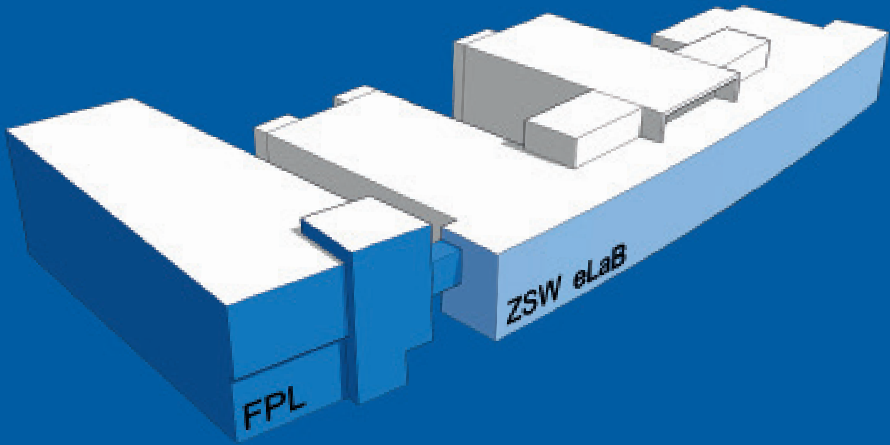
// ZSW Laboratory for Battery Technology (eLaB)



"Now that the eLaB has been extended with industrial manufacturing technology, we have all the areas of battery research housed uniquely under one roof with around 10,000 m² of space for materials research, electrode and cell technology, battery systems engineering, and the battery test center. Join us on a tour of the eLaB as we present our research, objectives, and infrastructure to you on the following pages."

Prof. Dr. Werner Tillmetz, Member of the Board of Directors

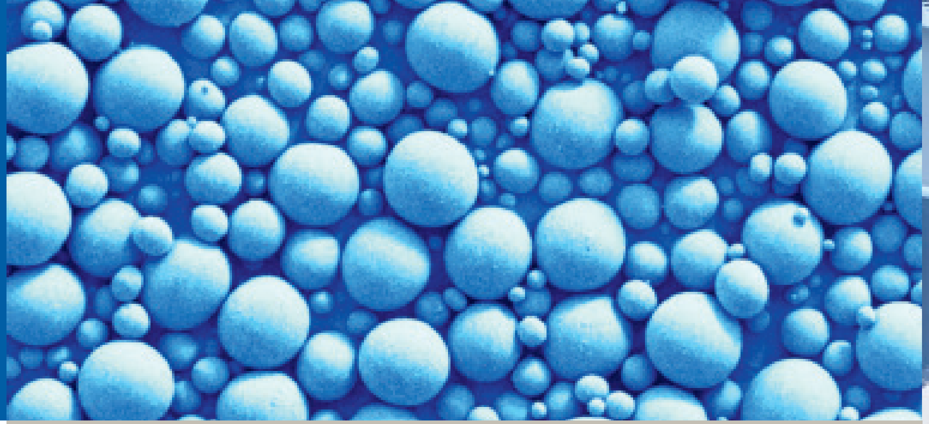
// The eLaB at a Glance

Batteries are the key to tackling one of the most important scientific, social and economic challenges of the 21^{st} century – the ability to store electrical energy for decentralized stationary or mobile applications.

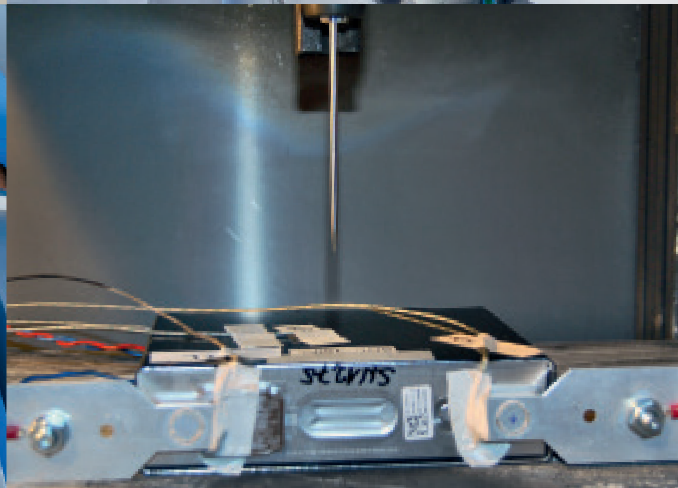
Lithium-ion cells not only deliver the power for electrical or hybrid drives, they are also the driving force in terms of cost, energy consumption, range, and reliability of the vehicle. This is why lithium-ion technology has become a strategic necessity for tomorrow's automotive industry. With their excellent cycle stability, lithium-ion batteries allow decentralized electricity storage, providing a unique opportunity to optimize the self-consumption of power that has been generated locally, e.g. by a local photovoltaic system. They can also help to optimize electrical grids and provide emergency power.

