Amphenol Sensors

Pragmatic Approach to Robust Multiphysics-Based Cell Venting Detection

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SAE Battery Standards Steering Committee

Chair: SAE J2990 First/Second Responders Task Force

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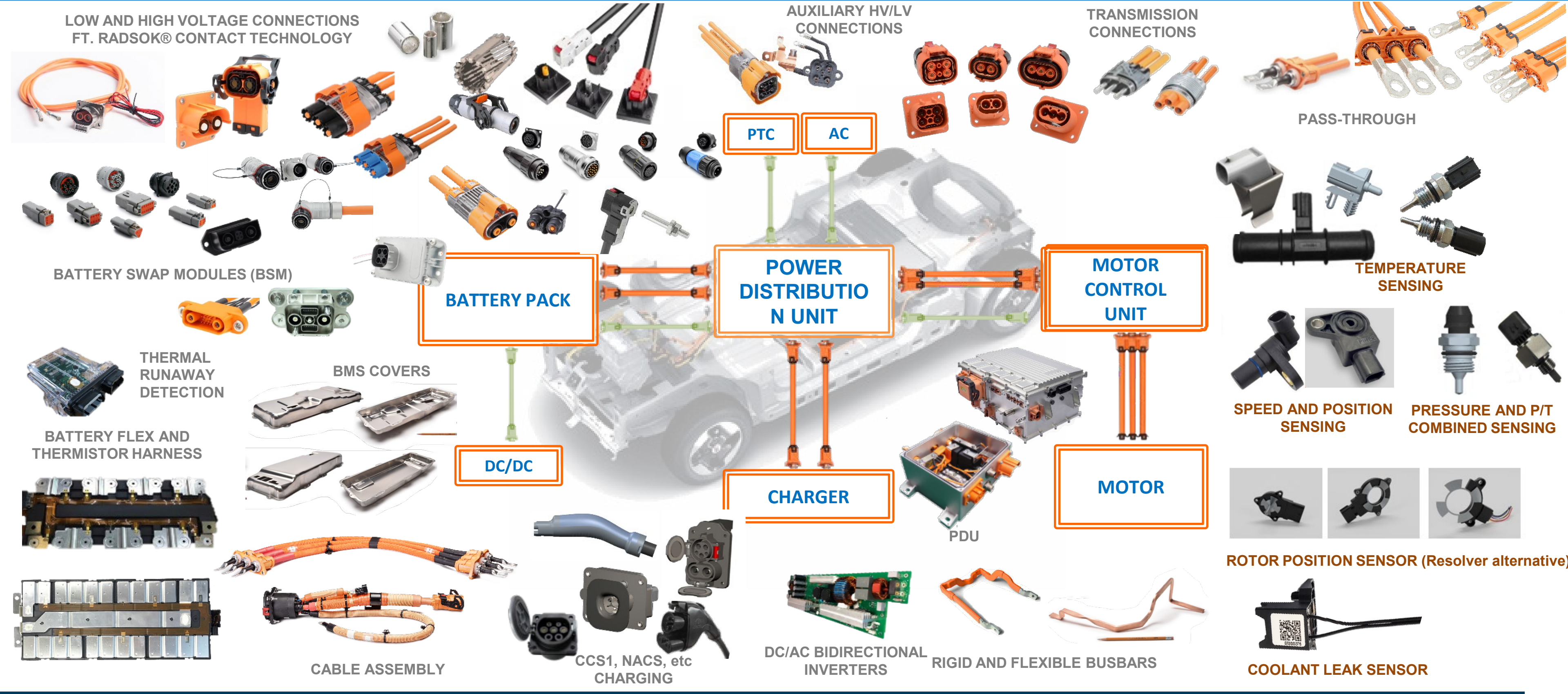
Electrification Portfolio



Interconnect & Sensor technologies

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Extending the reach of the interconnect system

Connectors	Antennas	Sensors	Flex	PCB	Cables	Value-add

Core pillars of technology innovation

Harsh Environment	High Speed	Power	Sensors	Radio Frequency	Fiber Optics

"Typical" Battery Sensor portfolio

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Delivering Value-Add Sensors

Battery Cell, pack/Module, Rack, & Enclosure

- Voltage
- Current – Hall Effect, Shunt, & Tunneling Magnetoresistsance (TMR) design
- Busbar, Cell Temperature – NTC wired and surface-mount thermistors, RTD's, IR (non-contact)
- Connector temperature
- High voltage component temperature – Infrared (non-contact)
- Cell venting detection
- Electrolyte leakage
- Humidity / condensation monitoring
- Water intrusion/coolant breach
- Electrical Impedance Spectroscopy (EIS) for cell impedance (cell degradation)

