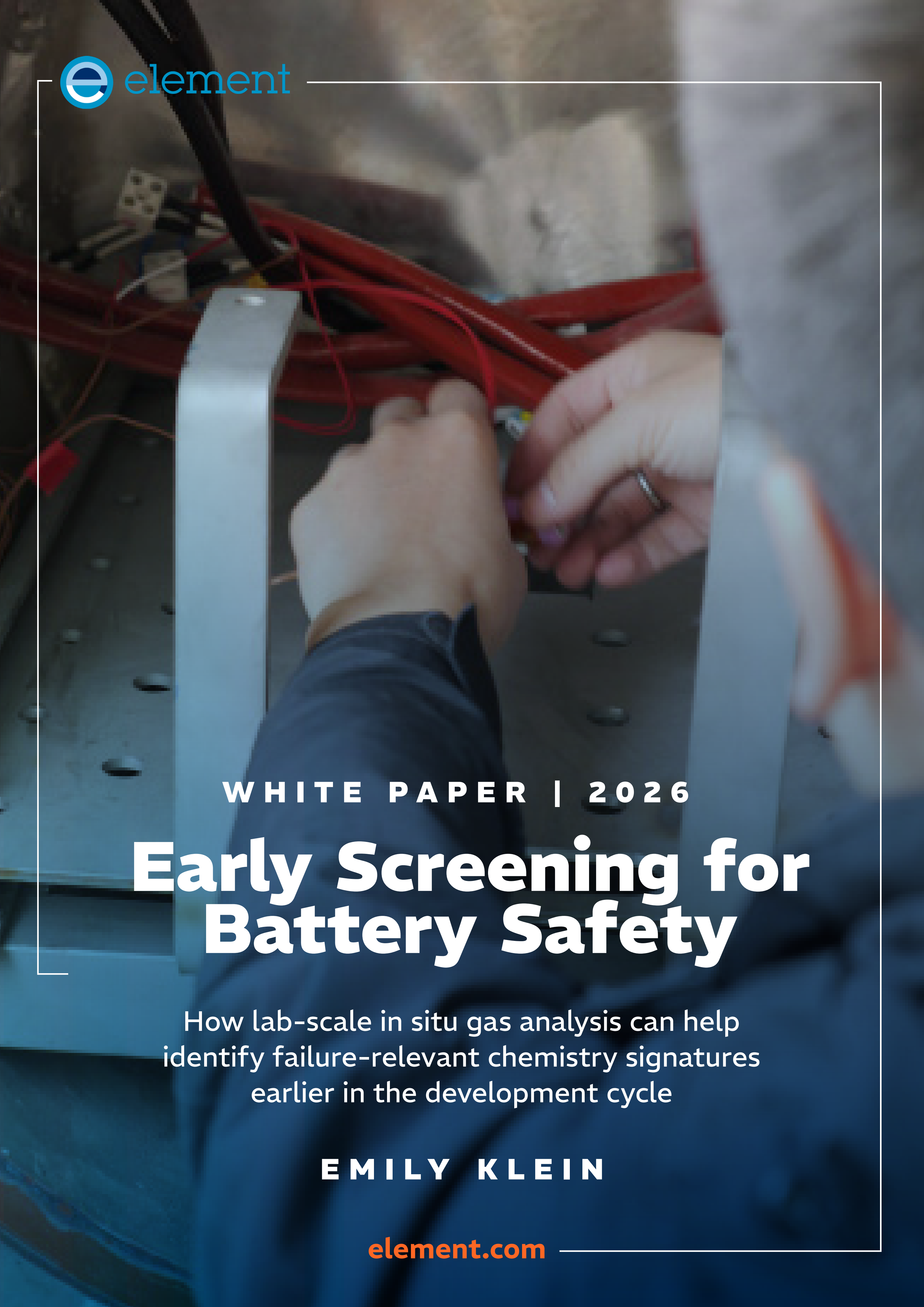

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Early Screening for Battery Safety

How lab-scale in situ gas analysis can help identify failure-relevant chemistry signatures earlier in the development cycle

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CONTENTS

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Emily Klein, Element Gainesville's Lead Failure Analysis Engineer, emphasizes the critical importance of understanding failure mechanisms at both the cell and pack levels. With expertise in failure analysis and regulatory testing, she brings a unique perspective to the design and execution of custom abuse and performance tests. Her hands-on experience spans cell- and battery-level abuse testing, performance evaluation, and the development of specialized methods to uncover failure mechanisms. Working closely with her team, she designs experiments that generate relevant, data-driven insights to inform safety, reliability, and performance improvements.

