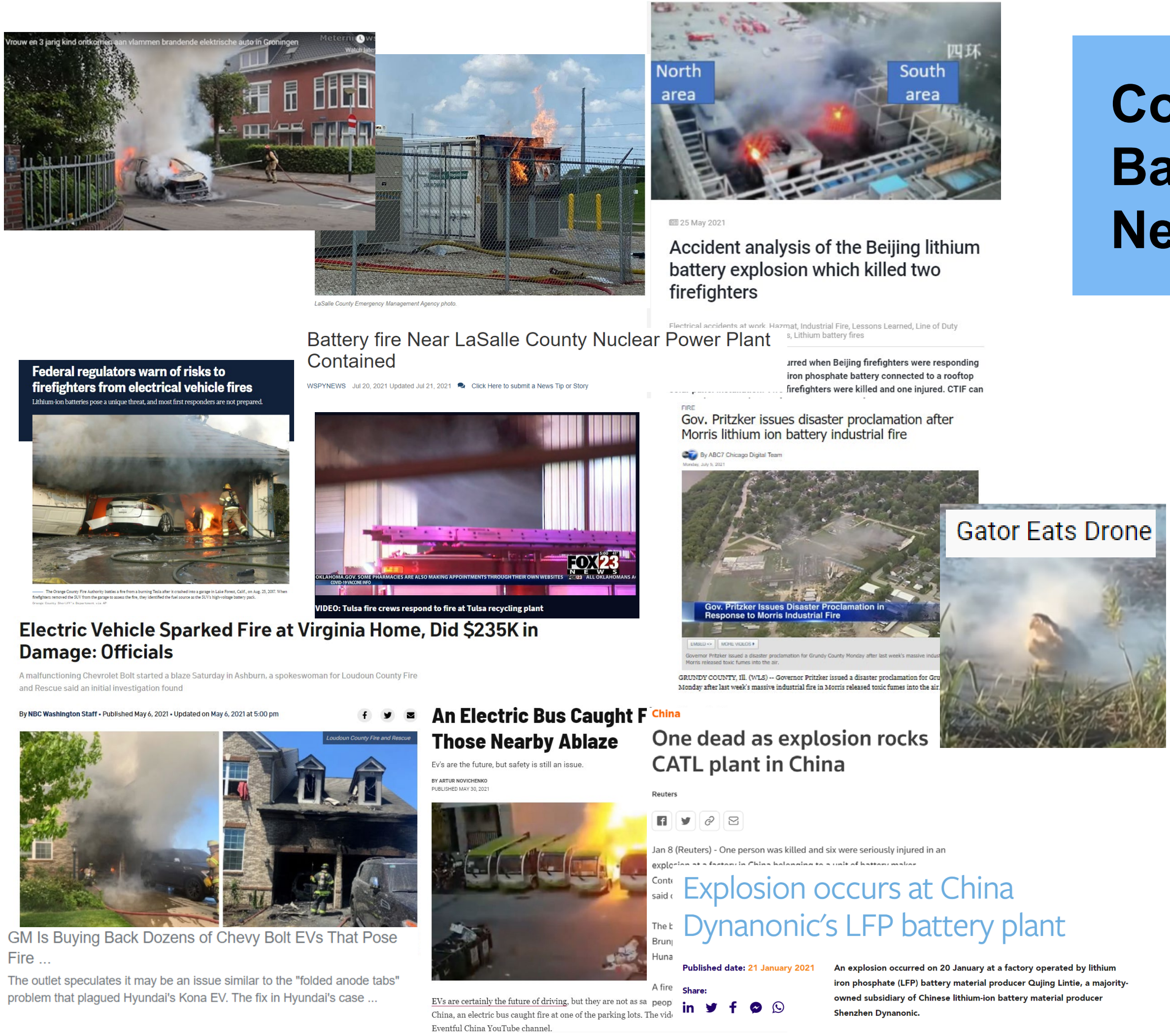

Controlling Lithium Battery Fire Propagation: New Strategies

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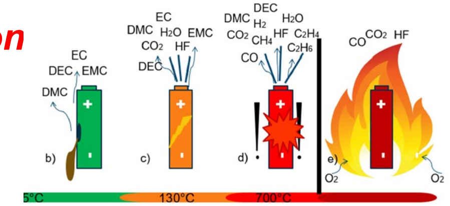
Why are lithium ion battery fires so pernicious?