The experts at ZSW have been exploring the ways and means of electrochemical energy storage for more than 25 years. Past research focused mainly on materials, battery safety, and systems engineering, but in 2010 we branched out into lithium-ion cell manufacturing technologies. Our eLaB, a world-class laboratory manufacturing small standard cells (18650 format and 5-Ah pouch cells), was up and running a year later.

A research platform for the industrial production of large scale cells such as those used in electric and hybrid vehicles was added in 2014. And with that, all the areas of battery research have been unified under one roof. Our scientists' expertise now extends to research into new active materials (cathode, anode and electrolytes) and methods of incorporating these into high-quality electrodes and cells. These specialists also have the skills and tools to comprehensively characterize cells and entire battery systems as well as conduct post-mortem analyses to assess aging mechanisms and causes of failures. With these human and hardware assets, ZSW is able to furnish to our industry and research partners a lab unrivalled the world over.

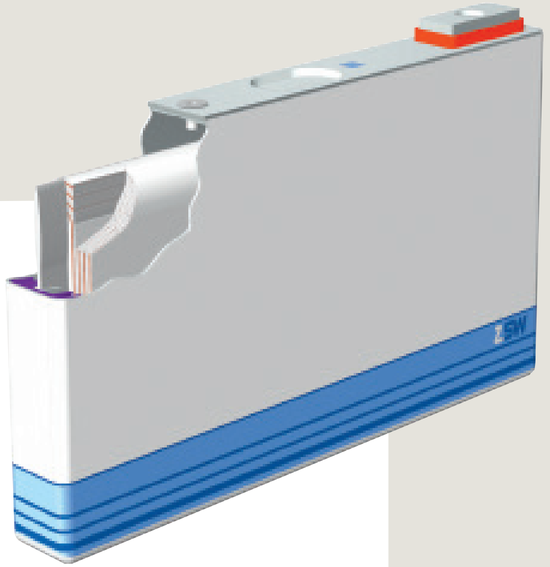


// Join us on a whirlwind tour of our newly extended ZSW eLaB and discover on the following pages this unique 10,000 m^2 research facility.



// eLaB Activities at a Glance

An innovative active material alone does not make for a good battery. Interaction between the electrodes and the electrolyte determine performance and lifetime. Suitable electrodes can only be produced on the basis of the right particle morphology and selected additives. Cost and quality of the end product depend on the cell design and the quality and speed of manufacturing processes. Sophisticated durability and safety tests confirms the ability of a cell to meet the customers' manifold needs is confirmed. ZSW has brought all these skills together at one location: the eLaB.



ZSW Cell compliant to DIN standard

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// Materials research and post-mortem analysis

