ACCURE
Battery Intelligence

Predictive diagnostics to improve battery safety

WHITE PAPER

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Lithium-ion batteries (LIB) are a key enabler of our clean energy future. Today, LIB already power devices from electric scooters to ships and grid-connected storage systems. However, as with all energy sources, batteries carry a certain risk of failure. For LIB this can result in gassing and burning, potentially harming people and property. The ongoing trend towards ever higher energy densities literally adds fuel to the fire.

Figure 1 shows the trade-offs typically made in the design of LIB. To achieve higher energy densities, manufacturers use more reactive materials while minimizing safety margins. With more energy stored in a single battery, larger amounts of energy are released in case of a failure.

With the fast growth of the battery industry, the number of battery incidents has also increased. One prominent example is the 2019 fire at an APS site in McMicken, Arizona. A battery failure led to a massive explosion in one of the storage containers, causing millions in damages and hospitalizing several firefighters. In the automotive world, General Motors, Hyundai, and Kia had to recall over 200,000 electric vehicles between 2020 and 2021 after more than 30 battery fires. All these incidents involved world leading companies with decades of experience in the battery sector.

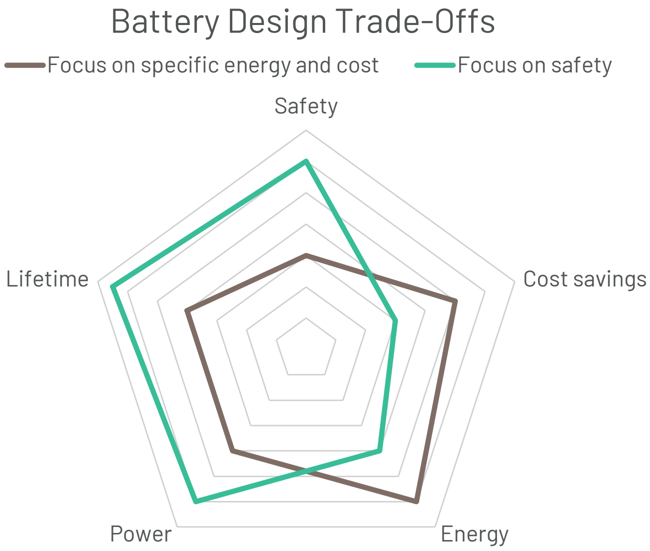

Figure 1: Illustration of the typical trade-offs in battery cell design

1. Types of battery faults

Critical battery incidents include cell openings that lead to the release of toxic gasses (including hydrofluoric acid), internal short circuits and fires. Once a LIB ignites, it becomes practically impossible to extinguish the fire, as the decomposition of its active materials generates oxygen, continuously fuelling the fire – the dreaded thermal runaway. A major thread lies in the fact that once a cell goes into thermal runaway, the incident can easily cascade into neighbouring cells, ultimately destroying the whole storage system and/or adjacent facilities.

Figure 2 illustrates the causes, cell internal processes, and resulting failure mechanisms of a battery system. One of the main root causes of battery faults are **manufacturing defects**. These can occur on cell, module, or system level.

- Common problems on **cell level** include contamination of materials, inhomogeneities in the production process or insufficient safety margins. General Motors stated in late 2021 that internal investigations of the series of Chevrolet Bolt fires suggest a torn anode tab and a folded separator to be the root cause.
- On **module level**, poor cell connections, a faulty thermal management or a mismatch of the cells can cause safety issues. Semi- or even fully automated welding for instance, does not only apply a short but distinct thermal stress to the battery cells, but also brings along a specific failure rate. With millions of cells being assembled into modules each day, even thorough QM procedures sometimes miss these errors.
- On **system level**, a bad coordination of multiple battery modules or faulty state estimation can start a devastating error chain. Errors on system level like these are likely the reason for a significant part of the docents of fires in large-scale battery storage systems in South Korea between 2018 and 2019.

Additional danger can come from **operational faults**. LIBs are designed to work within a clearly specified range of boundary conditions regarding temperature, voltage and current. Operating a LIB outside of these limits does not only cause accelerated aging but can trigger critical failure mechanisms like a thermal runaway. While every LIB is equipped with a battery management system (BMS) that is responsible for keeping the battery in a safe operating range, reality has shown that even BMS from world-leading suppliers can fail – with sometimes devastating effects (see next chapter).

