WORKSHOP ON BATTERY TESTING PROCEDURES

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Post Doc

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DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

Agenda

10:00-11:00 –	Round the table, battery cells' connection methods, battery holders, low resistance cell connection for EIS and internal resistance measurements, battery testing stations, etc.
11:00-12:00 –	Methods for battery cell capacity and OCV and quasi OCV measurements (tempering times, C-rates, pulse lengths, etc.)
12:00-13:00 –	Lunch + lab visit
13:00-14:00 –	Internal resistance and EIS measurements, (tempering times, C-rates, etc.). Abuse tests.
14:00-15:00 –	Battery cells calendar and lifetime testing (optimal test matrices, reference performance test procedures, accelerated lifetime tests, cells allocation for experiments, etc.)
15:00-16:00 –	Thermal characterization of the lithium ion batteries (heat capacity, emissivity, thermal conductivity, entropic heat coefficient, heat generation measurement, battery cell temperature monitoring, temperature sensor placement, etc.)

Motivation behind the workshop

- The lack of standardization in regards to li-ion battery testing – different procedures depending on the research group
- To exchange the knowledge and experience about differrent aspects related to battery testing (with focus on Li-ion batteries) in the Danish Battery Society
- To come up with the ideas regarding optimal in terms of accuracy and time efficiency battery testing protocols
- Possibly initiate future outsourcing of different battery tests in Danish Battery Society

Introduction to Cell Testing

- Manufacturers provide a limited amount of cell characteristics based on volume of cells purchased
- Cell characteristics influence decisions on choice of cell, sizing of module/pack, risk assessment, battery management system design
- A deeper understanding of cell used for storage application needs, allows user to protect and maximize return of investment
- Measurement of cell personality is necessary before design, for quality control during production and continually during operation
- Battery modeling

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Review of Cell Testing Standards

- Cell testing is typically labeled into three categories:
  - Performance or Characterization
  - Cycle and Calendar Life
  - Abuse or Safety

- Test standards are in early stages of development in transportation and stationary applications

Cell Testing Standards by Industry

Type of Testing	Transportation	Grid Storage Including Renewables	UPS	Telecom
Performance or Characterization	USABC PHEV Manual IEC 62660-1 IEC 61982 ISO 12405-1	PNNL 22010 IEC 61427	Need Standard	Need Standard
Cycle and Calendar Life	FreedomCAR (SAND 2005-3123) EUCAR* IEC 62660-2 IEC 61982 ISO 12405-1	PNNL 22010 IEC 61427	Need Standard	Need Standard
Abuse or Safety	SAE J2464 FreedomCAR (SAND 2005-3123) EUCAR* BATSO UN 38.3 UL 2271 UL 2580 ISO 12405-1	UN 38.3 UL 1973	UN 38.3 UL 1973	UN 38.3 UL 1973

Source: Southwest Research Institute

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Performance and Abuse Test Metrics

	Test	Industry Vertical			
		Transportation	Grid Storage	Telecom	UPS
Performance	Static Capacity	•	•	•	•
	HPPC	•	•		
	Cold Cranking	•		•	
	Constant Power	•		•	
	Energy Efficiency	•	•		
	Self Discharge	•	•		•
	Response Time		•		•
	Ramp Rate		•		
Electrical Abuse/Safety	External Short Circuit	•	•	•	•
	Abnormal Charge	•	•	•	
	Forced Discharge	•	•		
	Continuous low rate charging	•	•	•	
	Reverse Charge	•	•		
	Internal short circuit	•	•	•	•

Source: Southwest Research Institute

Cell Testing Standards by Industry

	Test	Industry Vertical			
		Transportation	Grid Storage	Telecom	UPS
Mechanical Abuse/Safety	Impact	•	•	•	
	Shock				
	Vibration	•			
	Drop	•	•	•	
	Molded casing stress test	•	•	•	•
	Penetration	•			
	Altitude Simulation	•			
Thermal Abuse/Safety	Thermal Stability	•	•	•	•
	Temperature cycling (Thermal shock)	•			

Source: Southwest Research Institute

Part 1, 10:00 – 11:00

- Round the table
- Battery cells' connection methods, battery holders
- Low resistance cell connection for EIS and internal resistance measurements
- Battery test stations

Round the table – battery testing

Discussion

Short presentation of the workshop participants:

- particular interest
- type of tests performed
- main competences
- to add/remove/change something from the meeting agenda

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Round the table - AAU battery personel

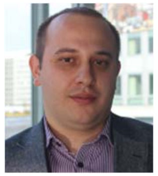
Søren Knudsen Kjær
Professor

Remus Teodorescu
Professor

Søren Juhl Andreasen
Associate Professor

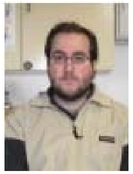
Erik Schaltz
Associate Professor

Maciej Swierczynski
Postdoc



Daniel Stroe
PhD Fellow

Irina Stan
PhD Fellow



Jorge Varela Barreras
PhD Fellow

Mohammad Rezwan Khan
PhD Fellow

Vaclav Knap
Research Assistant

Round the table–AAU main competences

- Battery cells characterization and performance testing
- Battery cells accelerated calendar and lifetime testing
- Battery cells lifetime and performance modelling
- Energy managment strategies development for stationary and automotive applications
- Simulation of the Li-ion batteries with renewable and automotive applications
- Economic analyses for different energy storage applications
- Battery pack design and construction
- V2G applications: EVs to Support Large Wind Power penetration in Future Danish Power Systems

Round the table - Batteries under test at AAU

Battery packs:

Kokam

39.6V, 18.4Ah

172V, 56Ah

Source: Aalborg University

Battery cells:

Cylindrical

2.5Ah

Pouch

50, 60Ah

Prismatic

50Ah

Why is proper connection so important?

- to ensure the reproducibility and reliability of the data
- to ensure low conenction resistance (losses, heating)
- good design allows for connections to be easily, quickly, reliably and safely done

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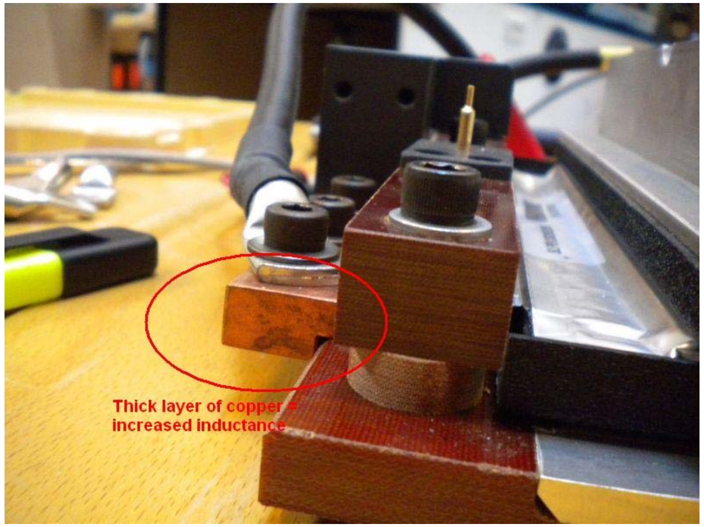
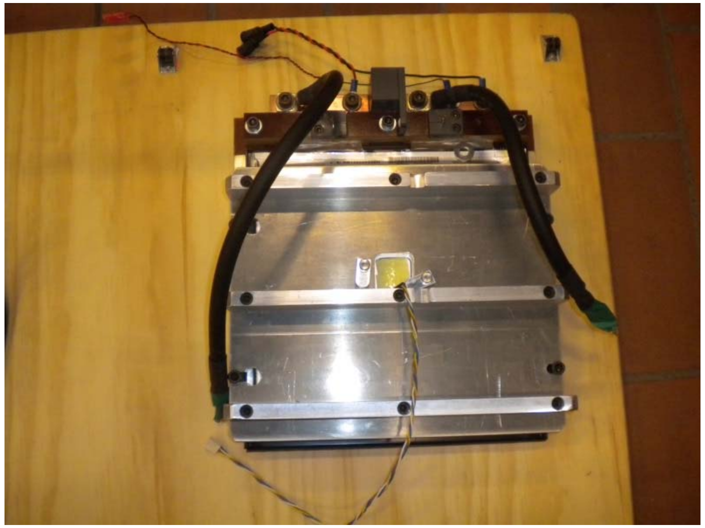
Battery cells' connection methods



