Reliability & Safety of Lithium Battery Packs

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FIVE ELEMENTS OF THE POWERTRAIN

- Battery
- IC Engine
- Transmission
- Electric Motor
- Control Strategy
OVERVIEW ABOUT AVL´S BATTERY ACTIVITIES

Testing & Benchmarking

Test equipment development

Cell/Pack Production Process Assurance

System validation

<table>
<thead>
<tr>
<th>Validation target:</th>
</tr>
</thead>
<tbody>
<tr>
<td>300,000 km cycle life</td>
</tr>
<tr>
<td>12 years calendar life</td>
</tr>
<tr>
<td>EMC targets fulfilled</td>
</tr>
<tr>
<td>System interaction ok</td>
</tr>
</tbody>
</table>

Battery

BMS series development (SW & HW)

Prototype built-up

Thermal simulation

Design Engineering
AVL Battery Pack Development Market Overview

Battery Cell Manufacturers → Battery Module Integrators → Powertrain Integration “Opportunity” → Hybrid/Electric Vehicle Manufacturers

- Battery cell & module developers have limited automotive experience
- OEMs have market demand for hybrid powertrains and a need for “Proven” component suppliers
- OEMs can not invest the time, resources and capital to develop component suppliers & therefore need trusted engineering service providers to take on this development role

AVL has established this trusted partnership with the automotive OEMs

AVL is now focused on the development of strategic alliances with component suppliers who have unique product offerings suitable for automotive market introduction
AUDI A1 E-TRON
with AVL RANGE EXTENDER

Range Extender generator module
Exhaust system
Fuel tank for range extender
High voltage harness
High voltage Li-Ion rechargeable battery pack

Source: AUDI
BATTERY RELIABILITY PROCESS

Concept
Prototype development
Preproduction development
Product validation

SOP

Functional Safety
RA & FMEA
Statistical analysis
Usage space analysis
Reliability allocation
DVP
DoE / Robustness
Load Matrix
Concern & FTA
Reliability chart and health monitoring
Warranty risk estimation
TYPICAL SITUATION

High innovation pressure by legislation and competition
Reliability problems diminish profit and market reputation
For new systems / applications no test programs are available
Test program is not capable to demonstrate reliability targets
Acceleration factors of tests are estimated globally
Certain modes of operation and applications are not tested at all
Optimization of the test time and resources is required

⇒ Load Matrix
**LOAD MATRIX PROCESS**

<table>
<thead>
<tr>
<th>System Analysis</th>
<th>Component oriented analysis w.r.t. damaging operating conditions, risk based prioritisation of failure modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applications and Targets</td>
<td>Identification of usage space, definition of reference duty cycles and reliability targets</td>
</tr>
<tr>
<td>Test Program and Load Analysis</td>
<td>Determination of acceleration factors, damage modeling, adaptation of test program</td>
</tr>
<tr>
<td>Evaluation and Optimization</td>
<td>Reliability and durability analysis of test program, timing &amp; costs, warranty risk reduction</td>
</tr>
</tbody>
</table>
## LOAD MATRIX SYSTEM ANALYSIS
### SELECTION OF RELEVANT COMPONENTS

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Hybrid or Electric Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>Battery System</td>
</tr>
<tr>
<td>Subsystem</td>
<td>Battery module</td>
</tr>
<tr>
<td></td>
<td>Cooling system (air or liquid)</td>
</tr>
<tr>
<td></td>
<td>Electronic components</td>
</tr>
<tr>
<td></td>
<td>Battery housing</td>
</tr>
<tr>
<td></td>
<td>Connectors + wires</td>
</tr>
</tbody>
</table>

