BATTERY SAFETY SENSOR

EARLY DETECTION OF THERMAL RUNAWAY IN LITHIUM-ION BATTERY SYSTEMS

A Technical Perspective on Marquardt’s Approach to Battery Safety

More Information here:

https://www.marquardt.com/products-solutions/power-energy-management/battery-safety-sensor

V. 1.0 | 29.05.2026

MANAGEMENT SUMMARY

Battery safety is shifting from passive containment to active, predictive detection. The Chinese automotive standard GB 38031-2025, together with the BESS regulations UL 9540 / 9540A and the 2026 edition of NFPA 855, redefines the boundaries of technical feasibility – and forces a fundamental rethink of how thermal runaway is monitored in modern battery systems.

Conventional methods – surface temperature and voltage monitoring – react too slowly in high-density battery packs and are highly prone to false alarms. They register a failure only when the thermal chain reaction is already physically impossible to stop.

Marquardt's Battery Safety Sensor (BSS) platform addresses this gap with a MEMS-based thermal conductivity detector (TCD) for highly selective hydrogen (H_2) detection. Combined with intelligent environmental compensation (temperature, pressure, humidity) and optional add-ons – accelerometer for post-crash diagnostics and a MOX sensor for slow electrolyte seepage detection – the BSS delivers a fast, false-alarm-resistant, and long-term-stable indicator of the first venting event.

Combined with the Marquardt Cell Module Controller (CMC), the High-Voltage Sensor (HV-Sensor), and the Battery Management System (BMS), the BSS forms a closed mechatronic safety chain that reliably prevents fires and container explosions – engineered to automotive-grade reliability and produced on validated mass-production lines.

Takeaway: Single stage OBC technology is a future-oriented architecture option for OEMs that want to improve packaging, efficiency potential and V2X readiness without increasing system complexity at the vehicle interface.

MOTIVATION

The global volume of installed lithium-ion battery systems has reached approximately 1.59 terawatt-hours (TWh). While electromobility remains the volume-dominant segment, stationary battery energy storage systems (BESS) show the most dynamic growth, with an annual rate exceeding 50%.[1]

The ppm Risk in Mass Production

Modern lithium-ion cells benefit from highly mature manufacturing processes. The statistical rate of catastrophic, manufacturing-related cell defects among quality manufacturers is extremely low, ranging from 0.1 ppm (1 in 10 million) down to 0.025 ppm (1 in 40 million).[2] At the massive volumes currently in circulation, however, even this negligible-sounding probability translates into real-world damage incidents.
A typical 5 kWh residential storage system contains roughly 1,000 to 1,500 cylindrical cells (18650 / 21700 format). At a failure rate of 0.1 ppm, this corresponds to a statistical risk of approximately one critical cell defect per 7,000 to 10,000 installed systems.[2] For industrial BESS containers in the megawatt or gigawatt range, which concentrate hundreds of thousands of cells in highly confined spaces, this risk multiplies along with a drastic increase in the extent of potential damage.

Electrochemical Aging and the Influence of SOH

In addition to manufacturing-related contamination, electrochemical aging is a primary driver of thermal runaway events. Cyclic charging and discharging cause mechanical expansion and contraction (swelling) of the electrodes, generating continuous stress on the cell housing and internal jelly rolls. This promotes the formation of micro-cracks in the separator.

Particularly critical is the irreversible deposition of metallic lithium (lithium plating) on the anode surface, triggered by extreme fast charging or charging at low ambient temperatures. The resulting needle-like lithium dendrites slowly penetrate the separator and cause internal micro-short circuits. Recent research further reveals that the state of health (SOH) has a non-monotonic influence on TR risk: moderately aged cells (≈ 90% SOH) tend to undergo thermal runaway significantly earlier than fresh cells due to an unstable solid electrolyte interphase (SEI) film, whereas brand-new cells release the highest absolute amount of energy at the moment of collapse.

Cascading Effects and Extent of Damage

Once a single cell enters uncontrolled thermal runaway, thermal propagation – a cascading chain reaction – is imminent. Without countermeasures, the destructive heat can propagate from approximately 300 °C across up to 80% of a module within 60 seconds. Alongside extreme fire temperatures up to 1,100 °C, highly toxic and combustible gases are released. In enclosed spaces, hydrogen fluoride (HF) concentrations can rapidly exceed life-threatening levels above 500 ppm. Reliable early detection of the first venting event is therefore the physical prerequisite for effectively preventing chain reactions and ensuring timely evacuation of the hazardous area.

