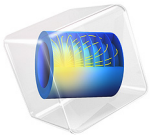

Pipeline Corrosion Protection Using Impressed Current Cathodic Protection

Introduction

Pipeline corrosion protection using an impressed current cathodic protection (ICCP) system is a commonly employed strategy to mitigate corrosion in the oil and gas industry. The impressed current anodes are strategically located around pipelines to provide adequate protection against corrosion.

In this example, three parallel pipelines of 68 km length and with a horizontal separation distance of 10 m between them are protected against corrosion by a series of impressed current anodes, were each anode is connected to all three pipelines.

The model considers two thin layers of soil of different electrolyte conductivity. The electrode potential and the total interface current density are plotted along the length of the pipelines to evaluate the level of corrosion protection.

The example is based on a paper by A.B. Peratta and others (Ref. 1).

Model Definition

The model geometry is shown in Figure 1.

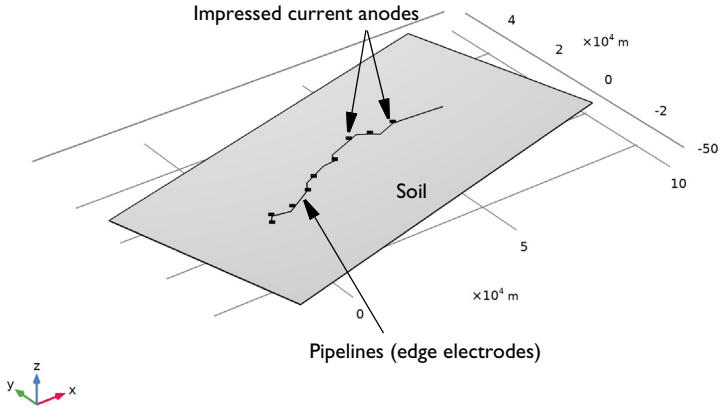

Figure 1: The model geometry consists of three pipelines, nine impressed current anodes, and two soil layers.

The model geometry consists of three parallel pipelines, nine impressed current anodes, which are distributed along the pipelines, and two thin soil domains. The three pipelines

are about 68 km long and are separated by a horizontal distance of 10 m from each other. The pipeline radii are 0.084 m, 0.203 m, and 0.137 m for the three pipelines, respectively. Pipeline 1 is located at 20 m below ground whereas the pipelines 2 and 3 are at 15 m below ground. The anodes are placed 200 m away from the closest pipeline and are located at 10 m below ground.

The two thin layers of soil are of height 35 m and 65 m, respectively. The electrolyte conductivity of the top layer is 0.02 S/m and that of the bottom layer is 0.005 S/m.

The Cathodic Protection interface is used to solve for the electrolyte potential, ϕ_l (SI unit: V), over the thin soil domains according to

$$\mathbf{i}_l = -\sigma_l \nabla \phi_l$$
$$\nabla \cdot \mathbf{i}_l = 0$$

where $\mathbf{i}_l$ (SI unit: A/m^2) is the electrolyte current density vector and σ_l (SI unit: S/m) is the electrolyte conductivity for the soil domain. The two Electrolyte nodes are used to set different electrolyte conductivity for the top and bottom layers.

The three pipelines are modeled using the Edge Electrode nodes. At each Edge Electrode node, the Ohm's Law electric potential model is set and kinetics of electrochemical reaction is prescribed as:

$$\mathbf{n} \cdot \mathbf{i}_l = f(\phi_{s,\,\text{edge}} - \phi_{l,\,\text{edge}})$$

where $f(\phi_{s,\text{edge}} - \phi_{l,\text{edge}})$ is an interpolation function obtained form the experimental polarization data available in the corrosion material library (Ref. 2).

For Edge Electrode 1 (pipeline 1), the Connection Point subnodes are placed at several points along the pipeline 1. The Connection Point subnode defines a global potential degree of freedom and is used to connect to the other pipelines, and to the respective impressed current anode. The Connection Point subnode also defines a reference electrode potential.

For Edge Electrode 2 and 3 (pipeline 2 and 3), nine External Short point subnodes each are used to connect to the respective connection points of pipeline 1.

The ICCP system controls the pipeline potential versus the reference electrode which is modeled using the Impressed Current Point nodes for nine anodes distributed along the length of three pipelines.

At each anode point, the control potential, $\boldsymbol{E}_{\text{impr}}$, which is difference between the protected surface sense potential, $\phi_{s,\text{sense}}$, and reference electrode potential,$\phi_{s,\text{ref}}$, is set to

–0.7 V versus CSE reference electrode. The desired potential difference is achieved by adding an electrolyte point source at the respective anode point, using an added global dependent variable, I_{impr}, left to "float" in order to fulfill the control condition according to

$$I_{impr}: \; E_{impr} = \phi_{s,sense} - \phi_{s,ref}$$

The protected surface sense potential and reference electrode potential are set equal to those defined in the respective Connection Point subnode of Edge Electrode 1 (pipeline 1).