Inverter:

- Voltage
- Inverter & FET temperatures
- Current sensing

Thermal Management:

- Coolant Temperature, Pressure
- Refrigerant Temperature
- Refrigerant Pressure/Temperature
- Evaporator Temperature
- Position sensors
- Coolant level Sensors
- Air temperature, flow, filter restriction
- Humidity

- ***Safety, Productivity, Reliability, & Durability driving ESS sensors***

Space Application battery challenges

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Unique challenges of space applications:

- High-value systems – best process is to design system with most benign potential outcomes
- Gravity conditions can exist between near-zero G to high G (re-entry) conditions
- Exceedingly low tolerance for risk with human space applications
- Slightly higher tolerance for failure in unmanned/"lower-value" applications
- Very high temperature variances
- High variability in life requirements and charge cycles (single mission v long-duration)

While small cylindrical cells may provide advantages in low energy-density applications, it is expected that future missions may require mission-specific electrochemical storage characteristics:

- Much higher energy density
- Lower mass
- Ability to deal with dynamic pressure, gravity, temperature, radiation environment
- Different mechanical packages (pouch, prismatic, etc)

Conventional active materials (such as silicon) swell and shrink substantially with charge/discharge. This behavior in near vacuum environments may have substantially different aging/health behaviors than their peers under earth conditions

Cell venting

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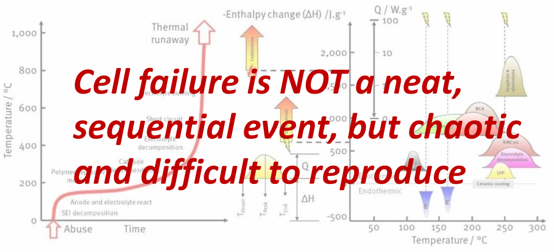
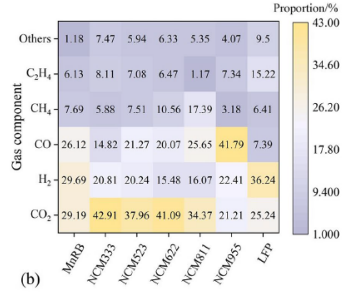
What is venting from the cell?

- Gases: CO_2, CO, H_2, C_2H_4, CH_4, other gases
- Electrolyte (VOC's, ACN)
- Fluorinated compounds / HF
- Water vapor
- Aluminum and copper particles from the current collectors
- Separator material (PE, PP)
- Carbonized electrolyte, binder, separator materials
- Anode materials (graphite, silicon)
- Cathode materials (LFP, NMC, etc – metals in pure form, oxidized, compounds)

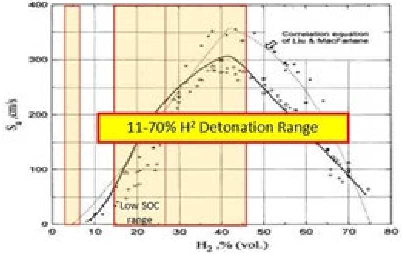


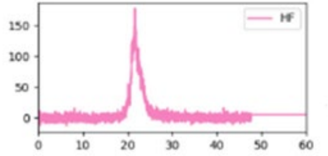
Cell failure is NOT a neat, sequential event, but chaotic and difficult to reproduce



Other conditions in space environment:

- High temperatures: LFP cells generate ~350C, NMC & NCA cells ~600C
- Large volume of gas and condensate
- Gas plume is both flammable and hazardous
- Gas release can occur in benign or very aggressive
- Particulate ejecta conductive and similar to ionized plasma at temperature
- Gas release can create thrust

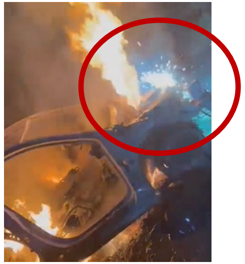




Cell failure can start at the molecular level and is a physics problem. Fire is a possible outcome, but not the only feature of the failure physics

Why are lithium ion battery fires so pernicious?