REGULATORY PRESSURE

In both the automotive sector and the stationary energy storage market, regulators and certification bodies are responding to escalating risks with a drastic tightening of safety standards.

Automotive: GB 38031-2025 as a Global Benchmark

With the publication of the new national standard GB 38031-2025 (mandatory from 1 July 2026), China is establishing one of the world's strictest regulatory frameworks for traction batteries.[5]

- The 2-hour mandate: While the predecessor (GB 38031-2020) only required a 5-minute warning to allow vehicle occupants to exit the cabin, the 2025 version mandates that the battery system structurally withstand a TR event for at least 120 minutes without catching fire or exploding.[5]

- Strict smoke protection: It must be proven that no smoke or toxic gases enter the passenger compartment before the alarm (which must be issued no later than 5 minutes after the TR trigger) and within 5 minutes thereafter.[5]

- Tightened testing procedures: The standard introduces challenging mechanical bottom-impact tests (150 J of energy input via a 30 mm steel ball to simulate underbody damage) as well as safety checks after 300 ultra-fast charging cycles.[5]

For globally operating OEMs, compliance with GB 38031-2025 currently represents the most stringent global safety benchmark; alignment with this standard typically covers the requirements of UNECE R100 and applicable US frameworks, although jurisdiction-specific provisions still need to be verified case by case.

BESS: UL 9540 / 9540A and NFPA 855 (2026)

For stationary utility-scale storage, UL 9540 (product safety standard), UL 9540A (test method for evaluating fire propagation), and the fire protection code NFPA 855 have established themselves as authoritative standards in the US and Europe. The 2026 revision of NFPA 855 shifts the focus heavily toward preventive monitoring, hazard analysis, and intelligent emergency control:

- Mandatory Hazard Mitigation Analysis (HMA): This formal hazard analysis is elevated to a standard requirement for almost all BESS installations, removing previous exemptions for smaller systems. It explicitly demands proof of the reliability and fault-tolerance of detection, ventilation, and extinguishing systems, alongside a precise technical evaluation of hazardous gas generation, dispersion, and potential deflagration risks.

- Energy Storage Management System (ESMS) requirements: The standard tightens criteria for the ESMS, which must be capable of precisely monitoring abnormal operating conditions and automatically disconnecting the storage system from the grid at the first signs of instability. Integrating a highly sensitive H_2 sensor inside the container becomes a core technical prerequisite for compliance with the required HMA safety level.

THE PHYSICS AND CHEMISTRY BEHIND BATTERY SAFETY

A deeper understanding of the thermodynamics of common cell chemistries clarifies why rapid gas analysis is the key to complying with these standards.

Table 1. Comparison of NMC and LFP cell chemistries in a thermal runaway event.[4]

Property	NMC (e.g. NMC 811)	LFP
Self-heating onset	≈ 90 – 110 °C	≈ 150 – 170 °C
Critical TR temperature	≈ 170 – 190 °C	≈ 230 – 260 °C
Peak temperature in failure	> 800 °C	≈ 620 °C
Released energy	20 – 25 kJ/Ah	10 – 15 kJ/Ah10
Oxygen release	Yes — cathode releases O_2	No — stable iron-phosphate framework
Failure character	Violent, jet flames possible	Massive flammable gas release, deflagration risk
Dominant in	Automotive traction (range-focused)	BESS, entry/mid-segment EVs (>90% BESS share)

The Specific BESS Challenge

Because of its cost efficiency and cycle stability, LFP chemistry holds a market share of over 90% in the BESS sector.[1] This creates a specific physical hazard: LFP cells do not release oxygen at the moment of thermal runaway, so they usually do not burn off internally. Instead, they emit massive quantities of highly flammable and toxic gases – hydrogen, carbon monoxide, and hydrocarbons – during venting.[4]

In the enclosed housings of containerized storage systems, this massive outgassing leads to rapid pressure buildup and the formation of a highly explosive atmosphere. If this gas mixture meets an external ignition source or ambient oxygen, a devastating deflagration (room explosion) can destroy the entire container. In the BESS sector the primary goal is therefore not protecting a passenger cabin but absolutely preventing these gas explosions.

