Created in COMSOL Multiphysics 5.6

Atmospheric Corrosion of a Busbar

Introduction

In this model example, the Atmospheric Corrosion model is extended to a busbar which is a metallic strip typically used for high current power distribution. The busbar geometry considered here consists of a copper (Cu) flange, an aluminum (Al) flange and a zinc nut and bolt and is exposed to humidified air.

This tutorial model example solves for both the electric potential in electrode domain and the electrolyte potential in the thin electrolyte layer. A high current is applied at the Cu terminal and the Al terminal is grounded while solving for the electric potential. The electrolyte potential variation is solved only over the exterior surfaces of the busbar geometry. The electrolyte film thickness and conductivity depend on the relative humidity of the surrounding air. The limiting oxygen reduction current density depends on the oxygen diffusivity and solubility.

The example uses parameter data from Ref. 1, Ref. 2, and Ref. 3.

Model Definition

The model setup is shown in Figure 1.

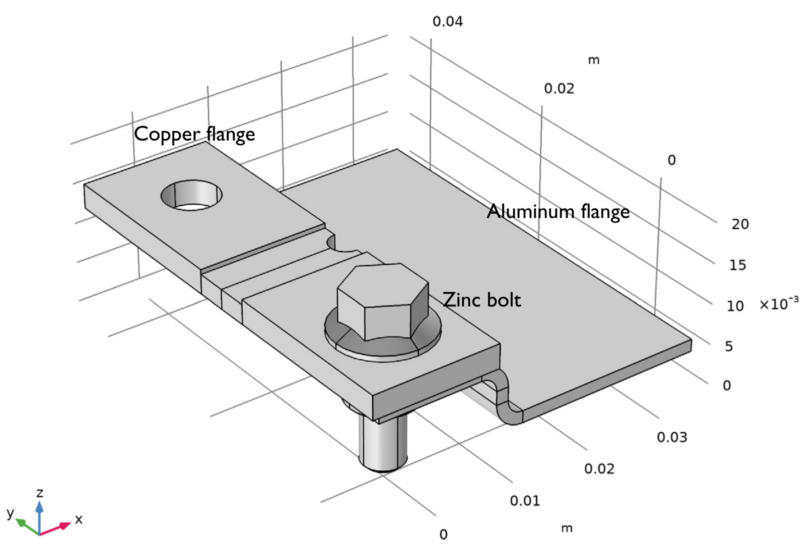

Figure 1: Model setup. The busbar geometry consists of a copper flange, an aluminum flange and a zinc nut and bolt.

The busbar model geometry consists of a copper flange, an aluminum flange, and a zinc nut and bolt. Use the Secondary Current Distribution interface to solve for the electric potential, ϕ_s (SI unit: V), over the metal electrode domains of aluminum, copper, and zinc according to:

$$\mathbf{i}_s = -\sigma_s \nabla\phi_s$$
$$\nabla \cdot \mathbf{i}_s = 0$$

where $\mathbf{i}_s$ (SI unit: A/m^2) is the electrode current density vector and σ_s (SI unit: S/m) is the electrical conductivity which is assumed to be a constant for all the three domains.

The aluminum terminal is grounded where as total current of 100 A is applied at the copper terminal.

Use the Current Distribution, Shell interface to solve for the electrolyte potential, ϕ_l (SI unit: V), over the thin electrolyte domain (over the exterior surfaces of the busbar geometry) according to:

$$\mathbf{i}_l = -\sigma_l \nabla_T\phi_l$$
$$\nabla_T \cdot (s\mathbf{i}_l) = 0$$

where $\mathbf{i}_l$ (SI unit: A/m^2) is the electrolyte current density vector, s (SI unit: m) the electrolyte film thickness and σ_l (SI unit: S/m) is the electrolyte conductivity which depends on relative humidity.

The thickness of the electrolyte film depends on both the salt load density and the relative humidity. The oxygen solubility and the electrolyte conductivity also depend on the relative humidity. The same expressions as used in the Atmospheric Corrosion model are used here for the electrolyte film thickness, oxygen solubility and electrolyte conductivity to account for the relative humidity dependence. The oxygen diffusivity is assumed to constant in this model.