While rare, Lithium ion battery failures pose unique challenges – cell failures can vary from benign to aggressive outcomes, and may provide minimal warning of iminent failure



1. **Lithium ion cells undergoing thermal runaway can provide their own oxygen as a reactant**

SEI Decomposition: $(CH_2OCO_2Li)_2 \xrightarrow{\Delta H} Li_2CO_3 + C_2H_4 + CO_2 + \frac{1}{2}O_2$

Carbonate combustion & Lithium rx with binder and electrolyte :

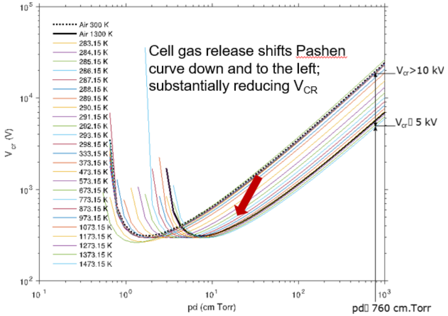
$$\frac{5}{2}O_2 + C_3H_4O_3(EC) \xrightarrow{\Delta H} 3CO_2 + 2H_2O$$

$$\text{-}CH_2\text{-}CF_2\text{-} + Li \xrightarrow{\Delta H} LiF + \text{-}CH{=}CF\text{-} + \frac{1}{2}H_2 \qquad CMC\text{-}OH + Li \xrightarrow{\Delta H} CMC\text{-}OLi + \frac{1}{2}H_2$$

2. **Battery TR releases hazardous and flammable gases and electrolyte**
   - Cells can achieve temperatures of >600C, transferring heat to adjacent cells
   - Electrolyte can cause external fires on other cells
   - ***Gas /particulate release increases potential for HV discharge***

3. **Solid state and other chemistries also evolve hydrogen, hydrocarbons as well as temperatures in excess of autoignition temperatures in many failure modes**

4. **In zero-g environments, condensate doesn't settle, and gas and particle dynamics need to be understood**



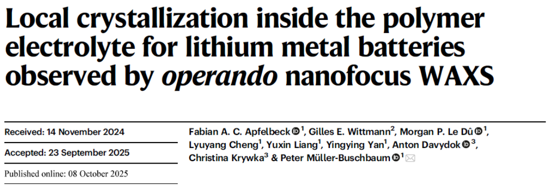
Courtesy Jeremy Riousset, FIT

Hazards proximate to pack include: fire/explosion, hazardous gas/asphyxiation, HV discharge

Factors effecting venting severity

Physical Factors affecting Severity of single cell venting outcome

Cell Size
Cell Cathode/Anode Chemistry / Electrolyte
State of Charge
State of Health
Temperature within the cell
Vent design
Electrolysis of water



Local crystallization inside the polymer electrolyte for lithium metal batteries observed by *operando* nanofocus WAXS

Received: 14 November 2024
Accepted: 23 September 2025
Published online: 08 October 2025

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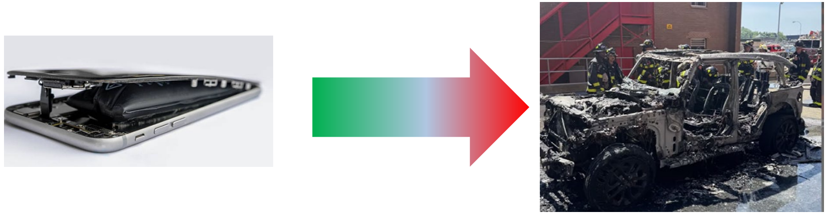
Factors affecting propagation:

Thermal behavior of interface
Interaction of plume with environment

- Arc flash
- Thermite rx
- Hot gases/particles mixing with available oxygen
- External short circuit
- Electrolysis of water / short circuits



Outcomes – benign/moderate/severe:

Deflagration/explosion
Hazardous gas exposure
Corrosion
Events can be extremely rapid or latency may be hours, days, or months

- ***System MUST manage venting from single cell and designs must drive toward non-propagating designs***
- ***Due to severity of outcomes, venting MUST be detected.***

Safety – Passive Propagation Resistance (PPR) & venting detection

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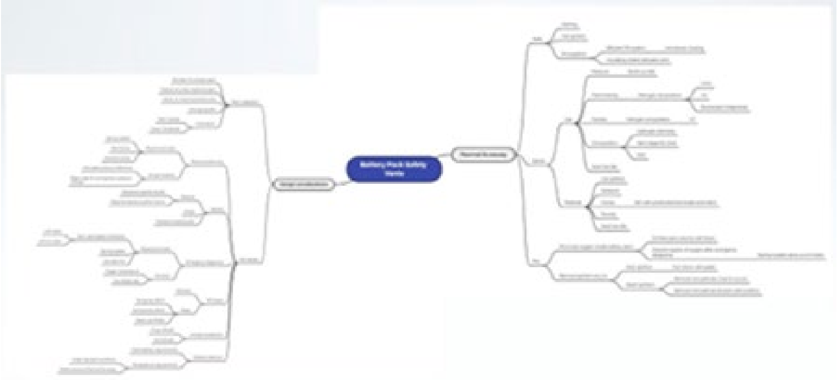
Control & prevention of TR:

