. Figure 3.5 shows a schematic presentation of the situation and Figure 3.6 the equivalent current flow loop with all actual resistors.
Figure 3.5  Schematic presentation of the current flow from the anode through the seawater into the coating failures and back through the pipewall.

Figure 3.6  Equivalent current flow loop for the cathodic protection.

where:

- $E_A$ = Anode potential (V vs. Ag/AgCl)
- $E_C$ = Potential on the pipe surface (cathode) (V vs. Ag/AgCl)
- $R_A$ = Anode resistance (ohm)
- $R_S$ = Resistance for current flow in seawater outside the pipe (ohm)
- $R_C$ = Resistance for current entering the pipe surface (ohm)
- $R_M$ = Resistance for current flowing in the pipe metal (ohm)
- $I_C$ = Total protection current in the loop (A)

As a simplification the following assumption are taken:

$$R_A, R_M >> R_C \text{ and } R_S$$  \hfill (3.18)

This gives the following equation for the potential drop in the simplified current loop:

$$\Delta E = |E_A - E_C| = (R_A + R_M) \times I_C$$  \hfill (3.19)

$$R_M = \frac{\rho \times L}{[\pi(D^2 - d^2)/4]}$$  \hfill (3.20)

$R_A$ = Defined by the anode type and size (see Table 3.1)
D, d = Outer and inner pipe diameter (m)

\[ I_c = I_p \times f_b \]  
\[ (3.21) \]

Where protection current density \( I_p \) and coating breakdown factor \( f_b \) is given in /4/.

Under the assumptions that:

1. Current density is constant along the pipeline
2. Coating failure is evenly distributed along the pipeline

the following simplified equation can be used to calculate the max. protection length \( L_{\text{max}} \):

\[ \Delta E = |E_A - E_C| = \left[ 2\rho I_p f_b D/(D^2 - d^2) \right] L^2 + R_A I_p f_b \pi D L_{\text{max}} \]  
\[ (3.22) \]

### 3.7 Monitoring and/or Inspection of CP performance

#### 3.7.1 Current output from sacrificial anodes

Sacrificial anodes are normally electrically connected to the structure to be protected through welding or bolting. One way to monitor the current output from selected anodes is to connect the anode through a resistor with known value to the structure. By measuring the potential drop across the known resistor, the current from the anode can be calculated. This principle is shown schematically in Figure 3.7. The use of a Swain-meter is an alternative if all the anodes are electrically connected without any resistor.

![Figure 3.7 Sacrificial anode instrumented for monitoring current output.](image)

#### 3.7.2 Potential measurements

Electrochemical potential on the surface is a good indicator for the protection level of an installation. Figure 3.8 shows schematically how the potential varies around a pipe with a coating failure (breakdown) protected by a sacrificial anode (bracelet type). Both the general potential level and the local level is shown (all potentials refereed to Ag/AgCl).
Figure 3.8 Potential distributions along a pipeline caused by sacrificial anodes protecting areas with coating breakdown in the pipeline.

Figure 3.9 Principle of potential measurements and electrical field gradient measurements.

Figure 3.9 shows two different principles for measuring the protection level:

**Potential level:** By measuring the actual potential on the structure relative to a reference electrode.

**Field gradient:** Potential difference between two reference electrodes mounted with a constant distance.

The first principle is the most frequently used and Figure 3.10 – 3.13 shows pictures of different methods that are used for measuring potential level.
Figure 3.10 Potential level along a pipeline by "trailing wire" with grounding (electrical connection) directly to the pipe.

Figure 3.11 "Trailing wire" using drop cells (increased accuracy with pipelines longer than 10 km).

Figure 3.12 Potential level along a pipeline by towed remote reference cells and contact point to the pipeline through a CP stab probe.
4 INTERNAL CATHODIC PROTECTION IN PIPES

4.1 Introduction

When designing a cathodic protection system for internal protection of a pipe, it is important to include all resistors that exist in the complete current flow loop. Figure 4.1 shows a schematic view of the current flow loop.

\[ \frac{E_A - E_C}{2} = (R_A + R_S + R_C + R_M) \times I_C \] (4.1)

where:

- \( E_A \) = Anode potential (V vs. Ag/AgCl)
- \( E_C \) = Potential on the pipe surface (cathode) (V vs. Ag/AgCl)
- \( R_A \) = Anode resistance (ohm)
- \( R_S \) = Resistance for current flow in seawater inside the pipe (ohm)
- \( R_C \) = Resistance for current entering the pipe surface (ohm)
- \( R_M \) = Resistance for current flowing in the pipe metal (ohm)
- \( I_C \) = Total protection current in the loop (A)

The following equation is valid for the current flow loop:
For a condition with a pipe of a restricted length, the following assumptions are valid:

\[ R_S \gg R_A, R_C, R_M \]  

(4.2)

This gives the following simplified equation to be used:

\[ |E_A - E_C| = R_S \times I_C \]  

(4.3)

\( R_S \), which is the potential drop inside the pipe, is defined by Ohm's law:

\[ R_S = \rho \times \frac{L}{A} \]  

(4.4)

where:

\( \rho \) = resistivity of the seawater (\( \Omega \) m)

\( L \) = pipe length where the current is transported inside the pipe (m)

\( A \) = internal cross section of pipe (m\(^2\))

### 4.2 Potential drop for current transport inside an insulated pipe

The simplest way to explain the potential drop inside a pipe caused by current transported in seawater is explained in the following, see Figure 4.2. It is assumed that an anode is located close to the inlet of a pipe. On the outlet side a metal surface that require a total current \( I_{MS} \) to be protected, is mounted. The anode and the metal surface are electrically connected through a wire, in addition to the connection through the water inside the pipe. The pipe itself is, however, made from an insulation material (e.g. plastic) and will not require any current from the anode.

