Under-Deposit Corrosion

Introduction

This example models the effect of corrosion product on galvanic corrosion between a magnesium alloy (AE44) and mild steel in contact with brine solution. The present model is based upon Galvanic Corrosion with Electrode Deformation model available in the Corrosion Module Application Library. In this model, deposition of magnesium hydroxide corrosion product is modeled using the interface tracking Level Set interface, in addition to dissolution of the magnesium alloy.

The example is based on a paper by W. Sun and others (Ref. 1).

Model Definition

The Galvanic Corrosion with Electrode Deformation model considered electrochemical reactions occurring at the magnesium and steel surfaces and deformation of magnesium surface due to the dissolution reaction, neglecting the effect of corrosion product formed at the electrode surfaces. The present model extends the Galvanic Corrosion with Electrode Deformation model by accounting for mass transport of Mg^{2+} and OH^- ions, precipitation reaction forming magnesium hydroxide corrosion product ($Mg(OH)_2$) and its effect on transport properties. The present model also tracks the corrosion product interface using the Level Set interface, which is used to describe transport properties separately for electrolyte and corrosion product deposition regions.
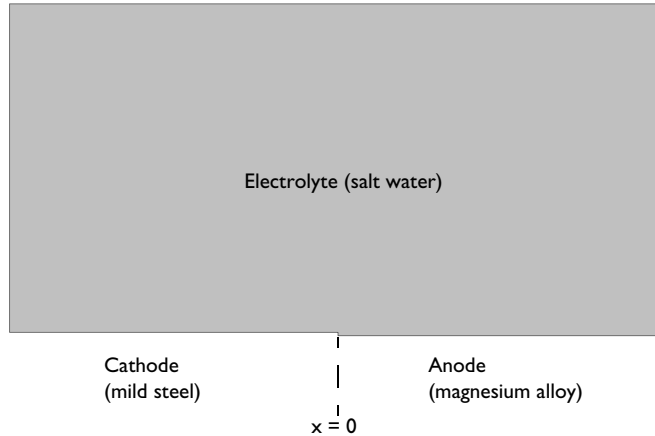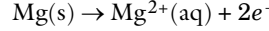

Electrolyte (salt water)

Cathode (mild steel) Anode (magnesium alloy)

x = 0

Figure 1: Model geometry.

The model geometry is the same as used in Galvanic Corrosion with Electrode Deformation model and is shown in Figure 1.

ELECTROCHEMICAL REACTIONS

The magnesium alloy is an anode of the galvanic couple, oxidizing magnesium according to

$$Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$$

The mild steel acts as a cathode for this galvanic couple, wherein oxygen reduction reaction occurs according to

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
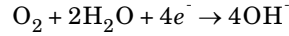
The same electrode kinetics as described in Galvanic Corrosion with Electrode Deformation model is used here.

MASS TRANSPORT

The transport of Mg^{2+} ions generated at the magnesium surface and OH^- ions generated at the mild steel surface is considered to be by diffusion and migration mechanisms. Assuming diluted species in a supporting electrolyte, mass transport of the ionic species is prescribed using a Transport of Diluted Species interface according to

$$\mathbf{N}_i = -D_{i,\,eff}\nabla c_i - z_i u_{i,\,eff} F c_i \nabla \phi_l$$

where $\mathbf{N}_i$ denotes the transport vector (SI unit: $mol/(m^2 \cdot s)$), $D_{i,eff}$ the effective diffusion coefficients of the ionic species, c_i the concentration in the electrolyte (SI unit: mol/m^3), z_i the charge for the ionic species, $u_{i,eff}$ the effective mobility of the charged species (SI unit: $m^2/(s \cdot J \cdot mole)$), F Faraday's constant (SI unit: $A \cdot s/mole$), and ϕ_l the potential in the electrolyte (V).

The material balances are expressed through

$$\frac{\partial c_i}{\partial t} + \nabla \cdot \mathbf{N}_i = R_i$$

one for each species, that is $i = Mg^{2+}$ and OH^-.

The transport properties such as effective diffusion coefficients, are defined using the electrolyte volume fraction:

$$D_{i,\,eff} = \varepsilon_l D_i + (1 - \varepsilon_l) D_{i,\,cp}$$

where ε_l is the electrolyte volume fraction which is defined in terms of level set variable and varies from 1 in the electrolyte domain to 0 in the corrosion product deposition region, D_i is the diffusion coefficients of the ionic species in the electrolyte domain and $D_{i,\text{cp}}$ is the diffusion coefficients of the ionic species in the corrosion product deposition region.