ELECTROCHEMICAL REACTIONS

The aluminum, copper, and zinc surfaces account for both the metal dissolution reaction and the oxygen reduction reaction. The metal dissolution electrode reaction kinetics is described by a Anodic Tafel expression whereas the oxygen reduction electrode kinetics is described by a Cathodic Tafel expression.

The oxygen reduction reaction is limited by oxygen transport through the film. The limiting current density, $i_{\mathrm{lim,\,O2}}$ (SI unit: $\mathrm{A/m^2}$), depends on the film thickness, the oxygen solubility and the oxygen diffusivity according to:

$$i_{\mathrm{lim,\,O_2}} = \frac{4FDc_{\mathrm{sol}}}{d_{\mathrm{film}}}$$

where F (96485 C/mol) is Faraday's constant, D (SI unit: $\mathrm{m^2/s}$) is the diffusivity of oxygen in the film, c_{sol} (SI unit: $\mathrm{mol/m^3}$) is the solubility of oxygen, and d_{film} (SI unit: m) is the film thickness.

By assuming a first order dependency of the oxygen reduction kinetics on the local current density of the oxygen concentration, the following expression for the current density, $i_{\mathrm{lim,\,O2}}$ (SI unit: $\mathrm{A/m^2}$), can be derived:

$$i_{\mathrm{loc,\,O_2}} = \frac{i_{\mathrm{expr}}}{1 + \left|\frac{i_{\mathrm{expr}}}{i_{\mathrm{lim,\,O_2}}}\right|}$$

where i_{expr} is the local current density of the electrode reaction in absence of mass transport limitations.

Results and Discussion

Figure 2 shows the electric potential variation in the metal. It can be seen that the applied current of 100 A is causing a potential drop of about 2.5 mV over the busbar.

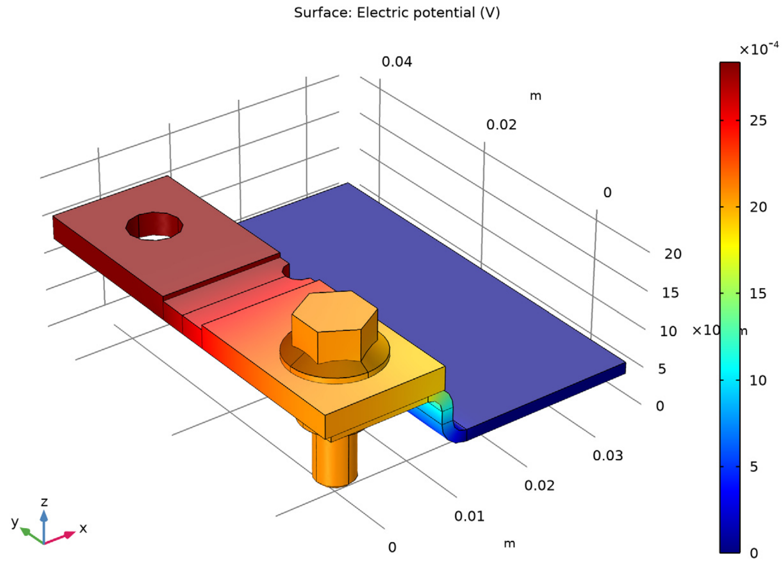

Figure 2: The electric potential in the metal.

Figure 3 shows the variation in electrode potential versus adjacent reference, which is the difference between the electric potential in the metal and the electrolyte film potential. The electrode potential versus adjacent reference is positive over the copper flange and negative over the zinc nut and bolt and aluminum flange surfaces.