FOREWORD

WHY EARLIER SAFETY SCREENING MATTERS

At the laboratory level, those working in battery testing and abuse analysis observe chemistry and format changes before those changes reach consumers. This vantage point has made clear that chemistry screening in early development can benefit from addressing not only capacity and longevity targets but also safety and abuse behavior.

A pattern that has become increasingly common across both legacy OEMs and newer cell manufacturers is one where time and resources are concentrated on improving cell performance, and questions about failure behavior arise later in the development cycle than is ideal. The observation that more energy stored in a cell tends to produce more energy during failure is not new, but the manner in which that energy appears is evolving. Higher temperatures, explosive behavior, and gas release containing species that require toxicity evaluation have all become more frequent as energy density has increased.

This paper describes options available to screen cell chemistries before committing to larger formats, with the goal of better informing production decisions and reducing surprises during abuse testing at the cell or system level. It is offered as a tool that can help inform testing strategy and is not intended to replace existing qualification or certification frameworks.

The General Motors (GM) in situ gas analysis approach is presented as a well-designed screening tool that can help evaluate next-generation cell chemistries. While it may not be a substitute for production-format abuse testing or regulatory certification, it can support safety qualification within the screening context. These two regimes are complementary positions in the development process.

A point worth stating before reviewing any screening data: pouch, prismatic, and cylindrical cells can exhibit qualitatively different failure modes under both thermal and electrical abuse. Any screening result must be validated in the production-intent format before production decisions are made. The format-specific considerations in Section 3 address this in more detail.

WHAT STANDARD TOOLS CAN AND CANNOT TELL US

THE ROLE OF ACCELERATING RATE CALORIMETRY

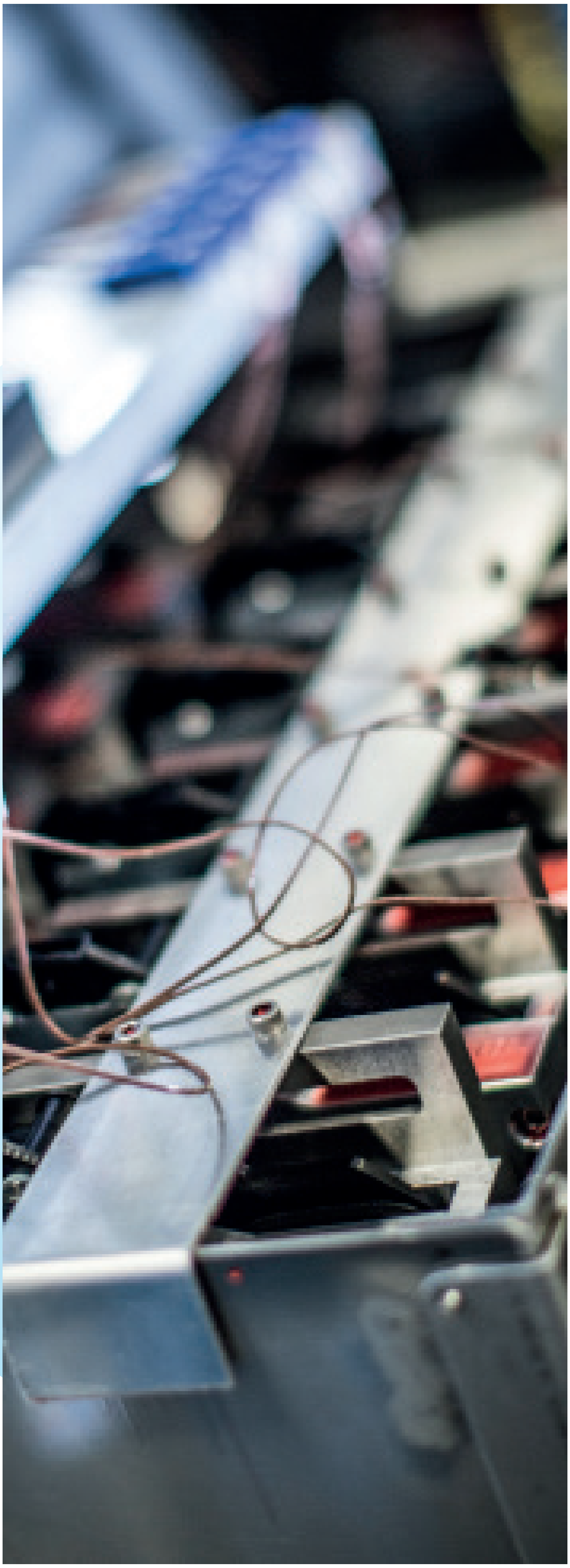
Accelerating Rate Calorimetry (ARC) is the established approach for thermal onset characterization in battery development. The heat-wait-seek protocol identifies self-heating onset temperature and the thermal runaway acceleration point with high reproducibility, providing kinetic parameters that can inform thermal runaway propagation models and battery management system temperature thresholds.

