

## **Critical Warning: VOC Detection for Safer Lithium-Ion Battery Systems**

### **Introduction**

Lithium-ion batteries have become the backbone of modern energy storage, powering everything from smartphones to electric vehicles and grid-scale storage systems. However, their widespread adoption brings significant safety challenges, particularly the risk of thermal runaway events. During these catastrophic failures, batteries release a complex mixture of toxic and flammable gases, including volatile organic compounds (VOCs) that pose serious health and safety risks.

Understanding and detecting these VOC emissions is critical for preventing injuries, deaths, and property damage. This white paper examines the current state of VOC detection technologies, identifies key challenges, and outlines best practices for implementing effective monitoring systems.

### **Understanding Thermal Runaway and VOC Emissions**

Thermal runaway occurs when a lithium-ion battery cell experiences rapid, uncontrolled heating that triggers a self-sustaining chain reaction. This process typically begins with a single cell reaching temperatures above 130 °C to 150 °C, causing the electrolyte to decompose and generating heat faster than it can dissipate. The reaction spreads to adjacent cells, creating a cascading failure that can engulf entire battery packs.

During thermal runaway, batteries release a dangerous cocktail of gases. The primary VOCs include:

- **Organic carbonates:** Dimethyl carbonate (DMC), diethyl carbonate (DEC), and ethyl methyl carbonate (EMC) are common electrolyte solvents that vaporize and decompose during thermal events. These compounds are moderately toxic and highly flammable.
- **Alcohols and esters:** Methanol, ethanol, and various organic esters form as electrolyte components break down. While less immediately dangerous than some other emissions, these compounds contribute to overall toxicity and fire risk.
- **Aromatic compounds:** Benzene, toluene, and other aromatic hydrocarbons can form during high-temperature decomposition. These compounds are particularly concerning due to their carcinogenic properties and low detection thresholds.
- **Fluorinated compounds:** Lithium hexafluorophosphate (LiPF<sub>6</sub>) electrolyte salt decomposes to produce hydrogen fluoride and various fluorinated organic compounds. These substances are extremely toxic and corrosive.

The concentration and composition of VOC emissions vary significantly based on battery chemistry, state of charge, temperature, and environmental conditions. This variability makes detection particularly challenging, but also critically important.

## Current Detection Technologies

### Photoionization Detectors (PIDs)

PIDs represent the most common approach for real-time VOC detection in battery applications. These devices use ultraviolet light to ionize gas molecules, generating electrical current proportional to the VOC concentration. Modern PIDs can detect total VOC levels down to the parts-per-billion range with response times under 10 seconds.

The main advantages of PIDs include their broad-spectrum detection capability, rapid response, and relatively low cost. However, they cannot distinguish between different VOC species and may experience interference from high-humidity or high-temperature conditions typical during thermal runaway events.

### Gas Chromatography-Mass Spectrometry (GC-MS)

GC-MS systems provide the gold standard for VOC identification and quantification. These instruments separate gas mixtures into individual components and identify each compound based on its mass spectrum. This specificity allows for the precise monitoring of particularly toxic compounds like benzene or hydrogen fluoride.

The primary limitation of GC-MS is analysis time, which is typically 5 to 30 minutes per sample. This delay makes GC-MS unsuitable for real-time safety applications but valuable for detailed forensic analysis and system validation.

### Infrared Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy offers a middle ground between PIDs and GC-MS. FTIR systems can identify specific VOC compounds in real time by measuring their characteristic infrared absorption patterns. Modern portable FTIR units provide results within seconds and can simultaneously monitor multiple gas species.

The main challenges with FTIR include high equipment costs, sensitivity to environmental conditions, and potential interference from water vapor and carbon dioxide.

### Microelectromechanical Systems (MEMS)-Based Gas Sensors

MEMS technology has revolutionized VOC detection by enabling miniaturized, low-power sensors with excellent sensitivity and selectivity. MEMS gas sensors use various detection principles, including metal oxide semiconductors, capacitive sensing, and resonant frequency changes.

MEMS VOC sensors offer several advantages for battery applications. Their small size allows integration directly into battery management systems, while their low power consumption makes them suitable for continuous monitoring. Response times are typically under 30 seconds, and many MEMS sensors can operate at elevated temperatures better than traditional electrochemical devices.

Modern MEMS sensors can detect specific VOCs at part-per-million levels while maintaining selectivity through surface functionalization and pattern recognition algorithms. Some advanced MEMS devices incorporate sensor arrays that create “electronic noses” capable of identifying complex gas mixtures and distinguishing between different failure modes.