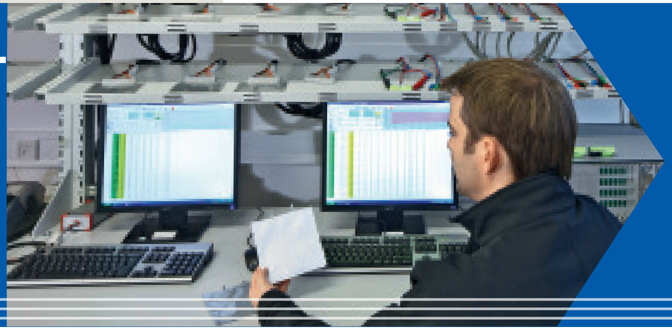
2

// Laboratory production: electrode and cell technologies

3

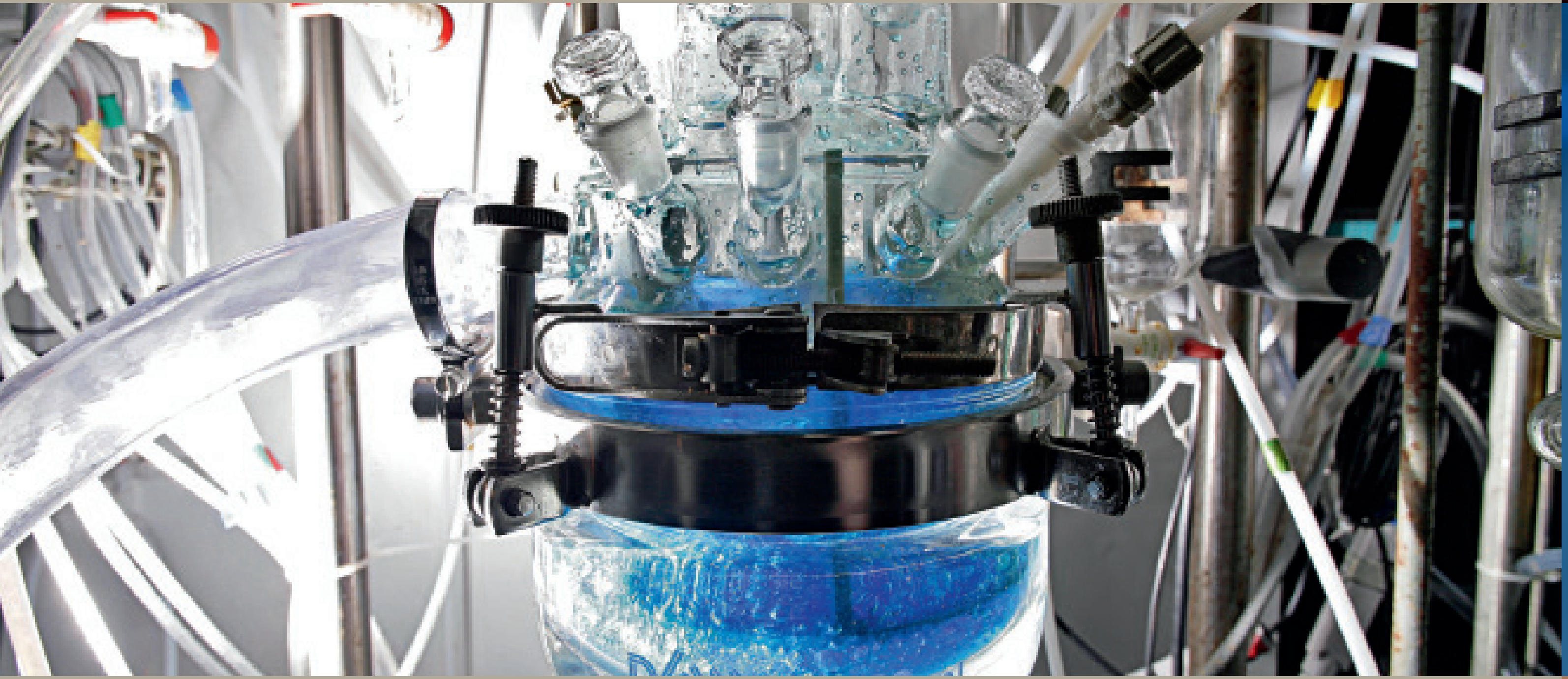
// Research platform for the industrial production of lithium-ion cells (FPL)

4



// Battery test center and battery system engineering

// Materials Research and Post-Mortem Analysis



In 25 years dedicated to researching materials, we learned much about the relationships between structure and powder morphology. With this insight, we are able to attain the desired functions and properties in materials. Our scientists are now busy exploring new cathode materials such as high-voltage spinels and lithium transition metal phosphates and silicates as well as anode materials such as optimized carbon modifications, titanates, and alloy anodes for lithium-ion batteries. Intensive research into new electrolyte systems with special additives and into electrode materials for future lithium-sulfur and lithium-air batteries is also underway.

We specialize in post-mortem investigations to perform failure analysis and evaluate new cell designs. The lessons learned here help us understand aging processes, pinpoint potential safety risks and optimize cell designs.

