# Battery Entropic Heating Coefficient Testing and Use in Cell-level Loss Modelling for Ultra Fast Charging

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## Introduction

- To achieve accurate losses estimate, it is necessary to consider **reversible entropic losses, which may constitute over 20% of peak total loss**
  - **Modelling of reversible losses requires knowledge of entropic heating coefficient**, which is the rate of change of the cell's OCV with respect to temperature (function of SOC and temperature)
- Entropic heating coefficient determined by exposing cell to range of temperatures at each SOC, OCV is recorded at each point
- Once determined experimentally, **entropic heating coefficient is used to model reversible losses**. The total cell losses are calculated as sum of reversible and irreversible losses

## Model

- Modified **Bernardi heat generation model** [1] for **reversible** and **irreversible** losses:

$$\dot{Q}_{rev} = -I\,T\left(\frac{\partial OCV}{\partial T}\right),$$

where $\partial OCV/\partial T$ is the entropic heating coefficient, and

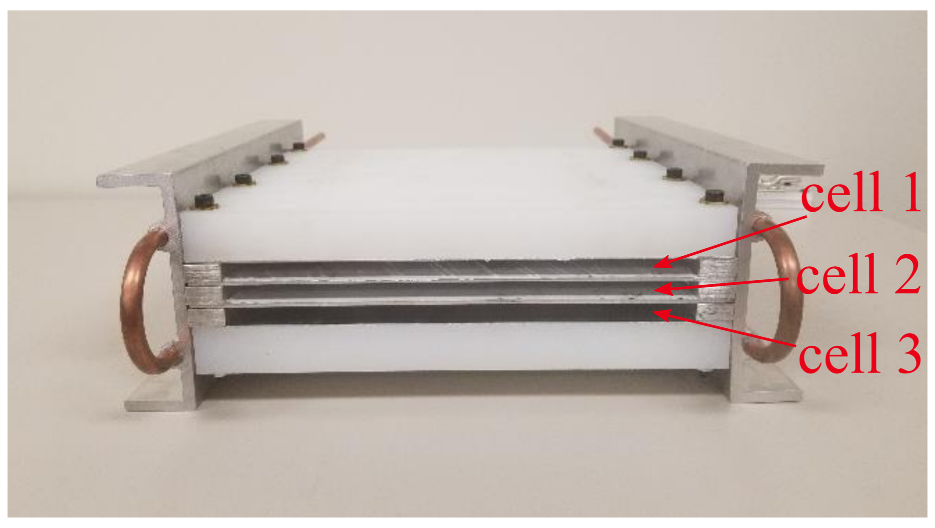
$$\dot{Q}_{irrev} = I\,(OCV - V_T)$$

The total cell loss is given by the sum of the two components

$$\dot{Q}_{total} = \dot{Q}_{rev} + \dot{Q}_{irrev}$$

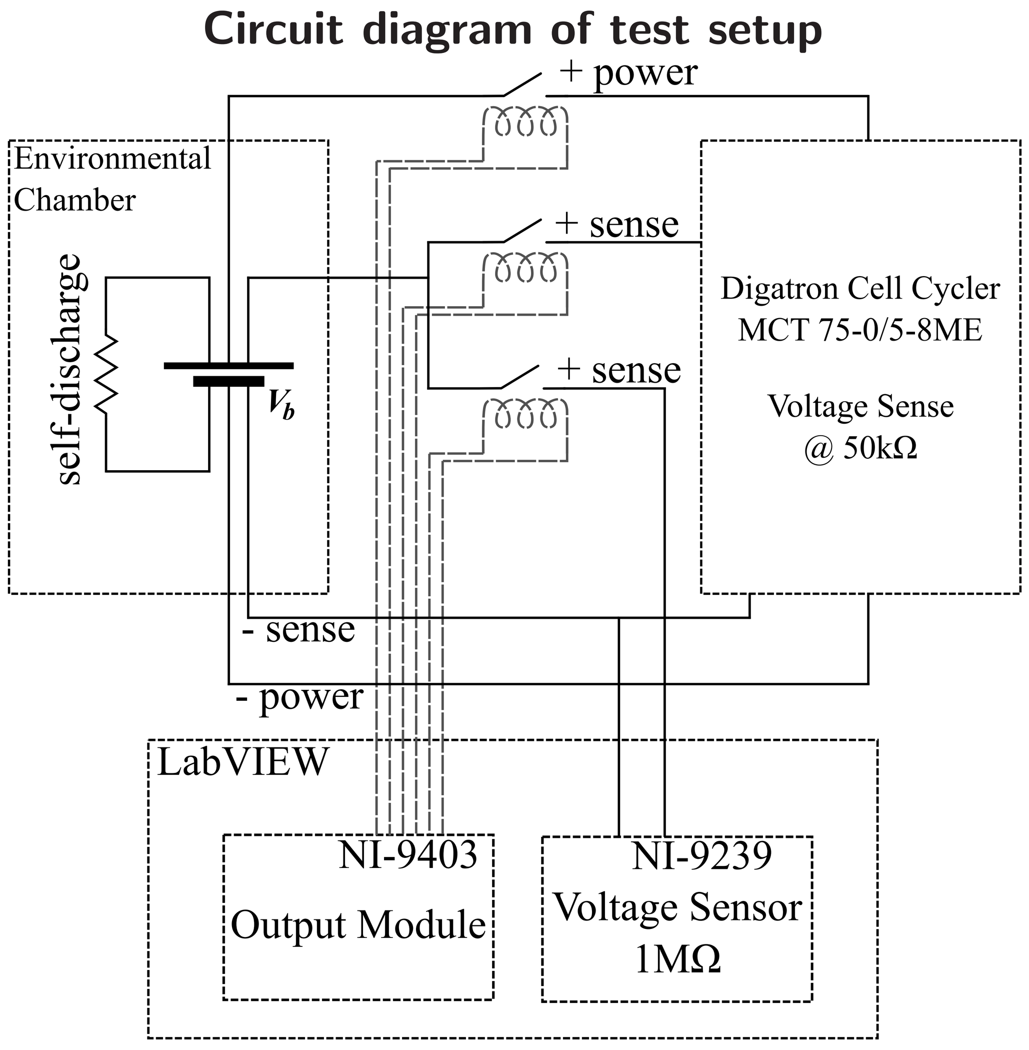
## Test Apparatus

### 3P1S Fast Charge Test Fixture




- Fixture is liquid-cooled, allowing the study of higher charge rates

### Circuit diagram of test setup

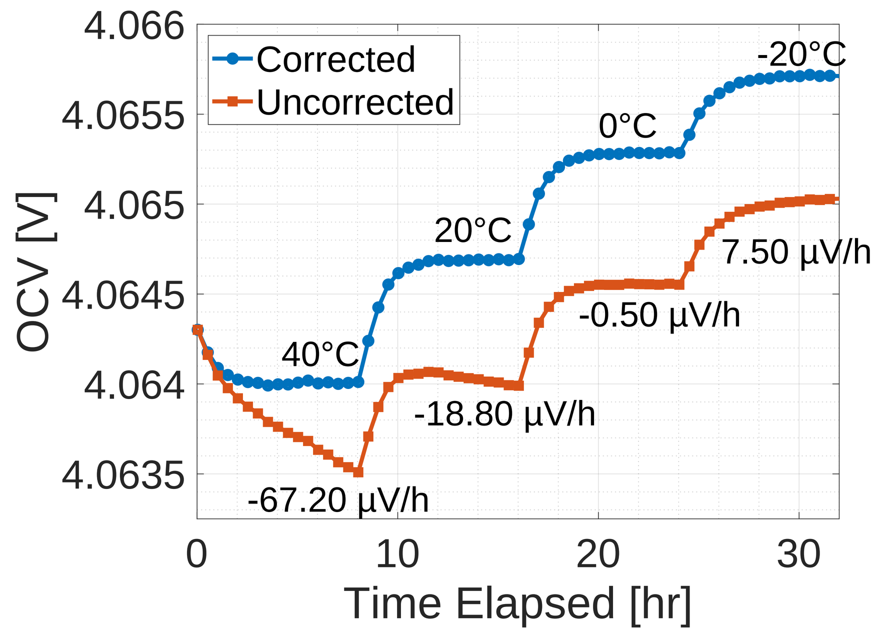



- A $\Delta T$ of 20 °C can result in a $\Delta OCV$ of 100 µV or less, so a high accuracy and high input impedance voltage sensor is critical
  - Voltage sensing and power leads connected periodically to monitor cell voltage while avoiding discharge through sensor and testing equipment