Pouch cells with fixture



Source: Aalborg University

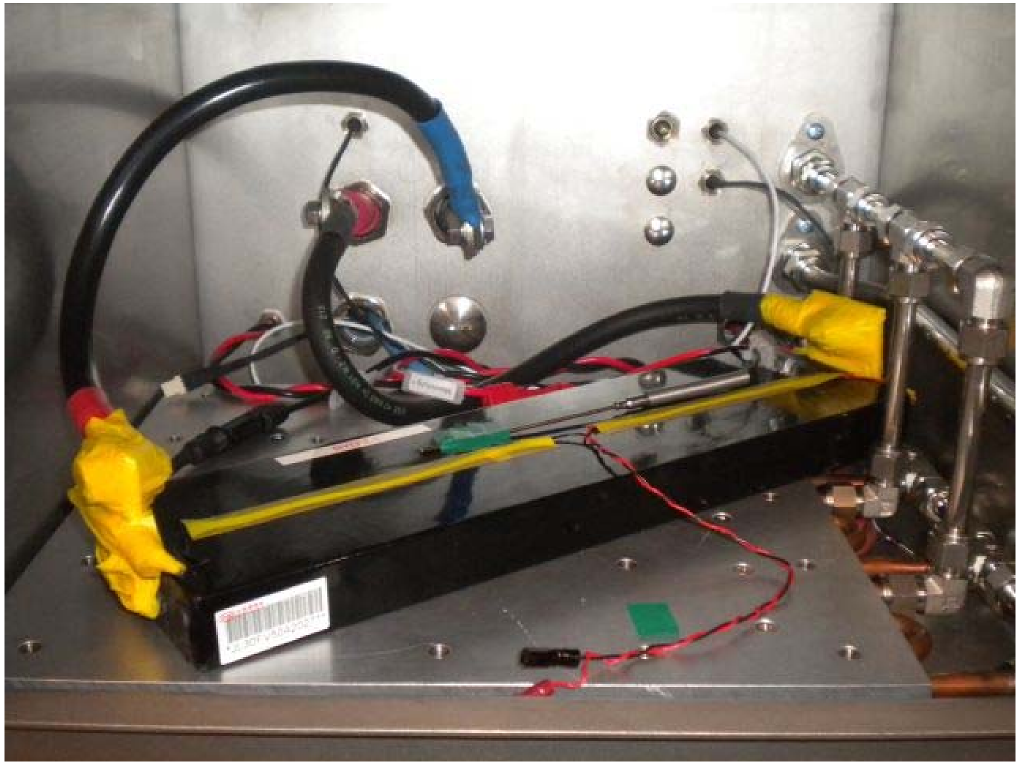
Battery cells’ connection methods

Pouch cells without fixture

Source: Ikerlan

Battery cells' connection methods

Prismatic cells



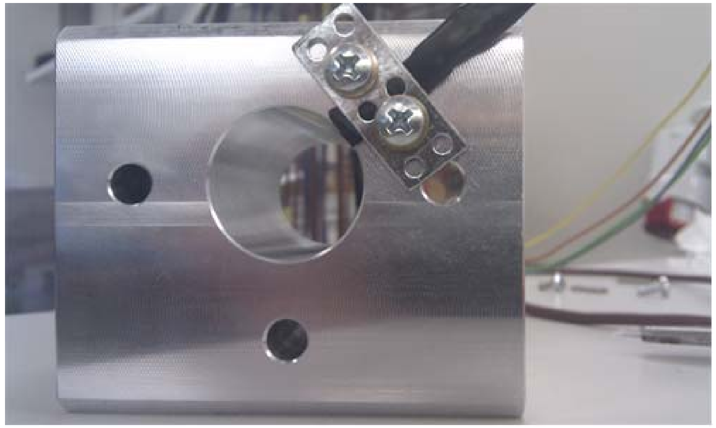
Source: Aalborg University

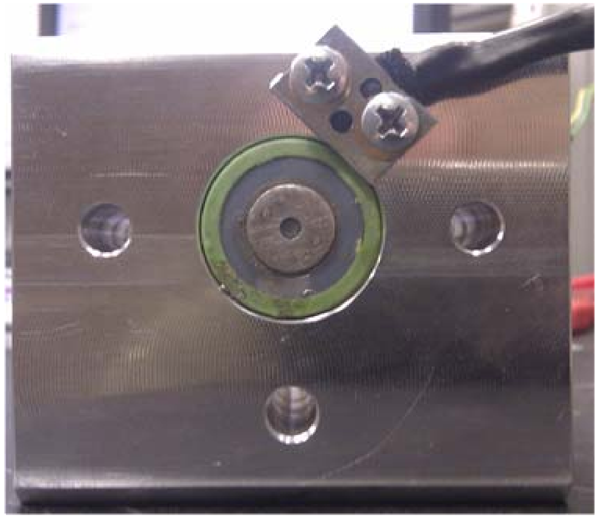
Battery cells' connection methods

Cylindrical cells

No fixture

With fixture



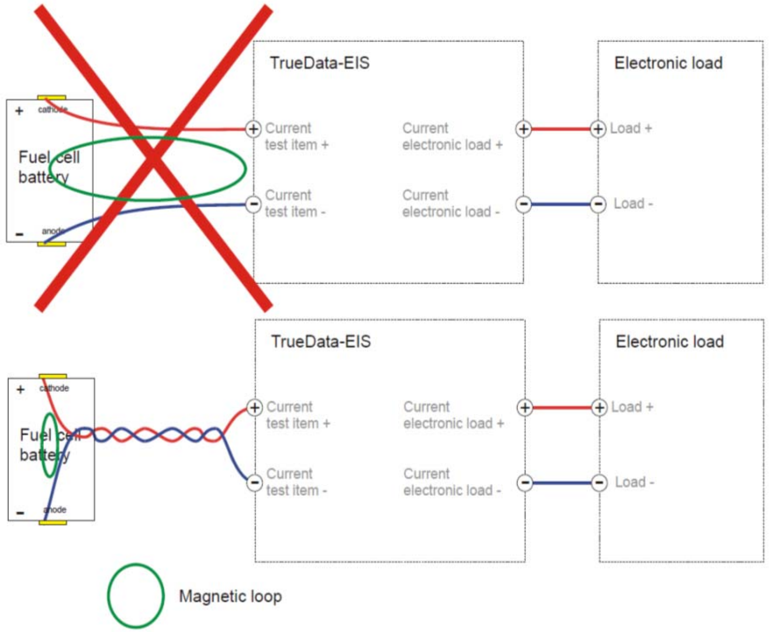


Discussion

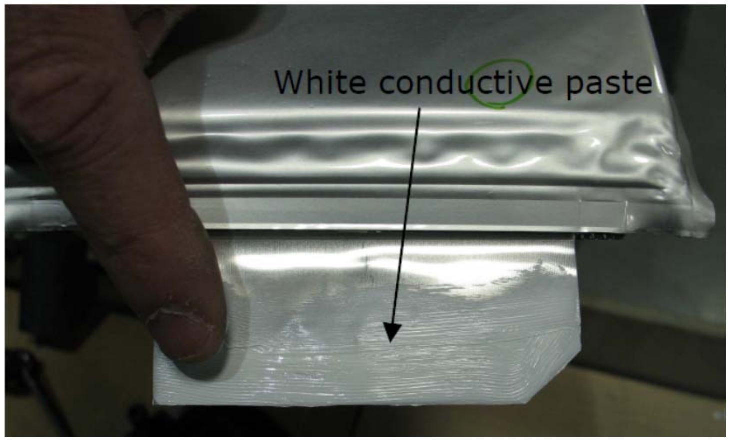
Source: Aalborg University

Low resistance cell connection for EIS and internal resistance measurements

- low resistance of modern li-ion batteries – difficult to measure accurately
- conduction paste
- low connection resistance verification taste



Source: FuelCon



Source: Altair Nano

Low resistance cell connection for EIS and internal resistance measurements

In order to assess the quality of the cell terminals connection following verification test is used at AAU:

1. Load the cell with 30 seconds charge or discharge constant current equal to 1C.
2. Measure the voltage drop (in mV) between the cell terminal and the copper block/nickel block (etc.) on both positive and negative terminals.
3. Calculate the resistance:

$$R = \frac{V_{measured}}{I_{applied}}$$

4. If the calculated resistance for both of the terminals is below 0.1mΩ, then connection is proper. If measured resistance for any of the terminals is higher than 0.1mΩ, then the state of the connection should be verified.