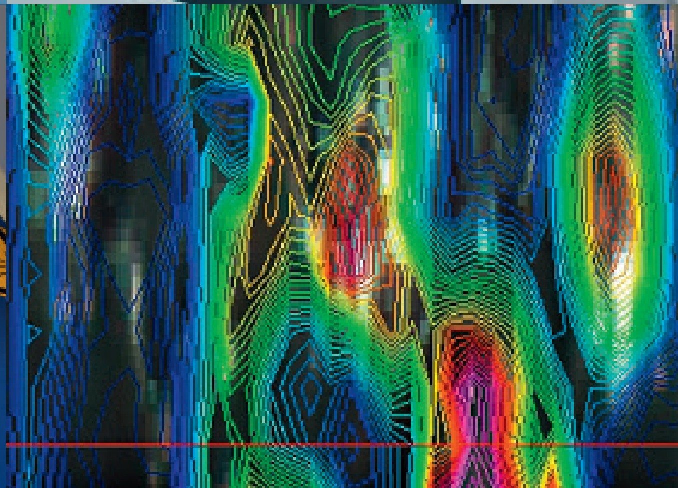
// Materials Research and Post-Mortem Analysis

Tasks

// Develop new active materials: high-voltage spinels, lithium transition metal phosphates and silicates as well as titanates, alloy anodes and electrolytes including additives
// Optimize 'classic' active materials: morphology, surface modification, etc.
// Research on future technologies: Lithium-sulfur, lithium-air, magnesium-air, organic batteries, supercapacitors, etc.
// Analyze interactions: electrode-electrolyte and anode-cathode
// Understand of battery materials and components aging mechanisms
// Investigate of individual battery components safety-related behavior
// Failure assessment and post-mortem characterizations of commercial cells

Tools

// Synthesis laboratory for inorganic powders up to the kg-scale
// Physicochemical methods for materials characterization: elementary analysis, scanning electron microscopy, structural analysis, thermal analysis, flash-point determination, vapor pressure determination, conductivity measurement
// Electrochemical test stations for materials and component characterization
// In-situ electrochemical methods: FTIR spectroscopy, Raman spectroscopy, dilatometry, gassing, etc.



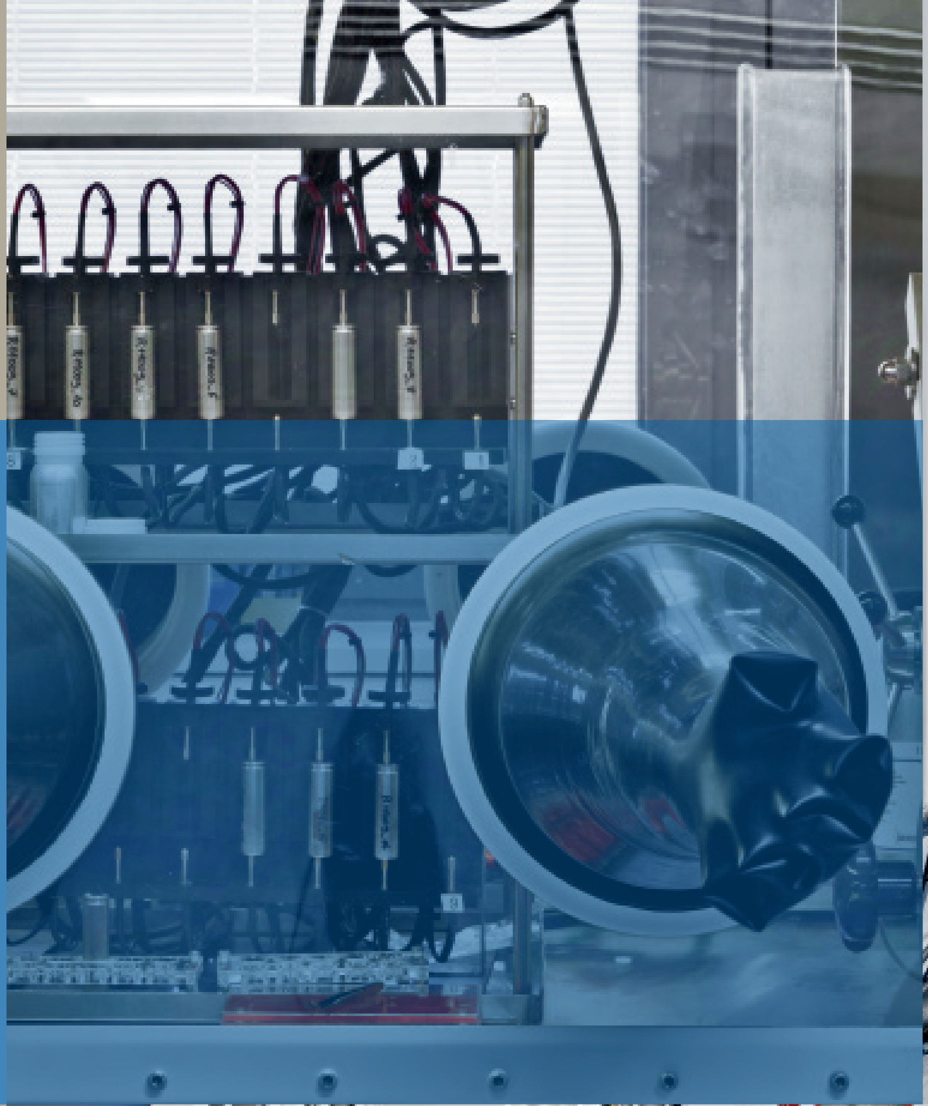
// Laboratory Production: Electrode and Cell Technologies