## Correction of Measured Voltage

- **self-discharge** and **voltage relaxation** produce measurable decrease in OCV over the test

### Voltage correction (example at 90% SOC)

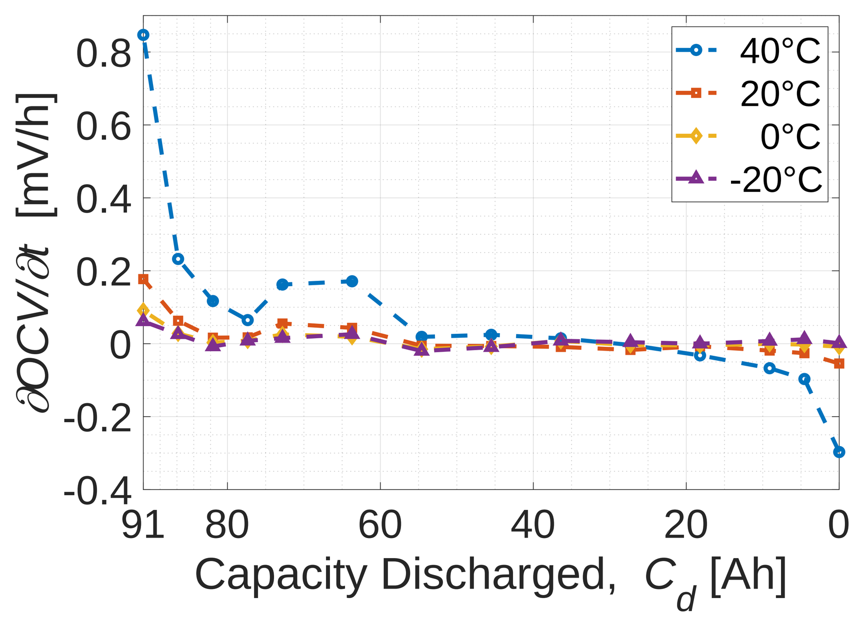



- Voltage measurement corrected by applying a cumulative, time-based correction factor to raw value:

$$OCV_{corr}(k) = OCV_{meas}(k) - \sum_{N=0}^{k}\left(\frac{\partial OCV}{\partial t}\right)_k (t_k - t_{k-1})$$

- Corrected OCV varies only with SOC and temperature

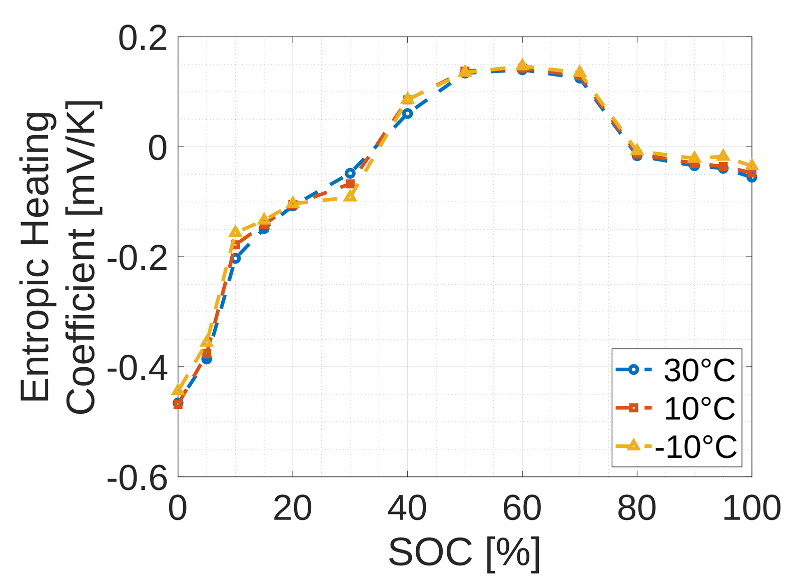
### Voltage correction factor map




- Effect is more pronounced at elevated temperature:

## Results

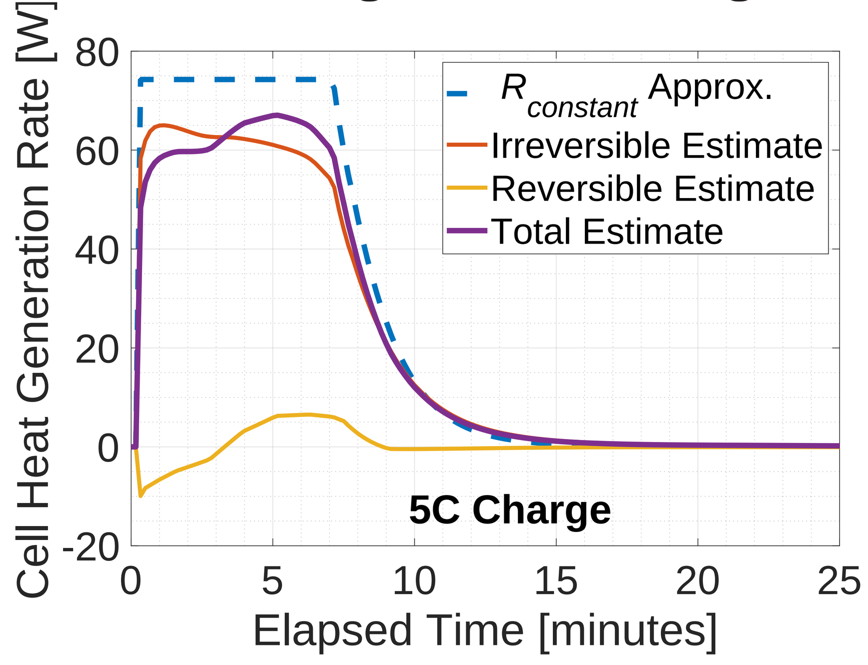
### Entropic Heating Coefficient Map



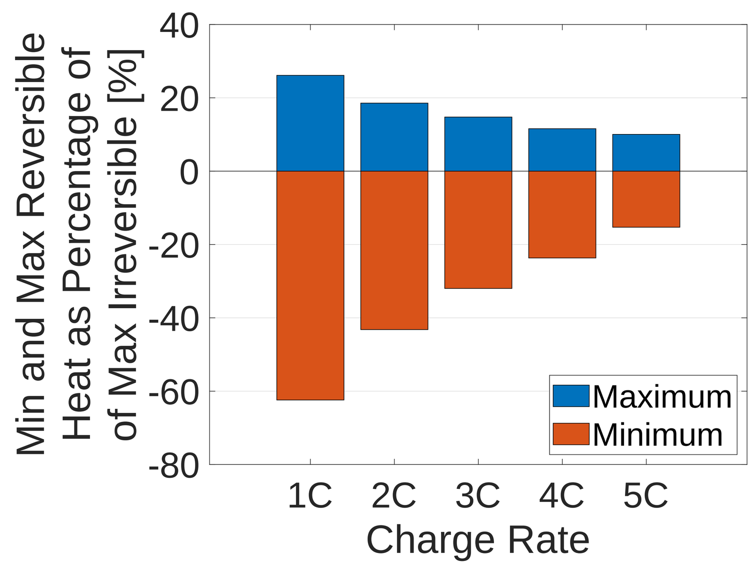

- Areas of negative coefficient lead to endothermic reversible reaction during charging