Due to a porous nature of corrosion product deposits, diffusion coefficients need to be updated to account for the effect of porosity. $D_{i,\text{cp}}$ is defined in terms of MacMullin number, N_M, and porosity of corrosion product region, ε_p, to define average characteristic of transport phenomenon in the deposited region according to (Ref. 1)

$$D_{i,\,\text{cp}} = D_i(1 - \varepsilon_p) + \frac{D_i}{N_M}\varepsilon_p$$

where ε_p is considered to be 0.55 and N_M is defined according to
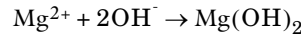
$$N_M = \frac{\tau}{\varepsilon_p}$$

where τ is the tortuosity of corrosion product region and is considered to be 1.

The effective mobilities are calculated using the Nernst–Einstein relation:

$$u_{i,\,\text{eff}} = \frac{D_{i,\,\text{eff}}}{RT}$$

The Mg^{2+} and OH^- ions react with each other to form magnesium hydroxide precipitates according to

$$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2$$

The precipitation reaction of magnesium hydroxide is assumed to be an irreversible reaction which initiates when the ion product, $c_{Mg^{2+}}c_{OH^-}^2$, exceeds the solubility product for magnesium hydroxide, k_{sp} (SI unit: mol^3/m^9). The rate of reaction for consumption of Mg^{2+} and OH^- ions (SI unit: $mol/(m^2 \cdot s)$) is described according to

$$R_{s,\,Mg^{2+}} = k(c_{Mg^{2+}}c_{OH^-}^2 - k_{sp}) \times H(\zeta)$$

$$R_{s,\,OH^-} = 2k(c_{Mg^{2+}}c_{OH^-}^2 - k_{sp}) \times H(\zeta)$$

where k is the precipitation reaction rate constant (SI unit: $m^7/(mol^2 \cdot s)$), $H(\zeta)$ is the Heaviside step function and ζ is the step function variable which is defined according to

$$\zeta = \frac{c_{Mg^{2+}}c_{OH^-}^2}{k_{sp}} - 1$$

The reaction source term (SI unit: $(mol/(m^3 \cdot s))$) is defined in terms of the reaction rate for consumption of Mg^{2+} and OH^- ions (SI unit: $mol/(m^2 \cdot s)$) according to

$$R_i = -R_{s,i}\delta$$

where δ is the level set delta function which is used to prescribe the deposition reaction at the corrosion product interface.

The boundary condition at the magnesium surface is:

$$-\mathbf{N}_{Mg^{2+}} \cdot \mathbf{n} = -\frac{i_{loc}}{2F}$$

where $\mathbf{n}$ denotes the normal vector to the boundary.

The boundary condition at the magnesium surface is:

$$-\mathbf{N}_{OH^-} \cdot \mathbf{n} = \frac{i_{loc}}{F}$$

The initial conditions and concentration at the top boundary are set according to

$$c_{Mg^{2+}} = 0$$
$$c_{OH^-} = c_0$$

All other boundaries are insulating:

$$-\mathbf{N}_i \cdot \mathbf{n} = 0$$

CORROSION PRODUCT INTERFACE TRACKING

The Level Set interface is used to keep track of the deformation due to corrosion product deposition. The Level Set interface automatically sets up the equations for the movement of the interface between the liquid electrolyte and the porous corrosion product. The interface is represented by the 0.5 contour of the level set variable ϕ. The level set variable varies from 1 in the electrolyte domain to 0 in the deposited region. The level set variable can thus be thought of as the electrolyte volume fraction. The transport of the level set variable is given by:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \gamma \nabla \cdot \left(\varepsilon \nabla \phi - \phi (1 - \phi) \frac{\nabla \phi}{|\nabla \phi|} \right)$$

The ε parameter determines the thickness of the interface and is defined as $\varepsilon = h_{max}/4$, where h_{max} is the maximum mesh element size in the domain. The γ parameter determines the amount of reinitialization. A suitable value for γ is the maximum velocity magnitude occurring in the model.