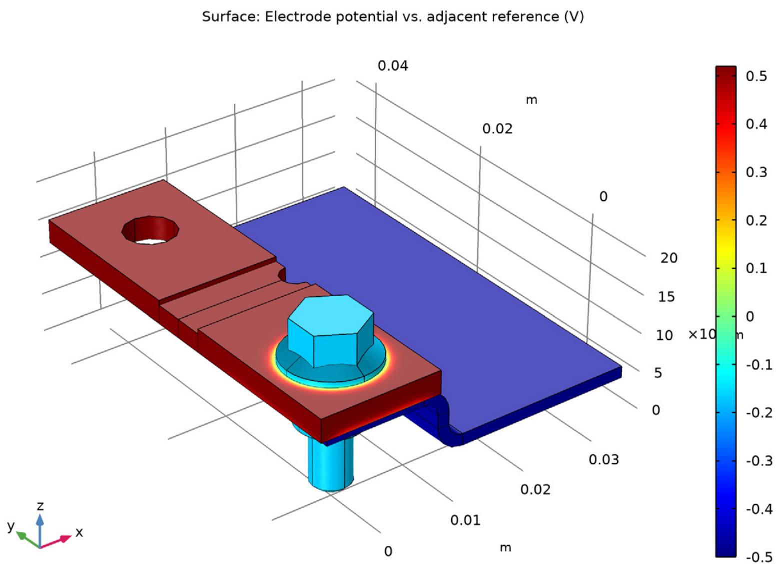

Figure 3: The electrode potential vs. adjacent reference.

Figure 4 shows the electrolyte potential variation in the electrolyte film.

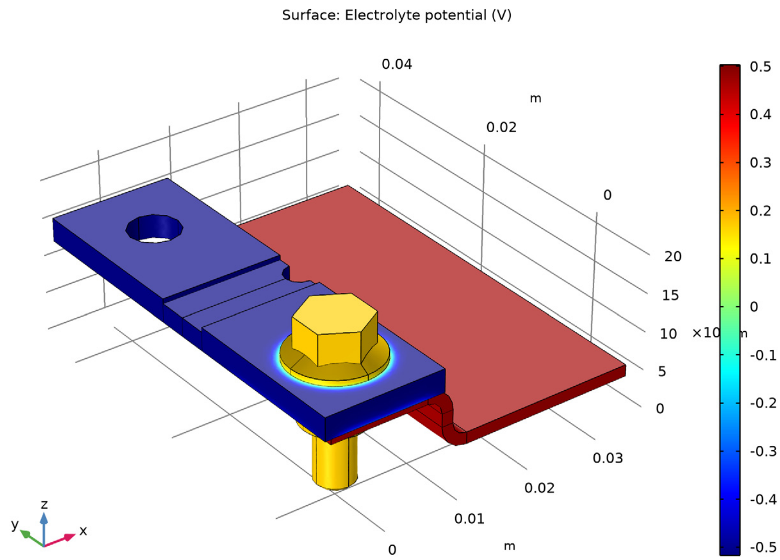

Figure 4: The electrolyte potential obtained in the electrolyte film covering the busbar.

Figure 5 shows the local current density variation for the anodic metal dissolution reaction. It can be seen that the metal dissolution electrode reaction predominantly occurs near the intersection region between the copper flange and the zinc bolt, at the zinc surface. (Zooming and rotating the plot in the model file also reveals metal dissolution occurring between the copper flange and aluminum flange at the aluminum surface.)

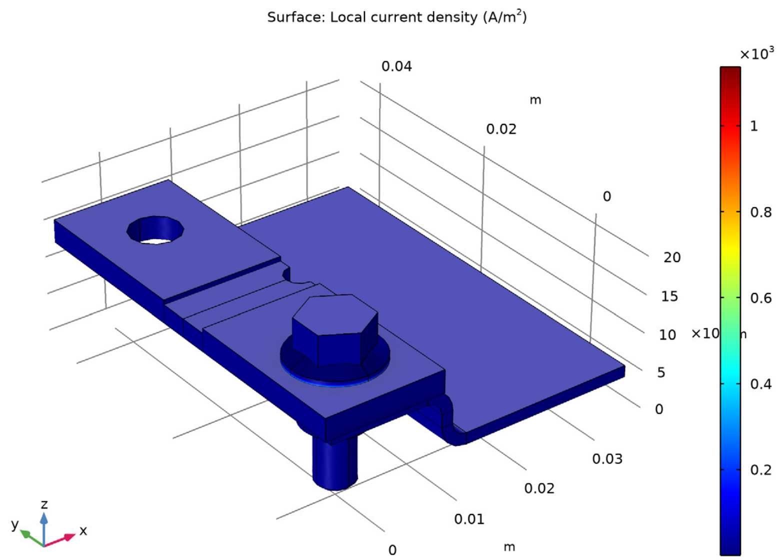

Figure 5: The local current density for metal dissolution electrode reaction over the exterior busbar surfaces.