5. Procedure 1-4 can be performed periodically during cell lifetime (especially in the situation when battery cells are disconnected from the fixture).

Battery testing facilities at AAU

FuelCon Battery Test Station 18V, 200A,

Maccor Battery Test Station 10V, 30A

Heinzinger Supply 100-800V, 500A

Kepko BOP 10V, 75A

FuelCon portable EIS analyzer.

Gamry FRA

Self-made Climatic Chamber

Source: Aalborg University

Memmert Universal Oven UNP 500.

Battery testing facilities at AAU

Digatron MCT cell tester, 36 testing circuits 6V, 50A

Digatron BNT module tester, 2 testing circuits 100V, 100A

Temperature Test Chamber for Battery Modules Weiss WT3-340/40

Discussion

dSpace 32-Cell Battery-Simulator

Cooled incubator Memmert ICP 600

Source: Aalborg University

6x Universal ovens Memmert UFP 600

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Part 2, 11:00 – 12:00

- Battery static capacity measurements
- OCV and quasi OCV measurements
- Additional tests (issues)

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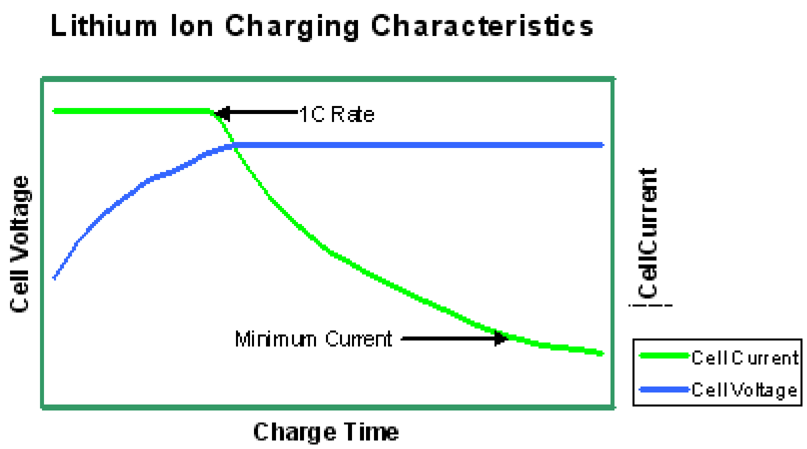
Static capacity measurment

- Performance testing (application dependent)
  - matrix – different temperatures, different C-rates, tempering

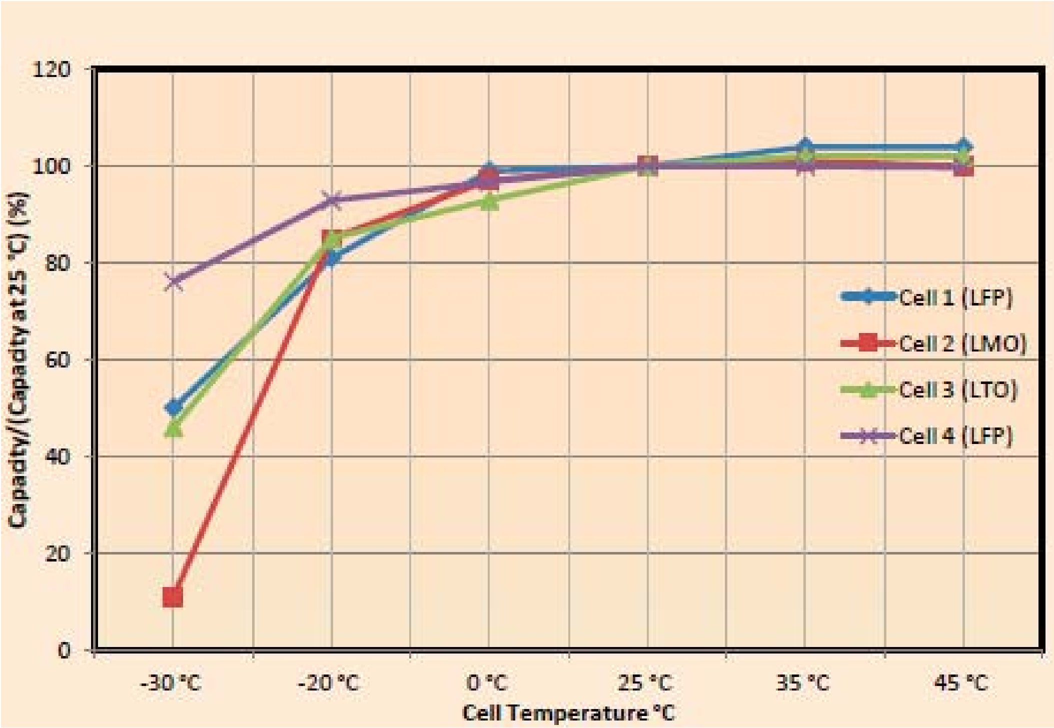
- Reference performance test (application dependent)
  - 25°C, 1C/1C test, tempering, 1 repetition