An Electric Ground condition is set at one end of one of the pipelines.

Results and Discussion

Figure 2 shows the electrolyte potential distribution along with streamline plot of the electrolyte current density over the thin soil domain. The higher electrolyte potential is seen around the impressed current point anodes.

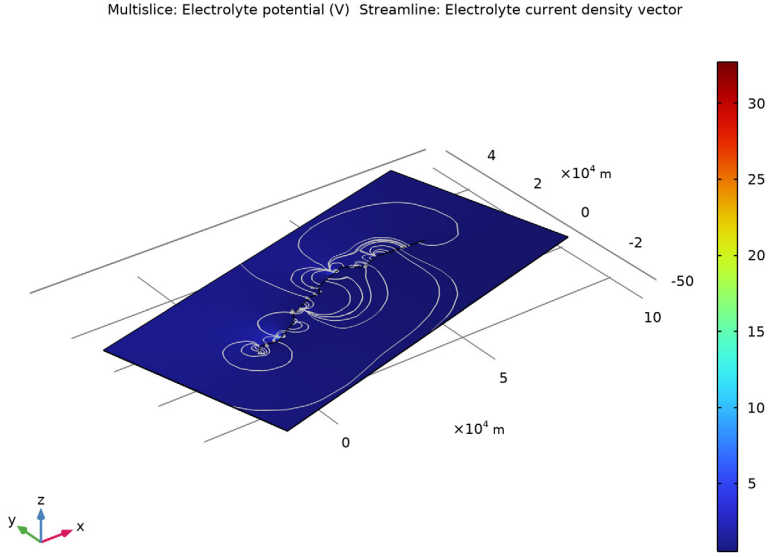

Figure 2: Electrolyte potential distribution along with a streamline plot for the electrolyte current density.

Figure 3 shows the electrode potential distributions over the length of the three pipelines. It can be seen that the electrode potential is below its equilibrium potential (–0.56 V/CSE) indicating that the pipelines are adequately protected.

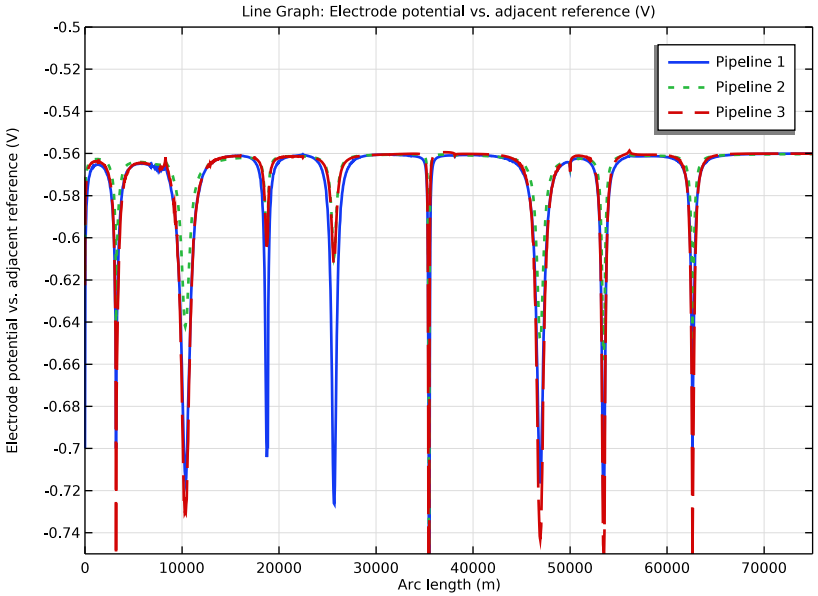

Figure 3: Electrode potential distributions over the length of the three pipelines.

Figure 4 shows the corresponding plot for the local current density along the three pipelines. The current density is negative throughout the length of all three pipelines, indicating that the pipelines are protected against corrosion.