- Cell chemistry/construction to reduce risk of failure venting
- Extremely high level of process control in battery manufacturing
- Control of current, voltage, temperature
- Monitor degradation of cells (force, EIS)

Passive Resistance:

- Dedicated vent path, separation of vent gas from HV bus
- Minimize heating of adjacent cells
- Intumescent materials where needed
- Minimize oxygen availability in unit to reduce risk of fire
- Control gas temperatures below autoignition point
- Trap/contain hot particles that can ignite plume causing external fire



Active: Detection and Active cooling

- Monitor for cell leakage/venting
- Alert/alarm – define threat condition (gas release, fire, explosion risk)
- If event detected, activate countermeasures (cooling/extinguishing agents)

Best practices show significant improvement in outcomes of cell venting

Safety and Health

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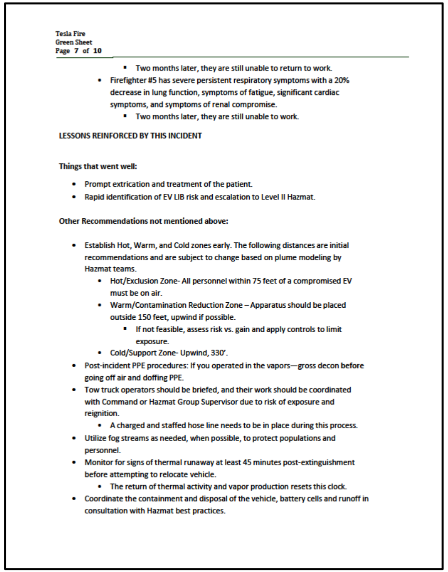
Incident Overview:

- April 11th, 2025 @ 22:04. MVA with electric vehicle (EV) lithium-ion battery (LIB) Fire Involvement.
- Initial dispatch for MVA with major injury.
- The vehicle's battery pack was compromised and had over 400 scattered battery cells across the roadway.
- Hazmat 30, Hazmat 7 and Special Ops (2293) were called to the scene.
- ***The main EV LIB pack reignited when the vehicle was moved for tow operations.***
- **Later, as the tow truck operator began to move the vehicle, a thermal runaway event occurred within the main EV LIB pack.**
- ***This event produced a large volume of white gas.***
- ***Crews attempted to disconnect their hoses and evacuate the area but were overcome by the vapor plume prior to being able to clear the area.***
- While escorting the tow truck to the tow yard, three out of the four firefighters in the engine complained of feeling ill.
- One of the four firefighters began vomiting out of their window.
- The company called a medic and had the firefighter that was vomiting transported in an ambulance.
- At the hospital, the two additional personnel that were symptomatic agreed to seek treatment for their injuries.
- By the end of the night, two additional firefighters that were overcome by the vapor plume felt ill and sought treatment.
- Ongoing testing indicates that toxic vapor plume composition can vary significantly throughout the plume.
- • **Firefighter #1** was nauseous and vomiting. Transported to the ER in a Medic. Within a week they felt recovered and returned to work.
- • **Firefighter #2** felt nauseated and had flu-like symptoms for several days. Flu-like symptoms persisted, but they felt well enough to return to work after a couple of weeks. They were able to work for 3 weeks.
- Placed back off-duty with a constant decrease in exercise tolerance. ***20% decrease in lung function***. They have remained off work since then.
- • **Firefighter #3** ***has significant respiratory and renal symptoms***, as well as low exercise tolerance, persistent hypertension, tachycardia, and fatigue. Two months later, they are still unable to work.
- • **Firefighter #4** has severe persistent fatigue, low exercise tolerance and persistent respiratory symptoms. Two months later, they are still unable to return to work.
- • **Firefighter #5** has ***severe persistent respiratory symptoms with a 20% decrease in lung function, symptoms of fatigue, significant cardiac symptoms, and symptoms of renal compromise***. Two months later, they are still unable to work.



Tesla Fire
Green Sheet
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- Two months later, they are still unable to return to work.
- Firefighter #5 has severe persistent respiratory symptoms with a 20% decrease in lung function, symptoms of fatigue, significant cardiac symptoms, and symptoms of renal compromise.
  - Two months later, they are still unable to work.

