



Model created in COMSOL Multiphysics 6.4

Decorative Plating

Introduction

This tutorial model of decorative electroplating models a secondary current distribution with full Butler–Volmer kinetics for both anode and cathode. The thickness of the deposited layer at the cathode is computed along with the surface thickness change on the anode caused by metal dissolution.

A more detailed description of how to build this model, including screenshots, can be found in the *Introduction to the Electrodeposition Module* book.

Model Definition

The model geometry is shown in [Figure 1](#). The anode is a planar dissolving anode. The cathode represents a furniture fitting that is to be decorated by metal plating.

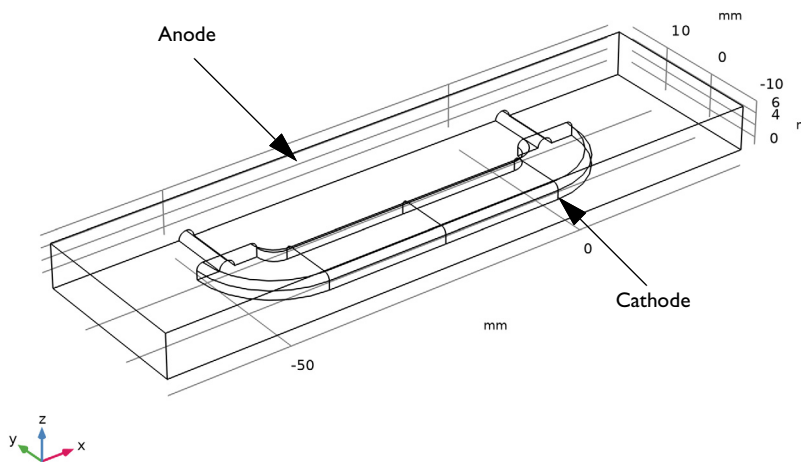


Figure 1: The model geometry.

The conductivity of the metal of the anode and cathode is very high compared to that of the electrolyte and it is thus assumed that the electric potential in the metal is constant. Variations in the activation overpotential are therefore caused by the potential in the electrolyte at the surface of the electrodes. Under these assumptions, the electrodes are treated as boundaries in the simulations.

Before beginning, one difficulty found in all current density distribution models needs to be discussed. The overpotential, η_m , for an electrode reaction of index m , is defined according to the following equation:

$$\eta = \phi_{s,0} - \phi_l - E_{\text{eq},m}$$

where $\phi_{s,0}$ denotes the electric potential of the metal, ϕ_l denotes the potential in the electrolyte, and $E_{\text{eq},m}$ denotes the difference between the metal and electrolyte potentials at the electrode surface, measured at equilibrium using a common reference potential. The electric potential of one of the electrodes may be bootstrapped, so that all other potentials are measured with this reference (this bootstrap can actually be achieved by fixing the potential at any point in the cell). In this case, the electric potential of the metal is selected at the cathode as a bootstrap by setting this potential to 0 V. This implies that the electric potential of the metal at the anode is equal to the cell voltage. The potential of the electrolyte floats and adapts to satisfy the balance of current, so that an equal amount of current that leaves at the cathode also enters at the anode. This then determines the overpotential at the anode and the cathode.

ELECTROLYTE CHARGE TRANSPORT

Use the Secondary Current Distribution interface to solve for the electrolyte potential, ϕ_l (SI unit: V), according to

$$\begin{aligned}\mathbf{i}_l &= -\sigma_l \nabla \phi_l \\ \nabla \cdot \mathbf{i}_l &= 0\end{aligned}$$

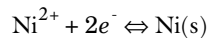
where \mathbf{i}_l (SI unit: A/m²) is the electrolyte current density vector and σ_l (SI unit: S/m) is the electrolyte conductivity, which is assumed to be a constant.

Use the default Insulation condition for all boundaries except the anode and cathode surfaces:

$$\mathbf{n} \cdot \mathbf{i}_l = 0$$

where \mathbf{n} is the normal vector, pointing out of the domain.

The main electrode reaction on both the anode and the cathode surfaces is the nickel deposition/dissolution reaction according to



Use a Butler–Volmer expression to model this reaction; this sets the local current density to

$$i_{\text{loc, Ni}} = i_{0, \text{Ni}} \left(\exp\left(\frac{\alpha_a F \eta_{\text{Ni}}}{RT}\right) - \exp\left(-\frac{\alpha_c F \eta_{\text{Ni}}}{RT}\right) \right)$$

The rate of deposition at the cathode boundary surfaces and the rate of dissolution at the anode boundary surface, with a velocity in the normal direction, v (m/s), is calculated according to

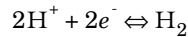
$$v = \frac{i_{\text{loc, Ni}} M}{nF \rho}$$

where M is the mean molar mass (59 g/mol) and ρ is the density (8900 kg/m³) of the nickel atoms and n is number of participating electrons. Note that the local current density is positive at the anode surface and negative at the cathode surfaces.