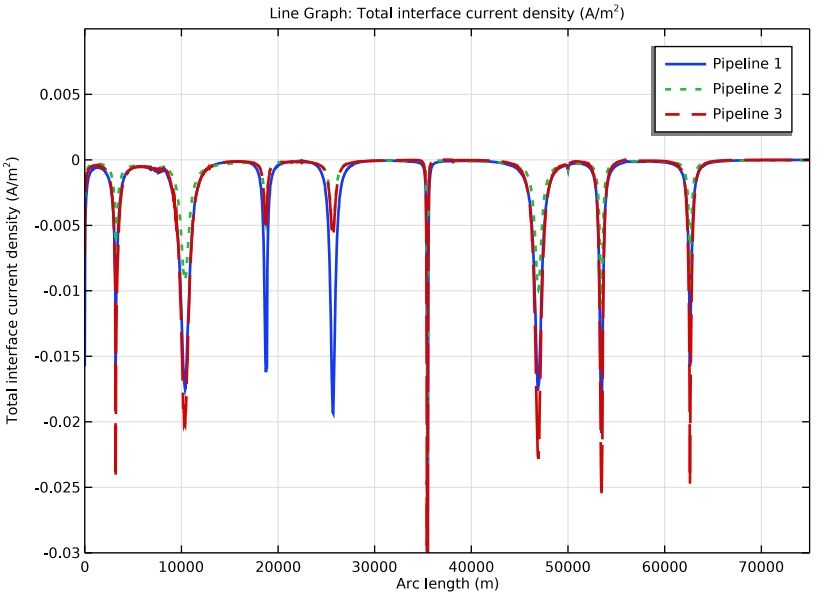

Figure 4: Total interface current density distributions over the length of the three pipelines.

Figure 5 shows the total impressed current for each ICCP anode. It can be seen that the impressed current varies significantly between the anodes.

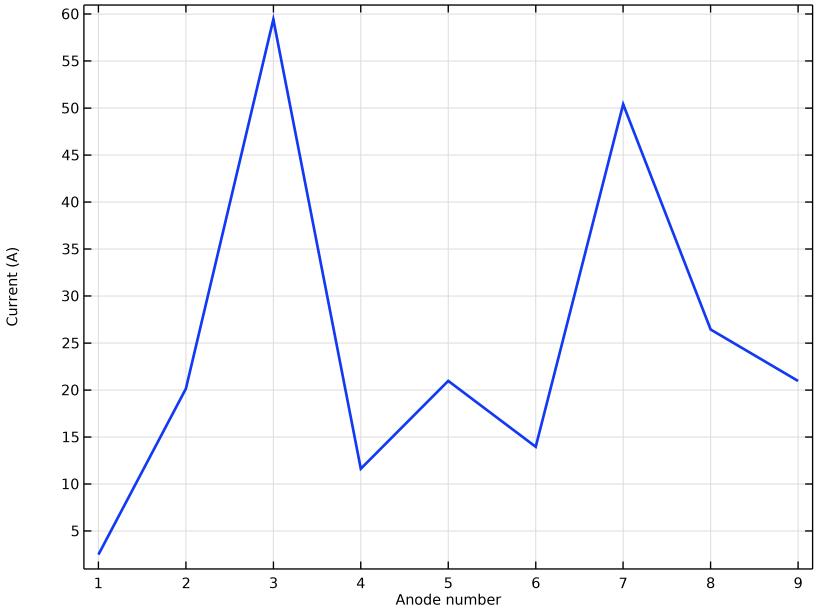

Figure 5: Impressed current for all anodes distributed across the length of the three pipelines.

Notes About the COMSOL Implementation

Three pipelines of length 68 km, radii varying from 0.08 m to 0.2 m and a horizontal separation distance of 10 m between them are modeled using the Edge Electrode feature. Considering a large aspect ratio, a special attention is given to refine the mesh near the edge electrodes and anodes.

References

1. A.B. Peratta, J.M.W. Baynham, and R.A. Adey, "Computational modelling of cathodic protection systems for pipelines in multi-layer soil," *Simulation of Electrochemical Processes III*, vol. 65, pp. 35–46, 2009.

2. G. Cui, Z. Li, C. Yang, and M. Wang, "The influence of DC stray current on pipeline corrosion," *Petroleum Science*, vol. 13, pp. 135–145, 2016.

Application Library path: `Corrosion_Module/Cathodic_Protection/pipeline_corrosion_protection_iccp`

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** > **Cathodic Protection (cp)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies** > **Stationary**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

Load the model parameters.

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

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

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `pipeline_corrosion_protection_iccp_parameters.txt`.

GEOMETRY 1

First, add a block to represent two layers of the soil domain.

Block 1 (blk1)

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

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

3 In the **Width** text field, type `120[km]`.

4 In the **Depth** text field, type `60[km]`.

5 In the **Height** text field, type `100`.

6 Locate the **Position** section. In the **x** text field, type `-25[km]`.

7 In the **y** text field, type `-20[km]`.

8 In the **z** text field, type `-100`.

9 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
`Layer 1`	65

Pipeline 1

Next, add work planes to represent three pipelines using polygons and a work plane to represent anodes.