The level set delta function is approximated by:

$$\delta = 6|\phi(1 - \phi)||\nabla \phi|$$

As the magnesium hydroxide corrosion product deposits at the electrode surfaces, the magnesium surface is also deforming due to dissolution reaction. The velocity field used in the transport equation for level set variable needs to account for both of these components: velocity representing magnesium hydroxide corrosion product deposition, $\mathbf{u}_{dep}$ (SI unit: m/s) and velocity representing magnesium dissolution, $\mathbf{u}_{corr}$ (SI unit: m/s).

The magnesium hydroxide corrosion product deposition velocity in normal direction is defined according to

$$\mathbf{u}_{dep} = R_{s, \, Mg^{2+}} \frac{M_{Mg(OH)_2}}{\rho_{Mg(OH)_2}}$$

where $M_{Mg(OH)_2}$ is the molar mass (58 g/mol) and $\rho_{Mg(OH)_2}$ is the density of $Mg(OH)_2$ (2450 kg/m^3).

The magnesium dissolution velocity in normal direction is defined according to

$$\mathbf{u}_{corr} = \frac{i_{loc} M_{Mg}}{2F \, \rho_{Mg}}$$

where M_{Mg} is the mean molar mass (25 g/mol) and ρ_{Mg} is the density (1820 kg/m^3) of the magnesium alloy. Since $\mathbf{u}_{corr}$ is available only at the deforming boundary, we use a general extrusion operator to make it available throughout the domain as well.

Assuming that deposits form parallel vertical rods type of porous structure, only y-component of dissolution velocity is used in the level set transport equation. Hence, the velocity field used in the transport equation for level set variable is defined according to

$$u = \mathbf{u}_{dep} \times n_{LS, \, x} \times H(0.6 - \phi)$$

$$v = (\mathbf{u}_{\text{dep}} \times n_{\text{LS},y} + \mathbf{u}_{\text{corr}} \times n_y) \times H(0.6 - \phi)$$

where $n_{\text{LS},x}$ and $n_{\text{LS},y}$ are the x- and y-components of the interface normal $\mathbf{n}_{\text{LS}}$, which is defined in terms of level set variable according to

$$\mathbf{n}_{\text{LS}} = \frac{\nabla\phi}{|\nabla\phi|}$$

n_y is the y-component of the unit normal vector $\mathbf{n}$, pointing out of the electrolyte domain.

The Heaviside step function $H(0.6 - \phi)$ ensures that the level set variable is convected only adjacent to the corrosion product region.

The level set variable of value 0 enters the domain from the bottommost boundaries of the domain, which are prescribed using the Inlet boundary condition. The rest of the boundaries are prescribed using the Outlet boundary condition.

ELECTROLYTE PROPERTIES

Finally, the effective electrolyte conductivity, σ_{eff}, is defined for the electrolyte domain and the porous corrosion product region separately using the electrolyte volume fraction defined in terms of level set variable according to

$$\sigma_{\text{eff}} = \varepsilon_l \sigma + (1 - \varepsilon_l)\sigma_{\text{cp}}$$

where σ is the electrolyte conductivity in the electrolyte domain and is considered to be equal to 2.5 S/m.

The electrolyte conductivity in the corrosion product deposition region, σ_{cp}, is described according to

$$\sigma_{\text{cp}} = s_L^m \varepsilon_p^n \sigma$$

where s_L is the fluid saturation and is considered to be 1, m is the cementation exponent and is considered to be 1 and n is the saturation coefficient and is considered to be 2 in this model.

Solve the model in a time-dependent study, simulating the corrosion for three days of immersion in salt water.

Results and Discussion

Figure 2 shows a surface plot of volume fraction of fluid 1 at the end of the simulation ($t = 72$ h). The region with volume fraction of fluid 1 of value 1 represents the corrosion