On the anode the electrolyte current density is set to the local current density of the nickel deposition reaction:

$$\mathbf{n} \cdot \mathbf{i}_l = i_{\text{loc, Ni}}$$

On the cathode, add a second electrode reaction to model the parasitic hydrogen evolution reaction:



Use a cathodic Tafel equation to model the kinetics of the hydrogen reaction on the cathode, this sets the local current density to

$$i_{\text{loc, H}} = -i_{0, \text{H}} 10^{-\eta_{\text{H}}/A_c}$$

The hydrogen reaction does not contribute to the rate of deposition of nickel, but it contributes to the total current density at the cathode surface:

$$\mathbf{n} \cdot \mathbf{i}_l = i_{\text{loc, Ni}} + i_{\text{loc, H}}$$

Solve the model in a time-dependent study, simulating the electroplating for 600 s.

Results and Discussion

Figure 2 shows the change in the total electrode thickness for the cathode surfaces indicating the deposition thickness after 600 s. It can be seen that the deposition thickness

is quite nonuniform. The lowest deposition thickness is found at the bottom end of the cathode geometry, farthest from the anode surface. The deposition thickness could be optimized further by changing design parameters such as plating cell geometry, distance between the anode and cathode surface, conductivity of the electrolyte and operational parameters such as applied current or potential.

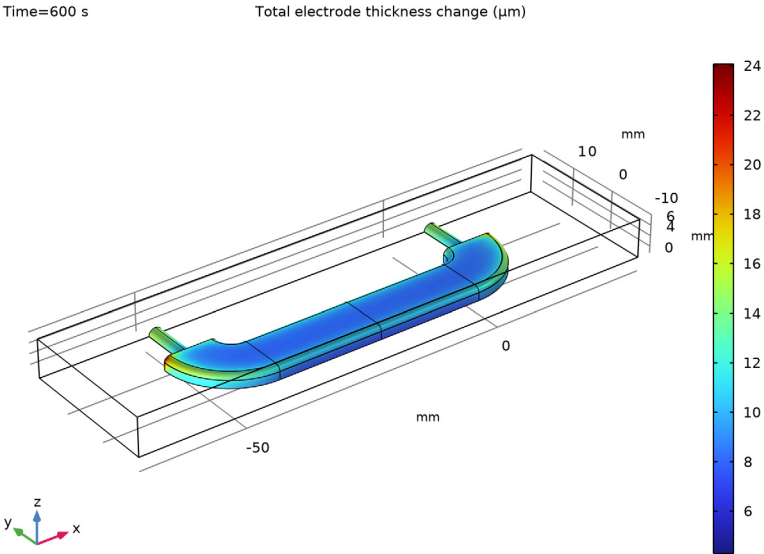


Figure 2: Change in total electrode thickness.

Figure 3 shows the local current efficiency over the cathode surface. The efficiency is calculated as the nickel deposition current density divided by the total current density at the cathode. The efficiency is about 97%.

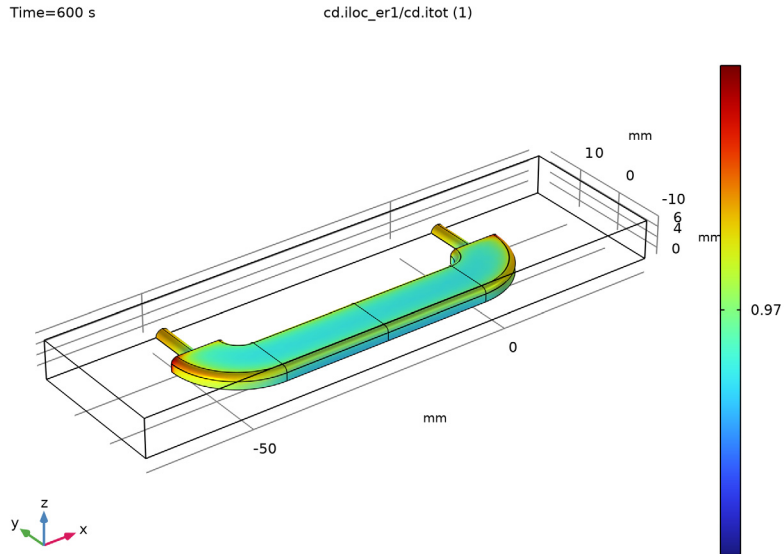



Figure 3: The current efficiency factor at the cathode.