While rare, Lithium ion battery fire pose unique challenges to suppression



Courtesy ViV

- **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 :

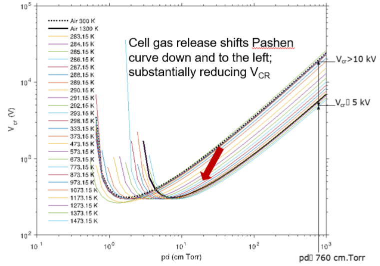
  $$\frac{5}{2}O_2 + C_3H_4O_3(EC) \xrightarrow{\Delta H} 3CO_2 + 2H_2O$$

  $$\text{-CH}_2\text{-CF}_2\text{-} + Li \xrightarrow{\Delta H} LiF + \text{-CH=CF-} + \frac{1}{2}H_2 \qquad \text{CMC-OH} + Li \xrightarrow{\Delta H} \text{CMC-OLi} + \frac{1}{2}H_2$$

- **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 release increases potential for HV discharge
  - Once external oxygen is consumed, flammable gases can reignite with reintroduction of O2
- **Stranded energy /damaged cells can cause reignition events**
- **Battery packs in EV's and ESS applications can be difficult to access**
- **It is often difficult to remotely assess the state of a battery cell**
- **Difficult to determine "End of Event"**

Figure 82: Mid-test, NMC (Bolt), ABC powder (A: ABC power deployed, B: first re-ignition, C: second re-ignition)

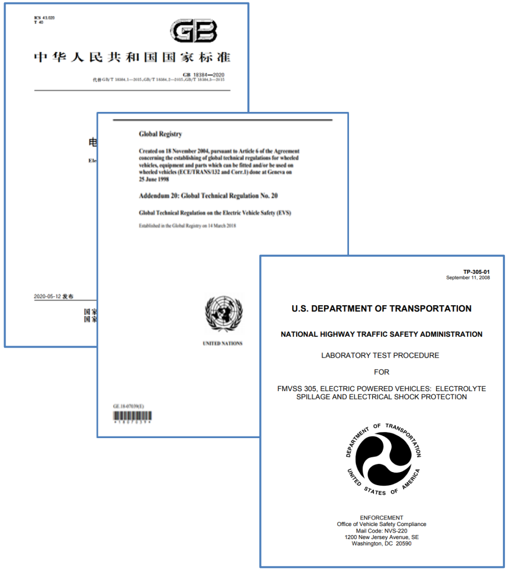
Courtesy SWRI



Courtesy Jeremy Riousset, FIT

xEV Thermal Runaway Regulations

CHINA EV Safety & EV Battery Safety Regulation: GB 18384 2020, GB 38031 2020, GB 38032 2020



New regulation released 12 May, effective 1/1/2021.

<u>AUTOMOTIVE THERMAL INCIDENT WARNING</u>

China leading, with EU following:

> 5.2.7.2 Battery pack or system shall have occupants' protection analysis and validation under thermal propagation per 8.2.7.2. The battery pack or system shall provide an alarm of thermal event 5 min prior to the hazard occurrence in passenger compartment. The hazard is caused by thermal propagation triggered by single cell thermal runaway.

5 Minute Warning Requirement:

- Initiate thermal runaway
- ***Detect*** and alert occupants
- Allow occupants to safely exit vehicle within 5 minute window

UN GTR 20 (EV Safety) cites requirement to protect occupants; does not contain pass/fail requirements yet