Finally, Figure 6 shows the local current density variation for the oxygen reduction electrode reaction over the exterior surfaces of the busbar. It can be seen that the oxygen reduction electrode reaction predominantly occurs on the aluminum and zinc surfaces. The magnitude of local oxygen reduction current density is close to the limiting current density, indicating that transport of oxygen is limiting the corrosion process.

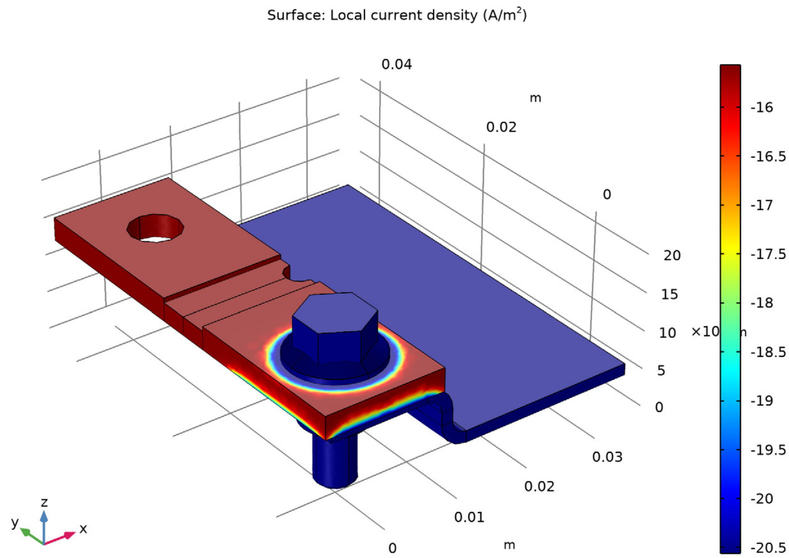

Figure 6: The local current density for oxygen reduction electrode reaction over the exterior surfaces of the busbar.

Notes About the COMSOL Implementation

The model is implemented using the Secondary Current Distribution interface to solve for the electric potential and the Current Distribution, Shell interface to solve for the electrolyte potential in the thin electrolyte film. Note that the Current Distribution, Shell interface is only applicable to the exterior boundary selections of the busbar domain.

References

1. Z.Y. Chen, F. Cui, and R.G. Kelly, "Calculations of the Cathodic Current Delivery Capacity and Stability of Crevice Corrosion under Atmospheric Environments", *J. Electrochemical Society*, vol. 155, no. 7, pp. C360–368, 2008.

2. D. Mizuno and R.G. Kelly "Galvanically Induced Interganular Corrosion of AA5083-H131 Under Atmospheric Exposure Conditions - Part II - Modeling of the Damage Distribution", *Corrosion*, vol. 69, no. 6, pp. 580–592, 2013.

3. D. Mizuno, Y. Shi, and R.G. Kelly, “Modeling of Galvanic Interactions between AA5083 and Steel under Atmospheric Conditions”, *Excerpt from the Proceedings of the 2011 COMSOL Conference in Boston*.

Application Library path: `Corrosion_Module/Galvanic_Corrosion/atmospheric_corrosion_busbar`

Modeling Instructions

Begin by loading the model geometry file which also includes customized selections.

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

Browse to the model’s Application Libraries folder and double-click the file `atmospheric_corrosion_busbar_geom.mph`.

ADD PHYSICS

1 In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.

Add physics interfaces **Secondary Current Distribution** to solve for the electric potential and **Current Distribution, Shell** to solve for the electrolyte potential.

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

3 In the tree, select **Electrochemistry>Primary and Secondary Current Distribution>Secondary Current Distribution (cd)**.

4 Click **Add to Component 1** in the window toolbar.

5 In the tree, select **Electrochemistry>Primary and Secondary Current Distribution>Current Distribution, Shell (cdsh)**.

6 Click **Add to Component 1** in the window toolbar.

7 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

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 `atmospheric_corrosion_busbar_parameters.txt`.