Hydrogen (H_2) as the Ideal Early Indicator

In both NMC and LFP cells, hydrogen is the most volatile and earliest-released gas. H_2 is not only generated during electrolyte decomposition but is also emitted in the much earlier phase of lithium plating (dendrite growth) through the spontaneous reaction of metallic lithium with the electrode binder. Scientific studies confirm that gas sensors detect this chemical signature on average up to 10 minutes before the actual thermal collapse – approximately 2 minutes faster than voltage sensors and up to 7 minutes faster than conventional surface-temperature sensors.[3]

In a BESS context, this extremely fast H_2 detection opens a decisive time window: the sensor signal allows the system to trigger explosion-protection measures (activating explosion-proof ventilation fans to dilute the gas mixture, or flooding with inert gas extinguishing systems) before the mixture in the container reaches the lower explosive limit (LEL).

LIMITATIONS OF CONVENTIONAL DETECTION METHODS

Many existing battery monitoring systems attempt to capture TR events using conventional sensors. Each runs into narrow physical boundaries when used in isolation.

- Temperature monitoring alone: Module-exterior or cooling-channel sensors react extremely slowly due to the thermal inertia of high-density packs.
  If the defect originates deep inside a dense jelly roll, the cell can already reach critical internal temperatures while measurement points still read normal values.

- Pressure measurement alone: Pressure sensors capture the sudden spike when a burst disk opens (venting) immediately, but are prone to false alarms in real-world operation. Barometric pressure changes (e.g. due to fast mountain climbs and tunnel entrances and exits) or normal thermal expansion under electrical load generate gradients simple pressure sensors cannot reliably distinguish from a true first-cell venting – especially in larger enclosures with increased dead volume.
- Cell voltage monitoring alone: Voltage monitoring registers a significant drop only after an internal short circuit has already destroyed the separator, at which point the thermal chain reaction is physically almost impossible to stop. During the crucial early phase of venting, terminal voltage usually remains stable or fluctuates minimally – drowned out by drivetrain or peripheral electromagnetic noise.

Direct Comparison of Detection Methods

Table 2. Comparative profile of common TR detection methods.[1]
Lead-time is referenced to the moment of thermal collapse based on the indicative timings in chapter 3.

Method	Detection lead-time[1]	Selectivity	False-alarm rate	Long-term stability
Surface temperature	Last (baseline)	Low	Low	High
Cell voltage	≈ 7 – 8 min after H_2	Low	Medium	High
Pressure (venting)	Concurrent with venting	Low	High	High
MOX gas sensor	Comparable to H_2 TCD	Medium	Medium	Low (drift, poisoning)
TCD H_2 sensor (Marquardt BSS)	Earliest — ≈ 10 min lead	Very high (physical, H_2-specific)	Very low (compensated)	Very high — maintenance-free

THE SOLUTION: THE BATTERY SAFETY SENSOR (BSS)

The BSS platform from Marquardt overcomes these limitations through high-precision physical detection methodology and intelligent data fusion.

The MEMS Thermal Conductivity Principle (TCD)

The heart of the BSS is a miniaturized, MEMS-based thermal conductivity detector (TCD).

- **Physical measurement effect:** Hydrogen possesses the highest thermal conductivity of all known gases except helium, conducting heat about seven times better than air. When H_2 escapes within the housing, the heat dissipation of a microsystem-controlled heated sensor element changes instantaneously fluctuates minimally – drowned out by drivetrain or peripheral electromagnetic noise.

- **Wheatstone bridge:** The sensor consists of two microelectronic dies on a single chip: an active die exposed to the ambient gas and an identical reference die hermetically sealed in a chamber containing air. Both are heated via a classic Wheatstone bridge. If the gas composition at the active die changes due to H_2 escape, the active die cools faster. The resulting resistance change yields a highly precise analog signal proportional to the H_2 concentration in the range from a few ppm up to 4 vol% (the lower explosive limit).

- **Advantage over MOX sensors:** Conventional semiconductor gas sensors (MOX) rely on chemical surface reactions. They are prone to severe drift, aging, and can be permanently poisoned by silicone-containing vapours or electrolyte components. The physical TCD principle of the Marquardt BSS operates without chemically active layers, is completely resistant to sensor poisons, and is maintenance-free over an operating life of many years.

Intelligent Data Fusion

To eliminate cross-sensitivities, the BSS integrates additional sensing of temperature, barometric pressure, and relative humidity into a compact housing alongside the H_2 sensing. An integrated algorithm performs real-time compensation. Simultaneously, the pressure channel serves to redundantly cross-check the venting pressure spike, reducing the probability of false alarms in the system to an absolute minimum.