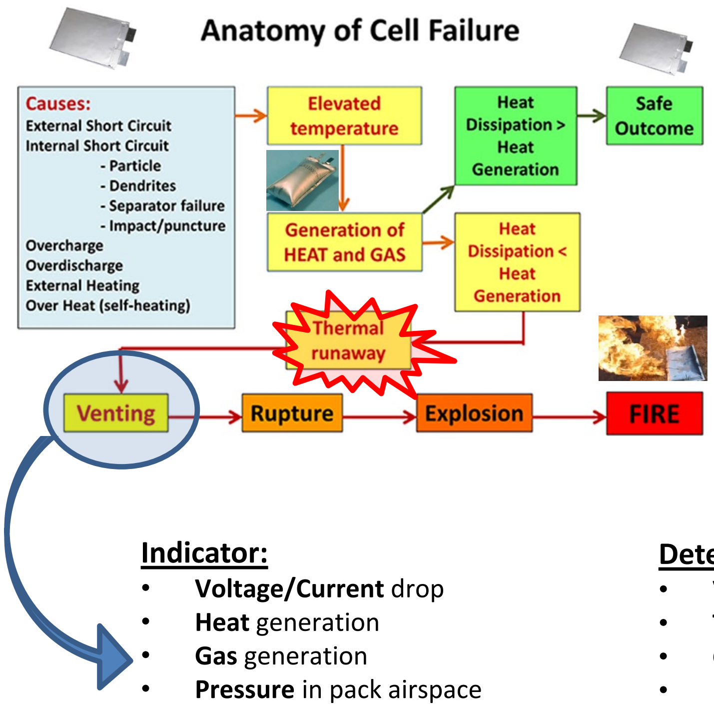
Developing Thermal propagation test procedure

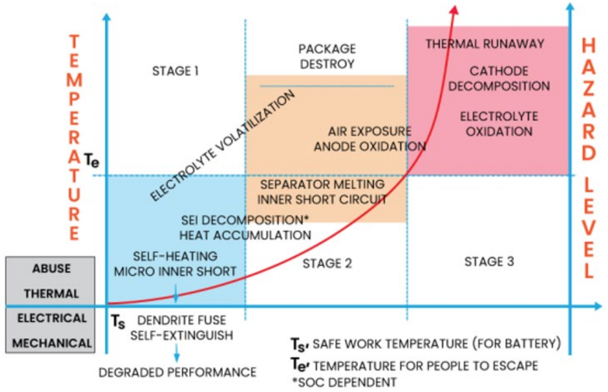
NA: FMVSS only specifies requirment to limit electrolyte leakage, retain batteries and isolate HV

Harmonizing with GTR; FMVSS draft for public comment planned release Q2 2022

Fire Industry Association – Guidance issued in 2021

Anatomy of Cell Failure and available detection technology:





Reference from Sinovoltaics

Indicator:

- **Voltage/Current** drop
- **Heat** generation
- **Gas** generation
- **Pressure** in pack airspace
- **Swelling** of cell
- **Smoke** generation

Detection Technologies:

- **Voltage** monitoring (slow / not effective for parallel strings)
- **Temperature** sensing (slow / not enough sense points)
- **Gas** sensing (need to prevent cross sensitivity / drift)
- **Pressure** sensing (cell v air volume/venting; pack shell breach)
- **Force** sensing (deconfound thermal/intercalation; signal/noise)
- **Particulate / Smoke** sensing (need particulate products)

Each sensor technology has strengths & weaknesses

Detecting Explosive Gases

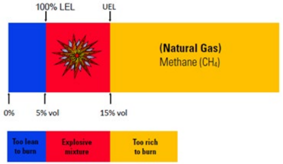
Cell venting :

- Venting products include 4 combustible gases above their Lower Explosion Limit (LEL)*
- Electrolyte leakage can release Ethyl/Methyl based compounds with low vaporization temperatures.

$$\% \text{ LEL} = \frac{\text{Gas Concentration (in \% vol)}}{\text{Lower Explosive Limit (in \% vol)}} \times 100$$

$$25\% \text{ LEL Pentane} = \frac{.35\% \text{ vol}}{1.4\% \text{ vol}} \times 100$$