What ARC cannot provide is mechanistic resolution and it cannot distinguish whether early-stage exotherms originate at the anode-electrolyte interface, from solid electrolyte interphase (SEI) decomposition, or from cathode-side reactions. I

It provides no information on which gas species are evolving, at what temperatures, or from which component. Researchers have noted this gap and called for complementary techniques to connect component-level characterization to cell-level observations.[5] Most published battery gas analysis studies collect data after initial venting or once thermal runaway is fully underway, which precludes attributing specific gas species to specific temperature windows or electrode reactions.

The GM in situ gas analysis system measures gas species generated inside a lab-scale lithium-ion battery cell during controlled thermal abuse, beginning as low as 80 degrees Celsius, well before any venting event. The system uses a modified flat cell with a three-electrode configuration incorporating a lithium iron phosphate (LFP) thin-film reference electrode, enabling simultaneous quantitative gas measurement and anode and cathode potential monitoring during heating.

By measuring gas in real time inside a precycled cell with an intact electrolyte-electrode interface, the system preserves the cell environment developed through cycling. By adding the LFP reference electrode, it resolves anode and cathode potentials independently during heating, enabling direct attribution of gas generation events to specific electrode reactions rather than post-hoc inference.



PLACING EACH METHOD IN THE DEVELOPMENT PROCESS

A STAGED APPROACH TO TESTING

A battery development program requires multiple testing regimes, each suited to a specific question at a specific stage. The table below offers one way to organize this relationship and clarify where the in-situ gas screening method fits relative to production-format abuse testing and regulatory certification.

Stage	Method	What It Can Do	What It Cannot Do
1 and 2 Screening and mechanism	In situ flat-cell gas analysis (GM approach), DSC, ARC on small-format cells	Rank electrolyte and cathode candidates by gas onset temperature and volume. Attribute gas generation to electrode-level reactions.	Predict absolute vent volumes, pressure dynamics, or inter-cell propagation behavior.
3 Hazard characterization	Production-format cell ARC, nail penetration, oven test, thermal propagation testing	Characterize vent gas volumes and pressure dynamics. Assess thermal runaway propagation between cells. Evaluate vent path direction.	Attribute gas generation to specific electrode reactions or electrolyte components.
4 Regulatory certifications	Full-format testing per applicable regional standards (UN38.3, IEC 62133-2, UL 9540A, GB/T 38031, and others)	Demonstrate that the production-format cell satisfies pass or fail criteria for the target market.	Provide mechanistic insight or rank chemistry candidates.

WHY FLAT-CELL DATA HAS KNOWN BOUNDARIES

The GM flat-cell system uses single-layer electrodes, excess electrolyte, and a continuous gas-release pathway. These design choices make quantitative real-time gas measurement possible. These same design choices mean flat-cell data cannot be directly translated to production-format predictions. In a sealed cell, gas pressure accumulates until venting occurs, and the timing and character of that vent event depend on cell format, housing rigidity, and safety valve design, none of which are present in the flat-cell system. Reaction kinetics may also differ because ongoing gas release continuously reduces internal pressure, which could affect reaction equilibria. These are known tradeoffs that define the boundary of the method's validity rather than flaws in its design.