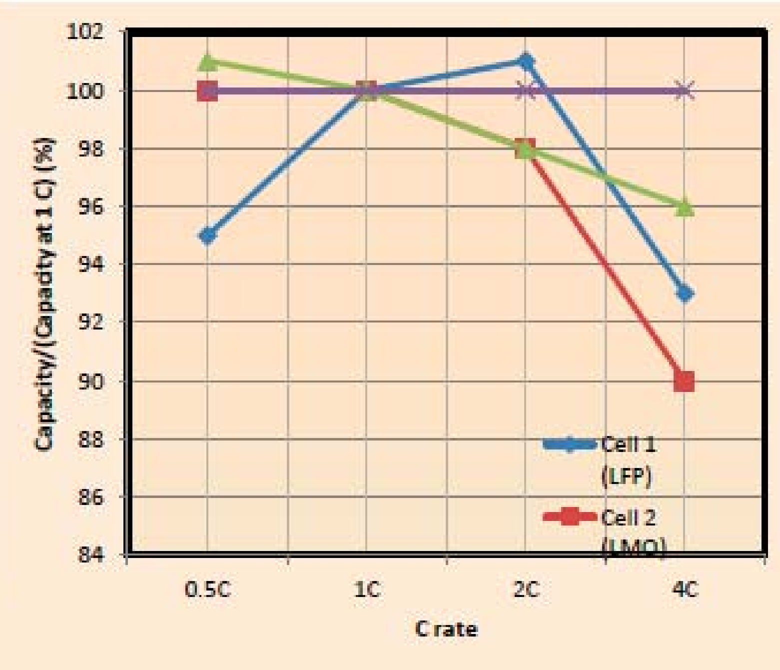
Case	Discharged Ah [Ah]	
	Cell 1	Cell2
1C 25°C	2.31	2.36
2C 25°C	2.31	2.35
4C 25°C	2.29	2.35
1C 35°C	2.34	2.39
2C 35°C	2.30	2.37
4C 35°C	2.30	2.38
1C 45°C	2.35	2.41
2C 45°C	2.34	2.40
4C 45°C	2.33	2.40



Source: Aalborg University

Static capacity measurment





Source: Southwest Research Institute

Static capacity measurment - AAU

Discussion

Step	Action	Current (A)	Limit
1	CC CHA	(C/1)	> EOCV
2	CV CHA	1	<0.05 C-Rate
3	Pause		15 min
4	PAU		15 min
5	DCH	(C/1)	< EODV
6	PAU		15 min

Source: Aalborg University

OCV measurements

- To determine the equilibrium voltage – battery modelling
- Different procedure for OCV and quasi OCV measurements
- Time consuming measurement
- Possible hysteresis
- Determination of the OCV-DOD Characteristic for each discharge step
- Determination of the OCV-DOD Characteristic for each charge step
- Characteristic changes with battery ageing

OCV measurements at AAU

Step	Action	Current (A)	Limit
1	CC CHA	(C/1)	> EOCV
2	CV CHA	1	<0.05 C-Rate
3	Pause		15 min
4	Pause (OCV Determination)		3-5h
5	Discharge	(C/3) example	ΔDOD=5%
6	Pause (OCV Determination)		3-5h
7	Repeat 5. - 6. until EODV		EODV
8	Pause (OCV Determination)		3-5h
9	Charge	(C/3) example	ΔDOD=5%
10	Pause (OCV Determination)		3-5h
11	Repeat 9. - 10. until EOCV		EOCV

Source: Aalborg University

Quasi-OCV measurements

- The “Quasi-OCV” - time efficient method to analyze the characteristic of the open circuit voltage over the state of charge;

- Calculation of the “Quasi-OCV” as average of the two voltage curves over Depth of Discharge;

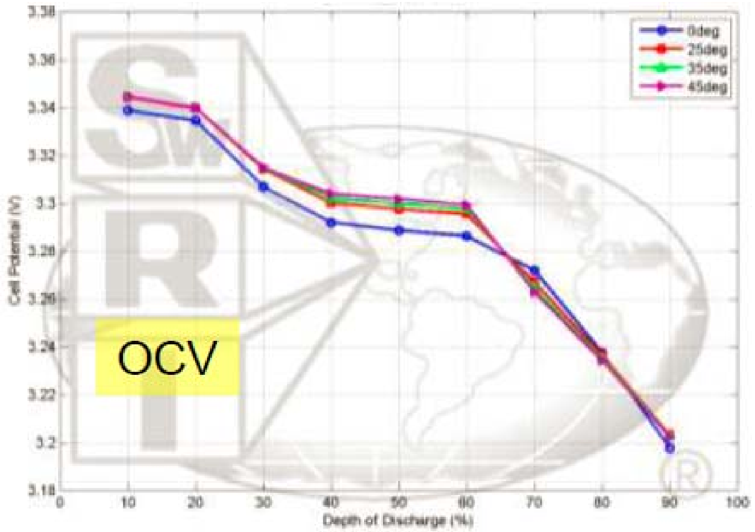
- Small C-rate, typically < C/4;

Quasi-OCV measurements at AAU

Step	Action	Current (A)	Limit
1	CC CHA	(C/1)	> EOCV
2	CV CHA	var	<0.05 C-Rate
3	Pause		15 min
4	Discharge	(C/5) example	< EODV
5	Pause		15min
6	Charge	(C/5) example	> EOCV

Source: Aalborg University

Discussion



Additional issues

Discussion

- Prelonged storage (before testing) to minimize ageing
- Cell pre-conditioning
- Tempering procedures

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Part 3, 13:00 – 14:00

- EIS measurements (impedance)
- DC resitance measurements
- Abuse tests

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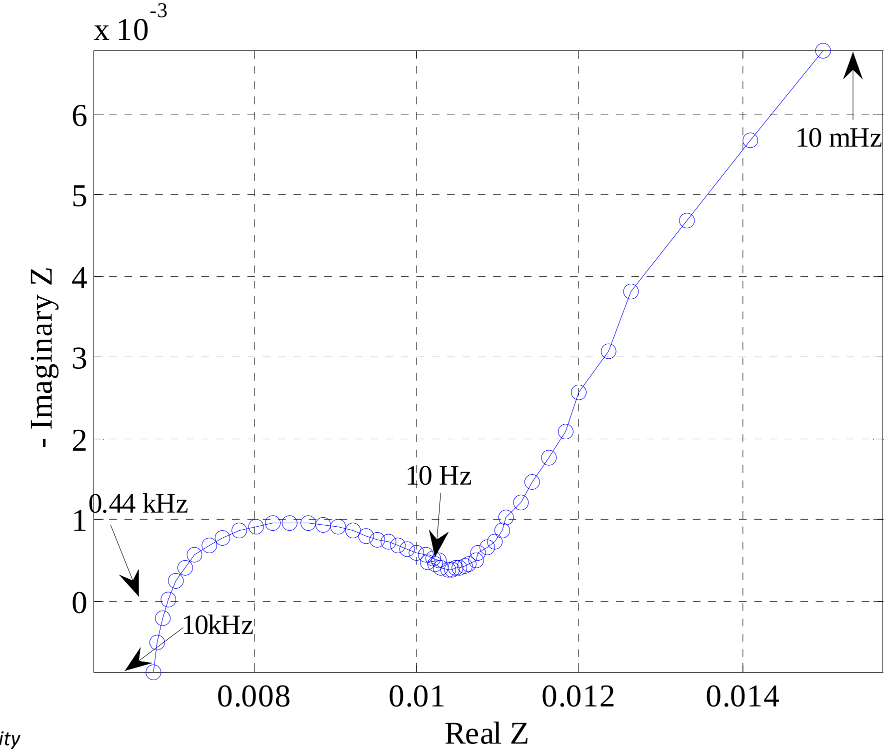
EIS measurements

