Work Package 1
Chemical Energy Storage Systems
Batteries and Supercapacitors

Monica Marinescu, Gregory Offer, David Howey,
Ricardo Martinez-Botas, Nigel Brandon

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Imperial College
London

FUTUREVehicles

WP1.1 Goal

Models to describe and predict failure and ageing of Batteries and Supercapacitors

$\rightarrow$ **diagnosis** - through parameter estimation $\Rightarrow$ control (WP 3.2)

$\rightarrow$ **prognosis** - in real time $\Rightarrow$ reduced order (WP 3.1)

Inform:

battery manufacturers

BMS design

hybrid control systems

WP1.1 Approach

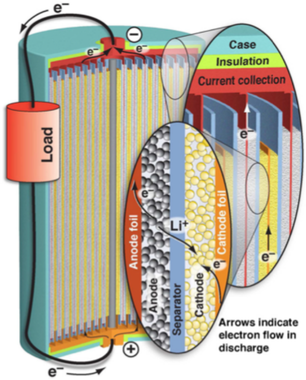
- transferable knowledge - cell size, geometry, chemistry

- **import/build high fidelity model(s) of healthy cell**
- validate (experiments/published data) - Study:
  - size, chemistry
  - dynamic loading
  - pack size/configuration
  - → define applicability
  - → improve model (1D→2D)

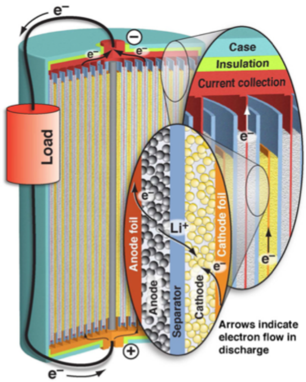
- **add on aging and degradation**
- validate (experiments/published data)

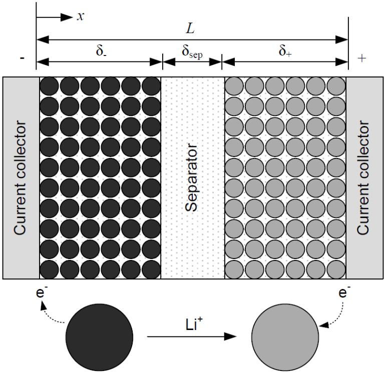
⇒ One comprehensive model yielding specialised reduced order models (e.g. EV vs. HEV)

Healthy battery cell



Healthy battery cell





Understanding degradation

Effects $\leftarrow$ Mechanisms $\leftarrow$ Causes

Capacity fade

Power fade

Increased internal resistance

Short circuit

Open circuit

Understanding degradation

Effects $\leftarrow$ Mechanisms $\leftarrow$ Causes

MECHANICAL: vibration, shock, electrode elasticity with lithiation

ELECTROCHEMICAL: method of fabrication, choice of system components

ELECTRICAL: load current & frequency, overcharging/discharging, contact resistances

THERMAL:

outside T (pack architecture, environmental)
inside T: high load, degradation

!COUPLED!

In collaboration with WMG, JLR, Oxford University

Understanding degradation

Effects $\leftarrow$ Mechanisms $\leftarrow$ Causes

- MECHANICAL: volume changes $\Rightarrow$ loss of contact electrode/current collector, loss of contact within electrode
- ELECTROCHEMICAL: SEI formation; current collector corrosion; dendrite deposition
- THERMAL: thermal expansion, increased reaction kinetics and diffusion

!COUPLED!

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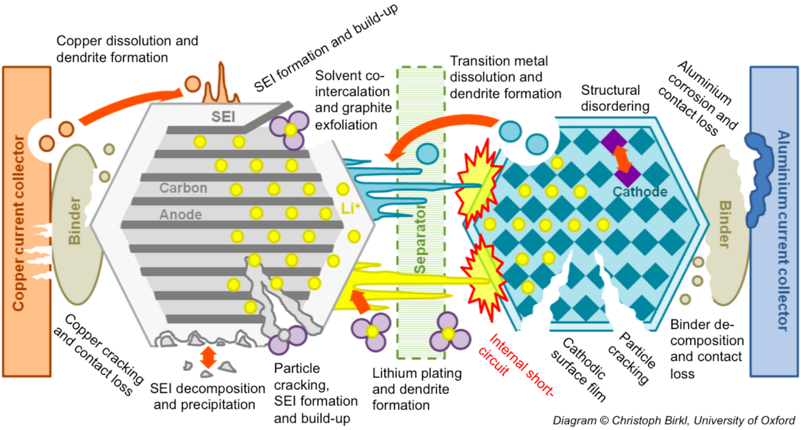
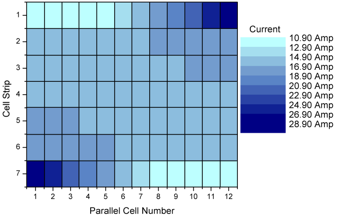
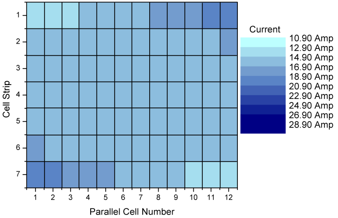
Understanding degradation