Example of Combustion



Priority **Secondary**

No.	Cell	SOC (%)	θ_R (°C)	θ_m (°C)	Δm (g)	n_{sum}^{ideal} (mmol)	H_2 (%)	CO_2 (%)	CO (%)	CH_4 (%)	C_2H_4 (%)	C_2H_6 (%)
1	NCA	0	—	302	—	65	1.7	94.6	1.6	1.6	0.3	—
2	NCA	0	160	316	4.4	52	1.8	94.7	1.9	1.2	0.4	—
3	NCA	0	160	315	4.5	55	1.2	96	1.5	1.1	0.2	—
4	NCA	0	161	214	4.4	39	0.9	96.2	1.1	1.4	0.3	—
5	NCA	0	150	243	4.4	59	0.8	96.6	1	1.3	0.3	—
6	NCA	25	150	739	5.9	67	15.5	62.7	5.5	8.7	7.5	—
7	NCA	50	140	970	8.5	157	17.5	33.8	39.9	5.2	3.2	0.4
8	NCA	75	140	955	—	217	24.2	20.8	43.7	7.5	3.3	0.5
9	NCA	100	144	904	—	273	22.6	19.7	48.9	6.6	2.4	—
10	NCA	100	138	896	20.5	314	26.1	17.5	44	8.9	2.7	0.9
11	NCA	100	136	933	20.9	244	28.5	22.7	41.5	5.9	1.3	0.3
12	NCA	112	144	—	19.2	252	25.1	18.8	48.1	5.9	2.1	—
13	NCA	120	80	929	—	281	23.5	20.8	48.7	5.4	1.6	—
14	NCA	127	80	983	—	317	28.8	16.2	46.6	6.4	1.3	0.3
15	NCA	132	80	943	17	262	25.8	18.9	49.2	4.7	1.4	—
16	NCA	143	65	1075	20.1	303	26.2	22	43.4	6.9	1.5	—
17	LFP	0	—	251	6.1	55	2.7	93.5	1.8	0.7	0.7	0.7
18	LFP	25	195	231	6.1	31	7.1	85.3	3.1	1.2	3.1	0.2
19	LFP	50	130	283	6.1	32	20.8	66.2	4.8	1.6	6.6	—
20	LFP	75	149	362	6.3	41	21.8	62.6	6.4	1.9	6.3	1
21	LFP	100	140	440	7.1	32	29.4	48.3	9.1	5.4	7.2	0.5
22	LFP	115	155	395	6.2	61	34	52.2	6.4	2.6	4.7	0.1
23	LFP	130	80	448	—	58	30.1	55.8	7.7	6.4	—	—

RSC Advances (2015) 5, 57171; Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge.

Combustible gases concentrations are far above the Lower Explosive Limit (LEL) (4% for H2, 4.4% for CH4, 12.5% for CO, 2.7% for Ethylene (C2H4), 3% for Ethane (C2H6)

Volume of pack vapor space and diurnal pack breathing will influence the concentration over time through air exchange/diffusion.

Cell Venting, even without fire, releases explosive gases into pack vapor space, where any ignition source could cause explosion

Hazardous Gas Release during venting

Cell venting gases:

- Venting products include respiration hazards gases in harmful concentrations in space around vehicle

Name	H phrase in case of leakage	PAC-levels (-1,-2,-3) / ppm
Carbonates		
Dimethyl carbonate (DMC)	H225: Highly flammable liquid and vapour	11, 120, 700
Ethyl methyl carbonate (EMC)	H225: Highly flammable liquid and vapour	n/a
Diethyl carbonate (DEC)	H226: Flammable liquid and vapour.	12, 140, 810
Propylene carbonate (PC)	H319: Causes serious eye irritation.	34, 370, 2200
Ethylene carbonate (EC)	H319: Causes serious eye irritation.	30, 330, 2000
γ-Butyrolactone (γ-BL)	H336: May cause drowsiness or dizziness.	n/a
…		
Ethers		
1,2-Dimethoxymethane (DMM)	H225: Highly flammable liquid and vapour	n/a
1,2-Dimethoxyethane (DME)	H360FD: May damage fertility. May damage the unborn child.	13, 140, 840
1,2-Diethoxyethane (DEE)	H360FD: May damage fertility. May damage the unborn child.	n/a
Tetrahydrofuran (THF)	H351: Suspected of causing cancer.	100, 500, 5000 (ERPG)
2-Methyl-Tetrahydrofuran (2-Me-THF)	H318: Causes serious eye damage.	4, 44, 260
1,3-Dioxolane (1,3-DL)	H360: May damage fertility or the unborn child.	60, 190, 1000
4-Methyl 1,3-Dioxolane (4-Me-1,3-DL)	H225: Highly flammable liquid and vapour.	n/a
2-Methyl 1,3-Dioxolane (2-Me-1,3-DL)	H225: Highly flammable liquid and vapour.	n/a
Others		
Acetonitrile (AN)	H331: Harmful if inhaled.	13, 50, 150 (AEGL)
Tetramethylene sulfone (TMSO)	H302: Harmful if swallowed.	4.1, 45, 400