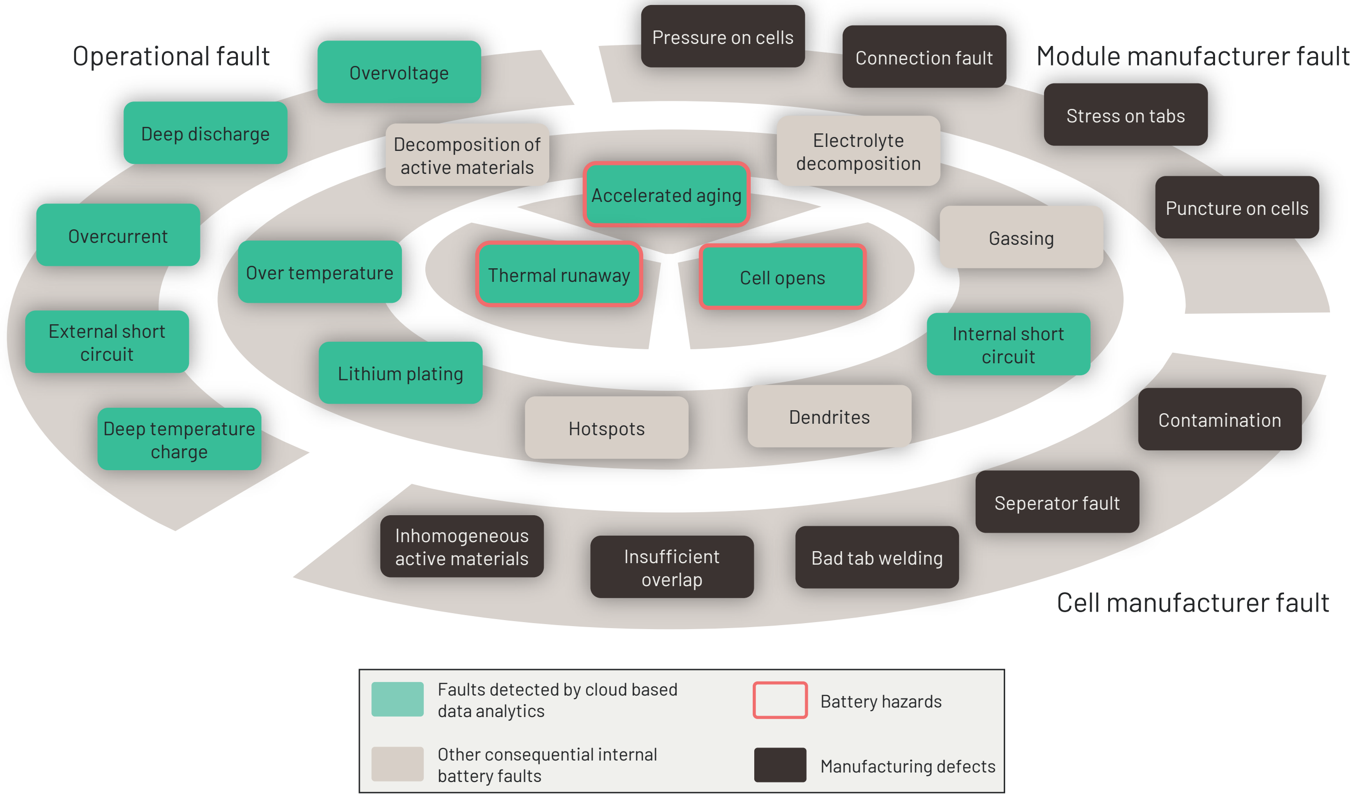

Figure 2: Illustration of root causes of battery failures (outer circle), cell internal processes (intermediate circle) and eventually resulting failure mechanisms (inner circle).

2. Battery protection measures and fault diagnostics

Well-designed LIBs always come with multiple layers of protective measures to ensure a safe operation. The most important protection measures are presented in the following.

