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# Corrosion Protection of an Oil Platform Using Sacrificial Anodes

## *Introduction*

Steel structures immersed in seawater can be protected from corrosion through cathodic protection. This protection can be achieved by an impressed external current or by using sacrificial anodes. The use of sacrificial anodes is often preferred due to its simplicity.

The principle for cathodic protection using sacrificial anodes is quite simple: the steel structure is electronically connected to a less noble metal, for example aluminum, which causes the sacrificial anode to be anodically polarized and the steel structure to be cathodically polarized when the electrodes are immersed in seawater. The anodes are dissolved through anodic dissolution of the metal while oxygen reduction takes place at the surface of the steel structure. The supply of oxygen is what often limits the current density for oxygen reduction, which means that a limiting current of an almost constant value over a few hundreds of millivolts in potential is obtained at the surface of the steel structure.

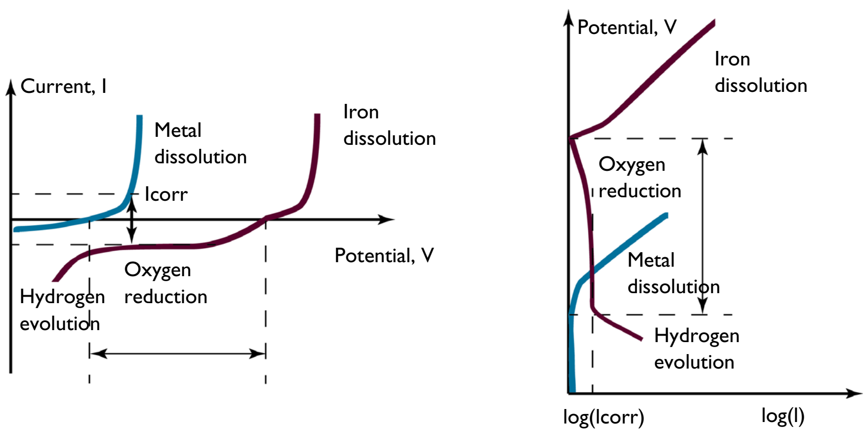



*Figure 1: Polarization behavior of the sacrificial anodes (blue) and steel surface (red).*

Figure 1 above shows the schematic polarization of the sacrificial anodes and of the oxygen reduction reaction at the surface of the steel structure. The red curve represents the polarization of the steel surface while the blue curve is the polarization of the sacrificial anode. On the left, the currents at the steel structure (red) and at the sacrificial anodes (blue) are plotted as functions of the electric potential measured relative to a common reference. The plot to the right shows the electric potential as a function of the logarithm of the absolute value of the current. As shown in the left graphs, oxygen reduction is achieved at the steel surface along the range of the cathodic limiting current represented by the flat horizontal part of the red curve. In the right plot, the vertical part of the red curve represents oxygen reduction. The system operates at the point where the cathodic current (red) is equal in size (but opposite in sign) as the anodic current.

The shape of the blue curve changes depending on the number and design of the anodes in the system, and the designer of the system needs to ensure that the different parts of the steel structure are well within the corrosion protected range of potentials (the "flat" part of the red cathodic curve); otherwise the structure is not fully protected and may start to corrode. The width of the oxygen reduction part of the curve is a few hundred millivolts. In addition, the anodes have to be able to deliver the required potential to keep the given current.

The first step in the design of a cathodic protection system is therefore to investigate the potential of the steel structure assuming a constant cathodic current (oxygen reduction). The potential has to be well within the required range where oxygen reduction protects the structure and also avoiding hydrogen evolution, which may eventually cause hydrogen embrittlement.

This example is based on a Recommended Practice for Cathodic Protection Design by DNV (Ref. 1).

## *Model Definition*

Figure 2 and Figure 3 show the model geometry. The sacrificial anodes are placed relatively close to the oil platform. The radius of the inner cylinder is chosen so that the main part of the charge transport occurs within this cylinder. The outer cylinder is modeled as an infinite Element Domain, which rescales the equations to represent an approximately thousand times larger cylinder.