Integration into Battery Systems

Since hydrogen is the lightest of all gases, it possesses high physical buoyancy inside a battery or container enclosure: it rises vertically immediately after escaping. To achieve minimum response time, the BSS is logically positioned at the top of the battery housing or directly at the manifold / collection channels of the venting system. This ensures that the H_2 gas is routed past the sensor membrane without diffusion delay.

Application-Specific Add-ons

- **Integrated 3-axis accelerometer (shock & service diagnostics):** Optionally, a highly precise 3-axis accelerometer can be integrated into the platform. This sensor accurately captures mechanical shock impacts (e.g. accidents, ground impacts, or rough transport). Providing these acceleration data via the sensor interface enables a well-founded external diagnostic evaluation during servicing — to determine whether the battery pack has suffered internal structural damage and must be replaced, or whether it can be safely operated further – counteracting unnecessary and cost-intensive replacement cycles.

- **MOX sensor for seepage detection (pouch cell applications):** Pouch cells, unlike rigid prismatic or cylindrical cells, do not possess a mechanically rigid burst disk; early cell defects often do not manifest as sudden bursting but as "seepage" – a slow escape of gaseous electrolyte components (volatile organic compounds, VOC) along the soft sealed seams of the foil packaging. The MOX sensor detects these organic solvent vapours in the ppm range long before complete mechanical failure of the cell seal, serving as a highly effective early indicator of beginning cell damage.

THE INTEGRATED SAFETY CHAIN

Marquardt's mechatronic system expertise enables seamless integration of the BSS into a closed, extremely fast safety chain, controlled centrally by the Battery Management System (BMS). The BMS acts as the central intelligence, coordinating all sensor signals and initiating appropriate defensive measures in milliseconds.

- **Real-time detection & signal fusion (BSS + CMC):** The strategically placed BSS detects the physical venting event within seconds and reports gas and pressure data to the BMS. Concurrently, the decentralized Marquardt Cell Module Controller (CMC) continuously monitors voltages and temperatures of individual cells in real time.[3] The BMS fuses these thermodynamic and chemical data, enabling conclusions about thermal propagation at the cell level and forming a plausible overall picture of the damage progression.

- **Prioritized warning output:** Immediately after verifying the fault, the BMS generates a prioritized warning signal — for safe occupant evacuation under GB 38031-2025, or to the control room of a utility-scale BESS. Operators and emergency personnel receive a critical time window for preventive reactions long before visible smoke or open flames develop.

- **Activation of active countermeasures:** The BMS can coordinate further protection mechanisms: activating emergency ventilation (explosion-proof fans to lower gas concentration below the LEL in BESS containers), injecting inert gases to reduce oxygen content, or selectively initiating cooling and extinguishing sequences in the affected housing area.

- **Emergency shutdown (HV-Sensor + Pyro-Switch):** Concurrently, the highly precise, shunt-based Marquardt High-Voltage Sensor (HV-Sensor) monitors currents and voltages in the system.[3] Upon confirmation of a critical fault, the BMS triggers the pyro-fuse. The HV-Sensor ignites the pyro-switch in under 2 milliseconds, galvanically isolating the high-voltage battery from the on-board electrical system.[3] This immediately interrupts the flow of electrical energy, reducing the overall thermal load and significantly slowing propagation.

INDUSTRIALIZATION AND MANUFACTURING EXPERTISE

Translating advanced sensor technology into economically viable mass-produced products requires profound industrialization expertise.

Automotive-Grade Mass Production

Marquardt manufactures complex mechatronic systems in millions of units per year on highly automated production lines. Consistent compliance with the ASPICE Level 2 standard in software and system development guarantees maximum process reliability from initial specification to final validation. Precise temperature and humidity compensation of the TCD sensor is ensured in the factory through regular, automated end-of-line calibration in environmental climate chambers.

Advantages for the Non-Automotive Market

This automotive manufacturing DNA offers significant economic benefits to customers outside the classic passenger car sector. Operators of stationary energy storage systems (BESS), material handling equipment (forklifts / industrial trucks), or marine propulsion systems receive a fully validated, highly reliable product from an established mass-production line. This eliminates the high development costs and risks typically associated with customized niche solutions.

WHY MARQUARDT

The BSS is more than a hydrogen sensor. It is a building block in a complete, mechatronic safety system supplied by a single partner with deep automotive engineering heritage.

Table 3. Differentiators of the Marquardt BSS platform.