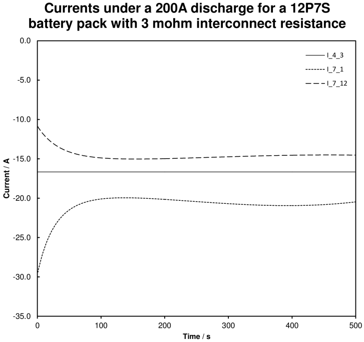


Thermal and electric coupling in a pack

Current distribution





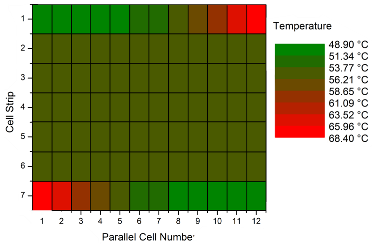


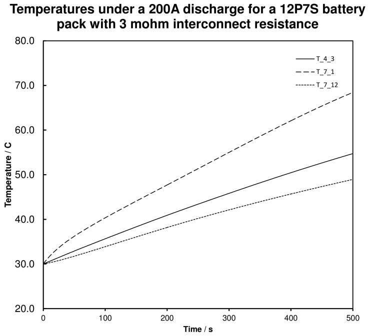
4.8Ah Kokam (LCO), from 90% SOC

M Marinescu, B Wu, M von Srbik, V Yufit and G J Offer, The effect of thermal gradients on the performance of battery packs in automotive applications, HEVC Proceedings, 2013

Thermal and electric coupling in a pack

Heat generation





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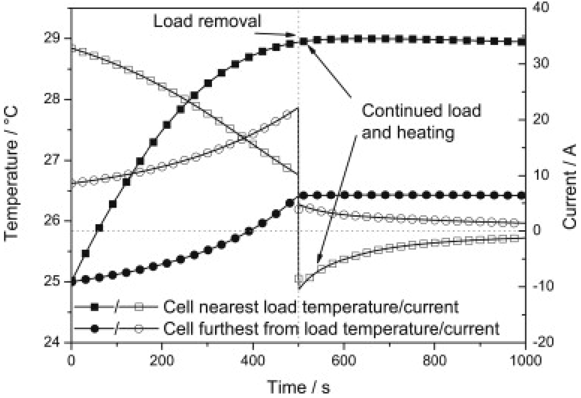
Pack effects

Balancing

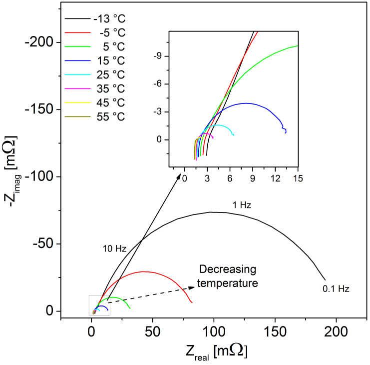


8P1S, 3C, $R_c = 1m\Omega$

B Wu, V Yufit, M Marinescu, G Offer, R Martinez-Botas, N Brandon, Coupled thermalelectrochemical modelling of uneven heat generation in lithium-ion battery packs, JPS **243**, 2013

Cell effects

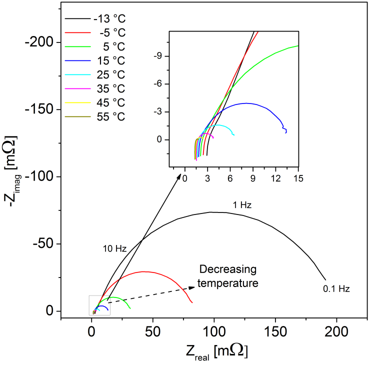
Equal temperatures

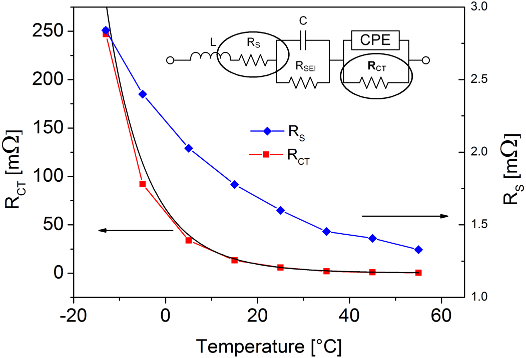


Y Troxler, B Wu, M Marinescu, V Yufit, Y Patel, A Marquis, N Brandon, G Offer, The effect of thermal gradients on the performance of lithium-ion batteries, JPS, **247, 2014**