2.1 Passive Safety Features

LIB systems usually contain several passive components to ensure the safety of the overall system, including:

- Fuses and relays that break circuits at high currents or in case of failures
- Vents that let out gasses to release pressure from the cell [1]
- Current Interrupt Devices (CID) that interrupt the current path if the internal pressure of a cell exceeds a predefined level
- Positive Thermal Coefficient (PTC) thermistors that reduce the current at high battery temperatures
- Thermal insulation materials such as mica sheets to limit thermal propagation
- Fire-proof housings which can contain a fire inside a battery module, although toxic gas is still released

However, passive safety components are last resorts to minimize the damage from critical situations that are already happening – in many cases they cannot prevent them.

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[1] The released toxic gasses, however, can contaminate facilities or be blown into residential areas.

2.2 Battery Management Systems

Battery management systems (BMS) are electronic circuits containing sensors, logical units, actors, and a communication interface. BMS make sure that a battery is operated within its specifications and usually cover the following tasks:

- Continuously monitor the voltage, current and temperature of the battery system via sensor measurements
- Estimate values such as state of charge (SOC), state of power (SOP) and state of health (SOH)[2]
- Perform active or passive cell balancing to ensure that all battery cells are working at the same SOC
- Communicate with other parts of the overall system (e.g. inverters and energy management system) to ensure smooth operation

While BMS are crucial to the safety of LIB, they also have noticeable shortcomings:

They only see the cells within the corresponding battery pack, have little to no access to historic data or data from other battery systems and are limited in their computing power. Due to these limitations, their capability of detecting anomalies or analysing long-term trends are usually slim to none.

2.3 Predictive diagnostics

An effective strategy to improve battery safety in mobility and energy applications is the use of predictive diagnostics. By detecting critical faults at an early stage, battery operators can act before any damage is done. As the diagnostics are solely based on existing data streams, they can be applied to any LIB system without the need for any product modification. The concept of predictive diagnostics is presented in **Figure 3** and summarized in the following.