## Loss Modelling

### Modelling of 5C-rate charge

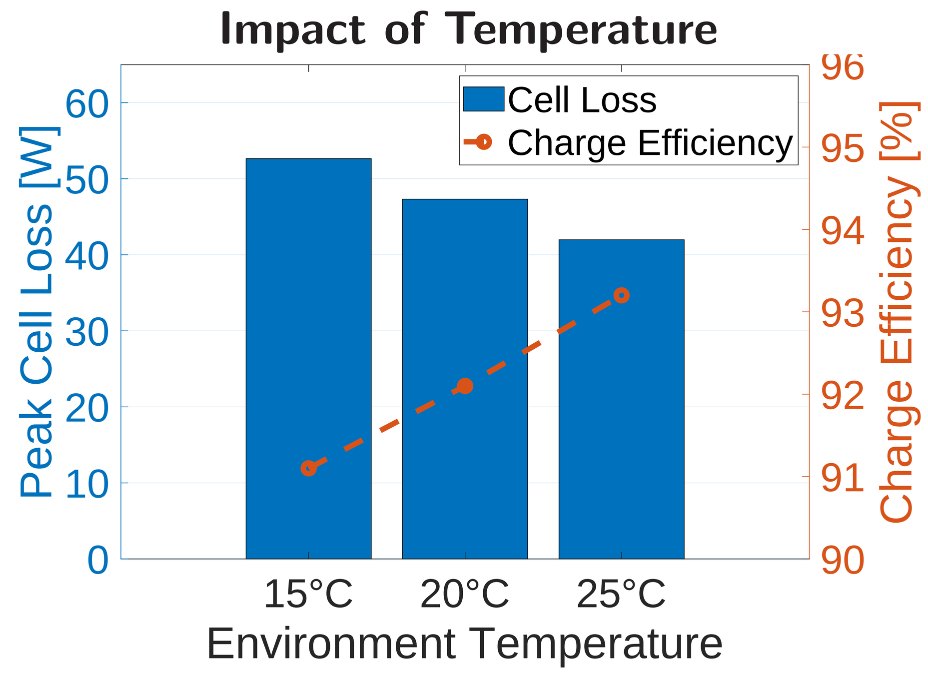



### Reversible Heating Contribution

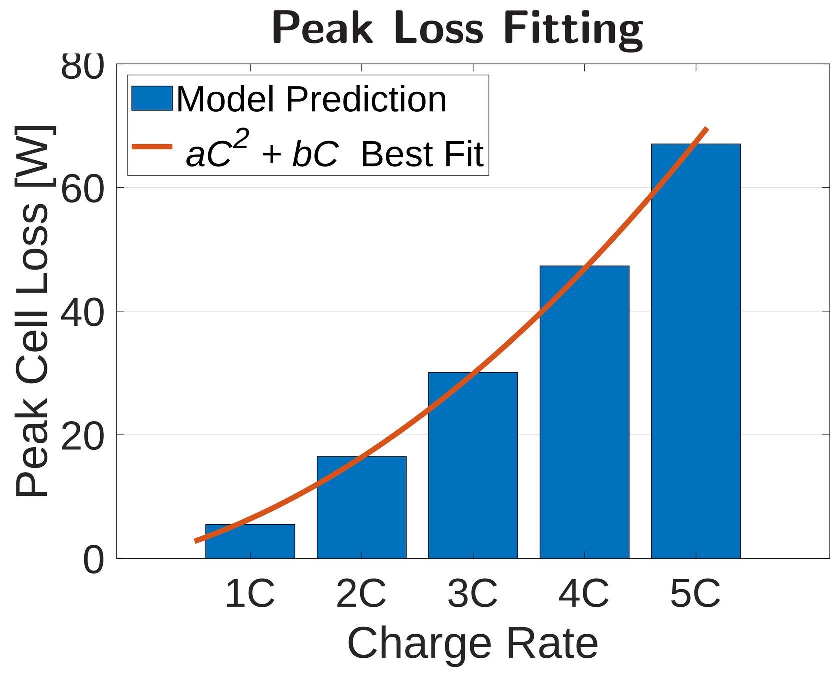



- Reversible heat most significant at lower charge rates, but **effect is still significant even at 5C**

### Impact of Temperature




### Peak Loss Fitting




- Fit coefficients $a$ and $b$ have values of 1.8W/1C$^2$ and 4.7W/1C, respectively
- **Accurate fitting requires a term linear with charge rate**, represents reversible losses

## Summary and Future Work

- Entropic heating coefficient determined experimentally and used to model reversible heat generation during charging. **High charge rates, temperature effects investigated.**
  - Self-discharge and voltage relaxation corrected following testing to isolate for SOC and temperature dependence.
- **Test time can be reduced by testing multiple, identical cells in parallel**, and by minimizing thermal mass of fixture. **Validation likely requires use of a calorimeter**.

[1] Bernardi, D., E. Pawlikowski, and John Newman. "A general energy balance for battery systems." *Journal of the electrochemical society* 132.1 (1985): 5-12.

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