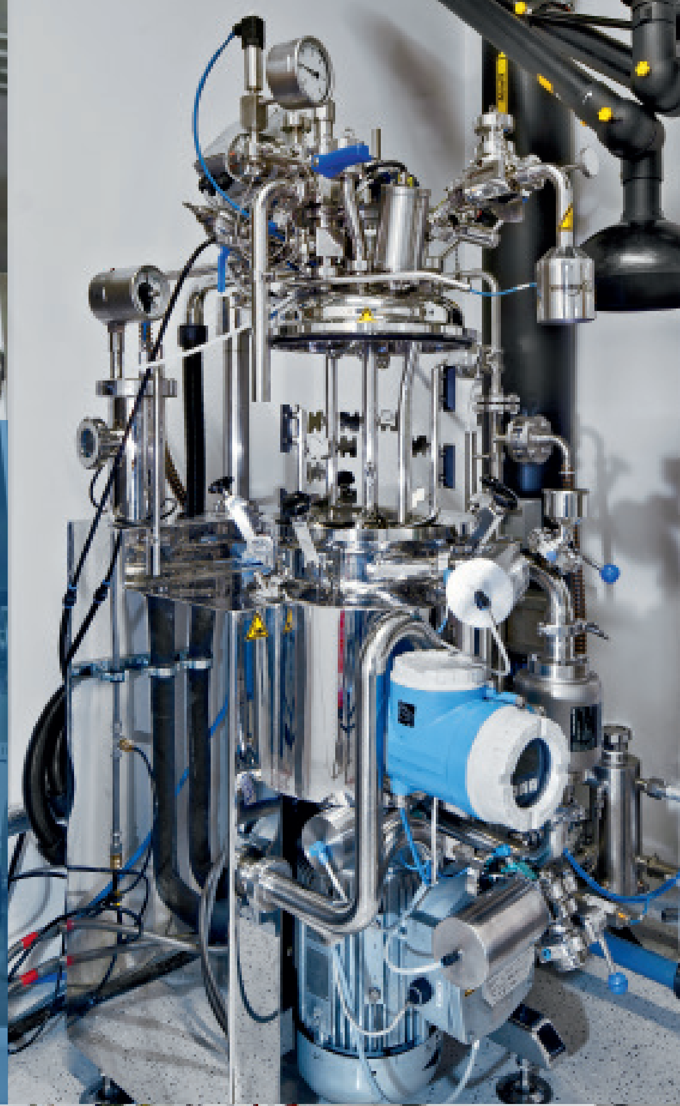
Advanced active materials cannot be brought to market without first mastering the intricacies of electrode and cell technology.

Our lab manufactory has all the equipment and infrastructure, including a dry room and analytical tools, needed to make fully functional cells with new active materials or advanced cell components. Much of the lab production effort is geared towards developing slurries with innovative cathode and anode materials, producing electrode sheets and validating them in standard small scale cells (18650 or pouch format).

An experienced team of more than 45 scientists and technicians bridges the divide between materials research and manufacturing technology.

// Laboratory Production: Electrode and Cell Technologies





Tasks

// Produce sample electrodes (up to 150 m) and standard cells (18650 and pouch format)

// Develop suitable coating slurries with new active materials and additives, including particle pretreatment

// Improve electrode microstructure and manufacturing process (e.g. with water-based coating)

// Balance electrodes and optimize cell design to boost lifetime, energy density and performance of the cell

// Elucidate the interaction between materials, components, and mechanical and electrochemical properties in real cells

Tools

// Laboratory equipment for slurry preparation, electrodes and cells: mixing stations as well as coating, calendering, and slitting machines, laser welding, laminating, and electrolyte filling systems

// Analytics lab for characterization: rheology, adhesion, porosimetry, etc.