1 In the **Geometry** toolbar, click  **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Pipeline 1` in the **Label** text field.

3 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `-20`.

4 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

5 From the **Show in physics** list, choose **Edge selection**.

Pipeline 1 (wp1) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Pipeline 1 (wp1) > Polygon 1 (pol1)

1 In the **Work Plane** toolbar, click  **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Object Type** section.

3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. Click  **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `pipeline_corrosion_protection_iccp_pipeline1_coordinates.txt`.

Pipeline 2

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Pipeline 2` in the **Label** text field.

3 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `-15`.

4 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

5 From the **Show in physics** list, choose **Edge selection**.

Pipeline 2 (wp2) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Pipeline 2 (wp2) > Polygon 1 (pol1)

1 In the **Work Plane** toolbar, click **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Object Type** section.

3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `pipeline_corrosion_protection_iccp_pipeline2_coordinates.txt`.

Pipeline 3

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Pipeline 3` in the **Label** text field.

3 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `-15`.

4 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

5 From the **Show in physics** list, choose **Edge selection**.

Pipeline 3 (wp3) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Pipeline 3 (wp3) > Polygon 1 (pol1)

1 In the **Work Plane** toolbar, click **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Object Type** section.

3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `pipeline_corrosion_protection_iccp_pipeline3_coordinates.txt`.

Anode Positions

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Anode Positions` in the **Label** text field.

3 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `-10`.

4 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

5 From the **Show in physics** list, choose **Off**.

Anode Positions (wp4) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Anode Positions (wp4) > Point 1 (pt1)

1 In the **Work Plane** toolbar, click **Point**.

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

3 In the **xw** text field, type `100`.

4 In the **yw** text field, type `-200`.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

6 From the **Show in 3D** list, choose **All levels**.

Anode Positions (wp4) > Point 2 (pt2)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 1 (pt1)** and choose **Duplicate**.

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

3 In the **xw** text field, type `2[km]`.

4 In the **yw** text field, type `3[km]-200`.

5 Locate the **Selections of Resulting Entities** section. Clear the **Resulting objects selection** checkbox.

Anode Positions (wp4) > Point 3 (pt3)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 2 (pt2)** and choose **Duplicate**.

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

3 In the **xw** text field, type `8.5[km]`.

4 In the **yw** text field, type `2.8[km]+200`.

Anode Positions (wp4) > Point 4 (pt4)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 3 (pt3)** and choose **Duplicate**.

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

3 In the **xw** text field, type `16[km]`.

4 In the **yw** text field, type `7[km]-200`.

Anode Positions (wp4) > Point 5 (pt5)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 4 (pt4)** and choose **Duplicate**.

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

3 In the **xw** text field, type `21[km]`.

4 In the **yw** text field, type `11[km]+200`.

Anode Positions (wp4) > Point 6 (pt6)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 5 (pt5)** and choose **Duplicate**.

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

3 In the **xw** text field, type `30[km]`.

4 In the **yw** text field, type `14.75[km]-200`.

Anode Positions (wp4) > Point 7 (pt7)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 6 (pt6)** and choose **Duplicate**.

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

3 In the **xw** text field, type `39[km]`.

4 In the **yw** text field, type `20.5[km]+200`.

Anode Positions (wp4) > Point 8 (pt8)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 7 (pt7)** and choose **Duplicate**.

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

3 In the **xw** text field, type `45[km]`.

4 In the **yw** text field, type `20[km]-200`.

Anode Positions (wp4) > Point 9 (pt9)

1 Right-click **Component 1 (comp1)** > **Geometry 1** > **Anode Positions (wp4)** > **Plane Geometry** > **Point 8 (pt8)** and choose **Duplicate**.

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

3 In the **xw** text field, type `53[km]`.

4 In the **yw** text field, type `20.5[km]+200`.

5 Click  **Build Selected**.

Pipeline 1 Contour for Meshing

1. In the **Model Builder** window, right-click **Geometry 1** and choose **Transforms** > **Copy**.
2. In the **Settings** window for **Copy**, type `Pipeline 1 Contour for Meshing` in the **Label** text field.
3. Locate the **Input** section. From the **Input objects** list, choose **Pipeline 1**.
4. Locate the **Displacement** section. In the **z** text field, type `20`.
5. Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.
6. From the **Show in physics** list, choose **Off**.
7. Locate the **Selections on Input Objects** section. Clear the **Propagate selections to resulting objects** checkbox.

