Electrode Utilization in a Large Format Lithium-Ion Battery Pouch Cell

Introduction

Large lithium-ion batteries are widely employed in electric vehicles and for stationary energy storage applications. In the (stacked) pouch battery cell design, all current exits the cell on the cell “tabs”, and as the cell size and power increases, the voltage gradients in the highly conductive metal foil current collectors may come into play, resulting in a nonuniform current distribution and electrode utilization in the cell. A nonuniform utilization results in suboptimal use of the battery electrodes and may also result in nonuniform and accelerated electrode aging.

This tutorial models the current distribution and electrode utilization in a large format lithium-ion battery pouch cell, and how it depends on the cell current.

The model is in 3D. Note that all plots are scaled 100 times in the z direction due to the high aspect ratio of the geometric features.

Model Definition

Figure 1 shows the model geometry. The geometry defines one foil-to-foil unit cell, stacking five layers in the z direction:

- Negative metal current collector foil: 10 µm, Cu (due to symmetry, half of this thickness is used in the model geometry)
- Negative electrode: 60 µm, graphite
- Separator: 30 µm
- Positive electrode: 60 µm, LMO
- Positive metal current collector foil: 10 µm, Al (due to symmetry, half of this thickness is used in the model geometry)
- The electrolyte is LiPF6 in 3:7 EC:EMC
- Symmetry is assumed along the center of the cell

The positive and negative current terminals are located opposite to each other (but may easily be placed on the same side by altering the Geometry node in the model).

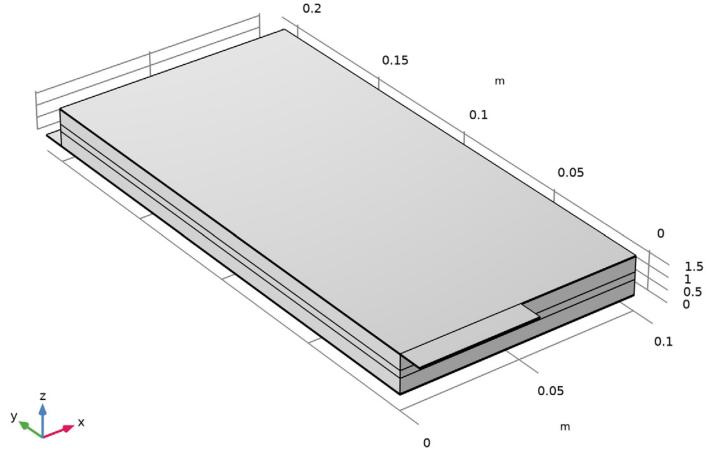


Figure 1: Model geometry, scaled 100 times in the z direction.

The Lithium-Ion Battery interface is used to set up the physics, using Material data from the Battery Material Library.

The Particle Intercalation subnodes to the Porous Electrode nodes model the solid lithium concentration in an additional particle dimension (extra dimension). The model hence defines a fully coupled “pseudo-4D” model.

The battery is charged from 20% to 90% cell state of charge (SOC). The SOC and Initial Cell Charge Distribution node is used to set the initial cell state of charge.

An Electrode Ground boundary condition is used on the negative tab whereas an Electrode Current boundary condition defines the cell current exiting the cell on the positive tab.

A Parametric Sweep is used to solve for two different charge rates (1C and 4C).

Results and Discussion

Figure 2 and Figure 3 show the potential distribution in the negative and positive metal foils (current collector and tab), respectively, at the beginning of the 4C charge. The potential variation is about 5 mV in the negative current collector and 9 mV in the positive current collector at a 4C charge current.

For a 1C charge current the corresponding potential variation is below 2 mV (results not shown here).

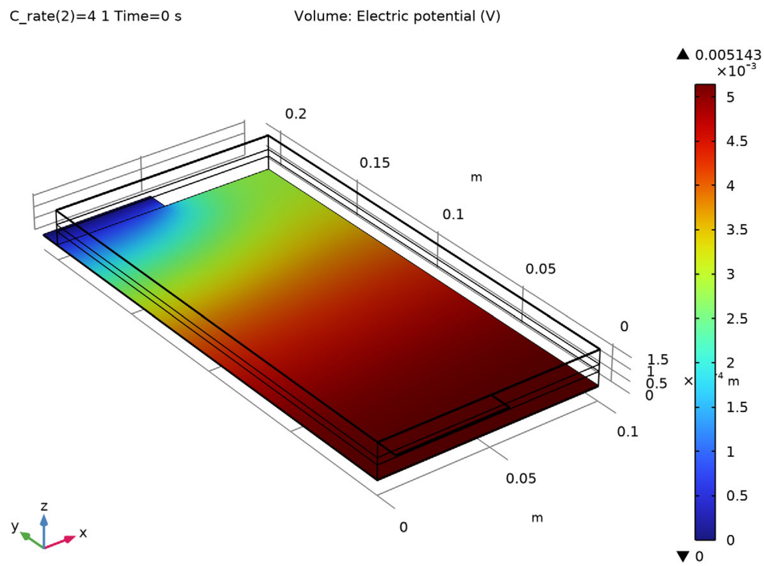


Figure 2: Potential distribution in the negative metal foil (current collector and tab) at the beginning of the 4C charge.