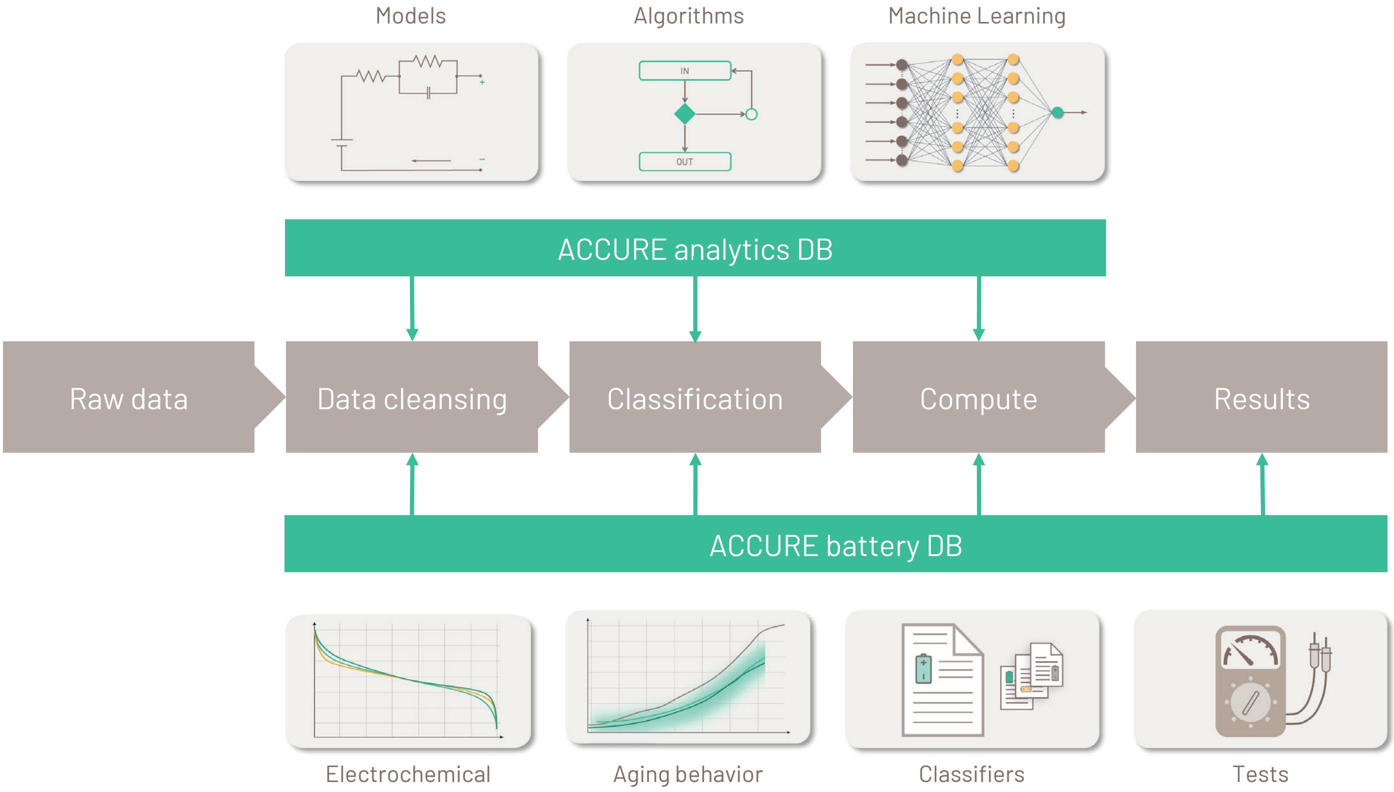

Figure 3: Schematic workflow of ACCURE's predictive diagnostics

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[2] Due to the limited computing capabilities of BMS, these estimations can be bad. As an example, Tesla faced severe trouble with their Chinese Model 3 cars due to bad SOC estimations. The batteries regularly went into deep discharge, permanently damaging the batteries.

Step 1: Data pre-processing
The starting point for all calculations is the continuous stream of measurements coming from the BMS ("raw data"). To leverage this data, extensive data cleansing needs to be performed: For one, outliers and systematic measurement errors need to be detected and flagged as such to avoid false interpretations. But more generally speaking, every BMS has its own (systematic and statistical) errors and idiosyncrasies that need to be understood to make sense of the data. A robust cloud platform must be able to work with any kind of input data and needs to draw the right conclusions from every new data point.

Step 2: Fault detection
Fault detection algorithms scrutinize the battery data to check for potential faults. A fault can be identified through changes in primary parameters such as voltage, temperature and current or in secondary parameters such as impedance, a shift in the open circuit voltage curve or the amount of active lithium in each cell. To track secondary parameters, model-based algorithms, which consider reduced order physical-/chemical processes through mathematical equations are used. Identifying and tracking specific patterns in these parameters for the millions of similar cells, which are in operation, enables these algorithms to find anomalies before they become dangerous.

Step 3: Reporting
If a battery is identified to be dangerous, automatic warnings are generated. A two-level system has proven to be effective in this regard.

- Yellow warnings indicate that a battery is experiencing systematic underperformance or showing unexpected behaviour – for example due to a miscalibration of the BMS or a loose cell connector. These issues can oftentimes be resolved by a technician or a software update before they become problematic.
- Red warnings require immediate action, as a critical fault is imminent. The battery system should be brought into a safe operational state and needs to be investigated or replaced by a trained expert.

3. Examples of predictive diagnostics

With hundred thousands of battery modules under management, ACCURE Battery Intelligence operates one of the largest battery databases in the world – including systems that experienced critical failures. Four examples of such systems are presented below. To protect the interests of our partners, all results are anonymized and slightly modified while preserving all relevant information.

BMS failure detection

It is the BMS's job to supervise the battery cells, but who supervises the BMS? Most BMS do not provide full redundancy. Hence, failures are not likely, but do occur and can result in devastating failures. **Figure 4** shows the voltage profile of a battery cell from a top-5 battery supplier.