Pipeline 2 Contour for Meshing

1. In the **Geometry** toolbar, click **Transforms** and choose **Copy**.
2. In the **Settings** window for **Copy**, locate the **Input** section.
3. From the **Input objects** list, choose **Pipeline 2**.
4. In the **Label** text field, type `Pipeline 2 Contour for Meshing`.
5. Locate the **Displacement** section. In the **z** text field, type `15`.
6. Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.
7. Locate the **Selections on Input Objects** section. Clear the **Propagate selections to resulting objects** checkbox.

Pipeline 3 Contour for Meshing

1. In the **Geometry** toolbar, click **Transforms** and choose **Copy**.
2. In the **Settings** window for **Copy**, locate the **Input** section.
3. From the **Input objects** list, choose **Pipeline 3**.
4. In the **Label** text field, type `Pipeline 3 Contour for Meshing`.
5. Locate the **Displacement** section. In the **z** text field, type `15`.
6. Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.
7. From the **Show in physics** list, choose **Off**.
8. Locate the **Selections on Input Objects** section. Clear the **Propagate selections to resulting objects** checkbox.

Anode Positions for Meshing

1 In the **Geometry** toolbar, click **Transforms** and choose **Copy**.

2 In the **Settings** window for **Copy**, type `Anode Positions for Meshing` in the **Label** text field.

3 Locate the **Input** section. From the **Input objects** list, choose **Anode Positions**.

4 Locate the **Displacement** section. In the **z** text field, type `10`.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

6 From the **Show in physics** list, choose **Point selection**.

7 Locate the **Selections on Input Objects** section. Clear the **Propagate selections to resulting objects** checkbox.

Rotate 1 (rot1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.

2 Select the object **blk1** only.

3 In the **Settings** window for **Rotate**, locate the **Rotation** section.

4 In the **Angle** text field, type `15`.

5 Locate the **Point on Axis of Rotation** section. In the **x** text field, type `30[km]`.

6 In the **y** text field, type `10[km]`.

Pipeline contours for meshing

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

2 In the **Settings** window for **Union Selection**, type `Pipeline contours for meshing` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Edge**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog, in the **Selections to add** list, choose **Pipeline 1 Contour for Meshing**, **Pipeline 2 Contour for Meshing**, and **Pipeline 3 Contour for Meshing**.

6 Click **OK**.

7 In the **Geometry** toolbar, click **Build All**.

DEFINITIONS

Create some selections to use later while setting up the physics and meshing the computational domain.

Anode 1

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

2 In the **Settings** window for **Explicit**, type `Anode 1` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Point**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `13` in the **Selection** text field.

6 Click **OK**.

Anode 2

1 Right-click **Anode 1** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 2` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `21` in the **Selection** text field.

6 Click **OK**.

Anode 3

1 Right-click **Anode 2** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 3` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `29` in the **Selection** text field.

6 Click **OK**.

Anode 4

1 Right-click **Anode 3** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 4` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `37` in the **Selection** text field.

6 Click **OK**.

Anode 5

1 Right-click **Anode 4** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 5` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `51` in the **Selection** text field.

6 Click **OK**.

Anode 6

1 Right-click **Anode 5** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 6` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `71` in the **Selection** text field.

6 Click **OK**.

Anode 7

1 Right-click **Anode 6** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 7` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `85` in the **Selection** text field.

6 Click **OK**.

Anode 8

1 Right-click **Anode 7** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 8` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `99` in the **Selection** text field.

6 Click **OK**.

Anode 9

1 Right-click **Anode 8** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Anode 9` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `113` in the **Selection** text field.

6 Click **OK**.

Pipelines

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

2 In the **Settings** window for **Union**, type `Pipelines` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Edge**.

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

5 In the **Add** dialog, in the **Selections to add** list, choose **Pipeline 1**, **Pipeline 2**, and **Pipeline 3**.

6 Click **OK**.

CATHODIC PROTECTION (CP)

Next set up the physics. Start by selecting the reference electrode potential and then set the discretization of the electrolyte potential to linear considering the size of the computational domain. Then, set the electrolyte conductivities for the two soil layers, add Edge Electrode features with a Connection Point and External Short subfeatures for the pipelines, and Impressed Current Point features for the anodes.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Cathodic Protection (cp)**.

2 In the **Settings** window for **Cathodic Protection**, click to expand the **Physics vs. Materials Reference Electrode Potential** section.

3 From the list, choose **0.314 V (CSE vs. SHE)**.

4 Click to expand the **Discretization** section. From the **Electrolyte potential** list, choose **Linear**.

Electrolyte 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Cathodic Protection (cp)** click **Electrolyte 1**.

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

3 From the σ_1 list, choose **User defined**. In the associated text field, type `sigma_top`.

Electrolyte 2

1 In the **Physics** toolbar, click  **Domains** and choose **Electrolyte**.

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

3 Click  **Paste Selection**.

4 In the **Paste Selection** dialog, type `1` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Electrolyte**, locate the **Electrolyte** section.