LESSONS REINFORCED BY THIS INCIDENT

Things that went well:

- Prompt extrication and treatment of the patient.
- Rapid identification of EV LIB risk and escalation to Level II Hazmat.

Other Recommendations not mentioned above:

- Establish Hot, Warm, and Cold zones early. The following distances are initial recommendations and are subject to change based on plume modeling by Hazmat teams.
  - Hot/Exclusion Zone- All personnel within 75 feet of a compromised EV must be on air.
  - Warm/Contamination Reduction Zone – Apparatus should be placed outside 150 feet, upwind if possible.
    - If not feasible, assess risk vs. gain and apply controls to limit exposure.
  - Cold/Support Zone- Upwind, 330'.
- Post-incident PPE procedures: If you operated in the vapors—gross decon before going off air and doffing PPE.
- Tow truck operators should be briefed, and their work should be coordinated with Command or Hazmat Group Supervisor due to risk of exposure and reignition.
  - A charged and staffed hose line needs to be in place during this process.
- Utilize fog streams as needed, when possible, to protect populations and personnel.
- Monitor for signs of thermal runaway at least 45 minutes post-extinguishment before attempting to relocate vehicle.
  - The return of thermal activity and vapor production resets this clock.
- Coordinate the containment and disposal of the vehicle, battery cells and runoff in consultation with Hazmat best practices.

Plume health effects significant in "open" environments, outcomes could be much more severe in enclosed spaces

How to detect? It depends….

Dectecting cell venting – How do I "see" a venting cell?

Cell current, voltage, Impedance (EIS)

Temperature – NTC thermistors, Thermal imaging camera

Gas/air pressure in enclosure (si-based IC surface mount)

"seeing the plume" –

- Condensate – Optical particulate sensing
- "Smoke" detector – (ionization, photoelectric)
- "Flame detector" – Infrared
- Gas Release – H2, CO2, CO, VOC's (IR, CMOS, Pellistor, TC,)

中国电子装备技术开发协会团体标准项目预研说明

项目中文名称	动力电池热失控监测传感器及模块			
项目英文名称	Thermal Runaway Monitoring Sensors and Modules for Power Batteries			
制定或修订	制定 ☑	修订 □	被修订标准号	——
联系人	李莹		手机	18010341517
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是否涉及专利	是□ 否☑	专利号及名称	——	

标准编制的目的和意义:
新能源汽车产业作为国家战略性新兴产业，是实现交通领域"双碳"目标的关键路径。动力电池作为新能源汽车的核心部件，其安全性直接关系到人民群众生命财产安全和产业可持续发展。随着全球电动汽车市场快速发展，2025年第一季度全球电动汽车销量达到 410万辆，比去年同期增长 29%，动力电池装机规模持续扩大。随着高能量密度电池技术的快速发展，电池热失控风险日益凸显，具有突发性强、蔓延迅速、破坏力大的显著特征。构建精准可靠的动力电池热失控监测体系，已成为保障新能源汽车产业可持续发展的关键环节。
《新能源汽车产业发展规划（2021-2035年）》明确要求加强新能源汽车安全隐患排查，提升安全技术水平。工业和信息化部等部门先后发布《关于进一步加强新能源汽车企业安全体系建设的指导意见》等文件，强调要完善安全标准体系。然而，现行标准体系在热失控监测传感器及模块领域存在明显不足。国家标准 GB 38031-2020《电动汽车用动力蓄电池安全要求》主要关注电池系统级安全，对热失控监测传感器及模块的技术要求较为笼统；而现有的标准体系在传感器精度、响应时间、环境适应性等具体性能参数方面缺乏统一规定。在此背景下，制定专项技术规范，建立完善的动力电池热失控监测传感器及模块技术体系，对提升
监测预警能力、防范安全事故具有重要战略意义。标准

编制必要性和可行性分析:
制定《动力电池热失控监测传感器及模块》技术规范是应对新能源汽车产业规模化发展、提升安全监测水平的紧迫需求。目前，动力电池热失控监测领域存在三大技术壁垒：极端环境适应性、长使用寿命可靠性和多参数集成性。这些特殊要求构成了储能传感器的核心技术壁垒，亟需通过标准化手段予以规范。
当前，动力电池热失控监测领域标准体系存在明显短板。一方面，现有标准覆盖面不足，现行相关标准主要关注电池系统级安全，对热失控监测传感器及模块的技术要求较为笼统；另一方面，技术参数不统一，导致不同厂商产品性能差异显著。本标准的制定将填补动力电池热失控监测传感器及模块领域的标准空白。通过规定监测范围、精度等级、环境适应性等核心参数，为产品研发、生产制造和质量控制提供技术依据。标准的实施将有效提升动力电池安全监测水平，为新能源汽车产业高质量发展提供坚实技术支撑。