### Components

<table>
<thead>
<tr>
<th>Cell</th>
<th>Fan</th>
<th>Battery control board</th>
<th>Housing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell sensors</td>
<td>Heat exchanger</td>
<td>System sensors</td>
<td>Overpressure valve</td>
</tr>
<tr>
<td>Cell connector</td>
<td>Pipe/channels/manifolds</td>
<td>Insulation monitoring</td>
<td>Pressure balance device</td>
</tr>
<tr>
<td>Module housing</td>
<td>Sensors</td>
<td>Fuse(s)</td>
<td>Electrical insulation</td>
</tr>
<tr>
<td>Module sensors</td>
<td>Gaskets</td>
<td>Interlock system</td>
<td>Thermal insulation</td>
</tr>
<tr>
<td>Gaskets</td>
<td></td>
<td></td>
<td>Gaskets</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main contactor and precharge relay</th>
<th>Signal wires</th>
<th>Signal- connectors to vehicle</th>
<th>High voltage wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV-connector to vehicle</td>
<td>Service disconnect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module connectors (busbar)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A3PS Conference 2010 / Vienna - AVL BATTERY SYSTEM DEVELOPMENT – 19.11.2010
### SELECTED KEY FAILURE MODES OF LITHIUM ION CELLS

<table>
<thead>
<tr>
<th>FAILURE MODE</th>
<th>CAUSE OF FAILURE</th>
<th>INFLUENCE FACTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Increase of internal resistance</td>
<td>Degradation of SEI at negative electrode</td>
</tr>
<tr>
<td></td>
<td>Reduced capacity</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>Increased self discharge</td>
<td>Lithium plating at negative electrode</td>
</tr>
<tr>
<td></td>
<td>Hard short circuit and subsequent cell venting</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>Increased resistance</td>
<td>Decomposition of electrolyte</td>
</tr>
<tr>
<td></td>
<td>Cell swelling and subsequent cell venting</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>Increased resistance and reduced power</td>
<td>Crack of conducting paths</td>
</tr>
<tr>
<td></td>
<td>Reduced capacity</td>
<td></td>
</tr>
</tbody>
</table>
DEFINITION OF THE OPERATING DIMENSIONS

...Battery load during real driving cycle (AVL Range Extender)

Graz – test drive route

Example real driving cycle with AVL Range Extender
LOAD MATRIX PROCESS

System Analysis

- Component oriented analysis w.r.t. damaging operating conditions, risk based prioritisation of failure modes

Applications and Targets

- Identification of usage space, definition of reference duty cycles and reliability targets

Test Program and Load Analysis

- Determination of acceleration factors, damage modeling, adaptation of test program

Evaluation and Optimization

- Reliability and durability analysis of test program, timing & costs, warranty risk reduction
USAGE SPACE ANALYSIS
IDENTIFICATION OF CRITICAL DRIVING CONDITIONS

Statistical analysis of relevant damaging parameters and variation of in-field use conditions

- Southern California ≠ Northern Europe
- City Driving ≠ Mixed Driving Cycle
- Sporty Driver ≠ Economic Driver
- Frequent Use ≠ Occasional Use

Identification of **Key Customers** for system validation
RELIABILITY TARGET ALLOCATION (RTA)

Our mission is a reliability target of 0 ppm.
This can not be demonstrated statistically.
⇒ Adequate targets for validation have to be determined
The target determines the validation effort

1. Optimize adequate system target regarding
   - legal requirements and warranty strategy
   - planned volume production incl. scale-up
   - available time to test
   - concentration of failure modes (Pareto principle)

2. Derive component- and subsystem specific targets
   consider development, production and economic risks

3. Adapt component targets iteratively throughout development process
   - take the feasibility of demonstration at certain time point into account
   - targets are stated separately for major failure modes

4. Evaluate resulting improvement using Load Matrix update
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A key element to reach the defined targets is the Validation Plan Design

A) General Validation Plan Design Issues
   - Overall number of testing hours for reliability demonstration for the different applications
   - Balancing between component, system and vehicle testing
   - Balancing between Generation 1, Generation 2 and Production Validation phase
   - ….

B) Detailed Analysis
   - Test cycle analysis
   - Length (number of hours or kilometers) of tests
   - Failure modes not validated due to not optimized test cycles
   - Failure modes only validated in the vehicles
   - ..

C) Validation Timing Analysis
   - Validation status at the end of the specific phases (Gen.1, Gen.2 and PV phase )
   - Validation beyond SOP
BATTERY TEMPERATURE WITHIN THE VEHICLE

Measured and calculated relation between outside and battery temperature.

With outside temperature profile over the whole year the battery temperature profile is calculated.