product deposition whereas the same of value 0 represents the electrolyte. A contour plot of volume fraction of fluid 1 of value 0.5 represents the position of corrosion product interface at the end of the simulation. It can be seen that the corrosion product deposition is maximum at the contact point of the metals and it decreases with distance away from the contact point along the magnesium and mild steel surfaces. The corrosion product thickness is also found to be thicker at the magnesium surface than the same at the mild steel surface. This behavior is attributed to the faster precipitation reaction at the magnesium surface, since OH^- ions transport faster than Mg^{2+} ions in the electrolyte. Figure 2 represents deformed boundaries due to deposition of corrosion product as well as dissolution of magnesium.
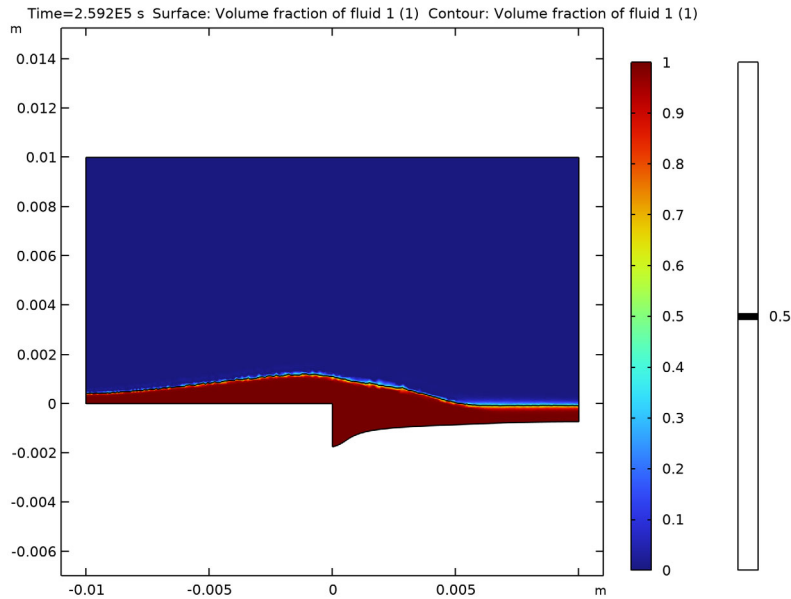
Figure 2: The corrosion product deposition and dissolution of magnesium after 72 h.

Figure 3 shows the electrode current densities at the beginning and the end of the simulation. As expected, the highest electrode current densities are found at the contact point between the two metals. However, the electrode current density distribution along the magnesium and mild steel surfaces is considerably different when compared to a scenario where the effect corrosion product is not considered (refer to Figure 2 in Galvanic Corrosion with Electrode Deformation model). It can be seen that the electrode current density at the end of the simulation is lower adjacent to the contact point between the two

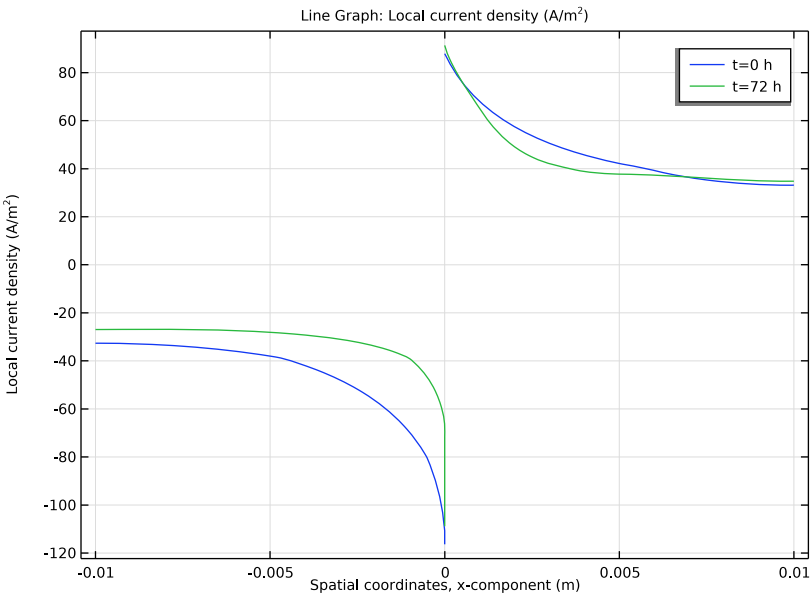metals which is attributed to the corrosion product deposited at the magnesium and mild steel surfaces.

Line Graph: Local current density (A/m^2)

Figure 3: Electrode current densities at t = 0 and t = 72 h.