SECONDARY CURRENT DISTRIBUTION (CD)

Start setting up the model for electric potential by first adding Electrode domain. Then, set electric ground at aluminum terminal boundary, set electrode current at copper terminal boundary and set the electrode current density at all other exterior boundaries.

Electrode 1

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

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

3 From the **Selection** list, choose **All domains**.

Electric Ground 1

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

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

3 From the **Selection** list, choose **Al Terminal Boundary**.

Electrode Current 1

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

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

3 From the **Selection** list, choose **Cu Terminal Boundary**.

4 Locate the **Electrode Current** section. In the $I_{s,total}$ text field, type `100[A]`.

Electrode Current Density 1

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

2 In the **Settings** window for **Electrode Current Density**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Exterior Surfaces**.

4 Locate the **Electrode Current Density** section. In the $i_{n,s}$ text field, type `-cdsh.itot`.

Note that the variable `cdsh.itot` appears in orange color since it is not yet defined. This variable will be available after adding Electrode Surface nodes in Current Distribution, Shell interface in the next step.

ADD MATERIAL

Now, add material properties.

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

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

3 In the tree, select **Built-in>Aluminum 3003-H18**.

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

5 In the tree, select **Built-in>Copper**.

6 Click **Add to Component** in the window toolbar.

MATERIALS

Aluminum 3003-H18 (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Aluminum 3003-H18 (mat1)**.

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

3 From the **Selection** list, choose **Al Domain**.

Copper (mat2)

1 In the **Model Builder** window, click **Copper (mat2)**.

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

3 From the **Selection** list, choose **Cu Domain**.

Zinc

1 In the **Materials** toolbar, click **Blank Material**.

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

3 From the **Selection** list, choose **Bolt (Zn)**.

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

Property	Variable	Value	Unit	Property group
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	1.66e7[S/m]	S/m	Basic

5 In the **Label** text field, type `Zinc`.

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

CURRENT DISTRIBUTION, SHELL (CDSH)

Now, set up the model for the electrolyte potential. Note that the **Current Distribution, Shell** interface is applied on all boundaries by default. Set the boundary selection for the interface to exterior boundaries of a busbar geometry. Set the electrolyte thickness and conductivity at the Electrolyte node first and then set the electrode kinetics appropriately.

1 In the **Settings** window for **Current Distribution, Shell**, locate the **Boundary Selection** section.

2 From the **Selection** list, choose **Exterior Boundaries**.

Electrolyte 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Current Distribution, Shell (cdsh)** click **Electrolyte 1**.

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

3 In the s text field, type `d_film`.

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

Electrode Surface 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Electrode Surface**.

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

3 From the **Selection** list, choose **Exterior Al Surface**.

4 Locate the **Electrode Phase Potential Condition** section. In the $\phi_{s,ext}$ text field, type `phis`.

Note that the electric potential `phis` solved in the **Secondary Current Distribution** interface is used here.

Electrode Reaction 1

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

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

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

4 Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Anodic Tafel equation**.

5 In the i_0 text field, type `i0_Al`.

6 In the A_a text field, type `A_Al`.

Electrode Surface 1

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

Electrode Reaction 2

1 In the **Physics** toolbar, click **Attributes** and choose **Electrode Reaction**.

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

3 In the E_{eq} text field, type `Eeq_O2`.

4 Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Cathodic Tafel equation**.

5 In the i_0 text field, type `i0_O2_on_Al`.

6 In the A_c text field, type `A_O2_on_Al`.

7 Select the **Limiting current density** check box.

8 In the i_{lim} text field, type `ilim`.

Electrode Surface 2

1 Right-click **Electrode Surface 1** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Exterior Cu Surface**.

Electrode Reaction 1

1 In the **Model Builder** window, expand the **Electrode Surface 2** node, then click **Electrode Reaction 1**.

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

3 In the E_{eq} text field, type `Eeq_Cu`.

4 Locate the **Electrode Kinetics** section. In the i_0 text field, type `i0_Cu`.

5 In the A_a text field, type `A_Cu`.

Electrode Reaction 2

1 In the **Model Builder** window, click **Electrode Reaction 2**.

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

3 In the i_0 text field, type `i0_O2_on_Cu`.

4 In the A_c text field, type `A_O2_on_Cu`.

Electrode Surface 3

1 In the **Model Builder** window, under **Component 1 (comp1)>Current Distribution, Shell (cdsh)** right-click **Electrode Surface 2** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Exterior Zn Surface**.