- To achieve information about the electrochemical properties at the beginning of life and during the ageing process of the cells;
- With and without superimposed DC-current;



Source: Aalborg University

Nyquist plot for a Li-Ion Battery Cell at 25°C, SOC=50%, and I_{dc}=0A

Other aspects EIS

Discussion

- Measuremnts with superimposed DC current – methods and accuracy
- Data fitting (tools)
- Equivalent electrical circuits
- Automatization of the entire procedure

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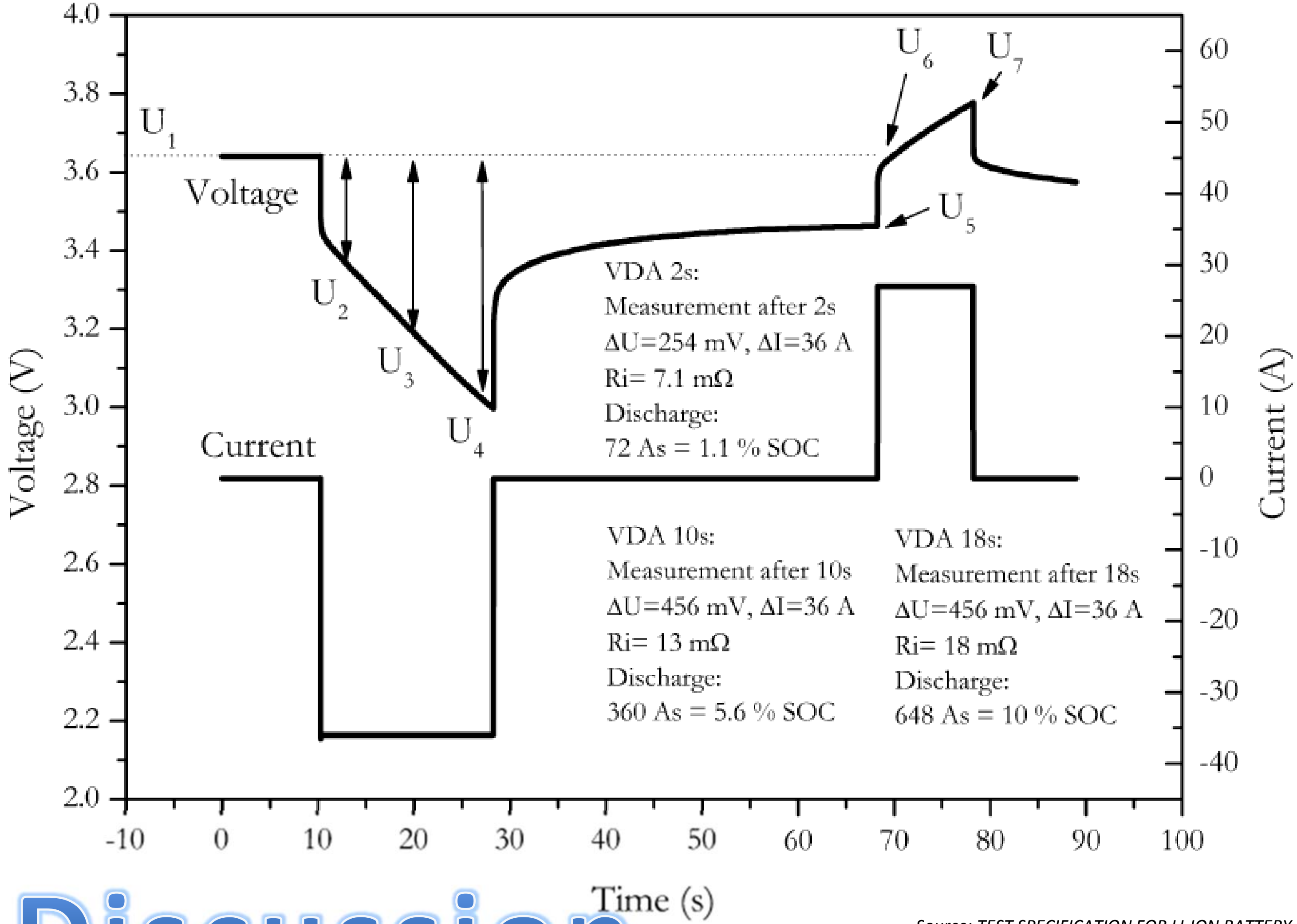
DC resitance measurements

- The internal resistance is the key parameter for determining power, energy efficiency and lost heat of a lithium ion cell
- A lot of different approaches
  - current step methods (many different approaches)
  - AC (alternating current) methods
  - electrochemical impedance spectroscopy
  - thermal loss methods
- Data fitting (tools)
- Equivalent electrical circuits
- Automatization of the entire procedure

DC resitance measurements at AAU



$$Ri_{discharge,2s} = \left| \frac{U_1 - U_2}{I_{discharge}} \right|$$

$$Ri_{discharge,10s} = \left| \frac{U_1 - U_3}{I_{discharge}} \right|$$

$$Ri_{discharge,18s} = \left| \frac{U_1 - U_4}{I_{discharge}} \right|$$

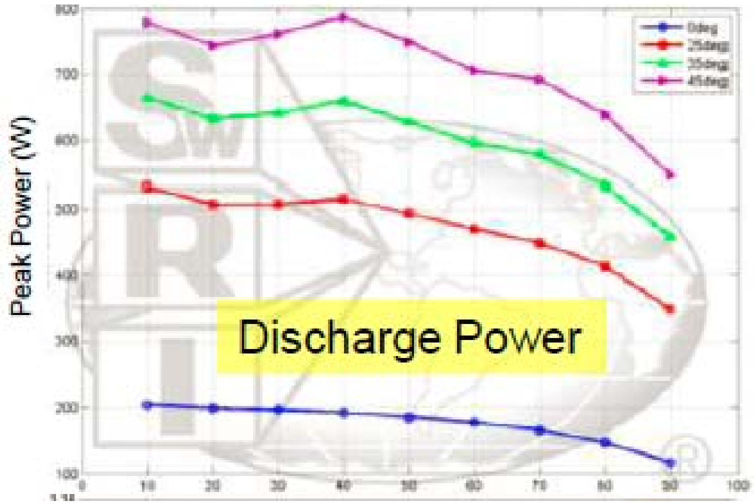
$$Ri_{charge,2s} = \frac{U_6 - U_5}{I_{charge}}$$