26	Sensors and Modules for Battery Energy Storage System Safety Monitoring	2025—026T—CAEE
27	Thermal Runaway Detection Sensors and Modules for Power Batteries	2025—027T—CAEE
28	NTC Thermistor for Integrated Busbar (CCS) Applications	2025—028T—CAEE
29	Technical Standards for Integrated Monitoring and Control Units of New Energy Vehicle Thermal Management Systems	2025—029T—CAEE

China recently established a working group to address safety and cell venting detection

Space Considerations….

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Delivering Value-Add Sensors

Typical requirements to meet application needs for cell control/monitoring sensors:

- Batteries need controlled environment to be durable and safe; monitoring for "imminent failure" can utilize voltage, current, temperature, impedance spectroscopy, and physical strain
- Low mass, proven technologies
- Very long mission life – MTTF's approaching 20+ years for components, minimal drift in specification
- Tighter accuracy requirements – especially for current, voltage
- Benign to aggressive temperature demands, vibration, shock, dielectric insulation, EMC requirements – High voltage and EM fields are a factor in design
- Designs need to consider redundancy for safety, critical single point of failure driving catastrophic outcomes
- Cell venting detection necessary, better to monitor cell health and disable prior to venting event

The cost of failure is expensive, but the cost of detection still needs to be affordable

Typical Battery Sensor Summary

Technology /Applications

Measurand	Need	Application space	Technology	Signal	Qty
Voltage	Control / charge balance	All	A-D Converter	Analog	Multiple
Current	Control	All	Hall effect, Shunt, Tunneling Magneto-resistive (TMR)	Analog / Digital	Multiple
Temperature	Control/Safety	All* - Battery, thermal management, connections	NTC Thermistor, RTD, Infrared	Analog resistive, digital	Multiple
Cell failure/venting	Safety	EV, BESS	Pressure (piezo si), gas(various), aerosol	Analog / Digital	one/two
Coolant leak/ water intrusion	Safety	BESS, EV	condutive /resistive	analog	1 or more
Humidity	Control	BESS, EV	capacitive polymer	Digital	one
Strain /Pressure	Control	Emerging	resistive, capacitive	Analog	Multiple
EIS	Control - SOC/SOH	Emerging	HF voltage injection	digital	tbd

Consumer / micromobility

Increasing Energy

HVOR, BESS

Pragmatic, cost effective solutions

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Cell failure detection – various technologies to "observe venting"

Sensor technology	Venting detection speed	Pros	Cons	Scalable	Energy consumption	Cost / sense point	Typical number / ESS	Typical Applications
Current/Voltage	Slow (10's of seconds and longer)	already deployed for control	Slow to respond to venting, especially for LFP and in parallel strings)	Yes	Low	no added cost	variable	All
Temperature (NTC)	Slow (10's of seconds and longer)	Inexpensive , available	Cannot be placed on every cell*, electronics/circuit traces become cumbersome, available inputs to BMS	Limited	Low (mA)	0.10-.25 USD	Small: 1/cell; medium and large: 6-40, BESS: ~100	Small to large applications
Temperature (IR)	milliseconds	Fast, modest cost, easy to deploy	Limited field of view	Medium(EV)	Low (mA)	~3.00-4.00 USD	Small: 0, Medium/EV: 2-3; large: TIC used	home ESS, EV,
Temperature (TIC)	Fast - seconds	Wide field visibility	Expensive, large, blind spots, generally requires human oversight / AI	Large scale only (BESS)	High (not portable)	~1k USD	1/BESS	BESS
Impedence (EIS)	Fast - "pre-venting"	Very good at SOH measurement	Difficult in large parallel strings, requires deep DoD for accuracy	Developing	Low (10's of mA)	~20 USD	1/array; Small: 1; medium: 4-5 chips; large:10-20 chips	Small to large applications
Air Pressure	medium: 3-20 seconds	ubiquitous, inexpensive	Cannot "see" slow events, only works for "sealed" enclosures	Limited - does not work for large air spaces	Low (mA)	~0.4 - 1.00 USD	small:0; medium(EV): 1-2; Large: not deployed)	mid-sized enclosures (EV's)
Particulates / condensate	medium: 3-20 seconds	Available	can drift, not good for dust-prone environments	mid-range	Low (10's of mA)	10-15 USD	small:0; medium(EV:1); large: not deployed	mid-sized enclosures (EV's)
"Smoke" (ionization/photoelectric)	Very slow - minutes	cited by AHJ's	does not recognize condensate release; placement for detection	Only for large applications (BESS)	med (20-50 mA)	50-300 USD	Small: 0, Medium/EV: 0; large: 1/"zone"* *no clear correlation between location and detection	Large enclosures (BESS)
"Flame" (Infrared)	fast - seconds	Fast, wide FOV	Expensive, large, blind spots	Large scale only (BESS)	High (not portable)	100-200 USD	Small:0; medium/EV:0; large: 1/BESS	Large enclosures (BESS)
Gas detection:								
H2 (Thermal conductivity)	Fast - seconds	Concentration of flammable gas against LEL standards, small	H2 stratfication /consumption; accuracy at low concntrations	small-large	Low (mA)	10-12 USD	Small:0-1; Medium:1-2; large: 10-20/BESS	medium (EV) to large (BESS)
CO2 (NDIR)	Fast-seconds	Large signal:noise, small	current draw	med ium-large	medium (1-20 mA)	10-12 USD	small:0; medium:1; large: 4-5	medium (EV) to large (BESS)
CO (Pellistor / CMOS)	fast- seconds	available; low cost	Sensor needs to determine "event" based on rate of change, drift	medium-large	low (mA)	3-4 USD	small:0; medium:1; large: 4-5	medium (EV) to large (BESS)
Carbonates/VOC's (Pellistor, CMOS)	Fast - seconds	available, low cost	Sensor needs to determine "event" based on rate of change, drift	medium-large	Low (mA)	10-20 USD	small:0; medium:1; large: 4-5	medium (EV) to large (BESS)