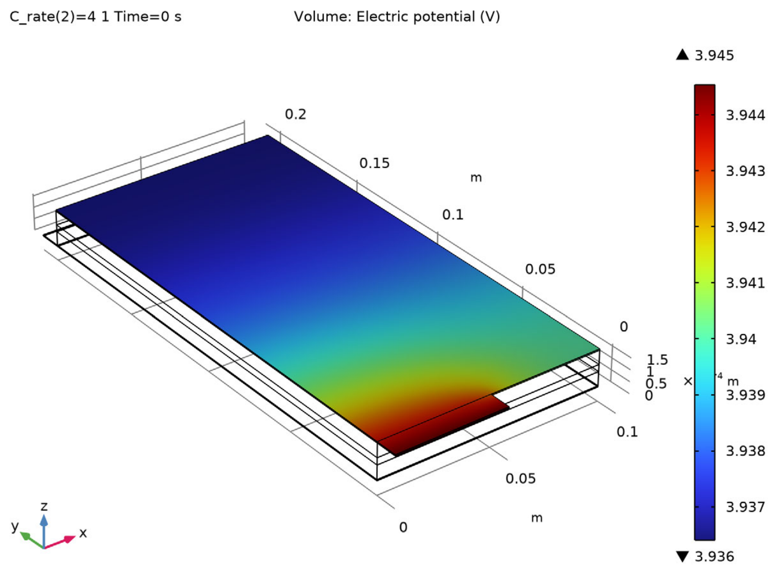


Figure 3: Potential distribution in the positive metal foil (current collector and tab) at the beginning of the 4C charge.

Figure 4 and Figure 5 show the current distribution for a cross section in the middle of the separator at the beginning and end of the 4C charge, respectively. This provides a measure of the electrode utilization for a given time. The current distribution varies about 6% in the separator plane over time. For 1C, the variation is generally smaller (results not shown here). Initially, the separator current density is higher close to the tabs whereas toward the end of the charge, the current density is higher in the central parts of the cell.

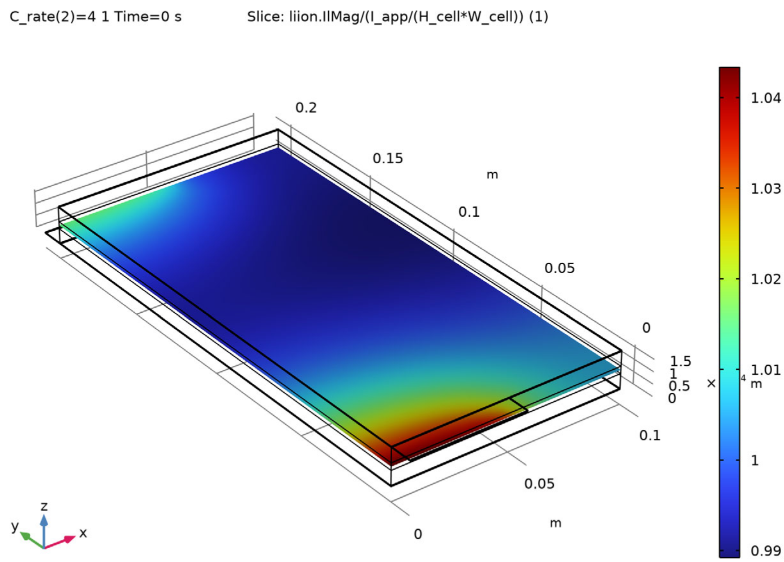


Figure 4: Current distribution in the middle of the separator at the beginning of the 4C charge.

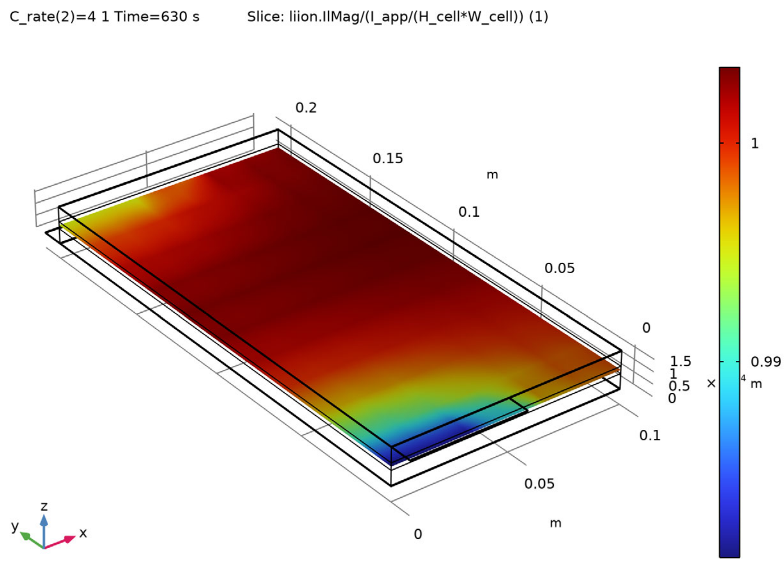


Figure 5: Current distribution in the middle of the separator at the end of the 4C charge.

To get a measure of the relative utilization over the whole charge period, General Projection operators are used to integrate the amount of lithium ($c_{s,avg}$) along the electrode depth (the z direction). Dividing the projected change of intercalated lithium by the average for the whole electrode gives a measure of the relative utilization (capacity throughput) U, as a function of the spatial independent variables x and y, at any time t.

$$U(x, y, t) = \frac{\varepsilon_s F \int_0^{L_{\mathrm{elec}}} (c_{s,\,\mathrm{avg}}(x, y, z, t) - c_{s,\,\mathrm{avg}}(x, y, z, 0))\mathrm{d}z}{\frac{1}{W_{\mathrm{cell}} H_{\mathrm{cell}}} \int_0^t I_{\mathrm{cell}}(t)\mathrm{d}t}$$

Figure 6 and Figure 7 show the relative utilization over the whole charge period for the 1C and 4C charges, respectively for the positive electrode. The utilization varies between 99.5% and 102% for the 4C charge and between 100% and 101% for the 1C charge. The cycle-averaged utilization is lower than the instantaneous utilization shown in Figure 4 and Figure 5.