Two additional boundaries are worth noting. The flat-cell configuration uses electrolyte volumes that produce an electrolyte-to-capacity ratio substantially higher than in production cells. Research on format-dependent electrolyte ratios has shown that small lab cells typically operate at 25 to 130 mL per Ah, while production cells run below 10 mL per Ah,[10] meaning that electrolyte consumption effects may not translate. Additionally, thermally-driven abuse results are not predictive of electrically-triggered failure behavior such as overcharge or external short circuit. Cell impedance differs substantially between lab-scale and production formats,[11] and data from thermally-driven flat-cell screening cannot be assumed to apply to electrically-triggered abuse scenarios.

FORMAT-SPECIFIC FAILURE BEHAVIOR

Both the research literature and industry observations confirm that cell format is a meaningful determinant of failure behavior at Stage 3. The production-intent format needs to be used, as different formats can produce qualitatively different failure signatures:

Pouch cells lack rigid housings and fixed-geometry pressure relief valves. Rupture can occur at variable seam locations, producing unpredictable vent directions and ejecta trajectories. Element's abuse labs have observed that vent path direction is an important inspection variable for pouch formats.

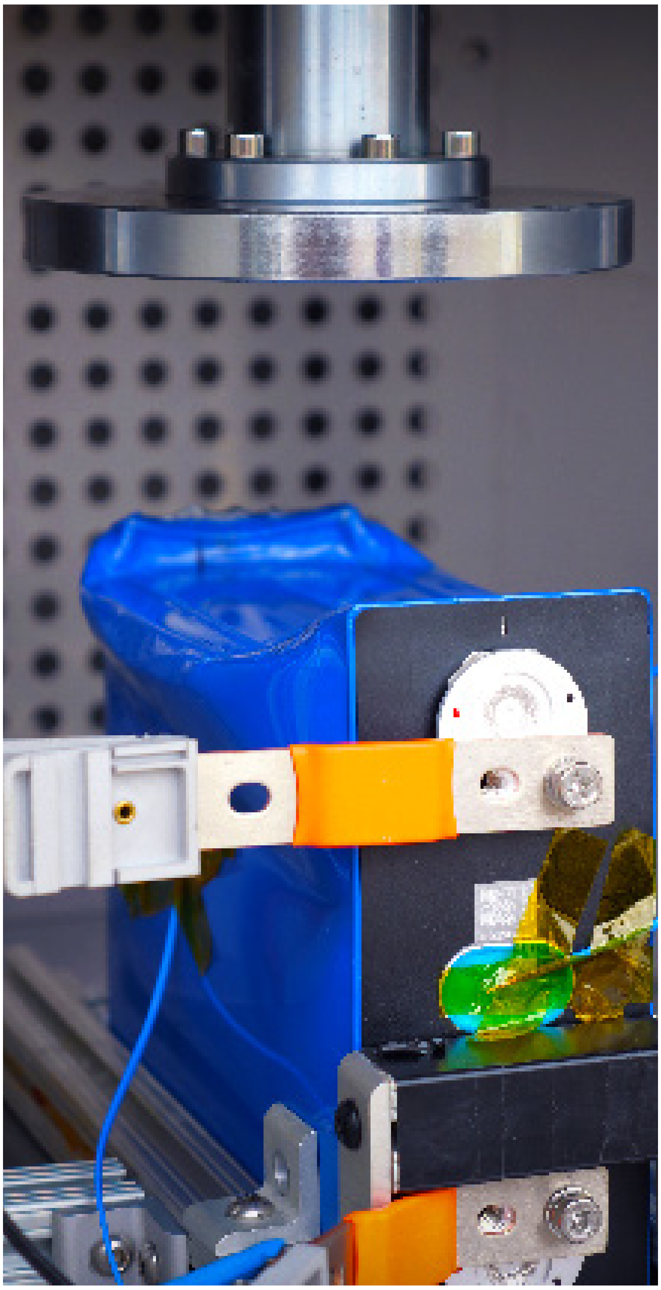
Prismatic cells with controlled safety vents provide more predictable directional gas release, but internal electrode stack compression and tab placement create distinct heat distribution patterns that can affect propagation timing and peak surface temperature.

Cylindrical cells have well-characterized vent behavior through fixed burst discs. Lower format variability makes them a reproducible geometry for inter-lab comparison. The FAA propagation study cited here[3] focused specifically on cylindrical cells, and its findings on onset temperature and propagation timelines are not directly generalizable to pouch formats, as each geometry is characterized separately in that work.