Combination of various technologies can improve detection capability and robustness

Cell monitoring and control– Capable technology and supply base

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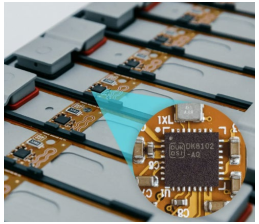
Early venting detection based on carbonate, CO, CO2, H2 sensing

- Gas sensing can have up to 10 minute advantage over VESDA systems
- Production Suppliers include Amphenol, Nexceris, Honeywell
- Data demonstrates combination of gas sensor technologies, often with additional pressure, temperature data provides resiliency/redundancy

"Pre-venting" monitoring:

- Cell surface strain: monitor reversible and irreversible strain / grain structure breakdown: Flexoo.com
- Electrochemical Impedance Spectroscopy (EIS): NXP, Sigmasense, ADI, STMicro, Panasonic, Marelli, Dukosi



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https://liiontamer.com/products/
https://automation.honeywell.com/us/en/products/sensing-solutions/sensors/electrification-sensors/battery-safety-sensors/bes-lite-series#resources

https://soteriabig.com/detector/

Best practices show significant improvement in outcomes with early detection of cell venting

Auto OEM testing observations:

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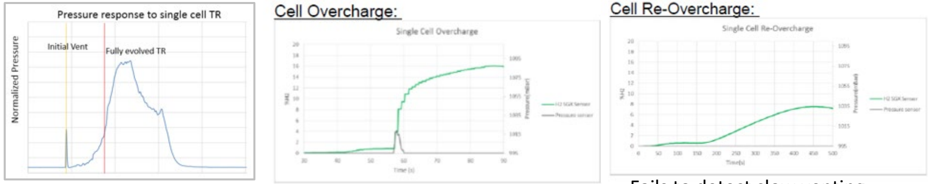
Air Pressure Sensor: Inconsistent performance

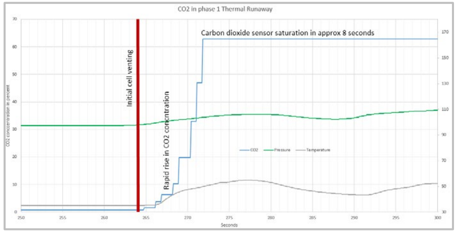
- ✓ Small, inexpensive, and ubiquitous
- ✓ Durable
- Too sensitive to Pack volume/venting effects
- Weak signal to noise ratio
- Must have fast ASIC to observe (<20 msec typ pressure rise)
- Cannot detect slow venting from lower SOH cells
- Cannot detect specific gases
- ***Type 1/Type 2 faults in the field***