Figure 4 shows the current density and potential distribution in the electrolyte, and the model geometry, at the beginning of the simulation. The electrolyte potential and current

density distribution at the beginning of simulations is the same as reported in Figure 3 of Galvanic Corrosion with Electrode Deformation model, as expected.
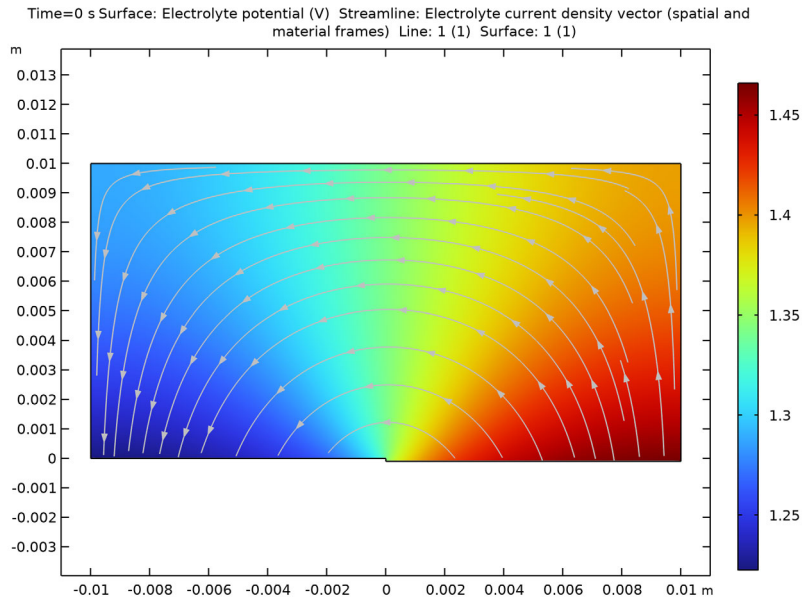
Figure 4: Model geometry, electrolyte potential, and current densities at t = 0.

Figure 5 shows the current density and potential distribution in the electrolyte, the changed geometry due to metal dissolution and corrosion product deposited region at the end of the simulation. Because the electrode current densities are highest at the contact point of the metals, the metal dissolution is also maximum at this point. A streamline plot of electrolyte current density vector at the end of simulations is slightly different than that reported in Figure 4 of Galvanic Corrosion with Electrode Deformation model. The difference in the electrolyte current density streamline plot is apparent in the corrosion product deposited region where streamlines are found to change the shape.
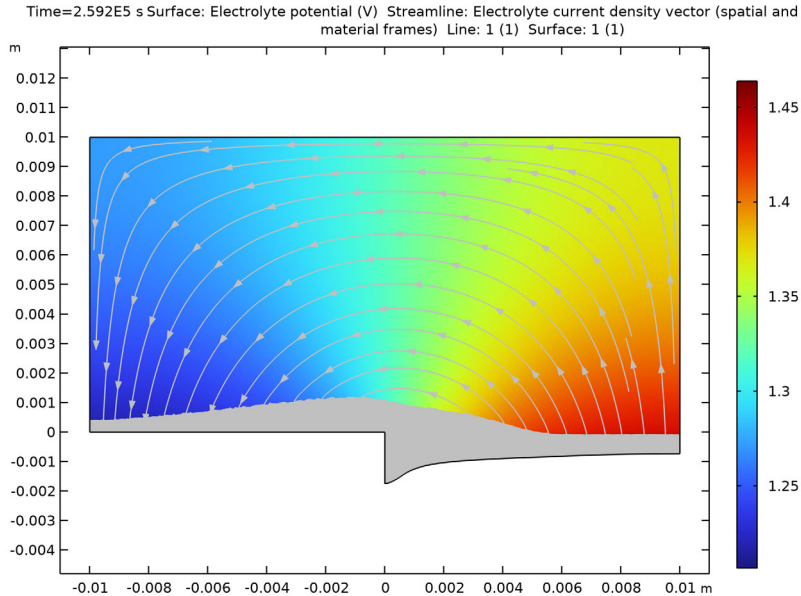
Time=2.592E5 s Surface: Electrolyte potential (V) Streamline: Electrolyte current density vector (spatial and material frames) Line: 1 (1) Surface: 1 (1)

Figure 5: Model geometry, electrolyte potential, and current densities after 72 h.

Reference

1. W. Sun, G. Liu, L. Wang, T. Wu and Y. Liu, "An arbitrary Lagrangian-Eulerian model for studying the influences of corrosion product deposition on bimetallic corrosion", *J. Solid State Electrochem.*, vol. 17, pp. 829–840, 2013.