Capability	What it means for the customer
Integrated safety chain	BSS + CMC + HV-Sensor + Pyro-Switch + BMS from one supplier — no integration risk between point sensors and downstream actuators.
Automotive-grade processes	ASPICE Level 2 software, end-of-line calibration, validated for safety-relevant series production.
Mass-volume economics	Scalable cost structure proven in millions of units — applicable directly to BESS, marine, and industrial applications.
Regulatory readiness	Architecture aligned with GB 38031-2025 warning, propagation, and disconnection requirements, and with the NFPA 855 (2026) HMA framework.
Long-term reliability	Physical TCD principle eliminates the drift and poisoning failure modes typical of chemical gas sensors over multi-year operation.

CONCLUSION

Securing battery systems against thermal runaway and thermal propagation no longer tolerates technological compromises. The tightened requirements of GB 38031-2025 and the fire-safety regulations of NFPA 855 for BESS installations can no longer be reliably met using conventional, slow measurement methods.

With the Battery Safety Sensor (BSS) platform, Marquardt offers a physically superior, long-term-stable, and false-alarm-resistant solution for the global market. Through the combination of highly selective H_2 thermal conductivity measurement, intelligent data fusion, and seamless integration into the mechatronic safety chain, battery applications are protected across geographies and operating conditions.

NEXT STEP

WORK WITH US:

Request a technical consultation. Discuss your battery architecture, regulatory targets, and integration constraints with our battery safety experts.

Request the BSS datasheet & evaluation kit. Obtain technical specifications, mechanical interface drawings, and an evaluation kit for your test bench.

Schedule an architecture workshop. Joint review of your safety chain – from sensor placement to BMS response logic and emergency disconnection.

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GLOSSARY

Term	Meaning
ASPICE	Automotive Software Process Improvement and Capability Determination — process maturity framework for automotive software development.
BESS	Battery Energy Storage System — stationary, often utility-scale, lithium-ion installation.
BMS	Battery Management System — central electronic controller of a battery pack.
BSS	Battery Safety Sensor — Marquardt's H_2-based TR detection platform (subject of this document).
CMC	Cell Module Controller — Marquardt's decentralized cell-level monitoring unit.
ESMS	Energy Storage Management System — supervisory layer above the BMS in stationary storage.
CMC	Cell Module Controller — Marquardt's decentralized cell-level monitoring unit.
GB 38031	Chinese national standard for the safety of power batteries in electric vehicles.
HF	Hydrogen Fluoride — toxic gas released during Li-ion thermal events.
HMA	Hazard Mitigation Analysis — formal hazard analysis required by NFPA 855.
HV-Sensor	Marquardt's shunt-based high-voltage current/voltage sensor; triggers the pyro-switch.
LEL	Lower Explosive Limit — lowest concentration at which a gas mixture can ignite.
LFP	Lithium Iron Phosphate — cell chemistry; dominant in BESS and many entry-segment EVs.
MEMS	Micro-Electro-Mechanical Systems — microfabricated sensor structures.
MOX	Metal-Oxide gas sensor — chemical-reaction-based sensor for VOC / gas detection.
NFPA 855	US fire-protection code governing stationary energy storage installations.
NMC	Lithium Nickel-Manganese-Cobalt oxide — high-energy cell chemistry common in EVs.
SEI	Solid Electrolyte Interphase — protective layer on the anode; instability drives aging.
SOH	State of Health — overall condition of a battery relative to its as-new state.
TCD	Thermal Conductivity Detector — physical gas-sensing principle used in the BSS.
TR	Thermal Runaway — self-sustaining, exothermic reaction inside a Li-ion cell.
UL 9540 / 9540A	US product safety standard for energy storage systems (9540) and test method for fire propagation (9540A).
VOC	Volatile Organic Compound — escaping electrolyte solvent vapours, e.g. during seepage.

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[4] Peer-reviewed comparison of NMC and LFP thermal runaway behaviour; see e.g. Feng et al., Journal of Power Sources, and corresponding industry analyses (Battery Design — “Objective Safety Analysis of NMC vs LFP,” 2024; Electric & Hybrid Vehicle Technology — “LFP vs NMC Thermal Runaway,” 2026).

[5] China National Standard GB 38031-2025, “Safety Requirements for Power Batteries for Electric Vehicles,” 2025 (primary source); ADT Media, “What China‘s GB 38031-2025 Means for EV Batteries,” 2025 (secondary).