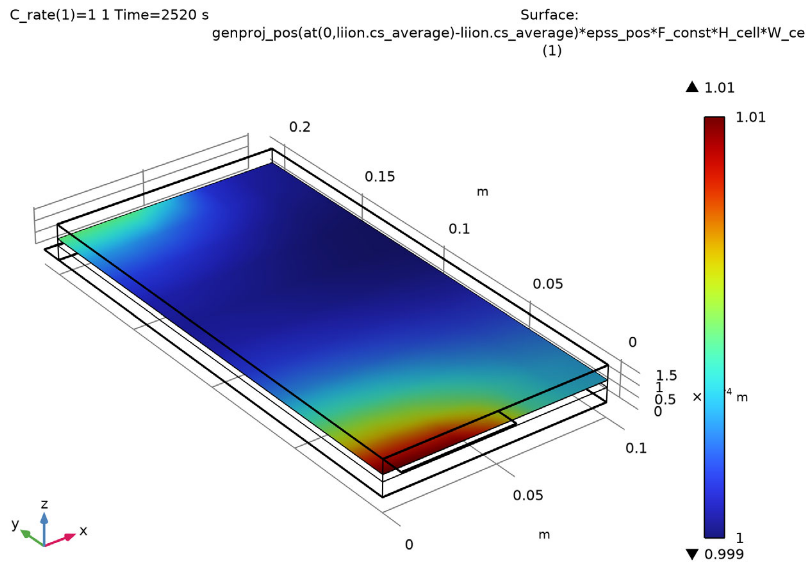


Figure 6: Relative electrode utilization during the 1C charge.

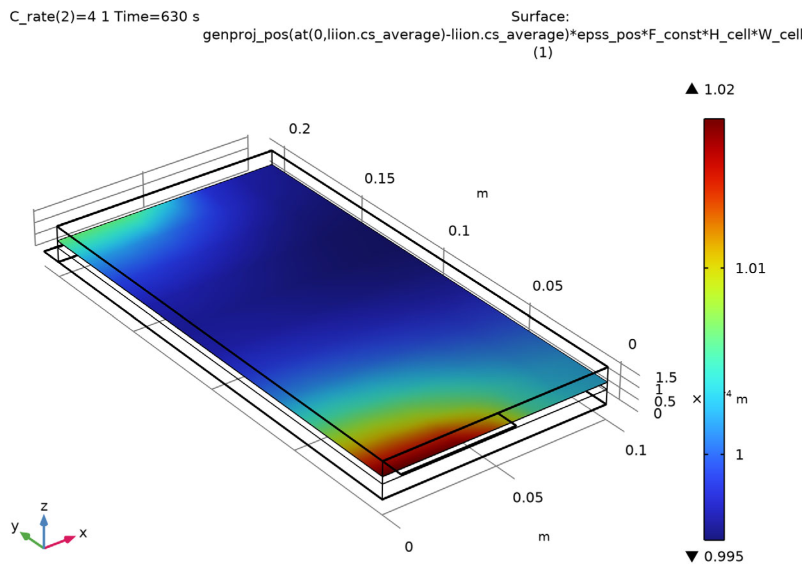


Figure 7: Relative electrode utilization during the 4C charge.

The tutorial demonstrates that the local electrode utilization along the metal foil (current collector and tab) changes over the course of a charge cycle. For this configuration, utilization is fairly uniform during a 1C charge, but a higher charge of 4C results in a slightly nonuniform utilization.

Application Library path: `Battery_Design_Module/Batteries,_Lithium-Ion/pouch_cell_utilization`

Modeling Instructions

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

NEW

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

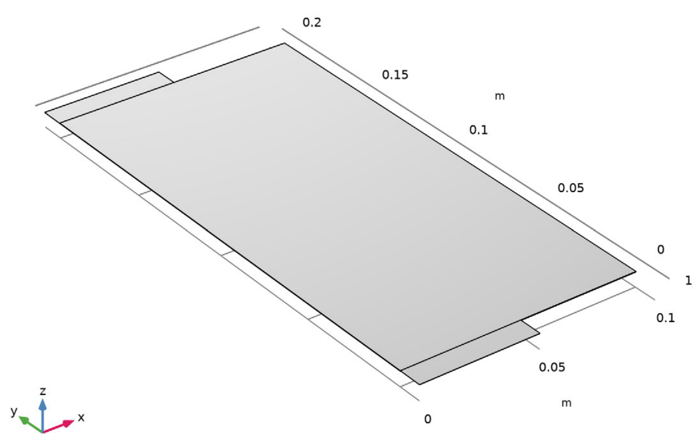
MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **Electrochemistry>Batteries>Lithium-Ion Battery (liion)**.
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**.

GEOMETRY 1

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 `pouch_cell_utilization_geom_sequence.mph`.
3 In the **Geometry** toolbar, click **Build All**.
4 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.



5 In the **Model Builder** window, collapse the **Geometry 1** node.

DEFINITIONS

The cell geometry has a high aspect ratio, with the cell thicknesses being very small in relation to the cross-sectional area. To facilitate setting up the physics, change the scaling in the *z* direction as follows:

View 1

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

Camera

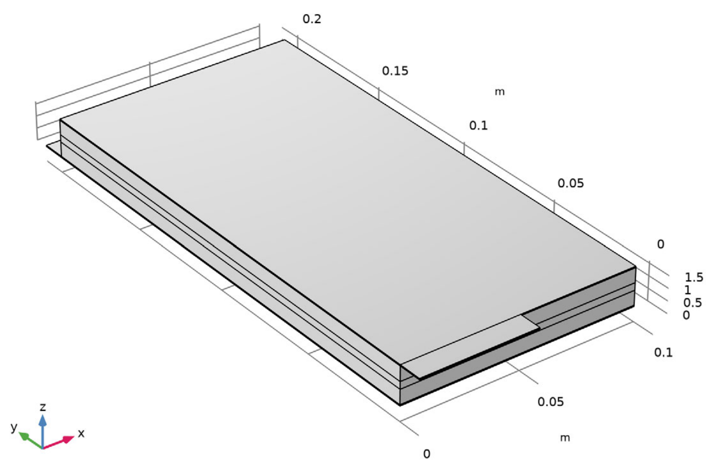
1 In the **Model Builder** window, expand the **View 1** node, then click **Camera**.

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

3 From the **View scale** list, choose **Manual**.

4 In the **z scale** text field, type `100`.

5 Click **Update**.



GLOBAL DEFINITIONS

Geometry Parameters

Some parameters were loaded with the geometry sequence.