Application Library path: `Corrosion_Module/Galvanic_Corrosion/under_deposit_corrosion`

Modeling Instructions

APPLICATION LIBRARIES

1 From the **File** menu, choose **Application Libraries**.

2 In the **Application Libraries** window, select **Corrosion Module>Galvanic Corrosion> galvanic_corrosion_with_deformation** in the tree.

3 Click ⬥ **Open**.

Add **Transport of Diluted Species** and **Level Set** interfaces to solve for the mass transport of Mg^{2+} and OH^- ions and to track the position of the $Mg(OH)_2$ corrosion product precipitate, respectively.

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

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

3 In the tree, select **Chemical Species Transport>Transport of Diluted Species (tds)**.

4 Click to expand the **Dependent Variables** section. In the **Number of species** text field, type 2.

5 In the **Concentrations (mol/m³)** table, enter the following settings:

cMg
cOH

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

7 In the tree, select **Mathematics>Moving Interface>Level Set (ls)**.

8 Click **Add to Selection** in the window toolbar.

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

Start by updating the parameters required for corrosion product modeling.

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 Click 📁 **Load from File**.

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

Define a step function for use when defining variables for precipitation reaction rate and corrosion product velocity.

Step 1 (step1)

1 In the **Home** toolbar, click $f(x)$ **Functions** and choose **Local>Step**.

2 In the **Settings** window for **Step**, click to expand the **Smoothing** section.

3 In the **Size of transition zone** text field, type 0.001.

Variables 1

Load the model variables from a text file.

1 In the **Home** toolbar, click $a=$ **Variables** and choose **Local Variables**.

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

3 Click 📁 **Load from File**.

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

The orange color for the variable v_corprod is caused by the undefined nonlocal
general extrusion coupling.

General Extrusion 1 (genext1)

Now, define the nonlocal general extrusion coupling.

1 In the **Definitions** toolbar, click 🔗 **Nonlocal Couplings** and choose **General Extrusion**.

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

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

4 Select Boundary 5 only.

5 Locate the **Destination Map** section. Clear the **y-expression** text field.

6 Locate the **Source** section. From the **Source frame** list, choose **Mesh (Xm, Ym, Zm)**.

7 Select the **Use source map** check box.

8 Clear the **Ym^i-expression** text field.

9 Click to expand the **Advanced** section. From the **Mesh search method** list, choose
Closest point.

TRANSPORT OF DILUTED SPECIES (TDS)

Next, set up mass transport physics.

1 In the **Model Builder** window, under **Component 1 (comp1)** click
Transport of Diluted Species (tds).

2 In the **Settings** window for **Transport of Diluted Species**, locate the **Transport Mechanisms**
section.

3 Clear the **Convection** check box.

4 Select the **Migration in electric field** check box.

5 Select Domain 1 only.

Species Charges

1 In the **Model Builder** window, under **Component 1 (comp1)> Transport of Diluted Species (tds)** click **Species Charges**.

2 In the **Settings** window for **Species Properties**, locate the **Charge** section.

3 In the z_{cMg} text field, type 2.

4 In the z_{cOH} text field, type -1.

Transport Properties 1

1 In the **Model Builder** window, click **Transport Properties 1**.

2 In the **Settings** window for **Transport Properties**, locate the **Diffusion** section.

3 In the D_{cMg} text field, type DMg*ls.Vf2+DMge*ls.Vf1.

4 In the D_{cOH} text field, type DOH*ls.Vf2+DOHe*ls.Vf1.

5 Locate the **Migration in Electric Field** section. In the V text field, type phil.

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the *cOH* text field, type cOH0.

Reactions 1

Use a **Reactions** node to define the sink terms for Mg^{2+} and OH^-. The use of the variable ls.delta ensures that the sink term is applied only at the corrosion product interface.

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

2 Select Domain 1 only.

3 In the **Settings** window for **Reactions**, locate the **Reaction Rates** section.

4 In the R_{cMg} text field, type -R_Mg*ls.delta.

5 In the R_{cOH} text field, type -R_OH*ls.delta.

Concentration 1

Define the concentration at the top boundaries of the domain.