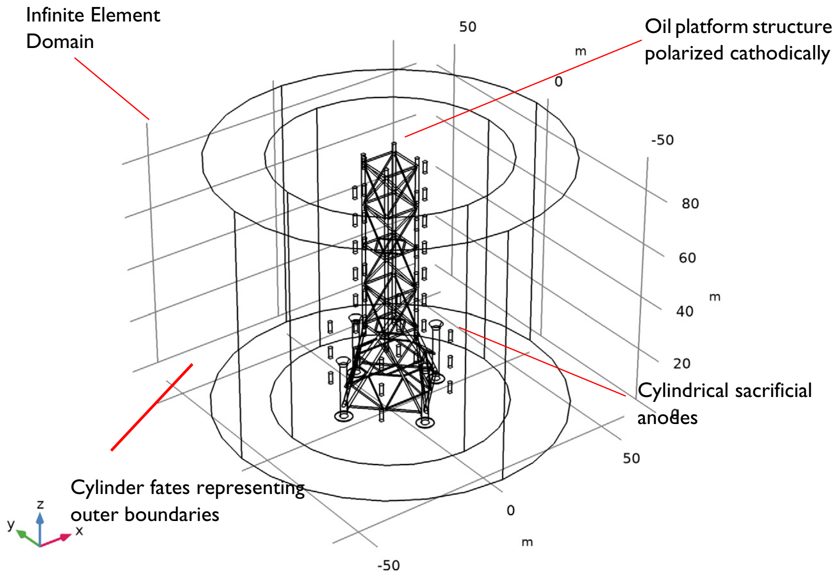



*Figure 2: Model geometry.*

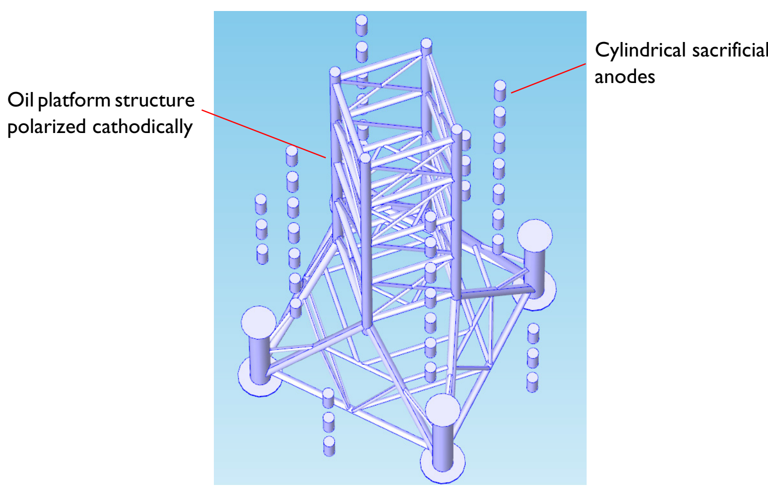



*Figure 3: Close-up view of the cylindrical sacrificial anodes and the oil platform structure.*

In seawater, the composition is assumed to vary to a very small extent and diffusion of the ions that carry the current is negligible compared to the contribution from migration of these ions in the electric field. This assumption, together with the boundary conditions, allows using a primary current density distribution analysis on the system where only the influence of ohmic effects in the given geometry are taken into account.

At the sacrificial anode surfaces, a constant potential is set assuming a relatively fast kinetics. This assumption implies that a very small change in surface overpotential leads to a very large change in current density and it is therefore reasonable to set a constant potential. Grounding the electronic phase potential (setting it to zero), the boundary condition for the electrolyte phase potential is:

$$\phi_{\mathrm{l,\ anode}} = \phi_s - E_{\mathrm{eq,\ Al}} = -E_{\mathrm{eq,\ Al}} \tag{1}$$

The value for the equilibrium potential of the aluminum anodes is -1.05 V vs Ag/AgCl in this model.

At the steel surface, it is assumed that oxygen reduction takes place at a limiting current density, limited to the rate of transport of dissolved oxygen to the surface, and that the surface is sufficiently protected so that metal dissolution currents can be neglected. This yields a constant normal current density boundary condition at the steel surfaces of the structure. The boundary condition for the steel surface is:

$$-\mathbf{n} \cdot \mathbf{i}_l = i_{\mathrm{lim,\ oxygen}} \tag{2}$$

The value for the limiting current is 0.1 $A/m^2$ in this model.

All other boundaries are insulated.