// Some 300 cycling stations for electrochemical characterization

Dr. Margret Wohlfahrt-Mehrens
Head of Department Accumulators Research

"Future mobility and renewable energies require new energy storage systems. We cover the entire value chain from powder to the finished cell and can thus make an important contribution."

// Research Platform for the Industrial Production of Lithium-Ion Cells (FPL)

Our research platform for industrial cell production encompasses all equipment and infrastructure used in commercial production. High quality and reproducible cells in small series can be produced on this line. The systems for slurry preparation, coating, calendering, slitting, assembly, and formation are not permanently linked, so new and advanced manufacturing processes can be flexibly integrated and tested in pilot runs.

A highly qualified team of interdisciplinary experts is in place to ensure these systems operate reliably. What's more, these specialists share their knowledge with our industry partners to facilitate cost analysis and put new methods of quality assurance into practice.

// Research Platform for the Industrial Production of Lithium-Ion Cells (FPL)

Tasks:

// Enable materials manufacturers to demonstrate advanced active materials and chemistries in standard cells

// Provide a practically industrial environment to assess new materials and components

// Furnish a reliable modular platform for testing and improving new manufacturing processes and system components

// Develop and improve process parameters and quality assurance methods that determine manufacturing quality and yield under real-world manufacturing conditions

Tools:

// Automated weighing and loading of materials

// Temperature controlled mixing stations for preparing slurries in 60-liter batches

// 500 mm thick electrode coating on both sides at 20 m/min. belt speed using various application systems

// High precision calender

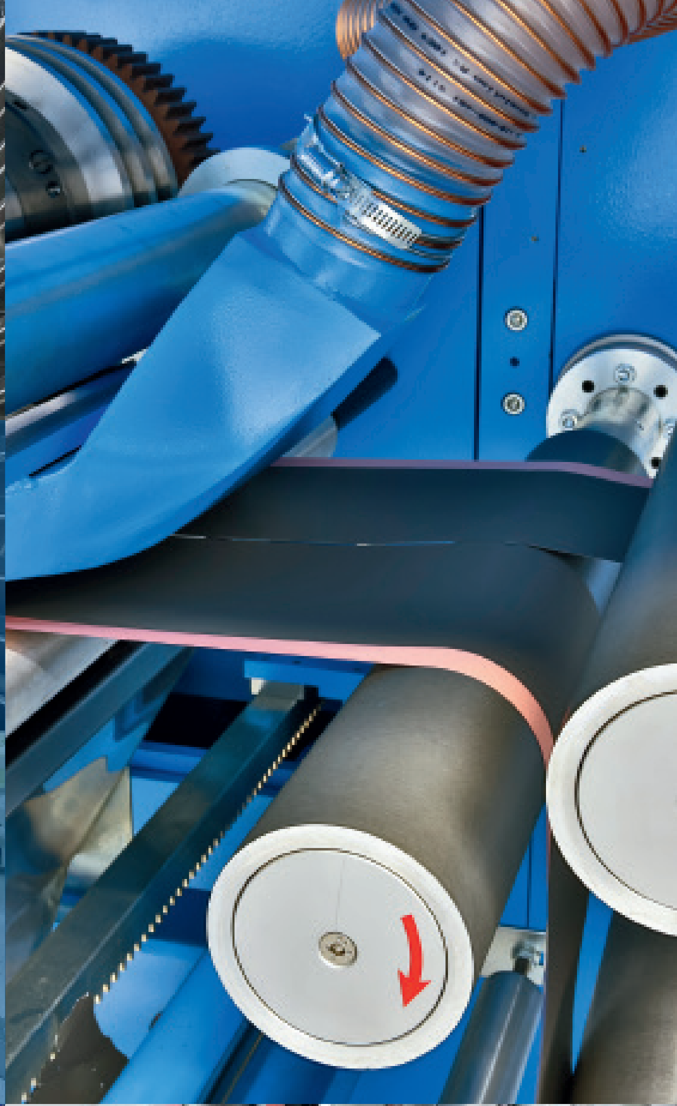
// Fully automated systems for winding, assembling, and filling of prismatic cells with a cycle time of 1 cell/min.