1 In the **Physics** toolbar, click ⬬ **Boundaries** and choose **Concentration**.

2 Select Boundaries 3 and 6 only.

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

4 Select the **Species cOH** check box.

5 In the $c_{0,\text{cOH}}$ text field, type cOH0.

Electrode Surface Coupling 1

Now, define the source terms for Mg^{2+} and OH^- at the anode and cathode boundaries, respectively, making use of the local current densities obtained from the **Secondary Current Distribution** interface.

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

2 Select Boundaries 2 and 4 only.

Reaction Coefficients 1

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

2 In the **Settings** window for **Reaction Coefficients**, locate the **Model Inputs** section.

3 From the i_{loc} list, choose **Local current density, Electrode Reaction 1 (cd/es1/er1)**.

4 Locate the **Stoichiometric Coefficients** section. In the n text field, type 4.

5 In the ν_{cOH} text field, type 4.

Electrode Surface Coupling 2

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

2 Select Boundary 5 only.

Reaction Coefficients 1

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

2 In the **Settings** window for **Reaction Coefficients**, locate the **Model Inputs** section.

3 From the i_{loc} list, choose **Local current density, Electrode Reaction 1 (cd/es2/er1)**.

4 Locate the **Stoichiometric Coefficients** section. In the n text field, type 2.

5 In the ν_{cMg} text field, type -1.

LEVEL SET (LS)

Now, set up the level set physics to track the position of the corrosion product interface.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Level Set (ls)**.

2 Select Domain 1 only.

Level Set Model 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Level Set (ls)** click **Level Set Model 1**.

2 In the **Settings** window for **Level Set Model**, locate the **Level Set Model** section.

3 In the γ text field, type `max(vn_corprod,eps)`.

4 In the ε_{ls} text field, type `ls.hmax/4`.

5 Locate the **Convection** section. Specify the **u** vector as

`u_corprod`	x
`v_corprod`	y

Note that the variables `u_corprod` and `v_corprod` use the step function variables defined in terms of the level set function to ensure that only the level sets adjacent to the corrosion product are advected.

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 Click the **Fluid 2 (φ = 1)** button.

Inlet 1

Set the inlet for level set function.

1 In the **Physics** toolbar, click ⬭ **Boundaries** and choose **Inlet**.

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

3 Click 📋 **Paste Selection**.

4 In the **Paste Selection** dialog box, type `2,4,5` in the **Selection** text field.

5 Click **OK**.

Outlet 1

Set the outlet for level set function.

1 In the **Physics** toolbar, click ⬭ **Boundaries** and choose **Outlet**.

2 Select Boundaries 1, 3, 6, and 7 only.

SECONDARY CURRENT DISTRIBUTION (CD)

Finally, define the electrolyte conductivity in terms of the level set function to prescribe a different value for the corrosion product.

Electrolyte 1

1 In the **Model Builder** window, expand the **Secondary Current Distribution (cd)** node, then click **Electrolyte 1**.

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

3 In the σ_l text field, type sigma*ls.Vf2+sigmae*ls.Vf1.

COMPONENT 1 (COMP1)

Now, refine the mesh at the magnesium and steel boundaries.

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

MESH 1

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

2 Right-click **Mesh 1** and choose **Edit Physics-Induced Sequence**.

Size

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

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

3 From the **Calibrate for** list, choose **Fluid dynamics**.

4 From the **Predefined** list, choose **Finer**.

Size 1

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

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

3 From the **Calibrate for** list, choose **Fluid dynamics**.

Size 1

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 **Boundary**.