The model can be easily extended to secondary current density distribution analysis in order to add the kinetics of the electrode reactions in a second stage, see for instance the Anode Film Resistance Effect on Cathodic Corrosion Protection example. A tertiary current density distribution analysis that also accounts for the transport of charged species is also possible in the Corrosion Module, although this would require the use of different physics interfaces.

## *Results and Discussion*

Figure 4 shows a slice plot of the potential in the electrolyte, $\phi_l$ . The potential close to the steel structure surface varies several hundreds of millivolts, depending on position. The further the distance from an anode – the lower the potential, an expected result since the current in the electrolyte flows from the anodes to the steel cathode.

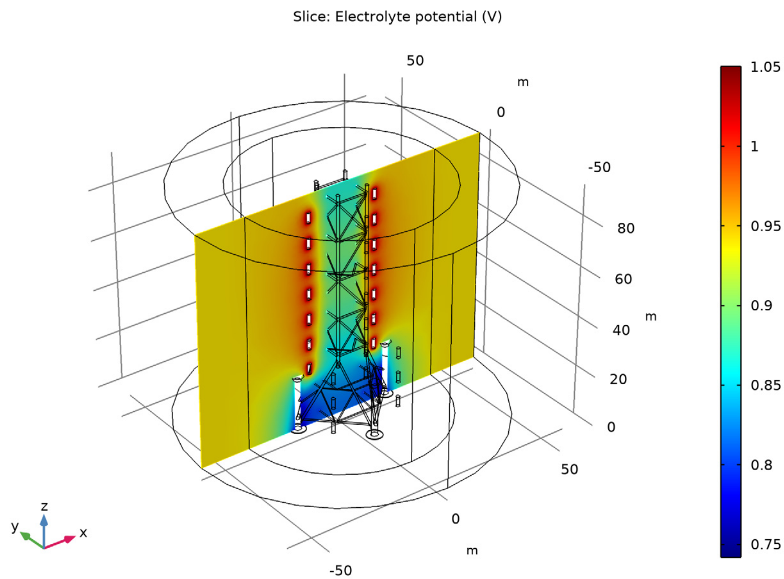



*Figure 4: Slice plot of the electrolyte potential.*

One can relate the electrolyte potential, $\phi_l$, to the electrode potential, shown in Figure 1, by considering a reference electrode placed in the electrolyte in close vicinity to the steel surface. The electric potential of a reference electrode, $\phi_{s,ref}$, is

$$\phi_{s,\mathrm{ref}} = E_{\mathrm{eq,\,ref}} + \phi_l \tag{3}$$

The electric potential of the steel surface, $\phi_s$, is constant due to the high conductivity of the metal, and the potential of the steel surface versus the reference electrode becomes

$$E_{\mathrm{steel\ vs\ ref}} = \phi_{s,\mathrm{steel}} - \phi_{s,\mathrm{ref}} = \phi_{s,\mathrm{steel}} - E_{\mathrm{eq,\,ref}} - \phi_l \tag{4}$$

In this model we chose the metal potential as ground, and assuming a Ag/AgCl reference we get:

$$E_{\mathrm{steel\ vs\ Ag/AgCL}} = -\phi_l \tag{5}$$

Figure 5 shows the potential of the steel surface according to Equation 5. The parts of the steel surface with the highest (most anodic) values in this plot are the least protected.