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

2 In the **Settings** window for **Parameters**, type `Geometry Parameters` in the **Label** text field.

Physics Parameters

Add some more parameters from a text file.

1. In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.
2. In the **Settings** window for **Parameters**, type `Physics Parameters` in the **Label** text field.
3. Locate the **Parameters** section. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `pouch_cell_utilization_physics_parameters.txt`.

MATERIALS

Most of the required material parameters are available in the material libraries. First add Copper and Aluminum for the current conductors.

ADD MATERIAL

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** and **Built-in>Copper**.
4. Click **Add to Component** in the window toolbar.

ADD MATERIAL

Next add the material properties for the electrolyte and electrode materials.

1. Go to the **Add Material** window.
2. In the tree, select **Battery>Electrodes>Graphite, LixC6 MCMB (Negative, Li-ion Battery)** and **Battery>Electrodes>LMO, LiMn2O4 Spinel (Positive, Li-ion Battery)**.
3. Click **Add to Component** in the window toolbar.
4. In the tree, select **Battery>Electrolytes>LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery)**.
5. Click **Add to Component** in the window toolbar.
6. In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Aluminum (mat1)

Assign the materials to the corresponding battery domains.

1. In the **Model Builder** window, click **Aluminum (mat1)**.
2. In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Positive Current Collector and Tab**.

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 **Negative Current Collector and Tab**.

Graphite, LixC6 MCMB (Negative, Li-ion Battery) (mat3)

1 In the **Model Builder** window, click **Graphite, LixC6 MCMB (Negative, Li-ion Battery) (mat3)**.

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

3 From the **Selection** list, choose **Negative Electrode**.

LMO, LiMn2O4 Spinel (Positive, Li-ion Battery) (mat4)

1 In the **Model Builder** window, click **LMO, LiMn2O4 Spinel (Positive, Li-ion Battery) (mat4)**.

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

3 From the **Selection** list, choose **Positive Electrode**.

LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery) (mat5)

1 In the **Model Builder** window, click **LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery) (mat5)**.

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

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

LITHIUM-ION BATTERY (LIION)

Porous Electrode - Negative

The **Separator** node was added to the interface by default. Keep the default settings for the **Separator**, and proceed to add and set up the physics in the porous electrodes and current collectors.

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Lithium-Ion Battery (liion)** and choose **Porous Electrode**.

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

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Negative Electrode**.

4 Locate the **Electrolyte Properties** section. From the **Electrolyte material** list, choose **LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery) (mat5)**.

5 Locate the **Electrode Properties** section. In the σ_s text field, type `sigmas_neg`.

6 Locate the **Porous Matrix Properties** section. In the ε_s text field, type `epss_neg`.

7 In the ε_l text field, type `1-epss_neg`.

Particle Intercalation 1

Leave the settings of the **Species Settings** section as is for now. The initial species concentration setting will be made inactive later when we define the cell state of charge (SOC) on a different node.

1 In the **Model Builder** window, click **Particle Intercalation 1**.

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

3 In the r_p text field, type `rp_neg`.

Porous Electrode Reaction 1

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

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

3 In the $i_{0,\mathrm{ref}}(T)$ text field, type `i0ref_neg`.

Porous Electrode - Positive

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

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

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Positive Electrode**.

4 Locate the **Electrolyte Properties** section. From the **Electrolyte material** list, choose **LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery) (mat5)**.

5 Locate the **Electrode Properties** section. In the σ_s text field, type `sigmas_pos`.

6 Locate the **Porous Matrix Properties** section. In the ε_s text field, type `epss_pos`.

7 In the ε_l text field, type `1-epss_pos`.

Particle Intercalation 1

1 In the **Model Builder** window, click **Particle Intercalation 1**.

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

3 In the r_p text field, type `rp_pos`.

Porous Electrode Reaction 1

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

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

3 In the $i_{0,\mathrm{ref}}(T)$ text field, type `i0ref_pos`.

Current Conductor 1

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

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

3 From the **Selection** list, choose **Metal Foil 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 **Negative Tab End**.

Enable the **Define cell state of charge (SOC) and initial charge inventory** on the interface top node. This will allow us to set the initial SOC of the battery cell.

4 In the **Model Builder** window, click **Lithium-Ion Battery (liion)**.

5 In the **Settings** window for **Lithium-Ion Battery**, locate the **Cell Settings** section.

6 Select the **Define cell state of charge (SOC) and initial charge inventory** check box.

SOC and Initial Charge Distribution 1

1 In the **Model Builder** window, click **SOC and Initial Charge Distribution 1**.

2 In the **Settings** window for **SOC and Initial Charge Distribution**, locate the **Initial Cell Charge Distribution** section.

3 In the SOC_0 text field, type `SOC_start`.

Negative Electrode Selection 1

1 In the **Model Builder** window, click **Negative Electrode Selection 1**.

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

3 From the **Selection** list, choose **Negative Electrode**.

Positive Electrode Selection 1

1 In the **Model Builder** window, click **Positive Electrode Selection 1**.

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

3 From the **Selection** list, choose **Positive Electrode**.

DEFINITIONS (COMP1)

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.

An internal 1C current variable (`liion.I_1C_cell`), based on the cyclable lithium capacity, is computed automatically by the **SOC and Initial Charge Distribution** node. Use this variable to set up a variable for the applied C rate current.

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
I_app	liion.I_1C_cell*C_rate	A	Applied current

LITHIUM-ION BATTERY (LIION)

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 **Positive Tab End**.

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

MESH 1

Set up the mesh for the model. Use a mapped mesh on the top boundaries, and a swept mesh for remaining of the geometry.

Mapped 1

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

2 Select Boundary 20 only.

Swept 1

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

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

3 Click to clear the **Activate Selection** toggle button.

Distribution 1

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

By the use of **Distribution** nodes you can control the resolution in the *z* direction of the individual layers of the cell.