4 Select Boundaries 2 and 5 only.

5 Locate the **Element Size** section. From the **Calibrate for** list, choose **Fluid dynamics**.

6 From the **Predefined** list, choose **Extremely fine**.

7 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

The mesh should look like this:
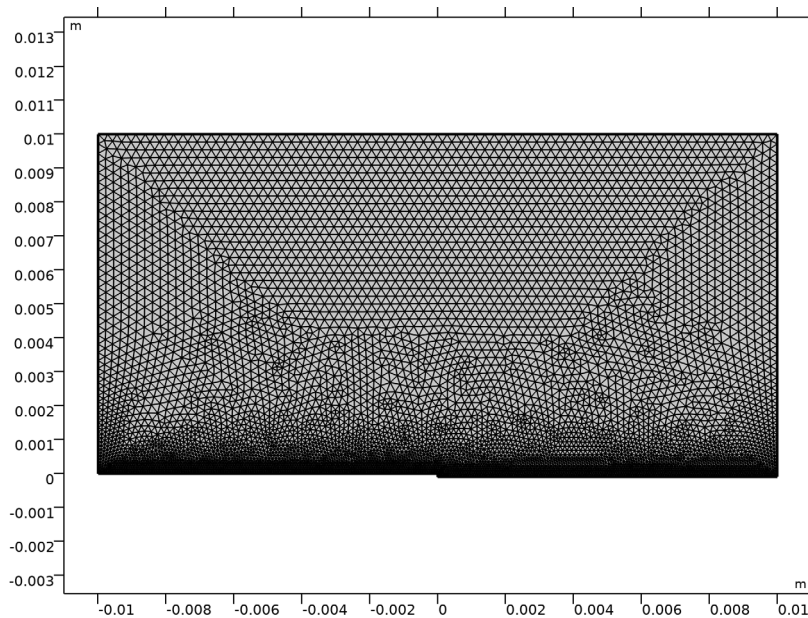
Before computing the solution, some solver settings need to be modified.

Step 1: Current Distribution Initialization

1 In the **Model Builder** window, expand the **Study 1** node, then 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 boxes for **Transport of Diluted Species (tds)**,
Level Set (ls), and **Deformed geometry (Component 1)**.

4 In the table, clear the **Solve for** check boxes for **Nondeforming Boundary 1 (ndbdg1)** and
Deforming Electrode Surface 1 (desdg1).

5 In the **Home** toolbar, click ▬ **Compute**.

RESULTS

Some plots are added by default. To reproduce the plots from the Results and Discussion
section, follow the instructions below.

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

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

3 In the **Separating distance** text field, type 0.035.

4 Locate the **Coloring and Style** section. Find the **Point style** subsection. From the **Arrow length** list, choose **Normalized**.

Electrolyte Potential (cd)

In the **Model Builder** window, click **Electrolyte Potential (cd)**.

Surface 2

1 In the **Electrolyte Potential (cd)** toolbar, click ▪ **Surface**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type 1.

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

Filter 1

1 In the **Electrolyte Potential (cd)** toolbar, click ▼ **Filter**.

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

3 In the **Logical expression for inclusion** text field, type ls.Vf1>=0.5.

Electrolyte Potential (cd)

1 In the **Model Builder** window, under **Results** click **Electrolyte Potential (cd)**.

2 In the **Electrolyte Potential (cd)** toolbar, click ▣ **Plot**.

The plot should look like Figure 4.

3 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

4 From the **Time (s)** list, choose **2.592E5**.

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

The plot should look like Figure 5.

Line Graph 1

To reproduce Figure 3 follow the instructions below.

1 In the **Model Builder** window, under **Results>1D Plot Group 6** click **Line Graph 1**.

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

3 From the **Time selection** list, choose **From list**.

4 In the **Times (s)** list, select **0**.

Local Current Density Change

1 In the **Model Builder** window, under **Results** click **1D Plot Group 6**.

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

3 In the **Local Current Density Change** toolbar, click ▣ **Plot**.

Corrosion Product Interface

Follow the instructions below to reproduce Figure 2.

1 In the **Home** toolbar, click ▦ **Add Plot Group** and choose **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type Corrosion Product Interface in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Remeshed Solution 1 (sol3)**.

4 From the **Time (s)** list, choose **2.592E5**.

Surface 1

1 In the **Corrosion Product Interface** 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)>Level Set>ls.Vf1 - Volume fraction of fluid 1 - 1**.

3 In the **Corrosion Product Interface** toolbar, click ▣ **Plot**.

Corrosion Product Interface

In the **Model Builder** window, click **Corrosion Product Interface**.

Contour 1

1 In the **Corrosion Product Interface** toolbar, click 🖑 **Contour**.

2 In the **Settings** window for **Contour**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Level Set>ls.Vf1 - Volume fraction of fluid 1 - 1**.

3 Locate the **Levels** section. From the **Entry method** list, choose **Levels**.

4 In the **Levels** text field, type 0.5.

5 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

6 From the **Color** list, choose **Black**.

7 In the **Corrosion Product Interface** toolbar, click **Plot**.

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