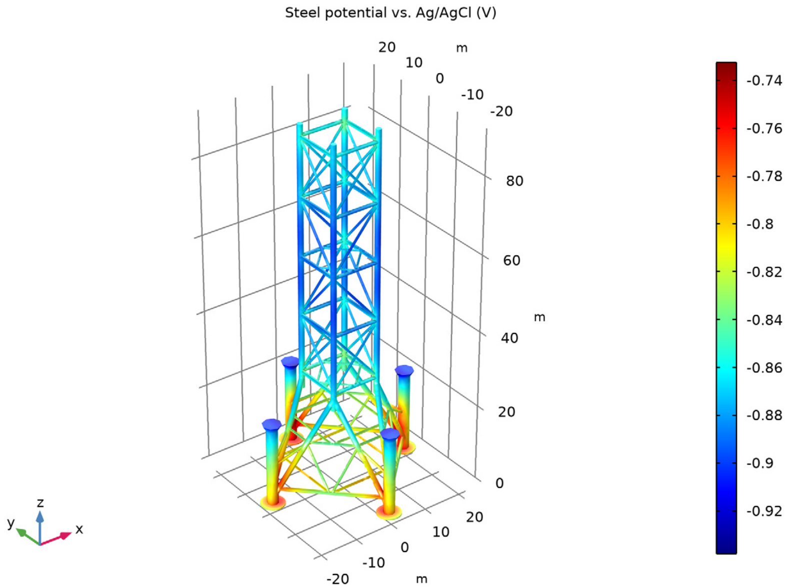



*Figure 5: Steel platform potential vs a Ag/AgCl reference.*

Figure 6 shows a close-up of one of the structure legs. The inside bottom part of the leg is the part most susceptible to corrosion.

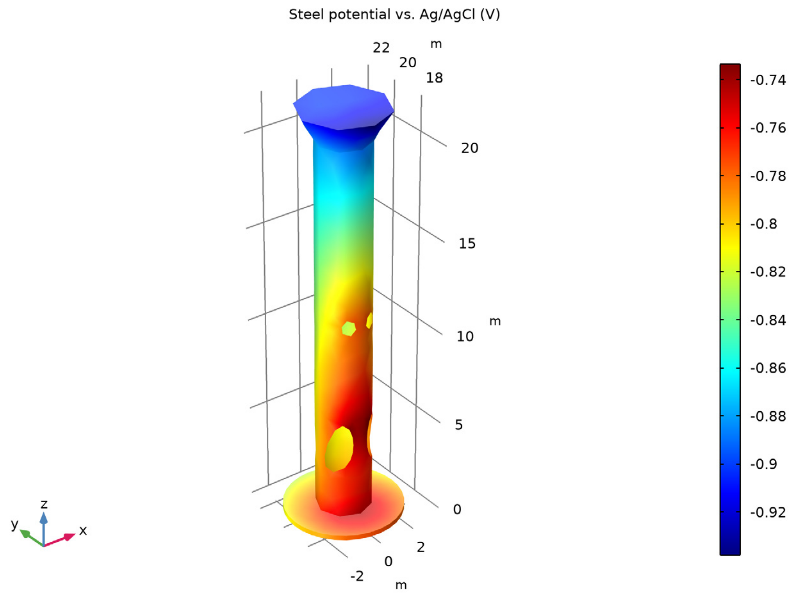



*Figure 6: Potential on one of the legs of the platform structure.*

Finally, Figure 7 shows the current densities on the anodes, which are of interest because their magnitudes are directly proportional to the consumption rate of the anode metal. The highest current density for the anodes is about four times the lowest current density.

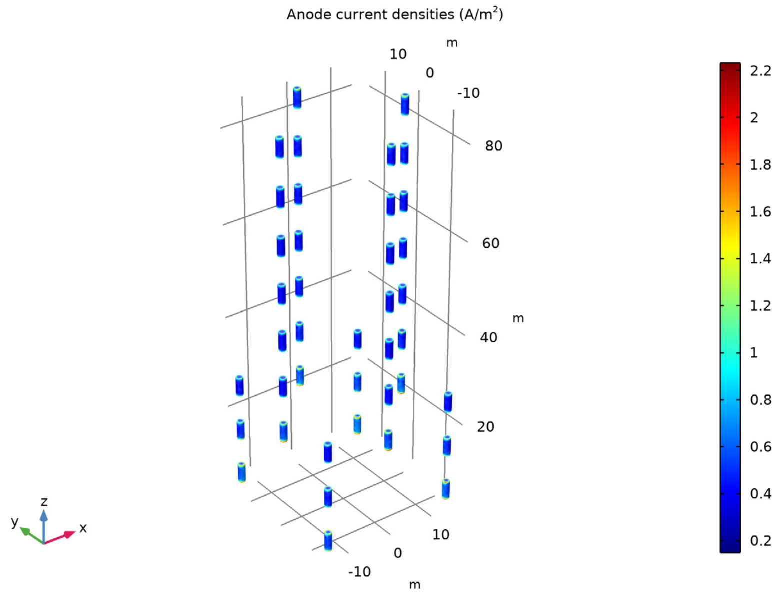



*Figure 7: Current densities on the anodes.*

## *Reference*

1. Det Norske Veritas, *Recommended Practice Cathodic Protection Design, NDV-RP-B401,* October 2010.

**Application Library path:** `Corrosion_Module/Cathodic_Protection/oil_platform`

## *Modeling Instructions*

From the **File** menu, choose **New**.