Application Library path: Electrodeposition_Module/Tutorials/
decorative_plating


Modeling Instructions



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

NEW

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

MODEL WIZARD


I In the **Model Wizard** window, click  **3D**.

- 2 In the **Select Physics** tree, select **Electrochemistry** > **Primary and Secondary Current Distribution** > **Secondary Current Distribution (cd)**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Time Dependent with Initialization**.
- 6 Click  **Done**.

GLOBAL DEFINITIONS




Load the model parameters from a text file.

Parameters I

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters I**.
- 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 `decorative_plating_parameters.txt`.

GEOMETRY I

The model geometry is available as a parameterized geometry sequence in a separate MPH file. If you want to build it from scratch, follow the instructions in the section [Appendix — Geometry Modeling Instructions](#). Otherwise load it from file with the following steps.

- 1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.
- 2 Browse to the model's Application Libraries folder and double-click the file `decorative_plating_geom_sequence.mph`.
- 3 In the **Geometry** toolbar, click  **Build All**.
- 4 Click the  **Wireframe Rendering** button in the **Graphics** toolbar.
- 5 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Geometry I** and choose **Plot**.
- 6 Click the  **Zoom Extents** button in the **Graphics** toolbar.

SECONDARY CURRENT DISTRIBUTION (CD)



Now start setting up the current distribution model, beginning with the settings for the electrolyte.

Electrolyte 1

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Secondary Current Distribution (cd)** 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 kappa.

Electrode Surface 1

Now define the anode and the nickel dissolution-deposition electrode reaction on this surface. The combination of the properties of the surface and the reaction stoichiometry will determine how the magnitude and direction of the growth velocity of the deposited layer relates to the electrode reaction currents.

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Electrode Surface**.
- 2 Select Boundary 4 only.
Keep the default boundary condition for this surface, setting the electric potential to zero (grounding the electrode).
- 3 In the **Settings** window for **Electrode Surface**, click to expand the **Dissolving–Depositing Species** section.
- 4 Click  **Add**.
- 5 In the table, enter the following settings:

Species	Density (kg/m ³)	Molar mass (kg/mol)
Ni	rho_Ni	M_Ni

Electrode Reaction 1

Set the first electrode reaction to be the nickel deposition reaction.

- 1 In the **Model Builder** window, click **Electrode Reaction 1**.
- 2 In the **Settings** window for **Electrode Reaction**, locate the **Stoichiometric Coefficients** section.
- 3 In the n text field, type 2.
- 4 In the **Stoichiometric coefficients for dissolving–depositing species**: table, enter the following settings:

Species	Stoichiometric coefficient (I)
Ni	1

- 5 Locate the **Equilibrium Potential** section. In the E_{eq} text field, type Eeq_Ni.

6 Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Butler–Volmer**.

7 In the i_0 text field, type i_{0_Ni} .

Electrode Surface 1

Now duplicate this node to define the cathode.

Electrode Surface 2

1 In the **Model Builder** window, under **Component 1 (comp1) > Secondary Current Distribution (cd)** 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 **Cathode**.

4 Locate the **Electrode Phase Potential Condition** section. From the **Electrode phase potential condition** list, choose **Average current density**.

5 In the $i_{l,average}$ text field, type I_{avg} .

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 **Stoichiometric Coefficients** section.

3 In the **Stoichiometric coefficients for dissolving–depositing species** table, enter the following settings:

Species	Stoichiometric coefficient (l)
Ni	1

Electrode Surface 2

Add the hydrogen evolution reaction.

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

Electrode Reaction 2



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

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

3 From the **Kinetics expression type** list, choose **Cathodic Tafel equation**.

4 In the i_0 text field, type i_{0_H} .

MESH 1


- 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**.
- 4 Click  **Build All**.
- 5 Right-click **Component 1 (comp1)** > **Mesh 1** and choose **Plot**.
- 6 Click the  **Zoom Extents** button in the **Graphics** toolbar.

STUDY 1

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 **Study Settings** section.
- 3 From the **Current distribution type** list, choose **Secondary**.



Step 2: Time Dependent

- 1 In the **Model Builder** window, click **Step 2: Time Dependent**.
- 2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
- 3 In the **Output times** text field, type range (0, 60, 600).
- 4 In the **Study** toolbar, click  **Compute**.