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

3 From the **Selection** list, choose **Negative Electrode**.

4 Locate the **Distribution** section. From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 15.

6 In the **Element ratio** text field, type 3.

Distribution 2

1 In the **Model Builder** window, right-click **Swept 1** and choose **Distribution**.

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

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

4 Locate the **Distribution** section. In the **Number of elements** text field, type 4.

Distribution 3

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

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

3 From the **Selection** list, choose **Positive Electrode**.

4 Locate the **Distribution** section. From the **Distribution type** list, choose **Predefined**.

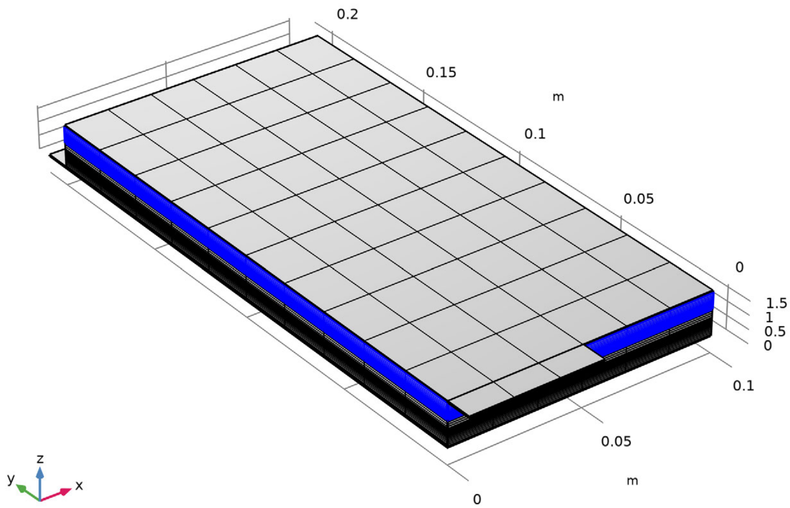
5 In the **Number of elements** text field, type 15.

6 In the **Element ratio** text field, type 3.

7 Select the **Reverse direction** check box.

8 Click **Build All**.

The finalized mesh should now look as follows.



DEFINITIONS (COMP1)

Before solving, add also a probe for an automatically defined voltage variable created by the **Electrode Current** condition at the positive tab. Since the negative tab is grounded, this voltage corresponds to the cell voltage. The probe will store the cell voltage for every time step taken by the solver in a table, and a dynamically updated plot of the cell voltage will also be available while solving.

Cell Voltage Probe

1 In the **Definitions** toolbar, click **Probes** and choose **Global Variable Probe**.

2 In the **Settings** window for **Global Variable Probe**, type `Cell Voltage Probe` in the **Label** text field.

3 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Lithium-Ion Battery>liion.phis0_ec1 - Electric potential on boundary - V**.

4 Locate the **Expression** section.

5 Select the **Description** check box. In the associated text field, type `Cell Voltage`.

STUDY 1

Use a **Parametric Sweep** to solve for two different C rates.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
C_rate (C-rate during simulation)	1 4	1

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,sim_time/2,sim_time)`.

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

RESULTS

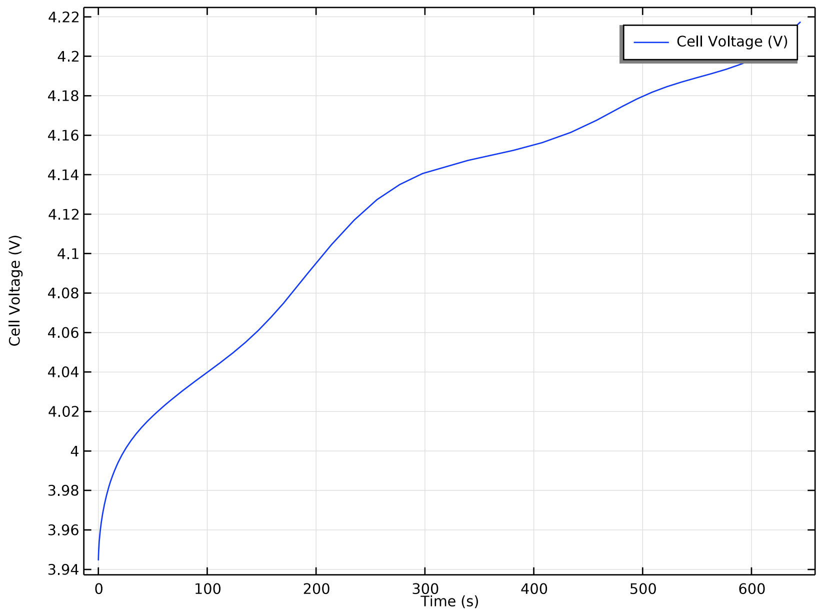
A plot of the battery voltage vs time is created automatically by the probe you added earlier.

Cell Voltage Probe Plot

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

2 In the **Settings** window for **1D Plot Group**, type `Cell Voltage Probe Plot` in the **Label** text field.

3 In the **Cell Voltage Probe Plot** toolbar, click **Plot**.



Potential in Negative Current Collector and Tab

The following steps create a plot of the potential at the negative current collector and tab.

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

2 In the **Settings** window for **3D Plot Group**, type `Potential in Negative Current Collector and Tab` in the **Label** text field.