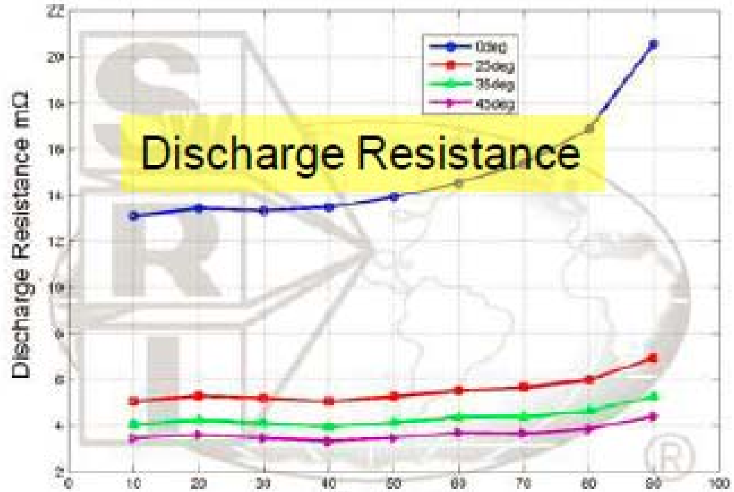
$$Ri_{charge,10s} = \frac{U_7 - U_5}{I_{charge}}$$

Source: TEST SPECIFICATION FOR LI-ION BATTERY SYSTEMS FOR HYBRID ELECTRIC VEHICLES, 2007

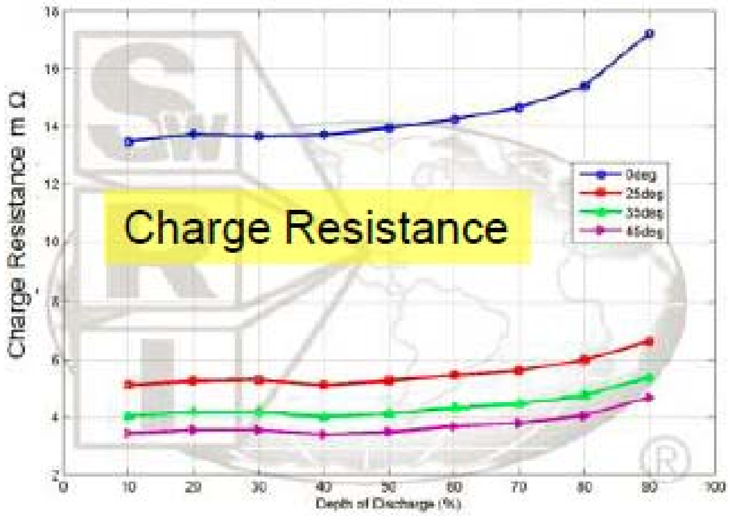
Discussion

DC resitance measurements HPPC test





Source: Southwest Research Institute



Abuse tests

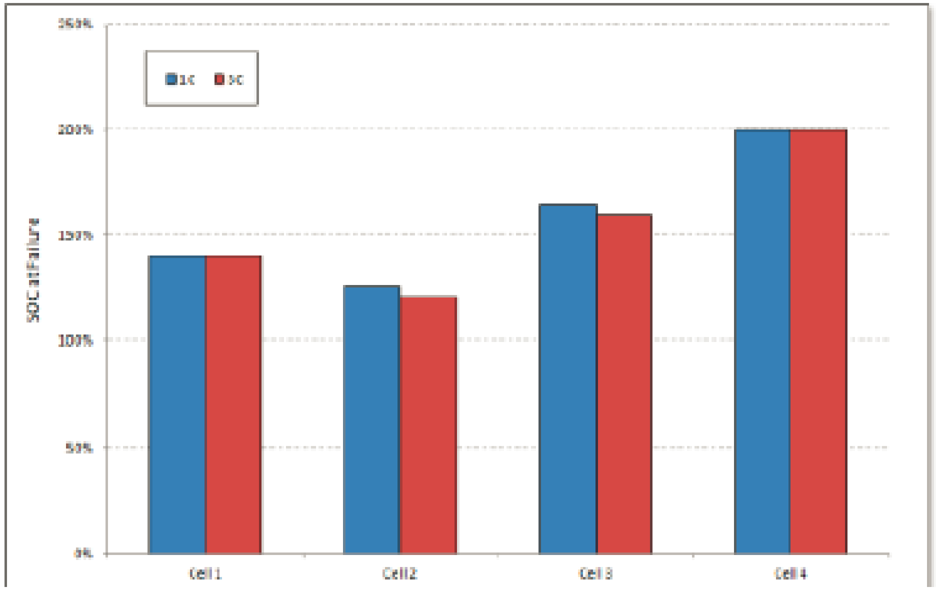
	Test	Industry Vertical			
		Transportation	Grid Storage	Telecom	UPS
Mechanical Abuse/Safety	Impact	•	•	•	
	Shock				
	Vibration	•			
	Drop	•	•	•	
	Molded casing stress test	•	•	•	•
	Penetration	•			
	Altitude Simulation	•			
Thermal Abuse/Safety	Thermal Stability	•	•	•	•
	Temperature cycling (Thermal shock)	•			

Source: Southwest Research Institute

Abuse tests

		Cell 1	Cell 2	Cell 3	Cell 4
Penetration		5	3	2	3
Overcharge	1C	3	3-4	3	2
	3C	3-4	3	6	5
Overdischarge		2	2	2	4
Short Circuit		4	3	2	3
Thermal Stability		4	5	3	5
Thermal Shock		0	0	0	0

Hazard Severity	Description
0	No effect
1	Passive protection activated
2	Defect/Damage
3	Minor Leakage/Venting
4	Major Leakage/Venting
5	Rupture
6	Fire or Flame
7	Explosion



Threshold SOC as a function of C rate during Overcharge test

Discussion

Part 4, 14:00 – 15:00

- Battery lifetime testing (accelerated lifetime testing)
- Battery cells calendar liftime testing
- Battery cells cycle liftime testing

Accelerated lifetime testing

Battery lifetime testing is very time and resources consuming

Solution: Accelerated lifetime testing

Challenges:

- Complex degradation behaviour – many factors influence the lifetime;
- Wide variety of operating conditions for ;i-ion batteries in targeted applications
- Difficulty to accurately extrapolate/interpolate to working conditions
- Difficulty to choose acceleration factor

Calendar Life Test Metrics

Temperature	Industry Vertical			
	Transportation	Grid Storage	Telecom	UPS
Low (<= 20 degC)		•	•	
Medium (25-30 deg C)	•*	•	•	•*
High (>= 30 deg C)		•	•	

Source: Southwest Research Institute

*Active cooling

Knowing life at various temperatures will help with:

1. Design cooling systems if necessary
2. Estimate life by combining with cycle life and duty cycle information

Calendar Life Test Metrics

Challenges:

- Number of cells per test case to achieve statistical relevance
- Optimal matrix design for given service
- Reduce time and resources needed

Accelerated calendar ageing

Temp. level 1 SOC level 1	**Temp. level 2** **SOC level 1**	Temp. level 3 SOC level 1
Temp. level 1 **SOC level 2**	**Temp. level 2** **SOC level 2**	**Temp. level 3** **SOC level 2**
Temp. level 1 SOC level 3	**Temp. level 2** **SOC level 3**	Temp. level 3 SOC level 3