INSIGHT FROM ELEMENT'S GLOBAL ABUSE LABS (2025)

Across Element labs in the US and Korea, a consistent pre-certification signal has been observed. Cells that pass UN38.3 and IEC 62133 transport and electrical tests have subsequently shown violent directional venting and molten ejecta during early abuse assessments. The same cell part number tested across different regional facilities has shown divergent gas chemistry profiles linked to electrolyte supplier variation. This is a format-independent finding that underscores the value of chemistry-level screening as a complement to format-level abuse testing. It also illustrates that certification passage is not equivalent to predictable failure behavior.

Source: "Beyond Certification: What Our Global Abuse Labs Are Seeing Before Certification," Element Materials Technology, 2025.[1]



NAVIGATING A FRAGMENTED REGULATORY LANDSCAPE

Battery safety regulation is one of the fastest-moving areas of product compliance, and the global landscape is not converging toward a single framework. Understanding the standards hierarchy and the physical phenomena each standard is designed to detect is a prerequisite for compliance planning.

Standard / Region	What It Targets	Relevant Limitation
UN38.3 (Global transport	Altitude, vibration, thermal, short circuit, overcharge: transport simulation	Not an abuse-to-failure test; does not characterize thermal runaway venting physics
UL 1642 / UL 2054 (US domestic)	Cell-level safety; household and commercial pack safety. UL 2054 accepts UL 1642 cell data	UL 2054 does not accept IEC 62133-2 or UL 62133-2 cell data
IEC 62133-2 / UL 62133-2 (Global / US)	Consumer and commercial portable battery safety; harmonized foundation for KC, JN, and NF deviations. UL 62133-2 testing is identical to IEC, enabling data reuse at the same lab[2]	Portable applications only; not designed for EV pack-level hazards
UL 9540A (US, ESS)	Ejecta, plume, and external fire propagation at installation level	Requires production-representative format; cell-level data alone is insufficient
GB/T 38031-2025 (China EV)	Vent direction, containment escape path; mandates no fire or explosion	Strictest current standard globally; extensive format and scale requirements
IEC 62619 / KC 62619 (Korea)	H2 and HF gas chemistry detection; forced internal short circuit (KC deviation)	Chemistry-specific emphasis; HF detection not addressed in most US standards

HARMONIZATION AND ITS LIMITS

IEC 62133-2 serves as the harmonized foundation from which multiple national standards derive, including KC 62133-2 (Korea), JN 62133-2 (Japan), and NF EN 62133-2 (France). Because UL 62133-2 testing is identical to IEC 62133-2, a qualifying laboratory can use IEC 62133-2 test data to obtain the UL certification without re-running tests, saving time, samples, and cost.[2] Teams that anticipate a UL 2054 requirement can benefit from planning the compliance sequence with UL 1642 cell testing first, as UL 2054 does not accept IEC or UL 62133-2 cell data and retrofitting the sequence mid-program is a common source of delay. UN38.3 and IEC 62133 are not abuse-to-failure tests. Cells that clear these standards can subsequently exhibit violent failure under production-representative abuse conditions.[1] EV pack-level standards such as UL 9540A, GB/T 38031, and ECE R100 reflect different regulatory philosophies and require production-representative testing that cannot be satisfied by data reuse from portable battery certifications.

EXAMPLE OF SUGGESTED COMPLIANCE SEQUENCING FOR LI-ION EV CELLS

Path A (where UL 62133-2 is accepted): UN38.3, then UL 1642 and IEC 62133-2 concurrently at the same lab, then UL 62133-2 via data reuse, then national deviations (KC, JN, NF EN 62133-2). This path maximizes efficiency through harmonization.[2]
Path B (where UL 2054 is required): UN38.3, then UL 1642, then UL 2054 with cell test exceptions where UL 1642 has already been passed. UL 2054 does not accept IEC or UL 62133-2 cell data.[2]
EV pack level (both paths): UL 9540A (US), GB/T 38031-2025 (China), ECE R100 (Europe), and applicable OEM-specific requirements require production-representative format testing and cannot be satisfied by data from earlier stages.
Timing consideration: Production-format abuse testing at Stage 3 can run in parallel with certification preparation. Waiting for certification outcomes before discovering abuse failure modes is a pattern that tends to surface as late-program surprises.[1]