Cell effects

Equal temperatures





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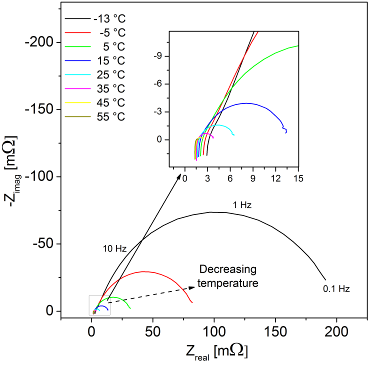
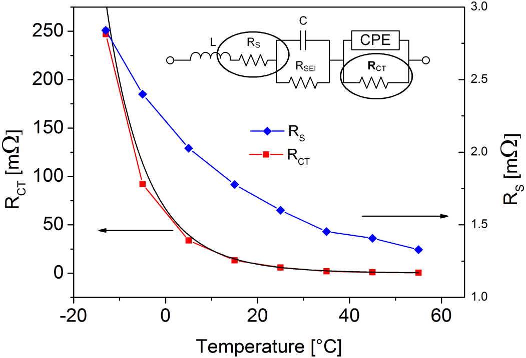




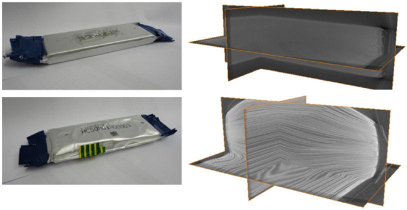
$$R_{\mathrm{ct}} = \tilde{R}_{\mathrm{ct}} \exp\left[\frac{E_{\mathrm{a}}}{R}\left(\frac{1}{T} - \frac{1}{\tilde{T}}\right)\right]$$

$$\tilde{T} = 25^\circ\mathrm{C}, \quad E_{\mathrm{a}} = 65\mathrm{kJ}$$

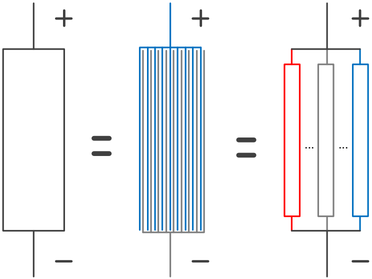
Y Troxler, B Wu, M Marinescu, V Yufit, Y Patel, A Marquis, N Brandon, G Offer, The effect of thermal gradients on the performance of lithium-ion batteries, JPS, **247, 2014**

Cell effects

Unequal temperatures - Interpretation



* V. Yufit et al, Electrochem. Comm. 13 (2011) 608-610



$$\frac{1}{R_{\mathrm{ct}}^{\mathrm{TG}}} = \sum_{1}^{80} \frac{1}{R_{\mathrm{ct},i}}, \qquad R_{\mathrm{ct},i} = \tilde{R}_{\mathrm{ct}} \exp\left[\frac{E_{\mathrm{a}}}{R}\left(\frac{1}{T_i} - \frac{1}{\tilde{T}}\right)\right]$$

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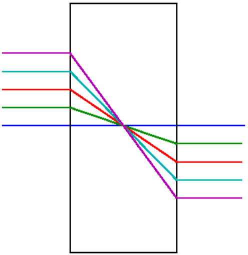
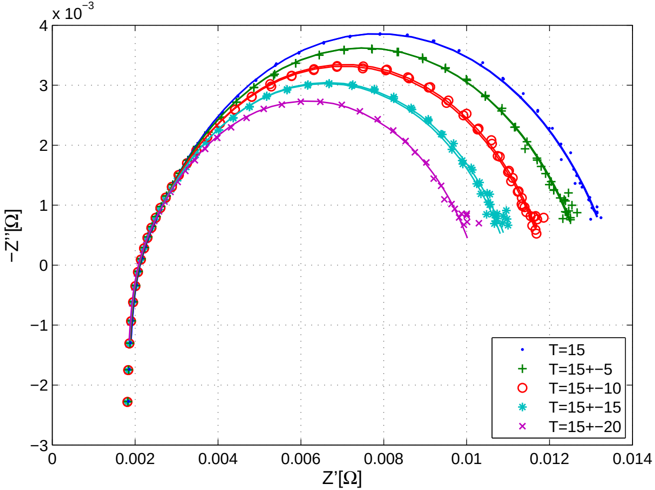
Cell effects