RESULTS

Deposited Thickness, Cathode

Modify the default plot for the electrode thickness change to show the deposited thickness on the cathode only.

- 1 In the **Model Builder** window, under **Results** click **Total Electrode Thickness Change (cd)**.
- 2 In the **Settings** window for **3D Plot Group**, click to expand the **Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.
- 4 From the **Selection** list, choose **Cathode**.
- 5 In the **Total Electrode Thickness Change (cd)** toolbar, click  **Plot**.
- 6 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 7 Right-click **Results** > **Total Electrode Thickness Change (cd)** and choose **Rename**.

8 In the **Rename 3D Plot Group** dialog, type Deposited Thickness, Cathode in the **New label** text field.

9 Click **OK**.

Deposited Thickness, Cathode I

Right-click **Deposited Thickness, Cathode** and choose **Duplicate**.

Surface I


1 In the **Model Builder** window, expand the **Deposited Thickness, Cathode I** node, then click **Surface I**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component I (comp1) > Secondary Current Distribution > Electrode kinetics > cd.iloc_er1 - Local current density - A/m²**.

Divide the current density of the nickel reaction with the total current density variable.

3 Locate the **Expression** section. In the **Expression** text field, type `cd.iloc_er1/cd.itot`.

4 In the **Deposited Thickness, Cathode I** toolbar, click  **Plot**.

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

Current Efficiency, Cathode

1 In the **Model Builder** window, right-click **Deposited Thickness, Cathode I** and choose **Rename**.

2 In the **Rename 3D Plot Group** dialog, type Current Efficiency, Cathode in the **New label** text field.

3 Click **OK**.

Appendix — Geometry Modeling Instructions

ADD COMPONENT

1 In the **Model Builder** window, expand the **Results** node.

2 Right-click the root node and choose **Add Component > 3D**.

DEFINITIONS

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

View I


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

- 2 In the **Settings** window for **View**, locate the **View** section.
- 3 Select the **Wireframe rendering** checkbox.


GEOMETRY I

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
- 2 In the **Settings** window for **Geometry**, locate the **Units** section.
- 3 From the **Length unit** list, choose **mm**.

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 100.
- 4 In the **Depth** text field, type 28.
- 5 In the **Height** text field, type 7.25.
- 6 Locate the **Position** section. In the **x** text field, type -70.
- 7 In the **y** text field, type -10.
- 8 In the **z** text field, type -1.25.
- 9 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Cylinder 1 (cyl1)

- 1 In the **Geometry** toolbar, click  **Cylinder**.
- 2 In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.
- 3 In the **Radius** text field, type 1.25.
- 4 In the **Height** text field, type 10.
- 5 Locate the **Position** section. In the **x** text field, type -48.
- 6 In the **y** text field, type 8.
- 7 In the **z** text field, type -1.25.
- 8 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

Cumulative Selections

In the **Geometry** toolbar, click  **Selections** and choose **Cumulative Selections**.


Objects to subtract

- 1 Right-click **Cumulative Selections** and choose **Cumulative Selection**.
- 2 In the **Settings** window for **Selection**, type **Objects to subtract** in the **Label** text field.

Cylinder 1 (cyl1)

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Geometry 1** click **Cylinder 1 (cyl1)**.
- 2 In the **Settings** window for **Cylinder**, locate the **Selections of Resulting Entities** section.
- 3 Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Objects to subtract**.


Work Plane 1 (wp1)

- 1 In the **Geometry** toolbar, click  **Work Plane**.
- 2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.
- 3 From the **Plane** list, choose **zx-plane**.
- 4 In the **y-coordinate** text field, type 8.


Work Plane 1 (wp1) > Plane Geometry

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

Work Plane 1 (wp1) > Rectangle 1 (r1)

- 1 In the **Work Plane** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type 2.5.
- 4 In the **Height** text field, type 10.
- 5 Locate the **Position** section. In the **xw** text field, type -1.25.
- 6 In the **yw** text field, type -53.

Work Plane 1 (wp1) > Fillet 1 (fil1)

- 1 In the **Work Plane** toolbar, click  **Fillet**.
- 2 On the object **r1**, select Points 2 and 3 only.
- 3 In the **Settings** window for **Fillet**, locate the **Radius** section.
- 4 In the **Radius** text field, type 1.

View 2


- 1 In the **Model Builder** window, expand the **Component 1 (comp1) > Geometry 1 > Work Plane 1 (wp1) > View 2** node, then click **View 2**.
- 2 On the object **r1**, select Point 3 only.