Fails to detect slow venting

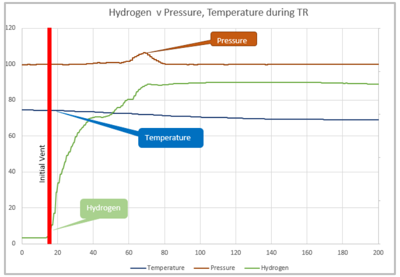
CO_2 IR Spectroscopy Sensor: consistent performance

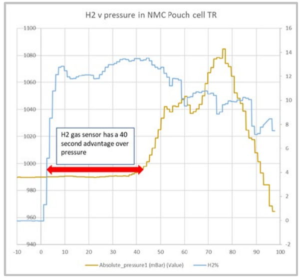
- ✓ 5 to 8 second response time
- ✓ Durable, stable in long term applications
- ✓ No cross sensitivity issues
- ✓ Strong signal to noise ratio
- ✓ Low risk of Type 1/Type 2 faults
- Higher power consumption
- Larger sensor footprint
- ➢ ***Useful for larger enclosure spaces for asphyxiation hazard***



H_2 Thermal Conductivity Sensor: consistent performance

- ✓ <1 to 3 second response time (faster than pressure)
- ✓ Durable, stable in long term applications
- ✓ Strong signal to noise ratio
- ✓ Only cross sensitive to He, not present in packs
- ✓ Low risk of Type 1/Type 2 faults
- ✓ Low power consumption
- ✓ Small sensor footprint
- ➢ ***Automotive/small pack applications for explosion hazard***





Gas sensors have substantial advantages in detecting even small cell TR venting

Gas evolution and cascading TR

Amphenol Sensors

Relationship between signals and environment:

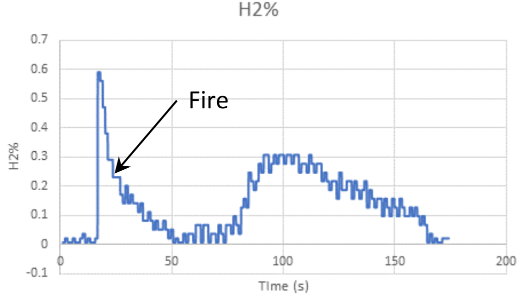
- Ratio of cell SOC/SOH(thermal capacity) to free air volume will drive sensor location, response characteristics (ie, smaller cells with lower SOC's venting will generate less gas to detect in large dilution volumes
- Current approach has been generally insensitive to dilution volumes
  - Superheated plume will initially drive gases to top of enclosure space, CO2 will cool and settle, hydrogen will try to escape via leaks/permeation
  - Gases can remain above LEL for hours inside enclosure

Cascading TR:

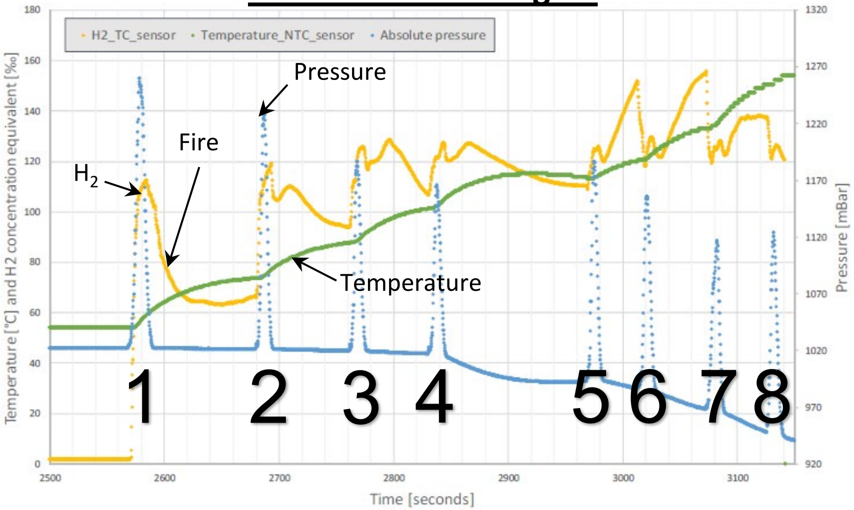
- Shown at right, prismatic cells in cascading TR in traction pack of ~150L dilution volume
- Concentration of H_2 (yellow) continues to rise after consuming available oxygen in the pack with each incremental cell venting
- Gas temperatures throughout the pack increase and sensor data limited by electronics overtemperature condition
- Gases can linger within enclosure for extended period
  - Once above LEL, diurnal temp changes can affect oxygen available for gas combustion

20 000l dilution volume (ISO container)

21700 cell



Prismatic cascading TR



Multiphysics sensors with high concentration calibrations can track performance of TR countermeasures