### NEW

In the **New** window, click **Model Wizard**.

## MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **Electrochemistry>Primary and Secondary Current Distribution>Primary Current Distribution (cd)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Stationary**.
6 Click **Done**.

## GLOBAL DEFINITIONS

Add some parameters for use in the model.

### *Parameters 1*

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 In the table, enter the following settings:

| Name | Expression | Value | Description |
|---|---|---|---|
| sigma_sea | 5[S/m] | 5 S/m | Seawater conductivity |
| i_oxygen | -0.1[A/m^2] | -0.1 A/m² | Limiting current for oxygen reduction at steel structure |
| Eeq_Al | -1.05[V] | -1.05 V | Anode equilibrium potential vs. Ag/AgCl |

## GEOMETRY 1

Import the geometry of the oil platform from a geometry file.

### *Import 1 (imp1)*

1 In the **Home** toolbar, click **Import**.
2 In the **Settings** window for **Import**, locate the **Import** section.
3 Click **Browse**.
4 Browse to the model's Application Libraries folder and double-click the file `oil_platform.mphbin`.
5 Click **Import**.
6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.
7 From the **Show in physics** list, choose **Boundary selection**.

8 Select the **Individual object selections** check box.

9 From the **Show in physics** list, choose **Boundary selection**.

This generates selections of the imported geometry, which you will use later on when setting up the physics on the boundaries (the anodes and the steel structure).

10 Click **Build Selected**.

*Cylinder 1 (cyl1)*

Add a surrounding cylinder around the platform.

1 In the **Geometry** toolbar, click **Cylinder**.

2 In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.

3 In the **Radius** text field, type 40.

4 In the **Height** text field, type 92.

Add a second cylinder with a larger radius, this cylinder will be used to define an Infinite Element Domain.

*Cylinder 2 (cyl2)*

1 Right-click **Cylinder 1 (cyl1)** and choose **Duplicate**.

2 In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.

3 In the **Radius** text field, type 60.

4 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

*Difference 1 (dif1)*

Create the final geometry as the difference between the cylinders and the imported oil platform structure.

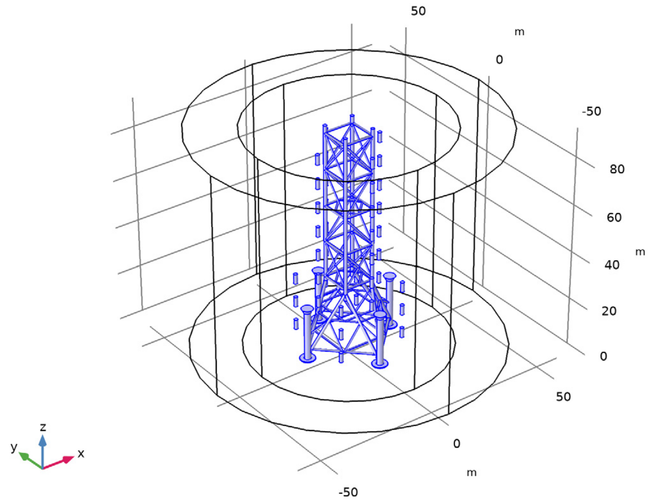
1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the objects **cyl1** and **cyl2** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Find the **Objects to subtract** subsection. Select the **Activate Selection** toggle button.