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

4 From the **Time (s)** list, choose **0**.

5 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

6 Click to expand the **Number Format** section. Select the **Manual color legend settings** check box.

7 In the **Precision** text field, type `4`.

Volume 1

1 Right-click **Potential in Negative Current Collector and Tab** and choose **Volume**.

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

3 In the **Expression** text field, type `phis`.

Selection 1

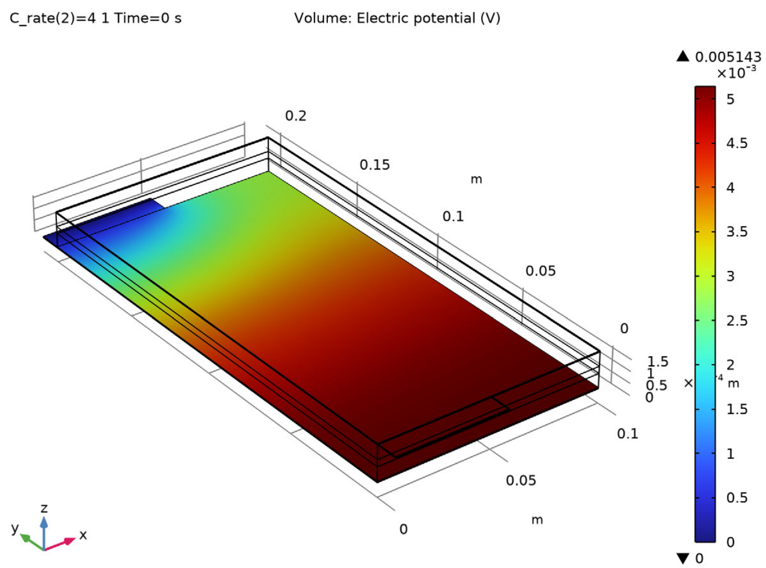
1 Right-click **Volume 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Negative Current Collector and Tab**.

4 In the **Potential in Negative Current Collector and Tab** toolbar, click **Plot**.

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



Potential in Negative Current Collector and Tab

Duplicate the plot and modify the copy in order to view the potential at the positive current collector and tab.

In the **Model Builder** window, under **Results** right-click **Potential in Negative Current Collector and Tab** and choose **Duplicate**.

Potential in Positive Current Collector and Tab

1 In the **Model Builder** window, under **Results** click **Potential in Negative Current Collector and Tab 1**.

2 In the **Settings** window for **3D Plot Group**, type `Potential in Positive Current Collector and Tab` in the **Label** text field.

3 In the **Model Builder** window, expand the **Potential in Positive Current Collector and Tab** node.

Selection 1

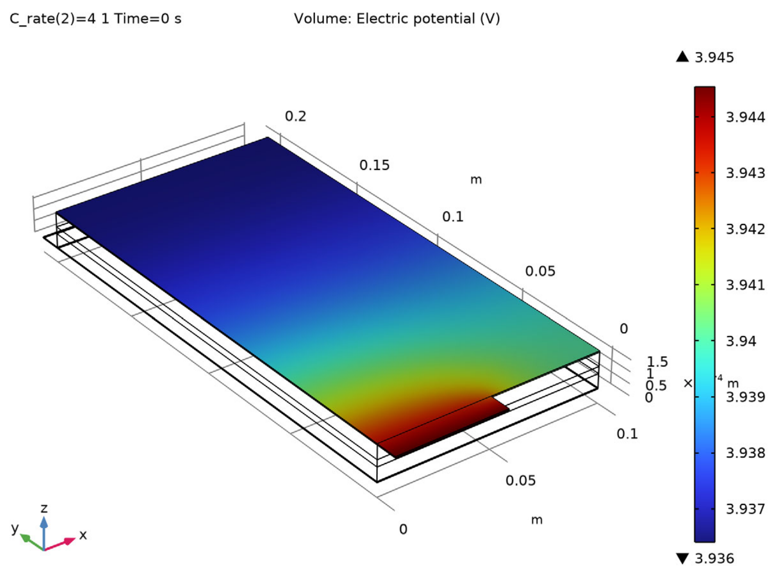
1 In the **Model Builder** window, expand the **Results> Potential in Positive Current Collector and Tab>Volume 1** node, then click **Selection 1**.

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

3 From the **Selection** list, choose **Positive Current Collector and Tab**.

4 In the **Potential in Positive Current Collector and Tab** toolbar, click **Plot**.

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



Relative Current Density Across Separator

Plot the relative current density across the separator using a slice plot.

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

2 In the **Settings** window for **3D Plot Group**, type `Relative Current Density Across Separator` in the **Label** text field.

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

4 From the **Time (s)** list, choose **0**.

Slice 1

1 Right-click **Relative Current Density Across Separator** and choose **Slice**.

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

3 In the **Expression** text field, type `liion.IlMag/(I_app/(H_cell*W_cell))`.

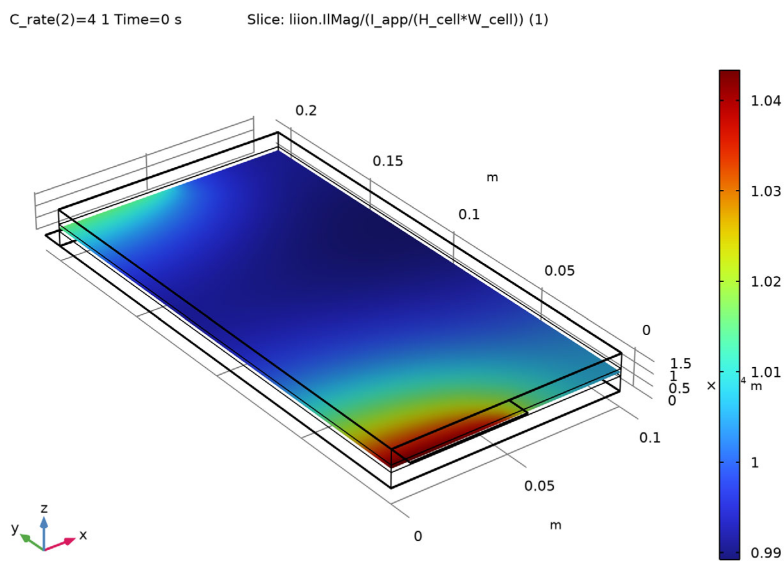
4 Locate the **Plane Data** section. From the **Plane** list, choose **XY-planes**.