Source: Aalborg University

Discussion

Cycle lifetime tests

Variable	Level	Definition
Frequency	Low	Hours
	Medium	Minutes
	High	Seconds
DOD	Low	10% or less
	Medium	Around 50%
	High	Close to 100%
Rest Period	Low	0 to a few seconds
	Medium	Minutes to hours
	High	Hours to days

Source: Southwest Research Institute

Frequency	DOD Magnitude	Rest Periods	Industry Vertical			
			Transportation	Grid Storage	Telecom	UPS
Low	Medium	Low			Towers without Grid Access	
Low	Medium	High			Towers with Grid Access	
Low	High	Low	PHEV, BEV			
Low	High	High		Peak Shaving		DCS Back up
Medium	High	High		Renewable Smoothing		
High	Low	Low		Frequency Regulation		
High	Low	High	HEV, Micro Hybrid			

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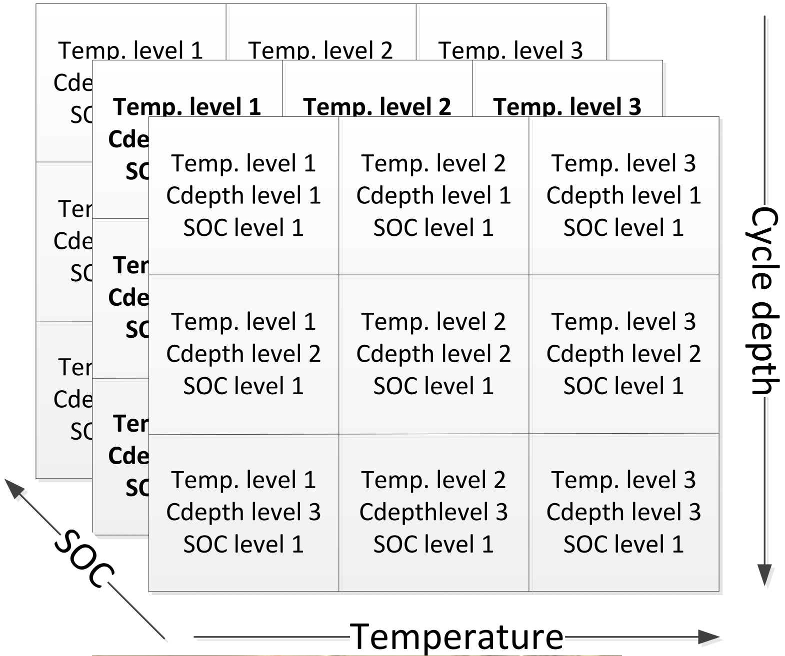
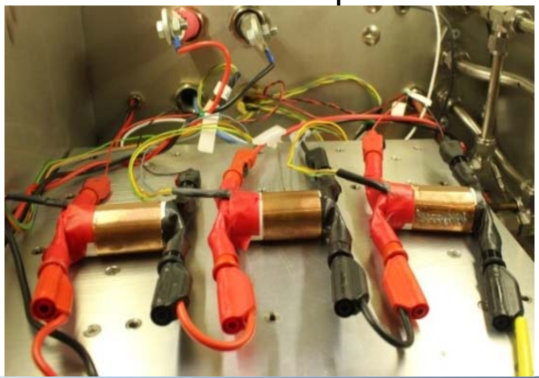
Cycle lifetime tests

Accelerated cycling ageing tests





Discussion

Challenges:

- Number of cells per test case to achieve statistical relevance
- Optimal matrix design for given service
- Reduce time and resources needed
- Proper choice of acceleration stress factors and stress levels

Source: Aalborg University

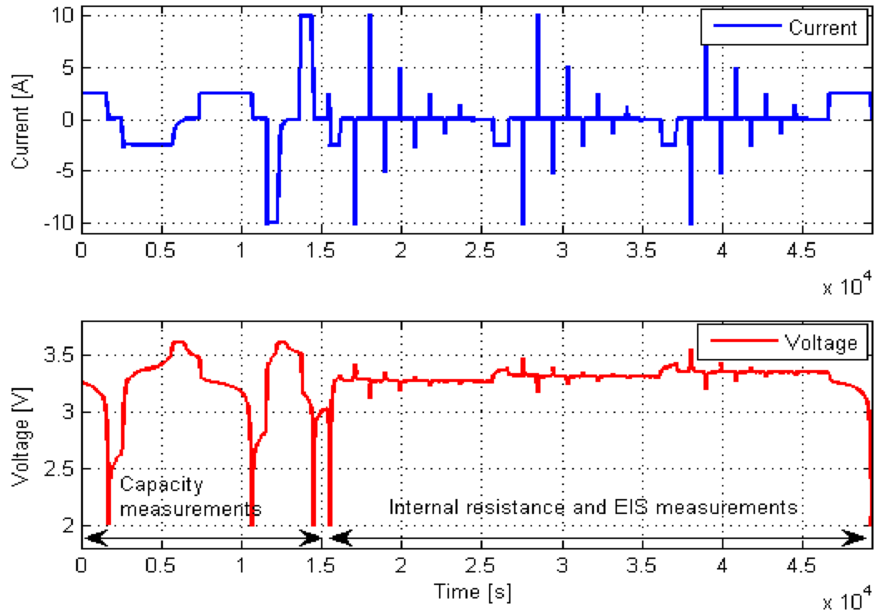
Reference Performance Tests

Discussion

Reference Performance Tests (RPT)

- To quantify the degradation of specific battery cell parameters, which are changing with ageing at specific conditions

Current and Voltage Profile during RPT



Source: Aalborg University

- Capacity Measurements
- Internal Resistance Measurements (Pulse Power Capability)
- AC Impedance Measurements

- RPTs performed at 25°C
- 1/month for accelerated calendar ageing tests
- 1/number of cycles (approx. 1 week) for accelerated cycling ageing tests

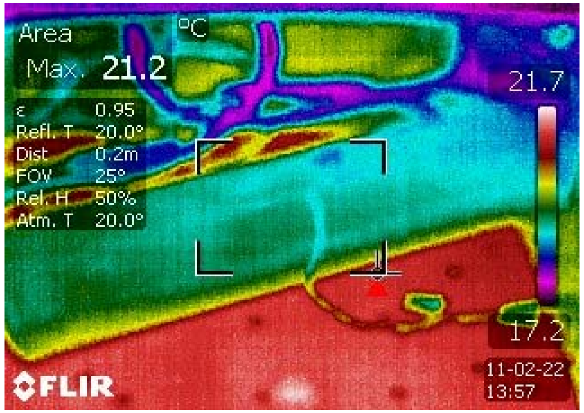
Source: D. Stroe et al. "Accelerated Lifetime Testing Methodology for Lifetime Estimation of Li-ion Batteries used in Augmented Wind Power Plants," IEEE Energy Conversion Congress and Expo, Denver, US, September 16-20, 2013

Part 5, 15:00 – 16:00

- Mohammed Rezwan Khan presentation
- Battery temperature monitoring
- Thermal characterization (heat capacity, emissivity, thermal conductivity, entropic heat coefficient, heat generation)

Battery temperature monitoring

- Temperature sensor placement (maximum or average temperature?)
- How many sensors per cell?