Solvent	Volume of evaporated solvent*, ml	
	PAC-2 level	PAC-3 level
Dimethyl carbonate (DMC), CAS # 616-38-6	25	149
Acetonitrile (AN), CAS # 75-05-8	6.6	19.2
	Volume of evaporated electrolyte*, ml	
	PAC-2 level	PAC-3 level
Hydrogen fluoride (HF), CAS # 7664-39-3	12.3 (20.5)**	22.1 (36.9)**

Can be achieved from **1 cell only**

* *Volume, solvent/electrolyte evaporates into, is defined as vehicle + 1-m clearance; 61.5 m³ in this study*
** *Dependent on the stoichiometry of $LiPF_6$ hydrolysis – 1:5 (1:3)*

N.P. Lebedeva, L. Boon-Brett, Considerations on the Chemical Toxicity of Contemporary Li-Ion Battery Electrolytes and Their Components, Journal of the Electrochemical Society 163 (2016) A821

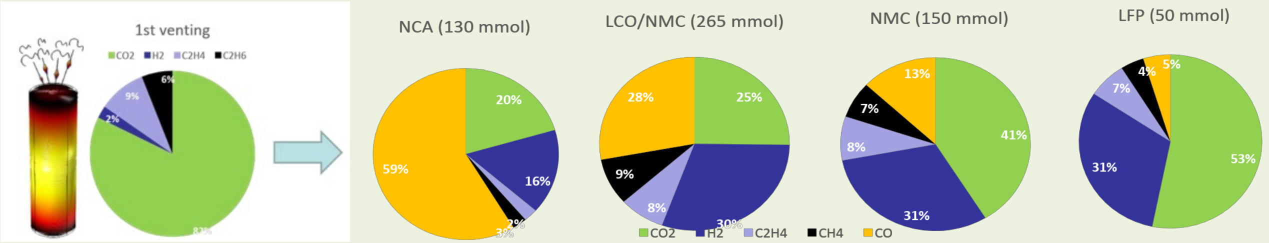
European Commission

PAC stands for **Protective Action Criteria**
PAC-2: Irreversible or other serious health effects that could impair the ability to take protective action
PAC-3: Life-threatening health effects

Release of HF gas from electrolyte vapor release poses imminent risk to respiration proximate to the failing cell

Li-ion cell TR gas release from various electrochemistries

Total gas released during thermal runaway for 100% SOC cells



Data adapted from: RSC Advances 7.39 (2017): 24425-24429.
RSC Advances 4.7 (2014): 3633-3642.

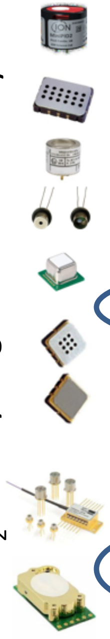
- Majority of total gas released during thermal runaway is CO_2, H_2
- Hydrogen release much higher than background concentration
- Gas concentration is 100 times background level