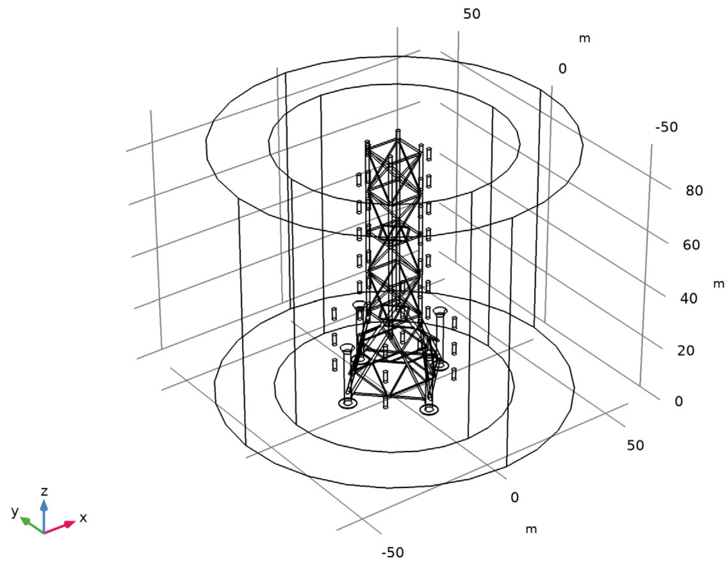
**5** Use the **Select Box** toolbar button to select the imported platform geometry.




**6** Click **Build Selected**.

**7** Click the **Zoom Extents** button in the **Graphics** toolbar.

The finalized geometry should now look like that in the figure below.




**DEFINITIONS**

Now set the outer cylinder to be an Infinite Element Domain, this will scale the equations of the outer cylinder to have an approximately 1000 times larger radius.

*Infinite Element Domain 1 (ie1)*

**1** In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

**2** Right-click **Definitions** and choose **Infinite Element Domain**.

**3** Select Domain 1 only.

**4** In the **Settings** window for **Infinite Element Domain**, locate the **Geometry** section.

**5** From the **Type** list, choose **Cylindrical**.

*Anodes*

Create a selection for the anodes by using a difference between selections that were created (by enabling Create selections) by the geometry node.

**1** In the **Definitions** toolbar, click **Difference**.

**2** In the **Settings** window for **Difference**, locate the **Geometric Entity Level** section.

3 From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Under **Selections to add**, click + **Add**.

5 In the **Add** dialog box, select **Import 1** in the **Selections to add** list.

6 Click **OK**.

7 In the **Settings** window for **Difference**, locate the **Input Entities** section.

8 Under **Selections to subtract**, click + **Add**.

9 In the **Add** dialog box, select **Object 41 (Import 1)** in the **Selections to subtract** list.

10 Click **OK**.

11 Right-click **Difference 1** and choose **Rename**.

12 In the **Rename Difference** dialog box, type `Anodes` in the **New label** text field.

13 Click **OK**.

## MATERIALS

Set the sea water conductivity in the Materials node.

### *Material 1 (mat1)*

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, click to expand the **Material Properties** section.

3 Click to collapse the **Material Properties** section. Locate the **Material Contents** section. In the table, enter the following settings:

| Property | Variable | Value | Unit | Property group |
|---|---|---|---|---|
| Electrolyte conductivity | sigmal_iso ; sigmalii = sigmal_iso, sigmalij = 0 | `sigma_sea` | S/m | Electrolyte conductivity |

## PRIMARY CURRENT DISTRIBUTION (CD)

Now add boundary conditions for the anodes and the steel structure.

### *Electrode Surface - Anodes*

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Primary Current Distribution (cd)** and choose **Electrode Surface**.

2 In the **Settings** window for **Electrode Surface**, type `Electrode Surface - Anodes` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Anodes**.

*Electrode Reaction 1*

1 In the **Model Builder** window, expand the **Electrode Surface - Anodes** node, then click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, locate the **Equilibrium Potential** section.

3 In the $E_{\mathrm{eq}}$ text field, type `Eeq_Al`.

*Electrolyte Current Density - Steel*

1 In the **Physics** toolbar, click **Boundaries** and choose **Electrolyte Current Density**.

2 In the **Settings** window for **Electrolyte Current Density**, type `Electrolyte Current Density - Steel` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Object 41 (Import 1)**.

4 Locate the **Electrolyte Current Density** section. In the $i_{n,1}$ text field, type `i_oxygen`.

## MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Mesh Settings** section.

3 From the **Sequence type** list, choose **User-controlled mesh**.

*Size*

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `10`.

5 In the **Minimum element size** text field, type `0.5`.

6 In the **Curvature factor** text field, type `0.9`.

The physics is now complete. Add mesh settings and solve the model.