Statistical analysis gives the frequency of occurrence and the dwell time in the different temperature bands.
CALENDARIC AGING FACTOR & DISTRIBUTION OF VEHICLES IN INDIA

Calendaric aging

Aging-distribution:
Out of supplier data or lifetime test program a relation between calendaric aging and temperature is established.

Aging Factor = 1 corresponds to a lifetime of the battery determined at 25 °C

<table>
<thead>
<tr>
<th>Region</th>
<th>No. of Vehicles</th>
<th>Aging Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangalore Urban</td>
<td>228570</td>
<td>1.1495</td>
</tr>
<tr>
<td>Mumbai City</td>
<td>354229</td>
<td>1.6933</td>
</tr>
<tr>
<td>New Delhi</td>
<td>1222706</td>
<td>1.5723</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>District 107</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

Number of vehicles and aging factor per region:

95% below 1.92
### AVL DOE TEST MATRIX FOR CELLS

<table>
<thead>
<tr>
<th>Aging Condition</th>
<th>Temperature</th>
<th>-15 °C</th>
<th>30 °C</th>
<th>70 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-15 °C</td>
<td>30 °C</td>
<td>70 °C</td>
<td></td>
</tr>
<tr>
<td>Storage tests (no cycling)</td>
<td>5 cells (SOC 10 %)</td>
<td>2 cells (SOC 10 %)</td>
<td>5 cells (SOC 10 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 cells (SOC 50 %)</td>
<td>2 cells (SOC 50 %)</td>
<td>2 cells (SOC 50 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 cells (SOC 90 %)</td>
<td>2 cells (SOC 90 %)</td>
<td>5 cells (SOC 90 %)</td>
<td></td>
</tr>
<tr>
<td>Constant current cycling</td>
<td>5 cells (SOC 20 %, DSOC 10 %)</td>
<td>3 cells (SOC 20 %, DSOC 10 %)</td>
<td>5 cells (SOC 20 %, DSOC 10 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 cells SOC 50 %, DSOC 80 %</td>
<td>3 cells (SOC 50 %, DSOC 80 %)</td>
<td>5 cells (SOC 50 %, DSOC 80 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 cells (SOC 80 %, DSOC 10 %)</td>
<td>3 cells (SOC 80 %, DSOC 10 %)</td>
<td>5 cells (SOC 80 %, DSOC 10 %)</td>
<td></td>
</tr>
</tbody>
</table>

Boundary test matrix is shown – intermediate matrix points are required. Number of cells at each matrix point depends on size of planned annual vehicle sales.
ENDURANCE LIFE PREDICTION / ACCELERATION FACTORS
ONGOING R&D PROGRAM

Data + Model

Temperature spectrum

Calculated calendar life (for simulated / measured temperature profile)

SOC load spectrum

Calculated cycle life (for simulated / measured SOC-profile)

Optimization

Combined life endurance of battery (estimated value, forecast)

Combined life endurance of battery (actual value from vehicle usage and validation program)
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LOAD MATRIX: OPTIMIZED TESTING AND VALIDATION

Reliability Validation Target

Demonstrable reliability

Load Matrix

- Systematic methodology to optimize the testing plan before start of development
- The reliability shown in the testing plan is demonstrated when the test runs are completed without failure
LOAD MATRIX RESULTS

Demonstrable reliability, durability coverage

Characterisation of tests

Optimised test procedures for maximum acceleration

Complete, balanced test program for
  - optimised duration, number of samples to test under given budgetary situation
  - optimised balance between rig, dyno, vehicle and supplier tests
  - optimised test sequence

Assessment check list for intermediate and final parts assessment

Test acceleration factors

Track analysis / customer usage profile analysis

Overview of critical and validation-relevant components and failure modes

Overall mileage accumulated for critical components / failure modes

Durability / reliability / warranty risk at SOP or other important milestones
AVL LOAD MATRIX SUMMARY

Analysis and optimization of product validation regarding

- Timing vs. product release
- Reliability demonstration and lifetime coverage
- Validation costs and warranty risks

Integration of internal and external contributions on a common platform

- Validation contributions of all departments and suppliers
- Economic, market, legal and sales requirements

Simple implementation into existing development process and tools

Generic methodology (Applicable to powertrain, hybrid, fuel cell, …)

Technical risk management and tracking

Demonstration of improved reliability reduces risk of failure and hence warranty costs.