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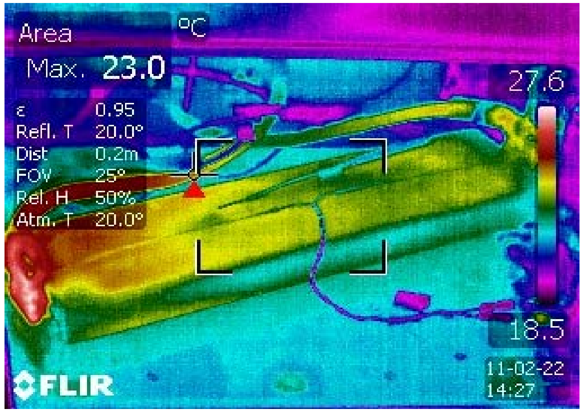
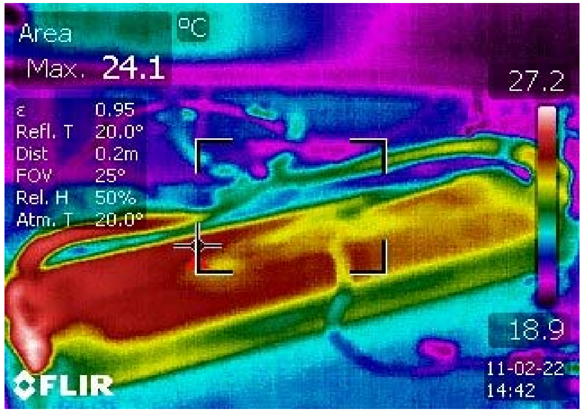


15 mins

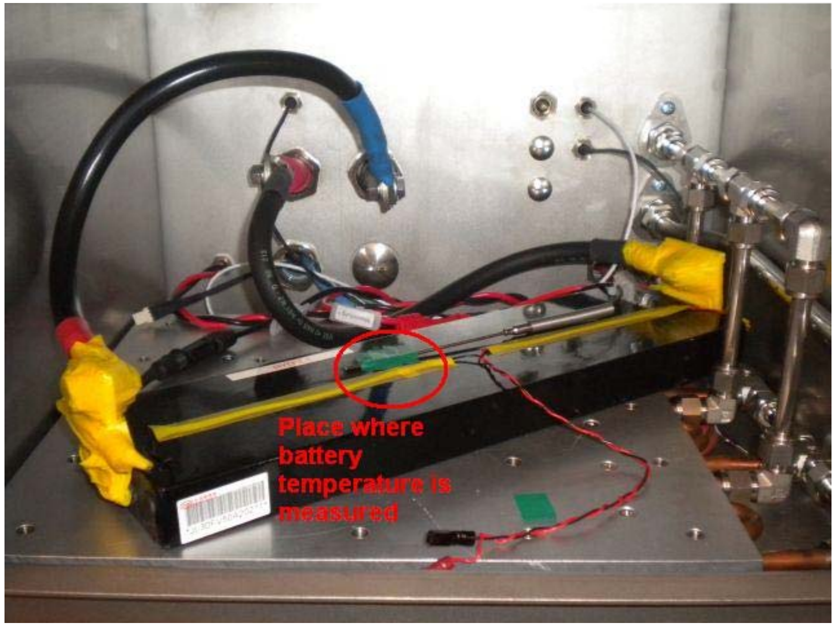


45 mins

Source: Aalborg University

Battery temperature monitoring AAU

Discussion



Source: Aalborg University

Thermal characterization

- Heat capacity
  - adiabatic calorimetry (not measured at AAU)
- Emissivity
  - thermal camera with adjustable emissivity
- Thermal conductivity
  - transient plane source (TPS) technique (not measured at AAU)
- Entropic heat coefficient
  - open circuit potentiometry (most often used)
- Heat generation
  - adiabatic calorimetry (not measured at AAU)

Discussion

Industrial/PhD Course

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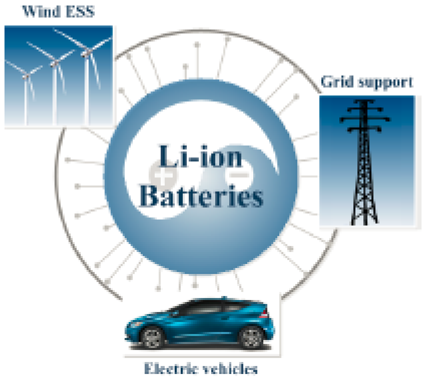
Industrial/Ph.D. Course in

Storage Systems based on Li-Ion Batteries for Grid Support and Automotive Applications

2 – 4 June, 2014



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Course Program

Day 1: Battery Technologies and Grid Applications

08:30	Course Registration
09:00	Overview of Electrochemical Battery Technologies
10:00	Coffee Break
10:30	Overview of Stationary Applications
12:00	Lunch
13:00	Industrial Guest Lecture
14:30	Coffee Break
15:00	Matlab Exercise: Optimal Sizing of Storage in Different Applications

Day 2: Modeling of Li-ion Batteries

08:30	Impedance-based Performance Modeling
10:00	Coffee Break
10:30	Life Time Modeling
12:00	Lunch
13:00	Matlab Exercise: Curve Fitting and Parameter Extraction
14:30	Coffee Break
15:00	Matlab Exercise: Performance Model

Day 3: Automotive Applications

08:30	Battery Management Automotive Applications
10:00	Coffee Break
10:30	Modeling, Sizing and Control of Battery Powered Vehicles
12:00	Lunch
13:00	Matlab Exercise: Battery Powered Vehicles
14:30	Coffee Break
15:00	Lab visit
15:30	End of Course

Language: English

Credits: 3.0 ECTS

Registration

To register, you must create an account by filling out the form available at:

https://phd.moodle.aau.dk/

You will be ready to register for course participation, after you will receive an email and confirm your registration.

Registrations close on **May 12, 2014.**

Course Location

Aalborg University
Department of Energy Technology
Pontoppidanstræde 101, Room 23
DK-9220 Aalborg East
Denmark

Organization

Further information

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Hotel and Transport

For hotel, transport information and booking please check: www.et.aau.dk/phd/phd-courses

Fee

The fee for the course is **10.000 DKK** for industry, **6.500 DKK** for PhD students/ Academics outside of Denmark, and **1.500 DKK** for PhD students in Denmark.

The registration fee includes: coffee and lunch for all days, gala dinner and the course materials.

Prerequisites

In order to be able to perform the exercises, the course participants should bring their own notebook with MATLAB software pre-installed (in case that it is not possible, some computers will be available).

Lab facilities

- FuelCon Battery Test Station
- Maccor Battery Test Station
- Digatron Cell and Module Tester
- FuelCon Portable EIS Analyzer
- Industrial Ovens and Climatic Chambers
- Real Time Digital Simulator (RTDS)
- dSpace 32-Cell Battery Emulator

Prof. Remus Teodorescu

Postdoc. Maciej Swierczynski

PhD Fellow Daniel Stroe

Assoc. Prof. Erik Schaltz

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