Gas sensor Selection Process

Electrolyte

Hydrogen

CO_2



Sensor Technology	Principle	Gases	Accuracy	Selectivity	Temperature	Life Expectancy (> 10 years)	Comments
Photoionization Detector (PID)	Photons break molecules into positive ions, bombarded with UV photons; ionized and form electrical current	non selective VOC's	Good	Good	Good	Poor	high current required
Metal Oxide Semiconductor (CMOS)	Heated catalyst interacts with gas, creating a vo	[illegible]	Good	Poor	Good	Poor	can suffer from drift and poisoning of the catalyst
Electrochemical (EC)	Oxidation or reduction reaction generates electrochemical reaction	Selective VOC's	Good	Good	Good	Poor	Catalyst can be poisoned
Pellistor	small "pellets" of catalyst loaded ceramic whose resistance changes in the presence of gas	Semi selective VOC's	Goods	Poor	Good	Poor	Catalyst can be poisoned
Photoacoustic	the measurement of the effect of absorbed electromagnetic energy (particularly of light) on matter by means of acoustic detection.	CO2 , VOC's	Poor	Very Good	Very Good	Good	particulate and humidity sensitive
Thermal conductivity	electrically heated filament in a temperature-controlled cell. Under normal conditions there is a stable heat flow from the filament to the detector body. When an analyte elutes and the thermal conductivity of the column effluent is reduced, the filament heats up and changes resistance. This resistance change is often sensed by a Wheatstone bridge circuit which produces a measurable voltage.	H2, He, VOC's	Very good	Good	Very Good	Very good	cross sensitive to helium
Tunable diode laser spectroscopy	technique for measuring the concentration of certain species such as methane, water vapor and many more, in a gaseous mixture using tunable diode lasers and laser absorption spectrometry.	CO2, CO, VOC's	Very Good	Very Good	Good	Very Good	substantial current draw when light source active
Non dispersive infrared spectroscopy	White light or narrow band light source projected down an optical chamber at a n IR sensor with selective band filter tuned to absorption frequency of gas. Intensity of receieved light is inversely proportional to gas concentration	CO2, VOC's	Very Good	Very Good	Good	Very Good	substantial current draw when light source active

Cross sensitivity/drift/aging effects

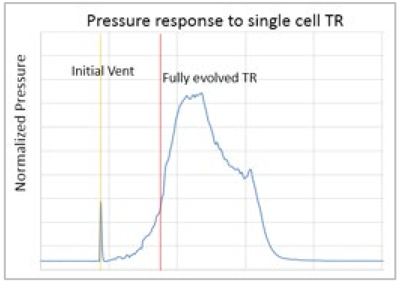
From the available technologies, it is critical to understand sensor response to analyte, cross sensitivity, signal to noise ratio as well as aging properties.

TC and Spectrosopy measure physics behavior, not chemical behavior.

Auto OEM testing observations / Summary:

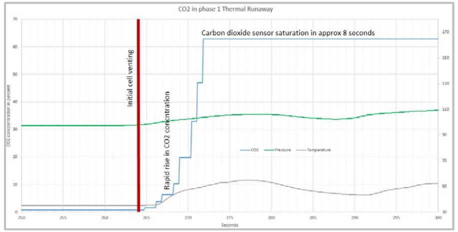
Pressure Sensor: Poor performance

- ✓ 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 phase 1 TR venting
- ‐ Cannot detect specific gases
- ‐ High risk of Type 1/Type 2 faults



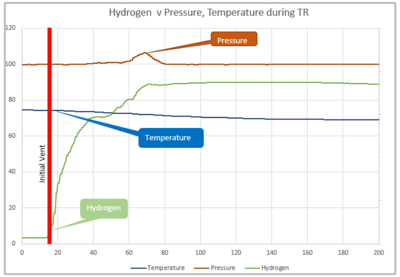
CO2 Sensor: very good performance

- ✓ 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
- ‐ Cost
- ‐ Larger sensor footprint



H2 Sensor: Excellent 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
- ✓ Lowest cost
- ✓ Small sensor footprint



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

TR plasma plume velocity:

Ejecta plume velocities:

(Srinivasan, ECS 2020)

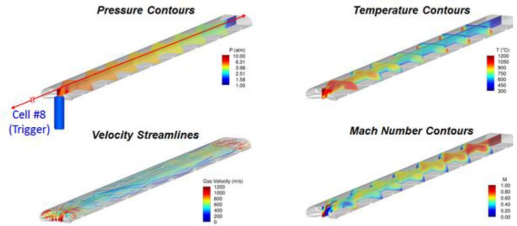
- LG HG2 18650 cells in pack arrangement
- Velocity profile modeled and verified with HS camera
- Ejecta plume velocity can exceed 200m/s and can even approach Mach
- Plume velocities and superheated gas substantially accelerate gas diffusion within the vapor space of a pack/enclosure
- From Johns Hopkins studies, DMC electrolyte ejected from cells can be a source of external fire for adjacent cells during TR as it recondenses, creating complications in preventing TR cascade, as secondary ignition of electrolyte creates external heat source that can trigger other cells into TR