7 From the σ_l list, choose **User defined**. In the associated text field, type `sigma_bottom`.

Edge Electrode 1

1 In the **Physics** toolbar, click **Edges** and choose **Edge Electrode**.

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

3 From the **Selection** list, choose **Pipeline 1**.

4 Locate the **Edge Electrode Properties** section. In the r_{edge} text field, type `rpipe1`.

Electrode Reaction 1

1 In the **Model Builder** window, click **Electrode Reaction 1**.

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

3 From the E_{eq} list, choose **From material**.

4 Locate the **Electrode Kinetics** section. From the $i_{loc,expr}$ list, choose **From material**.

Edge Electrode 1

In the **Model Builder** window, click **Edge Electrode 1**.

Connection Point 1

1 In the **Physics** toolbar, click **Attributes** and choose **Connection Point**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 7 in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Connection Point**, locate the **Reference Electrode** section.

7 Select the **Define reference electrode** checkbox.

Connection Point 2

1 Right-click **Connection Point 1** and choose **Duplicate**.

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

3 Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type 15 in the **Selection** text field.

6 Click **OK**.

Connection Point 3

1 Right-click **Connection Point 2** and choose **Duplicate**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 31 in the **Selection** text field.

6 Click **OK**.

Connection Point 4

1 Right-click **Connection Point 3** and choose **Duplicate**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 39 in the **Selection** text field.

6 Click **OK**.

Connection Point 5

1 Right-click **Connection Point 4** and choose **Duplicate**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 53 in the **Selection** text field.

6 Click **OK**.

Connection Point 6

1 Right-click **Connection Point 5** and choose **Duplicate**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 65 in the **Selection** text field.

6 Click **OK**.

Connection Point 7

1 Right-click **Connection Point 6** and choose **Duplicate**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `79` in the **Selection** text field.

6 Click **OK**.

Connection Point 8

1 Right-click **Connection Point 7** and choose **Duplicate**.

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

3 Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `93` in the **Selection** text field.

6 Click **OK**.

Connection Point 9

1 Right-click **Connection Point 8** and choose **Duplicate**.

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

3 Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `107` in the **Selection** text field.

6 Click **OK**.

Edge Electrode 2

1 In the **Physics** toolbar, click **Edges** and choose **Edge Electrode**.

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

3 From the **Selection** list, choose **Pipeline 2**.

4 Locate the **Edge Electrode Properties** section. In the r_{edge} text field, type `rpipe2`.

Electrode Reaction 1

1 In the **Model Builder** window, click **Electrode Reaction 1**.

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

3 From the E_{eq} list, choose **From material**.

4 Locate the **Electrode Kinetics** section. From the $i_{\text{loc,expr}}$ list, choose **From material**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 1

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 9 in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp1)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 2

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 17 in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp2)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 3

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 33 in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp3)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 4

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `41` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp4)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 5

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `55` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp5)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 6

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `67` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp6)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 7

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `81` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp7)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 8

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `95` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp8)**.

Edge Electrode 2

In the **Model Builder** window, click **Edge Electrode 2**.

External Short 9

1 In the **Physics** toolbar, click **Attributes** and choose **External Short**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `109` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **External Short**, locate the **External Short** section.

7 In the R text field, type `R_short`.

8 From the $\phi_{s,there}$ list, choose **Connected potential (cp/edge1/connp9)**.

Edge Electrode 3

1 Right-click **Edge Electrode 2** and choose **Duplicate**.

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

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

4 Locate the **Edge Electrode Properties** section. In the r_{edge} text field, type `rpipe3`.

External Short 1

1 In the **Model Builder** window, expand the **Edge Electrode 3** node, then click **External Short 1**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `11` in the **Selection** text field.

6 Click **OK**.

External Short 2

1 In the **Model Builder** window, click **External Short 2**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `19` in the **Selection** text field.

6 Click **OK**.

External Short 3

1 In the **Model Builder** window, click **External Short 3**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type `35` in the **Selection** text field.

6 Click **OK**.

External Short 4

1 In the **Model Builder** window, click **External Short 4**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 43 in the **Selection** text field.

6 Click **OK**.

External Short 5

1 In the **Model Builder** window, click **External Short 5**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 57 in the **Selection** text field.

6 Click **OK**.

External Short 6

1 In the **Model Builder** window, click **External Short 6**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 69 in the **Selection** text field.

6 Click **OK**.

External Short 7

1 In the **Model Builder** window, click **External Short 7**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 83 in the **Selection** text field.