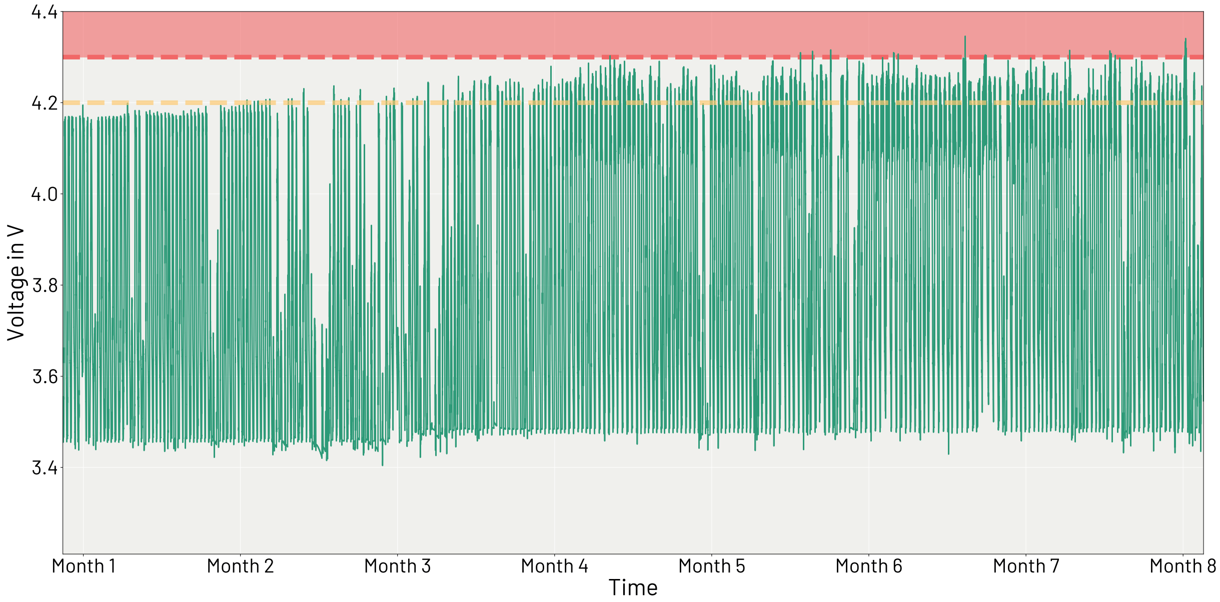

Figure 4: End-of-charge voltage increases over time causing voltages to reach critical values

The full charge voltage of this battery steadily increases over time, way beyond its specifications. Such overcharging not only causes accelerated aging but can also drive lithium-ion batteries into a thermal runaway. An online safety monitoring can reliably catch BMS shortcomings like these before they trigger critical battery failures.

Drifts between cell voltages

Whenever battery cells are connected in a serial configuration it is advisable to implement a balancing system. The balancing system levels the SOC of the individual cells to maximize the usable energy content. Accordingly, in normal operation, the voltage of the cells should be identical throughout a large SOC range. Persistent voltage drifts can be precursors for cell faults, which could lead to gassing and/or fires. **Figure 5** shows the voltage drift over time for a faulty battery module.

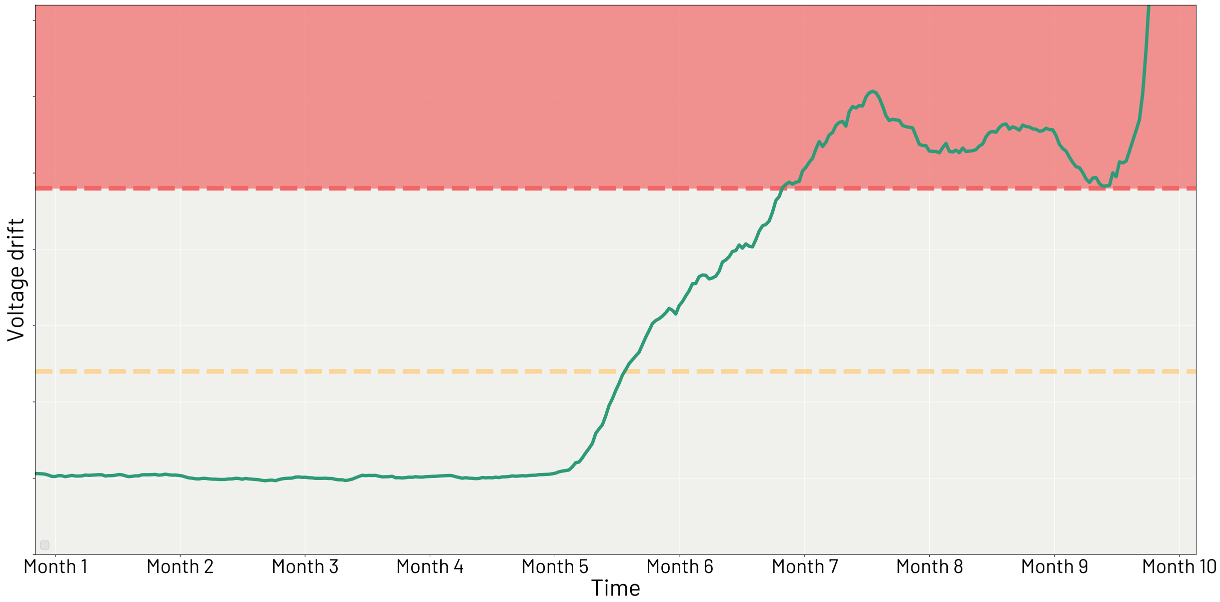

Figure 5: Voltage drift between battery cells exceeds acceptable limits, indicating a failure