Electrode Reaction 1

1 In the **Model Builder** window, expand the **Electrode Surface 3** node, then click **Electrode Reaction 1**.

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

3 In the E_{eq} text field, type `Eeq_Zn`.

4 Locate the **Electrode Kinetics** section. In the i_0 text field, type `i0_Zn`.

5 In the A_a text field, type `A_Zn`.

Electrode Reaction 2

1 In the **Model Builder** window, click **Electrode Reaction 2**.

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

3 In the i_0 text field, type `i0_02_on_Zn`.

4 In the A_c text field, type `A_02_on_Zn`.

MESH 1

Use the Physics-controlled mesh and set the element size to fine.

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

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

3 From the **Element size** list, choose **Fine**.

ADD STUDY

Add Study node and select Stationary with Initialization study step.

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Stationary with Initialization**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 1

Disable Generate default plots check box at Study 1 node, untick **Secondary Current Distribution** interface in Solve for field at the Current Distribution Initialization node and then model is ready to be solved.

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.

Step 1: Current Distribution Initialization

1 In the **Model Builder** window, under **Study 1** click **Step 1: Current Distribution Initialization**.

2 In the **Settings** window for **Current Distribution Initialization**, locate the **Physics and Variables Selection** section.

3 In the table, clear the **Solve for** check box for **Secondary Current Distribution (cd)**.

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

RESULTS

Reproduce the plots from the Results and Discussion section in the following way:

Electrode Potential vs. Ground (cd)

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

2 In the **Settings** window for **3D Plot Group**, type `Electrode Potential vs. Ground (cd)` in the **Label** text field.

Surface 1

1 In the **Electrode Potential vs. Ground (cd)** toolbar, click **Surface**.

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)> Secondary Current Distribution>cd.phis - Electric potential - V**.

3 In the **Electrode Potential vs. Ground (cd)** toolbar, click **Plot**.

Electrode Potential vs. Adjacent Reference (cdsh)

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

2 In the **Settings** window for **3D Plot Group**, type `Electrode Potential vs. Adjacent Reference (cdsh)` in the **Label** text field.

Surface 1

1 In the **Electrode Potential vs. Adjacent Reference (cdsh)** toolbar, click **Surface**.

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)> Current Distribution, Shell>cdsh.Evsref - Electrode potential vs. adjacent reference - V**.

3 In the **Electrode Potential vs. Adjacent Reference (cdsh)** toolbar, click **Plot**.

Electrolyte Potential in Film (cdsh)

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 Film (cdsh)` in the **Label** text field.

Surface 1

1. In the **Electrolyte Potential in Film (cdsh)** toolbar, click **Surface**.
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)> Current Distribution, Shell>phil2 - Electrolyte potential - V**.
3. In the **Electrolyte Potential in Film (cdsh)** toolbar, click **Plot**.

Corrosion Current Density (cdsh)

1. In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.
2. In the **Settings** window for **3D Plot Group**, type `Corrosion Current Density (cdsh)` in the **Label** text field.

Surface 1

1. In the **Corrosion Current Density (cdsh)** toolbar, click **Surface**.
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)> Current Distribution, Shell>Electrode kinetics>cdsh.iloc_er1 - Local current density - A/m^2**.
3. In the **Corrosion Current Density (cdsh)** toolbar, click **Plot**.

Oxygen Reduction Current Density (cdsh)

1. In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.
2. In the **Settings** window for **3D Plot Group**, type `Oxygen Reduction Current Density (cdsh)` in the **Label** text field.

Surface 1

1. In the **Oxygen Reduction Current Density (cdsh)** toolbar, click **Surface**.
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)> Current Distribution, Shell>Electrode kinetics>cdsh.iloc_er2 - Local current density - A/m^2**.
3. In the **Oxygen Reduction Current Density (cdsh)** toolbar, click **Plot**.