5 From the **Entry method** list, choose **Coordinates**.

6 In the **Z-coordinates** text field, type `L_neg_cc/2+L_neg+L_sep/2`.

7 In the **Relative Current Density Across Separator** toolbar, click **Plot**.

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



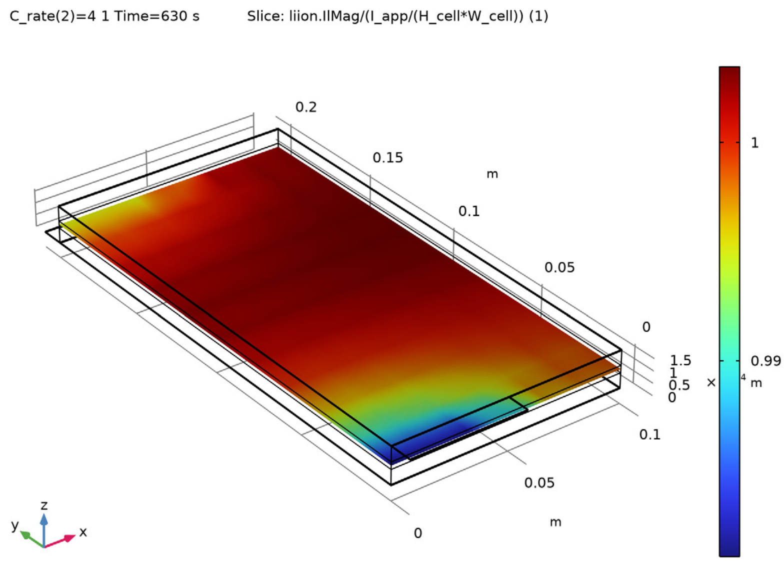
Relative Current Density Across Separator

1 In the **Model Builder** window, click **Relative Current Density Across Separator**.

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

3 From the **Time (s)** list, choose **630**.

4 In the **Relative Current Density Across Separator** toolbar, click **Plot**.



DEFINITIONS (COMP1)

As a final step we will evaluate the relative utilization of the electrodes during the whole charge.

First add two **General Projection** operators that will be used to integrate the amount of lithium along the electrode depth (the *z* direction).

General Projection - Negative

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

2 In the **Settings** window for **General Projection**, type `General Projection - Negative` in the **Label** text field.

3 In the **Operator name** text field, type `genproj_neg`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Negative Electrode**.

5 Right-click **General Projection - Negative** and choose **Duplicate**.

General Projection - Positive

1 In the **Model Builder** window, under **Component 1 (comp1)>Definitions** click **General Projection - Negative 1 (genproj_neg2)**.

2 In the **Settings** window for **General Projection**, type `General Projection - Positive` in the **Label** text field.

3 In the **Operator name** text field, type `genproj_pos`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Positive Electrode**.

STUDY 1

In order to make the operators available in the solution, you need to update the solution.

In the **Study** toolbar, click **Update Solution**.

RESULTS

Utilization (Relative Capacity Throughput)

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

2 In the **Settings** window for **3D Plot Group**, type `Utilization (Relative Capacity Throughput)` in the **Label** text field.

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

4 From the **Parameter value (C_rate)** list, choose **1**.

5 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

Surface 1

1 Right-click **Utilization (Relative Capacity Throughput)** and choose **Surface**.

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

3 In the **Expression** text field, type `genproj_pos(at(0,liion.cs_average)-liion.cs_average)*epss_pos*F_const*H_cell*W_cell/(I_app*t)`.

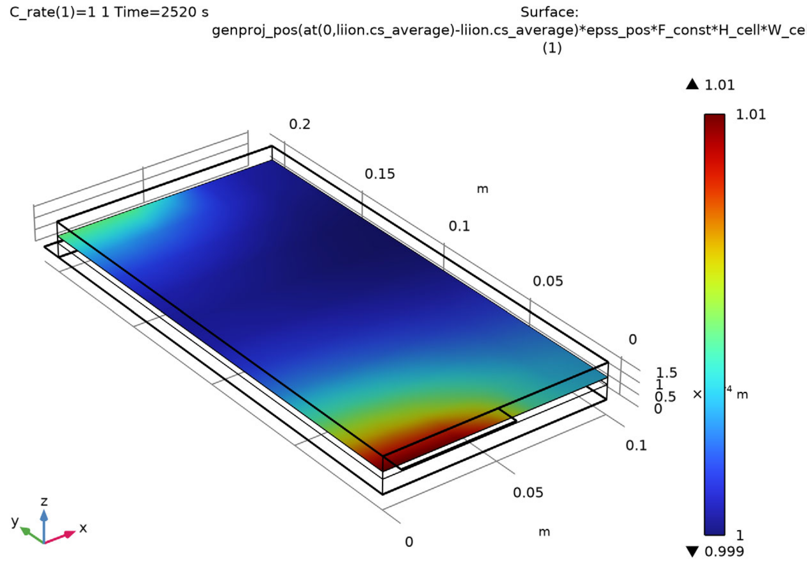
Selection 1

1 Right-click **Surface 1** and choose **Selection**.

2 Select Boundary 16 only.

3 In the **Utilization (Relative Capacity Throughput)** toolbar, click **Plot**.

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



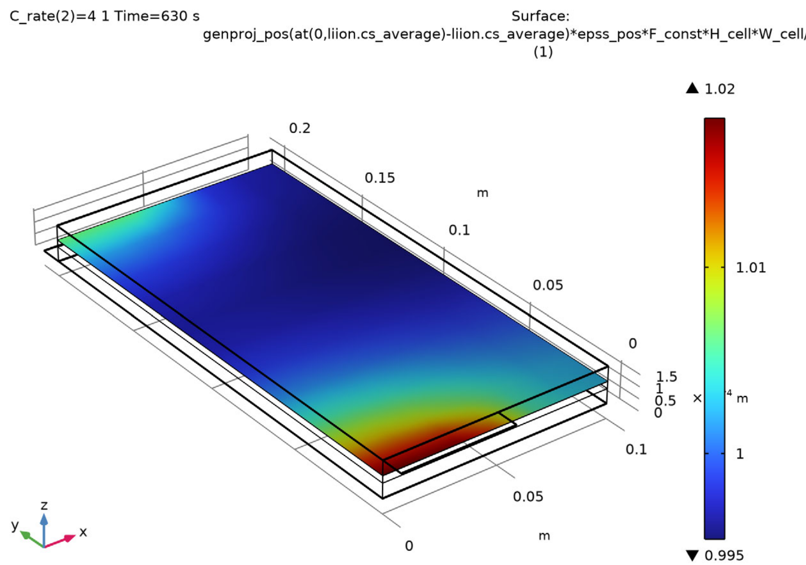
Utilization (Relative Capacity Throughput)

1 In the **Model Builder** window, under **Results** click **Utilization (Relative Capacity Throughput)**.

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

3 From the **Parameter value (C_rate)** list, choose **4**.

4 In the **Utilization (Relative Capacity Throughput)** toolbar, click **Plot**.



Appendix - Geometry 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 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

Import the parameter file.