Unequal temperatures - Experimental



$T_{\text{eff}} > T_{\text{avg}}$



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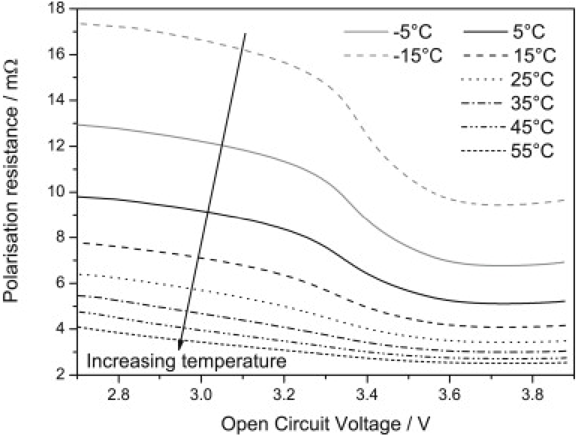
Pack $\rightarrow$ cell conundrum

T $\nearrow$ R $\searrow$ I $\nearrow$ SOC $\searrow$ R $\nearrow$ I $\searrow$ T ?



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Cell - Pack thermal and electric coupling

Conclusions

- When are thermal differences important?
  - load cycle (frequency, amplitude)
  - pack architecture (electric, R_c, thermal)
  - inner cell structure
- Explore through coupled model
  - include history
  - R(SOC, I, T)
- Design
  - pack (architecture, cooling)
  - control strategy

Outlook

Model of healthy cell

- thermal coupling of cell electrochemistry both ways ✓
- cell $\rightarrow$ pack ✓, pack $\rightarrow$ cell
- homogeneous intercalation chemistry ✓, phase transition chemistry (LFP)
- lumped thermal ✓, distributed thermal

Add-on degradation

- SEI layer continuous ✓, discontinuous
- microstructural volume changes
- electrode corrosion
- lithium plating

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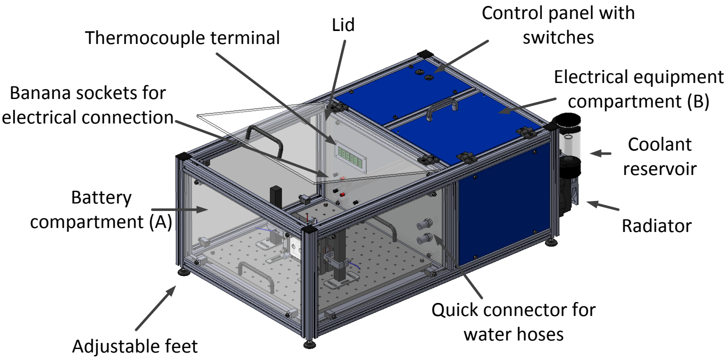
T gradients on a pouch cell

Experimental setup



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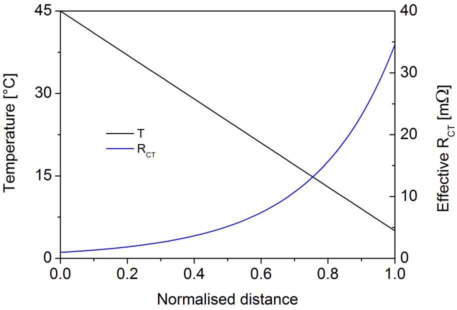
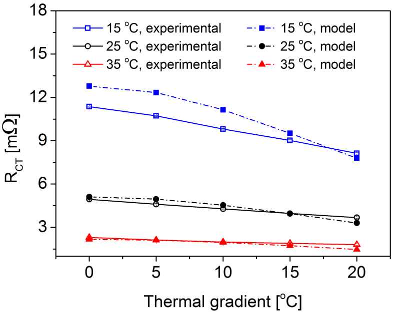
Unequal temperatures - Interpretation





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Cell effects - Learnings

- effect can be predicted from single T
  - Arrhenius equation for R(T) dependence
  - linear T-distribution inside pouch cell
- T-gradient $\Rightarrow T_{\text{eff}} > T_{\text{avg}}$
- effect currently tested under load