![Figure 4.2](image)

Figure 4.2 Schematic of a seawater pipe made from an insulation material "transporting" current from an anode to a metal surface.

If we assume that the current required for the protection \( I_{MS} \) is kept constant, Eq. (4.3) and (4.4) show that the following connection is valid

\[ |E_A - E_C| \propto L \]  

(4.5)

when \( \rho \) and \( A \) also are kept constant.

*In other words, the potential drop inside an insulation pipe (e.g. a plastic pipe) is proportional to the length of the pipe; i.e. the potential drop increases with increasing pipe length.*
Another effect is that if the anode potential is kept constant, then the electrochemical potential on the metal surface will be more positive the longer the pipe is.

4.3 Potential drop inside a metal pipe with constant current density on the internal wall

In this example we want to look at the potential drop inside a pipe that is cathodically protected by an anode and where a constant current density $i_c$ is assumed on the pipe wall. We have a situation as shown in Figure 4.3.

![Figure 4.3 Schematic of internal cathodic protection of a pipe from an anode. Constant current density is assumed on the internal pipe surface.](image)

By using Eq. (3) and (4) on this situation, the following connection can be found:

$$\Delta E = \left| E_A - E_C \right| = \frac{(2\rho i_c)/D}{X^2} \quad (4.6)$$

Eq. (4.6) shows that for the situation with constant current density on the surface, the potential drop along the pipe is proportional to the length squared.

Table 4.1 shows calculated potential drops along the pipe assuming a constant current density requirement along the pipe wall. As can be seen from the table a constant current density of 10 mA/m$^2$ gives a max. potential drop of 0.2 V in a 1 m long pipe while if increased to 100 mA/m$^2$, then the potential drop increases to 2 V.

On the other hand, if the pipe length is doubled the potential drop is quadrupled, if the pipe length is increased from 1 meter to 5 meter the potential drop increases with a factor of 25.

These calculations visualizes the practical limitations of protecting a pipe from one end with cathodic protection if the required current densities are relative high.

<table>
<thead>
<tr>
<th>CURRENT DENSITY (mA/m$^2$)</th>
<th>POTENTIAL DROP $\Delta E$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X = 0.5$ m</td>
</tr>
<tr>
<td>1</td>
<td>0.005</td>
</tr>
<tr>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>100</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Author: Professor Roy Johnsen, E-mail: roy.johnsen@ntnu.no
4.4 Potential drop inside a pipe with actual polarization curves

In a real situation the cathodic current density inside a pipe is not constant, but depends on the actual potential; real polarization curves exist. Under such conditions a numerical solution needs to be used to solve the potential and current distribution inside a pipe. Both Finite Difference Method (FDM) and Boundary Element Method (BEM) can be used to solve this problem.
ATTACHMENT – EXAMPLE
PROBLEM DESCRIPTION

A harbour is designed with several vertical pipes with a concrete cover on the top. The pipes have a certain wall thickness. The owner is afraid of corrosion damages since this will reduce the strength of the construction. Both general corrosion and bacterial corrosion is a potential threat. The engineering company has been asked to perform a corrosion protection design for the complete construction. Two alternatives for corrosion protection have been described:

1. Use of sacrificial anodes
2. Combined system with sacrificial anodes and coating.

The following “Design Basis” have been put up for the design:

<table>
<thead>
<tr>
<th>INFORMATION ABOUT THE PART OF THE CONSTRUCTION EXPOSED TO THE SEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe material</td>
</tr>
<tr>
<td>Number of pipes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INFORMATION ABOUT THE ANODE MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode capacity</td>
</tr>
<tr>
<td>Anode resistance (start)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INFORMATION ABOUT THE COATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown start</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INFORMATION ABOUT CURRENT DENSITY REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INFORMATION ABOUT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost pr. anode installed</td>
</tr>
</tbody>
</table>

Based on the “Design Basis” a calculation of necessary number of anodes shall be performed based on the two cases. Finally a solution based on a cost analysis shall be performed.

Author: Professor Roy Johnsen, E-mail: roy.johnsen@ntnu.no
PROPOSED SOLUTION (NB – SJEKK DENNE)

Copy of an Excel spread sheet with the calculation is shown below. As can be seen the following number of anodes have been calculated:

**No coating – only sacrificial anodes:** 354 anodes  
**Coating and sacrificial anodes:** 146 anodes

Based on the actual cost figures the preferred solution is the combined solution with coating and sacrificial anodes.

![Excel spreadsheet](image)

Author: Professor Roy Johnsen, E-mail: roy.johnsen@ntnu.no