Evaluate Safety of a Li-ion Battery in Water Immersion Scenarios Using AutoLion™

Introduction

The water immersion test is part of the SAE certification process for battery packs. This test involves submerging a battery pack in a salt water solution, which creates an external short due to the salinity of the water (electronically conductive). As the salinity of the water is inversely proportional to the shorting resistance, in this case study, we show the effect of short resistance on shorting behavior. We additionally simulate the temperature rise of the water bath during immersion short. To somewhat simplify the problem we have shorted one cell; however, the water immersion test of an entire pack can be performed with AutoLion-ST™ software.

Technology Used

- AutoLion-ST™

Setup

- A 16 Ah NMC/graphite energy cell (180 Wh/kg at 1C/25°C) is designed using the AutoLion-ST™ GUI; standard material database values for all properties are utilized.
- An energy balance for the water bath was developed in the Simulink workspace and coupled to the Li-ion battery, as represented by AutoLion-ST™. Both natural convection and insulated water tub conditions were simulated.
- For simplicity, a single cell is simulated in this water immersion test. However, multiple cell packs can be simulated using AutoLion-ST™.
- The salt water short resistance of 0.84 Ω (baseline value for the case study) corresponds to approx. 2.5%-3% water salinity.
- In this case study, we simulate two different aspects of the water bath and the resultant effects on the response of the Li-ion battery: (1) the volume of the water bath used, and (2) the boundary condition between the water tub and the ambient. The water bath volume is described by γ, which is defined as the ratio of water bath volume to cell volume, i.e. γ = V_{WaterBath}/V_{cell}.
- In all simulations, the ambient and initial temperature is 25°C.

Results

<table>
<thead>
<tr>
<th>R (Ω)</th>
<th>T_{max} (°C)</th>
<th>t_{discharge} (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24</td>
<td>91.2</td>
<td>1.1</td>
</tr>
<tr>
<td>0.84</td>
<td>48</td>
<td>3.7</td>
</tr>
<tr>
<td>2.52</td>
<td>33.4</td>
<td>11.1</td>
</tr>
<tr>
<td>4.2</td>
<td>30.4</td>
<td>18.5</td>
</tr>
</tbody>
</table>

In the external short resistance simulation (not immersion) carried out in figure 6, there is natural convection (h = 10 W/m²/K) to ambient air and no heat transfer from the I²R external short back to the cell.

Figure 1: Cell Temperature vs. time for natural convection between water tub and ambient; R = 0.84 Ω; γ = V_{WaterBath}/V_{cell}; dashed lines are water bath mean temperature, solid lines are battery mean temperature.
**Figure 2**: Cell Temperature vs. time for **insulated** water tub; $R = 0.84 \, \Omega$; $\gamma = V_{\text{Water Bath}}/V_{\text{cell}}$; dashed lines are water bath mean temperature, solid lines are battery mean temperature.

**Figure 3**: Cell voltage vs. time for natural convection between water tub and ambient; $R = 0.84 \, \Omega$; $\gamma = V_{\text{Water Bath}}/V_{\text{cell}}$.

**Figure 4**: Heat sources in water bath and cell; $R = 0.84 \, \Omega$, natural convection, $\gamma = V_{\text{Water Bath}}/V_{\text{cell}} = 1$.

**Figure 5**: Ratio of heat sources in water bath to cell; $R = 0.84 \, \Omega$, natural convection, $\gamma = V_{\text{Water Bath}}/V_{\text{cell}} = 1$.

**Figure 6**: Cell temperature vs. time for immersion test (insulated bath tub and natural convection between tub and ambient) and external short of cell with no heat transfer from short to cell; $R = 0.84 \, \Omega$; $\gamma = V_{\text{Water Bath}}/V_{\text{cell}}$.

**Analysis, Conclusions, and Benefits**

- Figure 6 shows the **radical difference between the temperature rise of the cell in salt water immersion versus an external short with the same resistance**, where none of the FR external heat source is transferred back to the cell. The temperature rise in the externally shorted cell is only a few degrees over the short duration, while there is ~ 20°C temperature rise for the immersion with natural convection to ambient, and boiling conditions are reached for the immersion with insulated tub. Physically, as outlined in detail below, the much greater temperature rise during the immersion test is due to tremendous FR direct
heating of the water. This figure also illustrates that the external short of a cell in a laboratory setting is not representative of a cell that is immersed in a salt water bath.

- As highlighted in figures 4 and 5, a substantially larger (>100x) heat source is generated in the water via $\dot{I}R$ resistance heating than inside the battery via reversible and irreversible heat, under these conditions. This may seem counter-intuitive, but considering the following, this is physically consistent:
  - The cell-internal heat is a sum of the reversible heat and the overpotential due to irreversibilities within the cell. $\Delta S/F$ and the cell overpotential are both $\sim 0.05V$ or less under these conditions.
  - The heat source in the water is $I^2R = V_{cell}I$. Under these conditions, $V_{cell} \sim 3.7V$, which is orders of magnitude larger than $\sim 0.05V$ due to reversible and irreversible heat within the cell.

- In this case study we have demonstrated three parameters of the water immersion test that have a strong influence on the resultant shorting behavior and safety of the immersed battery:
  - Salinity of the water (or short resistance) – controls the discharge/shorting time of the battery in salt water and thereby indirectly influences the maximum temperature experienced by the battery and water bath during short.
  - Volume of water used during test – larger water volume is equivalent with larger thermal mass, and particularly in the case of an insulated bath tub strongly influences the maximum temperature reached (and therefore the safety of the battery).
  - Thermal condition between bath tub and ambient – an insulated tank leads to substantially more dangerous shorting conditions (max temperature up to 2-4x) as compared with tub natural convection with ambient.

- To run all simulations and perform post-processing of results in this case study took < 30 min. AutoLion-ST™ can easily be used to parametrically study the impact of various electrochemical, cell design, and test design parameters (e.g. thermal and salinity factors) in a time efficient manner.