7 In the **Model Builder** window, click **Size**.

8 In the **Settings** window for **Size**, locate the **Element Size Parameters** section.

9 In the **Maximum element size** text field, type `15`.

*Free Triangular 1*

1 In the **Mesh** toolbar, click **Boundary** and choose **Free Triangular**.

2 Right-click **Free Triangular 1** and choose **Move Up**.

3 In the **Settings** window for **Free Triangular**, locate the **Boundary Selection** section.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `17 19 145 147 314 316 368 370` in the **Selection** text field.

6 Click **OK**.

*Size 1*

1 Right-click **Free Triangular 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. Select the **Minimum element size** check box.

5 In the associated text field, type `1.08`.

6 Click **Build All**.

## STUDY 1

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, locate the **Study Settings** section.

3 Clear the **Generate default plots** check box.

4 In the **Home** toolbar, click **Compute**.

## RESULTS

Proceed as follows to create a slice plot of the electrolyte potential:

*Electrolyte potential*

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Electrolyte potential` in the **Label** text field.

*Slice 1*

1 Right-click **Electrolyte potential** and choose **Slice**.

2 In the **Settings** window for **Slice**, locate the **Plane Data** section.

3 From the **Plane** list, choose **ZX-planes**.

4 In the **Planes** text field, type `1`.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

6 In the **Electrolyte potential** toolbar, click **Plot**.

Compare with Figure 4.

*Steel potential*

Plot the potential along the steel boundaries by first adding a selection for these boundaries.

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.
2 In the **Settings** window for **3D Plot Group**, type `Steel potential` in the **Label** text field.
3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
4 In the **Title** text area, type `Steel potential vs. Ag/AgCl (V)`.
5 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

*Surface 1*

1 Right-click **Steel potential** and choose **Surface**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `-phil`.

*Selection 1*

1 Right-click **Surface 1** and choose **Selection**.
2 In the **Settings** window for **Selection**, locate the **Selection** section.
3 From the **Selection** list, choose **Object 41 (Import 1)**.
4 Click the **Zoom Extents** button in the **Graphics** toolbar.
5 In the **Steel potential** toolbar, click **Plot**.

   The plot should look like that in Figure 5.

*Steel potential*

Proceed in a similar way to plot the potential along a close-up of one of the platform legs.

*Steel potential 1*

1 In the **Model Builder** window, right-click **Steel potential** and choose **Duplicate**.
2 Expand the **Steel potential 1** node.

*Selection 1*

1 In the **Model Builder** window, expand the **Results>Steel potential 1>Surface 1** node, then click **Selection 1**.
2 In the **Settings** window for **Selection**, locate the **Selection** section.
3 From the **Selection** list, choose **Manual**.
4 Click **Clear Selection**.
5 Click **Paste Selection**.

6 In the **Paste Selection** dialog box, type `212-214, 218-220, 223-224` in the **Selection** text field.

7 Click **OK**.

*Steel potential, close-up*

1 In the **Model Builder** window, right-click **Steel potential 1** and choose **Rename**.

2 In the **Rename 3D Plot Group** dialog box, type `Steel potential, close-up` in the **New label** text field.

3 Click **OK**.

4 Click the **Zoom Extents** button in the **Graphics** toolbar.

5 In the **Steel potential, close-up** toolbar, click **Plot**.

Compare the resulting plot with that in Figure 6.

*Anode current densities*

Finally, proceed in the following way to plot the current density on the anodes.

1 Right-click **Steel potential, close-up** and choose **Duplicate**.

2 In the **Model Builder** window, click **Steel potential, close-up 1**.

3 In the **Settings** window for **3D Plot Group**, type `Anode current densities` in the **Label** text field.

4 Locate the **Title** section. In the **Title** text area, type `Anode current densities (A/m<sup>2</sup>)`.

*Surface 1*

1 In the **Model Builder** window, click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Primary Current Distribution>cd.nIl - Normal electrolyte current density - $A/m^2$**.

3 Locate the **Expression** section. In the **Expression** text field, type `abs(cd.nIl)`.

*Selection 1*

1 In the **Model Builder** window, expand the **Surface 1** node, then click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Anodes**.

4 Select the **Activate Selection** toggle button.

5 In the **Anode current densities** toolbar, click **Plot**.

**6** Click the **Zoom Extents** button in the **Graphics** toolbar.

Compare with Figure 7.