6 Click **OK**.

External Short 8

1 In the **Model Builder** window, click **External Short 8**.

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

3 Click  **Clear Selection**.

4 Click  **Paste Selection**.

5 In the **Paste Selection** dialog, type 97 in the **Selection** text field.

6 Click **OK**.

External Short 9

1 In the **Model Builder** window, click **External Short 9**.

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

3 Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type 111 in the **Selection** text field.

6 Click **OK**.

Edge Electrode 3

In the **Model Builder** window, click **Edge Electrode 3**.

Electric Ground 1

1 In the **Physics** toolbar, click **Attributes** and choose **Electric Ground**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 119 in the **Selection** text field.

5 Click **OK**.

Impressed Current Point 1

1 In the **Physics** toolbar, click **Points** and choose **Impressed Current Point**.

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

3 From the **Selection** list, choose **Anode 1**.

4 Locate the **Impressed Current Point** section. In the E_{impr} text field, type `E_control`.

5 From the $\phi_{\text{s,sense}}$ list, choose **Connected potential (cp/edge1/connp1)**.

6 From the $\phi_{\text{s,ref}}$ list, choose **Electric reference potential (cp/edge1/connp1)**.

Impressed Current Point 2

1 Right-click **Impressed Current Point 1** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 2**.

4 Locate the **Impressed Current Point** section. From the $\phi_{\text{s,sense}}$ list, choose **Connected potential (cp/edge1/connp2)**.

5 From the $\phi_{\text{s,ref}}$ list, choose **Electric reference potential (cp/edge1/connp2)**.

Impressed Current Point 3

1 Right-click **Impressed Current Point 2** and choose **Duplicate**.

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

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

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp3)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp3)**.

Impressed Current Point 4

1 Right-click **Impressed Current Point 3** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 4**.

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp4)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp4)**.

Impressed Current Point 5

1 Right-click **Impressed Current Point 4** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 5**.

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp5)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp5)**.

Impressed Current Point 6

1 Right-click **Impressed Current Point 5** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 6**.

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp6)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp6)**.

Impressed Current Point 7

1 Right-click **Impressed Current Point 6** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 7**.

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp7)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp7)**.

Impressed Current Point 8

1 Right-click **Impressed Current Point 7** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 8**.

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp8)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp8)**.

Impressed Current Point 9

1 Right-click **Impressed Current Point 8** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Anode 9**.

4 Locate the **Impressed Current Point** section. From the $\phi_{s,sense}$ list, choose **Connected potential (cp/edge1/connp9)**.

5 From the $\phi_{s,ref}$ list, choose **Electric reference potential (cp/edge1/connp9)**.

MATERIALS

Use the Corrosion Material Library to set up the material properties for the electrode kinetics and electric conductivity at the Q235 steel electrode surface.

ADD MATERIAL

1 In the **Materials** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Corrosion** > **Iron Alloys (Steels)** > **Q235 steel in soil**.

4 Click the **Add to Component** button in the window toolbar.

5 In the **Materials** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Q235 steel in soil (mat1)

1 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

2 From the **Geometric entity level** list, choose **Edge**.

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

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	sigmas	S/m	Basic

MESH 1

Next, refine the mesh near the edge electrodes and anodes.

Free Triangular 1

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

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 7 in the **Selection** text field.

5 Click **OK**.

Size 1

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

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

3 From the **Geometric entity level** list, choose **Point**.

4 From the **Selection** list, choose **Anode Positions for Meshing**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type 1[m].

Size 2

1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Size**.

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

3 From the **Geometric entity level** list, choose **Edge**.

4 From the **Selection** list, choose **Pipeline contours for meshing**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** checkbox. In the associated text field, type 50.

8 Select the **Minimum element size** checkbox. In the associated text field, type 25.

Size 3

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

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 7 in the **Selection** text field.

5 Click **OK**.

Boundary Layers 1

1 In the **Mesh** toolbar, click **Boundary Layers**.

2 In the **Settings** window for **Boundary Layers**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type 7 in the **Selection** text field.

6 Click **OK**.

Boundary Layer Properties

1 In the **Model Builder** window, click **Boundary Layer Properties**.

2 In the **Settings** window for **Boundary Layer Properties**, locate the **Edge Selection** section.

3 From the **Selection** list, choose **Pipeline contours for meshing**.

4 Locate the **Layers** section. In the **Number of layers** text field, type 1.

5 From the **Thickness specification** list, choose **First layer**.

6 In the **Thickness** text field, type 1.

Swept 1

1 In the **Mesh** toolbar, click **Swept**.

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

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domain 2 only.