Work Plane 1 (wp1) > Fillet 1 (fil1)





- 1 In the **Model Builder** window, under **Component 1 (comp1) > Geometry 1 > Work Plane 1 (wp1) > Plane Geometry** click **Fillet 1 (fil1)**.


2 In the **Settings** window for **Fillet**, click  **Build Selected**.

Revolve 1 (rev1)


- 1 In the **Geometry** toolbar, click  **Revolve**.
- 2 In the **Settings** window for **Revolve**, locate the **Revolution Angles** section.
- 3 Clear the **Keep original faces** checkbox.
- 4 Click the **Angles** button.
- 5 In the **End angle** text field, type 90.
- 6 Locate the **Revolution Axis** section. From the **Axis type** list, choose **3D**.
- 7 Find the **Point on the revolution axis** subsection. In the **x** text field, type -40.
- 8 In the **y** text field, type 8.
- 9 In the **z** text field, type -1.25.
- 10 Find the **Direction of revolution axis** subsection. In the **y** text field, type 0.
- 11 In the **z** text field, type 1.
- 12 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Objects to subtract**.

Extrude 1 (ext1)

- 1 In the **Geometry** toolbar, click  **Extrude**.
- 2 In the **Settings** window for **Extrude**, locate the **General** section.
- 3 From the **Input objects** list, choose **Objects to subtract**.
- 4 From the **Extrude from** list, choose **Faces**.
- 5 From the **Input faces** list, choose **Objects to subtract**.
- 6 In the tree, select **cyll**.
- 7 Click the  **Remove from Selection** button for **Input faces**.
- 8 On the object **cyll**, select Boundaries 1–6 only.
- 9 On the object **rev1**, select Boundaries 1–8 only.
- 10 Click the  **Remove from Selection** button for **Input faces**.
- 11 On the object **cyll**, select Boundaries 1–6 only.
- 12 On the object **rev1**, select Boundaries 1–8 only.
- 13 In the tree, select **cyll > 1 (not applicable)**, **cyll > 2 (not applicable)**, **cyll > 3**, **cyll > 4**, **cyll > 5 (not applicable)**, and **cyll > 6 (not applicable)**.
- 14 Click the  **Remove from Selection** button for **Input faces**.

- 15 On the object **rev1**, select Boundaries 1–8 only.
- 16 In the tree, select **rev1 > 1**, **rev1 > 2 (not applicable)**, **rev1 > 3**, **rev1 > 4 (not applicable)**, **rev1 > 5**, **rev1 > 6 (not applicable)**, and **rev1 > 7 (not applicable)**.
- 17 Click the  **Remove from Selection** button for **Input faces**.
- 18 On the object **rev1**, select Boundary 8 only.
- 19 In the tree, select **rev1 > 8**.
- 20 Locate the **Distances** section. In the table, enter the following settings:


Distances (mm)
20

- 21 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Objects to subtract**.
- 22 Click  **Build Selected**.


Mirror 1 (mir1)

- 1 In the **Model Builder** window, right-click **Geometry 1** and choose **Transforms > Mirror**.
- 2 In the **Settings** window for **Mirror**, locate the **Input** section.
- 3 From the **Input objects** list, choose **Objects to subtract**.
- 4 Select the **Keep input objects** checkbox.
- 5 Locate the **Point on Plane of Reflection** section. In the **x** text field, type -20.
- 6 Locate the **Normal Vector to Plane of Reflection** section. In the **x** text field, type 1.
- 7 In the **z** text field, type 0.
- 8 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Objects to subtract**.

Difference 1 (dif1)

- 1 In the **Geometry** toolbar, click  **Booleans and Partitions** and choose **Difference**.
- 2 In the **Settings** window for **Difference**, locate the **Difference** section.
- 3 From the **Objects to add** list, choose **Block 1**.
- 4 From the **Objects to subtract** list, choose **Objects to subtract**.

Cathode

- 1 In the **Geometry** toolbar, click  **Selections** and choose **Box Selection**.
- 2 In the **Settings** window for **Box Selection**, type **Cathode** in the **Label** text field.
- 3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

- 4 Locate the **Box Limits** section. In the **x minimum** text field, type -55.
- 5 In the **x maximum** text field, type 15.
- 6 In the **y minimum** text field, type -8.
- 7 In the **y maximum** text field, type 15.
- 8 In the **z minimum** text field, type 0.
- 9 In the **z maximum** text field, type 4.