PRACTICAL CONSIDERATIONS FOR USING THIS APPROACH

HARMONIZATION AND ITS LIMITS

The GM flat-cell in situ gas analysis system is most useful at the chemistry selection stage, where the goal is to rank candidates and flag poor performers before large-format builds are committed. Potential applications include electrolyte formulation comparison by gas onset temperature and total gas volume, cathode chemistry evaluation by the temperature at which higher-temperature gas generation begins, SOC-dependent gas profiling to inform charge limit decisions, and generating gas fingerprint data that may help specify sensor requirements for early detection research.[8] Combined with structural characterization such as XRD, SEM-EDS, and XPS, the gas data can also contribute to mechanism attribution.

BOUNDARIES OF THE METHOD

The following may not be well-suited to flat-cell in situ gas data without additional supporting evidence from production-format testing: absolute vent gas volume prediction for pack-level hazard modeling, vent timing and pressure transient characterization, thermal propagation assessment between adjacent cells, and regulatory compliance demonstration. The GM study also uses fresh, precycled cells, so how cycle aging, calendar aging, and lithium plating affect the gas fingerprint may remain an open question.

INTERPRETING RESULTS CAREFULLY

A lower gas onset temperature or higher gas volume in the early thermal regime may serve as a flag for further investigation, though the significance of these observations depends on the broader chemistry context. SOC control is especially important, as the strong state-of-charge dependence documented in the Yadav study means even small deviations in SOC or formation protocol can shift onset temperatures meaningfully and obscure chemistry-level ranking. Formation protocol standardization is therefore not optional for comparative screening. A higher onset temperature in the higher-temperature gas regime is associated with a higher thermal runaway acceleration point in ARC, and running ARC on parallel small-format cells can help cross-validate this relationship. Reproducibility should be confirmed for each specific electrode batch and electrolyte fill condition, and the degassing protocol used prior to testing can affect results.

CROSS-VALIDATION

The most important gap in the current literature is a systematic cross-validation study. The GM in situ method can rank electrolyte formulations by their gas fingerprint profiles. An unresolved question is whether that ranking predicts the same ordering in production-format cell safety testing. If the ranking can be preserved, even approximately, the screening tool can be a genuine early-stage filter. If the ranking is not preserved, that is an equally important result, as it would help define the boundaries of the flat-cell method's predictive validity and focus attention on what the flat-cell environment may be missing.

Until a cross-validation study has been published, teams can use the flat-cell screening data to eliminate clearly inferior candidates and generate mechanistic hypotheses, then proceed to production-format validation for all advancing candidates before production commitment. The method is validated as a mechanistically informative screening tool for early-stage triage; its predictive validity for large-format behavior has not yet been demonstrated in the literature.

AFTERWORD

The GM and Yadav in situ gas analysis method represents a meaningful contribution to battery safety research and development. By measuring gas species inside a lithium-ion battery cell in real time during thermal abuse, with electrode-level resolution via a three-electrode LFP reference configuration, it can help close a diagnostic gap that ARC, DSC, and post-venting gas analysis cannot address on their own. Its ability to distinguish between early anode-driven gas generation and later cathode decomposition-driven activity is potentially useful for electrolyte formulation ranking and early-detection sensor research.

One possible use of this method in a development context is as a screening tool at Stages 1 and 2 of the development funnel. It is not a substitute for production-format abuse testing or regulatory certification. Those methods occupy Stages 3 and 4 and must use the production-intent cell format, which varies by program and is not universally defined by any single geometry.

The regulatory landscape is diverging rather than converging. UN38.3 and IEC 62133-2 provide a harmonized foundation for early compliance efficiency, but EV pack-level standards including UL 9540A, GB/T 38031-2025, and ECE R100 are different in their requirements. Observations from abuse labs identifying violent failure in cells that cleared early certification tests support the case for integrating chemistry screening upstream, before format-level testing begins.

The investment that could most extend the value of this screening approach is a systematic cross-validation study linking flat-cell gas fingerprints to large-format cell performance rankings. Until that study exists, teams could use this method for chemistry screening and mechanism investigation while continuing to validate advancing candidates in production-representative formats before making production commitments.

*This white paper is an independent engineering analysis prepared for internal use. It does not represent the official views of General Motors, Element Materials Technology, or the cited authors. Presentation content from Element is cited with permission.

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