The main limitations to MEMS sensors include sensitivity to humidity and potential drift over time, though newer designs incorporate compensation algorithms and self-calibration features to address these issues.

#### Electrochemical Sensors

Electrochemical sensors designed for specific VOCs offer targeted detection at lower costs than spectroscopic methods. These sensors work particularly well for compounds like hydrogen fluoride, which poses extreme health risks even at low concentrations.

However, electrochemical sensors typically monitor only single compounds and may experience cross-sensitivity to other gases present during thermal runaway events.

### **Implementation Challenges**

#### Environmental Conditions

Thermal runaway events create extremely harsh monitoring conditions. Temperatures can exceed 800 °C, humidity approaches 100 %, and corrosive gases attack sensor materials. Detection systems must function reliably in these environments while maintaining calibration accuracy.

Most commercial VOC detectors are rated for much milder conditions, requiring protective enclosures or remote sampling systems that introduce delays and potential sample contamination.

#### Response Time Requirements

Battery thermal runaway can progress from initial cell failure to full pack involvement in minutes or even seconds. Detection systems must provide warnings fast enough for personnel evacuation and fire suppression activation.

This requirement often conflicts with the need for accurate, species-specific detection. Faster detection typically means less specificity, forcing system designers to balance speed against precision.

#### Calibration and Maintenance

VOC detection systems require regular calibration using certified reference gases to maintain accuracy. This process becomes complicated in battery applications where the exact gas composition changes based on battery type, age, and failure mode.

Field calibration is particularly challenging because many VOCs are unstable, toxic, or difficult to handle safely. Some facilities resort to using surrogate gases for calibration, which may not accurately represent real-world conditions.

## Best Practices for VOC Detection Systems

### Multi-Technology Approach

No single detection technology addresses all requirements for battery safety applications. The most effective systems combine multiple detection methods:

- PIDs for rapid total VOC detection and alarm generation
- MEMS sensors for low-power, continuous monitoring with good temperature tolerance
- Specific electrochemical sensors for highly toxic compounds like hydrogen fluoride
- FTIR or GC-MS for detailed analysis and system validation

This layered approach provides both immediate safety warnings and detailed information for incident investigation.

### Strategic Sensor Placement

VOC concentrations vary dramatically based on location relative to the battery system. Sensors should be positioned to detect gases before they reach dangerous levels in occupied areas. This typically means placing detectors:

- In battery enclosures or rooms
- In ventilation system exhaust streams
- At potential leak points in containment systems
- In areas where personnel might be exposed

Modeling airflow patterns and gas dispersion helps optimize sensor placement for maximum effectiveness.

### Integration with Safety Systems

VOC detection should integrate with broader battery safety systems, including:

- Fire suppression systems that activate based on gas detection
- Ventilation controls that increase exhaust rates when VOCs are detected
- Personnel alert systems that provide evacuation warnings
- Emergency shutdown procedures that isolate affected battery systems

This integration ensures that detection translates into effective protective action.

### Regular Testing and Validation

Detection systems require ongoing testing to verify proper operation. This includes:

- Regular calibration using certified reference gases
- Functional testing of alarm systems and safety interlocks
- Validation of detection thresholds through controlled testing
- Documentation of system performance and any identified issues

## Future Developments

Emerging technologies promise to improve VOC detection in battery applications. MEMS sensor arrays are becoming more sophisticated, incorporating artificial intelligence for pattern recognition and predictive analytics. Machine learning algorithms are being developed to identify thermal runaway signatures in complex gas mixtures before catastrophic failure occurs.

Wireless sensor networks enable broader monitoring coverage at lower costs, while advanced materials research is producing sensors that better withstand harsh thermal runaway conditions. Integration of MEMS technology with wireless communication is creating distributed sensing networks that can provide real-time mapping of gas concentrations across large battery installations.

## Conclusion

VOC detection during lithium-ion battery thermal runaway events is a complex but critical safety requirement. Current technologies offer various approaches, each with distinct advantages and limitations. The most effective systems combine multiple detection methods, integrate with broader safety systems, and undergo regular testing and maintenance.

As battery technology continues to evolve and deployment scales increase, VOC detection systems will become increasingly important for protecting personnel and property. Investment in robust, well-designed detection systems is essential for the safe adoption of lithium-ion battery technology across all applications.

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