The accelerated voltage drift starting between month 5 and 6 is a strong indicator for a battery cell failure. Eventually, the voltage drift reaches a critical level. ACCURE's safety algorithms automatically warn about such irregular battery behavior.

Model-based safety diagnostics

An advanced and powerful way of tracking battery safety is via model-based approaches. These algorithms mirror electrochemical relationships and processes, thus revealing information about the internal states of the battery. One example for a LIB model parameter extracted from operational data is presented in **Figure 6**.

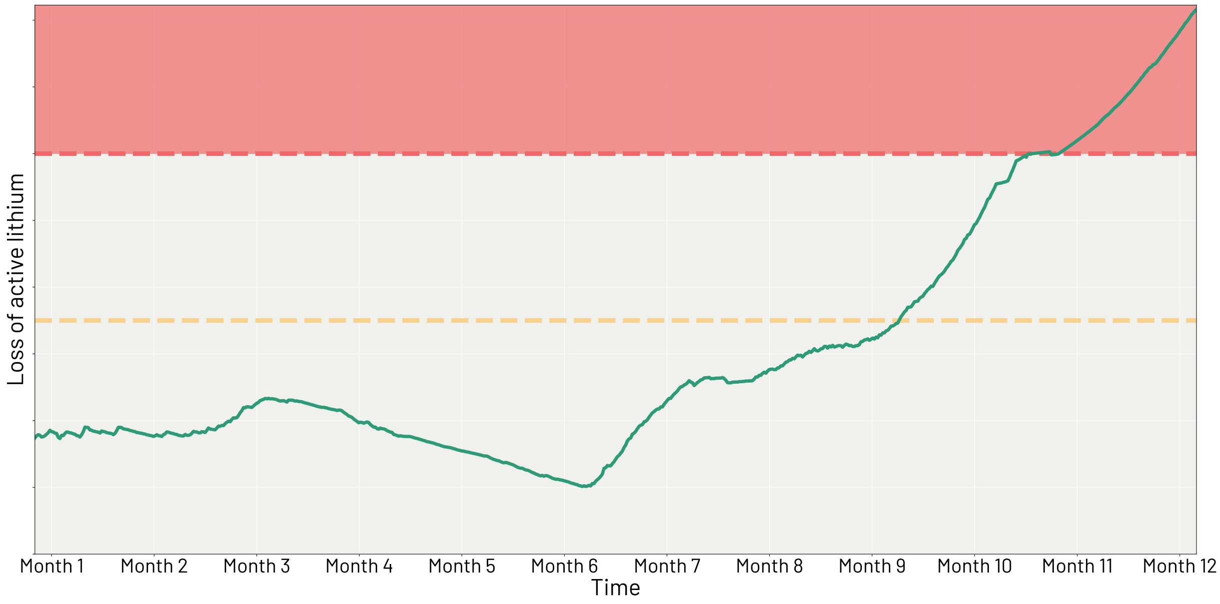

Figure 6: Model-based safety diagnostics track the loss of active lithium over time

If a battery is charged with comparably high current rates, possibly at low temperatures, lithium-plating may occur. Lithium-plating does not only age the cell, but it can also become a safety threat by forming metallic dendrites and triggering side reactions such as gassing. It manifests itself in a decrease of the lithium inventory which is no longer available for the main reaction. ACCURE's safety algorithms closely track the loss of active lithium in battery cells to predict safety critical events.

4. Conclusion

To be a key pillar of our energy and mobility world, batteries must be safe and reliable. Predictive diagnostics have proven to be an effective extra layer of safety that can be implemented without the need for additional hardware or product modifications. This also enables **smart insurance products**, which ACCURE is offering together with international partners.

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