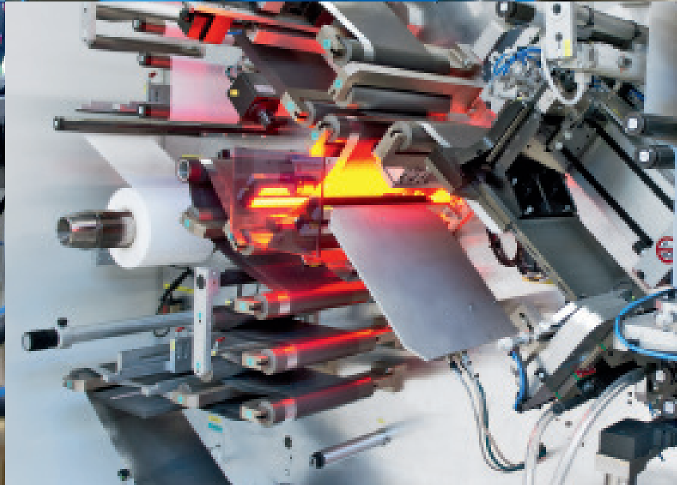
// 200 m^2 dry room with -60°C dew point for testing new assembly technologies

// Fully automated formation with 240 temperature controlled cycle stations and 1,920 storage stations

Wolfgang Brugger
Head of Department Production Research

"The blueprints for commercial manufacturing are drawn up with this research platform."



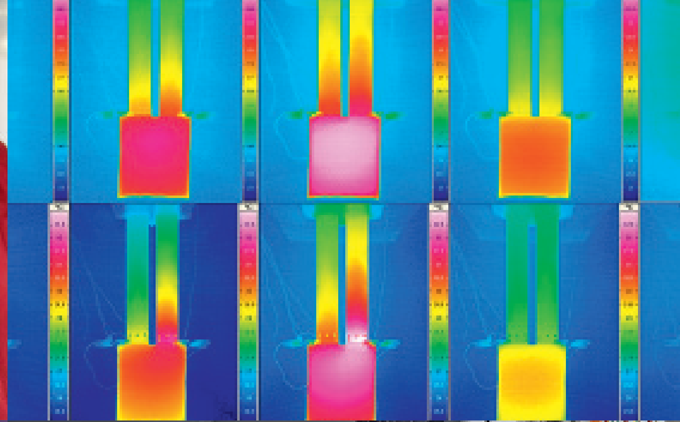


// Battery Test Center and Battery System Engineering

The mission of the battery test center is to conduct performance, lifetime, endurance, and safety tests on cells, modules, and batteries designed for portable, mobile, and stationary energy storage systems. A great deal of effort is devoted to characterizing batteries under various operating conditions and studying their behavior in response to abuse and crash.

Much of battery system engineering boils down to modeling thermal and electrical behaviour and simulating cells and battery systems. We also develop modules, battery management systems (BMS), and model-based algorithms, the latter to indicate state of health and state of charge to predict system performance and to manage charge control.

// Battery Test Center and Battery System Engineering



Tasks

// Conduct electrical tests on cells, modules, and systems for function, performance, and lifetime under defined loads and defined environmental conditions
// Carry out abuse tests to assess reactions and potential hazards in extreme situations
// Assess capability of resistance to various types of abuse and handling failures
// Electrochemical characterization of full cells and analysis of aging mechanisms
// Test, analyze, and model aging processes
// Design battery modules and systems and explore simulation-based system design options
// Develop algorithms, software and electronics for battery management systems (BMS)

Tools

// Testing equipment for large batteries, modules, and cells
// A safe, temperature-controlled test environment with CAN communication
// Three bunkers for safety tests with hydraulic crush and short-circuit test equipment, a fire test bed, data acquisition tools, a video surveillance system, shock and vibration tests
// Multi-cell battery simulator for hardware-in-the-loop validation of battery management systems
// Impedance spectroscopy for cells and modules
// Algorithms for analyzing data sourced from impedance spectra and voltage profiles
// Infrared cameras for thermal analysis of inhomogeneous temperature distribution in cells and modules
// A test bed for validating cooling concepts

Dr. Harry Döring
Head of Department Accumulators

"In the eLaB, we research, test, and analyze batteries and systems in flexible, standards-compliant, and innovative ways."

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