5 Click to expand the **Source Faces** section. Click **Paste Selection**.

6 In the **Paste Selection** dialog, type 7 in the **Selection** text field.

7 Click **OK**.

8 In the **Settings** window for **Swept**, click to expand the **Destination Faces** section.

9 Click **Paste Selection**.

10 In the **Paste Selection** dialog, type `6` in the **Selection** text field.

11 Click **OK**.

Distribution 1

1 Right-click **Swept 1** and choose **Distribution**.

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

3 From the **Distribution type** list, choose **Explicit**.

4 In the **Relative placement of vertices along edge** text field, type `0, 10/35, 15/35, 20/35, 1`.

Swept 2

1 In the **Mesh** toolbar, click **Swept**.

2 In the **Settings** window for **Swept**, click **Build All**.

STUDY 1

The model is now ready to be solved.

1 In the **Study** toolbar, click **Compute**.

RESULTS

Several plots are added by default. The following steps reproduce the plots from the Results and Discussion section:

Streamline 1

1 In the **Model Builder** window, expand the **Electrolyte Potential (cp)** node, then click **Streamline 1**.

2 In the **Settings** window for **Streamline**, locate the **Streamline Positioning** section.

3 In the **Points** text field, type `100`.

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

5 In the **Electrolyte Potential (cp)** toolbar, click **Plot**.

The plot should look like Figure 2.

Electrode Potential vs. Adjacent Reference

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Electrode Potential vs. Adjacent Reference` in the **Label** text field.

3 Locate the **Axis** section. Select the **Manual axis limits** checkbox.

4 In the **x minimum** text field, type `0`.

5 In the **x maximum** text field, type `75000`.

6 In the **y minimum** text field, type `-0.75`.

7 In the **y maximum** text field, type `-0.5`.

Line Graph 1

1 In the **Electrode Potential vs. Adjacent Reference** toolbar, click **Line Graph**.

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

3 From the **Selection** list, choose **Pipeline 1**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **cp.Evsref - Electrode potential vs. adjacent reference - V**.

5 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Cycle**.

6 From the **Width** list, choose **2**.

7 Click to expand the **Legends** section. Select the **Show legends** checkbox.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
Pipeline 1

Line Graph 2

1 Right-click **Line Graph 1** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Pipeline 2**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Legends** section. In the table, enter the following settings:

Legends
Pipeline 2

Line Graph 3

1 Right-click **Line Graph 2** and choose **Duplicate**.

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

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

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
Pipeline 3

5 In the **Electrode Potential vs. Adjacent Reference** toolbar, click **Plot**.

The plot should look like Figure 3.

Total Current Density

1 In the **Model Builder** window, right-click **Electrode Potential vs. Adjacent Reference** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Total Current Density` in the **Label** text field.

3 Locate the **Axis** section. In the **y minimum** text field, type `-0.03`.

4 In the **y maximum** text field, type `0.01`.

Line Graph 1

1 In the **Model Builder** window, expand the **Total Current Density** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Electrode kinetics** > **cp.itot - Total interface current density - A/m²**.

Line Graph 2

1 In the **Model Builder** window, click **Line Graph 2**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Electrode kinetics** > **cp.itot - Total interface current density - A/m²**.

Line Graph 3

1 In the **Model Builder** window, click **Line Graph 3**.

2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Cathodic Protection** > **Electrode kinetics** > **cp.itot - Total interface current density - A/m²**.

Total Current Density

1 In the **Model Builder** window, click **Total Current Density**.

2 In the **Total Current Density** toolbar, click **Plot**.

The plot should look like Figure 4.

Global Evaluation 1

Now evaluate the impressed current at each anode.

1 In the **Results** toolbar, click **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, locate the **Expressions** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `pipeline_corrosion_protection_iccp_Itot_expressions.txt`.

5 Click **Evaluate**.

Impressed Currents

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Impressed Currents` in the **Label** text field.

3 Locate the **Plot Settings** section.

4 Select the **x-axis label** checkbox. In the associated text field, type `Anode number`.

5 Select the **y-axis label** checkbox. In the associated text field, type `Current (A)`.

Table Graph 1

1 In the **Impressed Currents** toolbar, click **Table Graph**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 Select the **Row-based** checkbox.

4 From the **x-axis data** list, choose **Column index**.

5 From the **Plot rows** list, choose **Manual**.

6 In the **Rows** list, select **Row 1**.

7 Locate the **Coloring and Style** section. From the **Width** list, choose **2**.

8 In the **Impressed Currents** toolbar, click **Plot**.

The plot should look like Figure 5.

Electrode Potential vs. Adjacent Reference (cp), Electrolyte Current Density (cp)

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electrolyte Current Density (cp)** and **Electrode Potential vs. Adjacent Reference (cp)**.

2 Right-click and choose **Delete**.