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 `pouch_cell_utilization_geometry_parameters.txt`.

GEOMETRY 1

Set up the model geometry using the following steps.

Work Plane 1 (wp1)

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

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 `W_cell`.

4 In the **Height** text field, type `H_cell`.

Extrude 1 (ext1)

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

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
L_neg_cc/2
L_neg_cc/2+L_neg
L_neg_cc/2+L_neg+L_sep
L_neg_cc/2+L_neg+L_sep+L_pos
L_neg_cc/2+L_neg+L_sep+L_pos+L_pos_cc/2

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 `W_tab`.

4 In the **Depth** text field, type `H_tab`.

5 In the **Height** text field, type `L_neg_cc/2`.

6 Locate the **Position** section. In the **y** text field, type `H_cell`.

7 Click **Build Selected**.

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

Block 2 (blk2)

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 `W_tab`.

4 In the **Depth** text field, type `H_tab`.

5 In the **Height** text field, type `L_neg_cc/2`.

6 Locate the **Position** section. In the **y** text field, type `-H_tab`.

7 In the **z** text field, type `L_neg_cc/2+L_neg+L_sep+L_pos`.

8 Click **Build Selected**.

Form Union (fin)

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

DEFINITIONS

Scale the geometry in the *z* direction to make it easier to see the different layers in the model geometry.

View 1

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

Camera

1 In the **Model Builder** window, expand the **View 1** node, then click **Camera**.

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

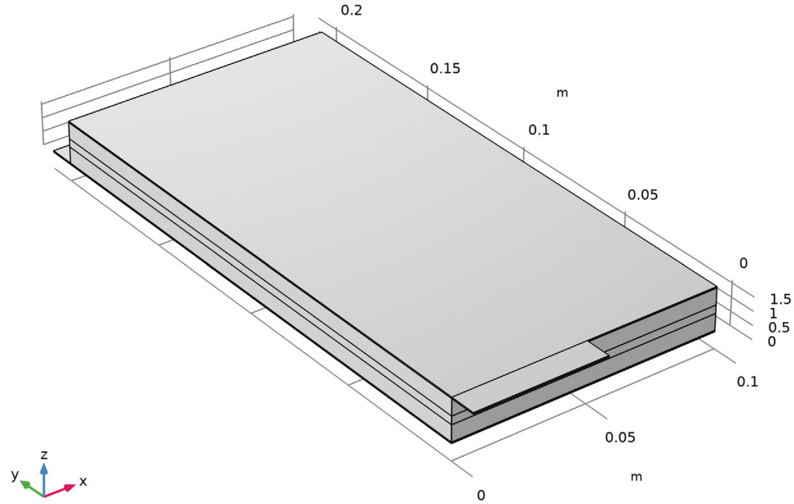
3 From the **View scale** list, choose **Manual**.

4 In the **z scale** text field, type `100`.

5 Click **Update**.

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

The finalized geometry should now look like as follows.



GEOMETRY 1

Create named selections of the different battery domains for ease of selection later in the model.

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

Positive Tab

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 In the **Settings** window for **Explicit Selection**, type `Positive Tab` in the **Label** text field.
3 On the object **fin**, select Domain 1 only.

Positive Current Collector

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 In the **Settings** window for **Explicit Selection**, type `Positive Current Collector` in the **Label** text field.
3 On the object **fin**, select Domain 6 only.

Positive Electrode

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

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

3 On the object **fin**, select Domain 5 only.

Negative Tab

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

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

3 On the object **fin**, select Domain 7 only.

Negative Current Collector

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

2 In the **Settings** window for **Explicit Selection**, type `Negative Current Collector` in the **Label** text field.

3 On the object **fin**, select Domain 2 only.

Negative Electrode

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

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

3 On the object **fin**, select Domain 3 only.

Separator

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

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

3 On the object **fin**, select Domain 4 only.

Negative Tab End

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

2 In the **Settings** window for **Explicit Selection**, type `Negative Tab End` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 Click the **Paste Selection** button for **Entities to select**.

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

6 Click **OK**.

Positive Tab End

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

2 In the **Settings** window for **Explicit Selection**, type `Positive Tab End` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 Click the **Paste Selection** button for **Entities to select**.

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

6 Click **OK**.

Negative Current Collector and Tab

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

2 In the **Settings** window for **Union Selection**, type `Negative Current Collector and Tab` in the **Label** text field.

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

4 In the **Add** dialog box, in the **Selections to add** list, choose **Negative Tab** and **Negative Current Collector**.

5 Click **OK**.

Positive Current Collector and Tab

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

2 In the **Settings** window for **Union Selection**, type `Positive Current Collector and Tab` in the **Label** text field.

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

4 In the **Add** dialog box, in the **Selections to add** list, choose **Positive Tab** and **Positive Current Collector**.

5 Click **OK**.

Metal Foil Domains

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

2 In the **Settings** window for **Union Selection**, type `Metal Foil Domains` in the **Label** text field.

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

4 In the **Add** dialog box, in the **Selections to add** list, choose **Negative Current Collector and Tab** and **Positive Current Collector and Tab**.

5 Click **OK**.