Testing performed in large format traction battery pack:
Multiple tests performed with sensor proximate to trigger cell and at maximum distance from trigger cell (approximately 2m)

- Gas sensor response characteristics support conclusions of Srinivasan's study
- Sensor location within the enclosure space has little to no impact on response time
- Response data within measurement error

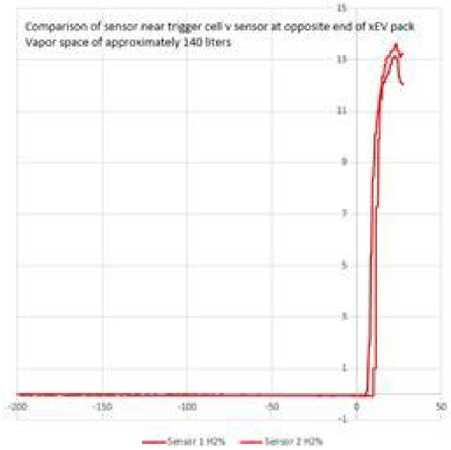
Sensors anywhere in "airspace" of pack can detect within seconds

Velocity flow field within pack



Supplementary Figure S5. Ejecta flow along the vent channels as predicted by CFD simulation.

H2 sensor location not critical



Gas evolution and cascading TR

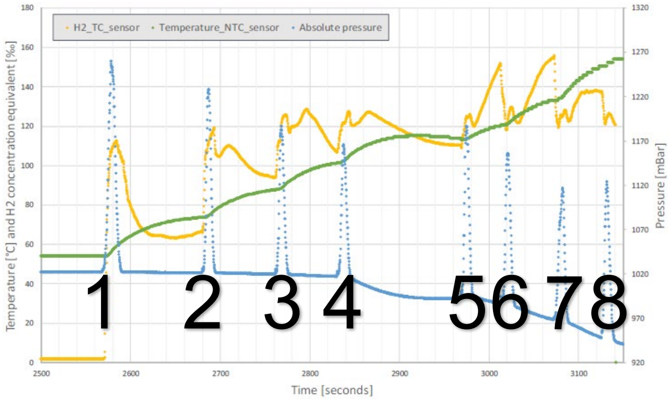
Relationship between signals and environment:

- 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
  - Superheated plume will initially drive gases to top of enclosure space, CO2 will cool and settle, hydrogen will try to escape via leaks/permeation
  - Large enclosure spaces can be simulated with small number of cells and appropriate venting/dilution volume
  - Leveraging NREL experience and modeling to optimize sensor placement for large volume applications

Cascading TR:

- Shown at right, prismatic cells in cascading TR in traction pack of approx. 150L
- Concentration of H2 (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

Cascading TR



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

Countermeasures and Field Experiences

State of the Industry for Thermal Propagation countermeasures

INTERNATIONAL

On vehicle:

- ✓ "Livestream" data to secure server
- ✓ Aggressive HX
  - ✓ Coolant
  - ✓ refrigerant
- ✓ Load dump from affected modules
- ✓ Phase change materials that absorb heat
- ✓ Disable regen braking contribution to pack charging
- ✓ Disable charging
- ✓ Thermal isolation
- ✓ On board extinguishing agents (busses)
- ✓ Dielectric coolant
- ✓ Access port

Off vehicle:

- ✓ ISO bath (ISO 17840 / SAE J2990)
- ✓ E lance
- ✓ Lots of water
- ✓ Fire blanket
- ✓ First Responder Survey Recommendations

ISO 17840-3:2019 Road vehicles — Information for first and second responders — Part 3: Emergency response guide template (K. Vollmacher)

EMERGENCY RESPONSE GUIDES (ERG'S)

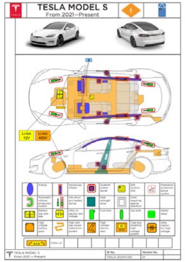
The ERG template provides a format for filling in the following necessary and useful emergency information:

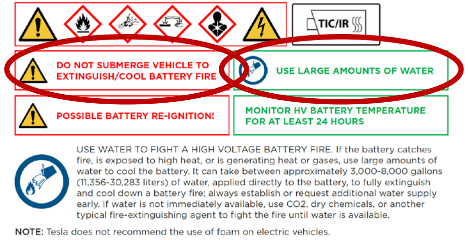
- Relevant information for a vehicle involved in a traffic accident (including immobilisation, disabling of hazards, access to occupants, shut-off procedures, handling of stored propulsion energy);
- Information in case of fire or submersion; and
- Information regarding towing, transportation and storage.

This document is applicable to passenger cars, buses, coaches, light and heavy commercial vehicles according to ISO 3833.
The proposed template can be beneficial for use also for other types of vehicles (e.g. trains, trams, airplanes), although this is out of the scope of this document.

Summary:
- Uses standard documentation and "EuroRescue" smartphone app to access database
- Enforced by EuroNCAP vehicle ratings

- ➢ ***ERG quality/content varies across industry***
- ➢ ***Procedures / recommendations vary across OEM's***
- ➢ ***Current immersion recommendations may work well for some passenger cars, won't work for HVOR applications***





SAE J2990 /ISO 17840 First Responder Training

Andrew Klock, NFPA / Kurt Vollmacher EU

- **In US, 300k trained; >800k need training**
- **Over 300k in EU still need training**
- **Training Cites SAE J2990**

With the increasing prevalence of electric (EV) and hybrid vehicles all over the world, it is important for the first and second responder communities to be educated on the various unique safety risk these vehicles may present. Since 2010, the National Fire Protection Association's (NFPA) Alternative Fuel Vehicle Safety Training Program has teamed up with major auto manufactures, subject matter experts, fire, law enforcement and safety organizations in order to address these safety needs. Through our years of research and work in this field we have developed a comprehensive curriculum for first responders when dealing with alternatively fueled vehicles which include instructor led classroom courses, fnteractive online learning, an Emergency Field Guide, and informational/educational videos.

Here are a few important takeaways on EV and hybrid fire safety for first responders:

1. When suppressing a vehicle fire involving an EV or hybrid, water is the recommended extinguishment agent. Large amounts of water may be required, so be sure to establish a sufficient water supply before operations commence.
2. As with all vehicle fires, toxic byproducts will be given off, so NFPA compliant firefighting PPE and SCBA should be utilized at all times.
3. ***DO NOT attempt to pierce the engine or battery compartment of the vehicle to allow water permeation, as you could accidentally penetrate high voltage components.***
4. Following extinguishment, use a thermal imaging camera to determine the temperature fluctuation of the high voltage battery before terminating the incident, to reduce re-ignition potential

Legacy philosophy of some manufacturers was to "Let it Burn" when dealing with damaged cells and thermal runaway; and this is challenged by First Responders, including FDNY from their experience with e bikes

Experience:

- ***Inconsistent ERG recommendations create confusion and increase risk***
- ***In absence of training, First Responders are driven by experience (Morris, Ill use of cement, FDNY e-bike experience)***
- ***Need improved guidance on "stranded energy" and "end of event"***
- ***Additional training needed***
  - ***First Responders letter of support from SAE (E. Melville)***
  - ***Proposal for SAE ERG document training***

NYC e-bike infernos: Scooter, e-bike batteries caused 55 fires, two deaths so far this year, FDNY says

Tesla big battery fire in Victoria under control after burning more than three days

Investigations into the cause of the blaze that began during testing on Friday can now begin

Get our free news app and our morning email briefing

"They are difficult to fight *because you can't put water on the mega packs* … all that does is extend the length of time that the fire burns for."
Firefighters have taken advice from experts including Tesla, the battery's creators, and UGL, who are installing the battery packs.
"The recommended process is you cool everything around it so the fire can't spread and *you let it burn out*," Beswicke said.

SAE INTERNATIONAL

Safety Risks to Emergency from Lithium Ion Battery Fires in Electric Vehicles

Recommendations:

To NHTSA (NTSB H-20-30 & 31):

1. Incorporate Emergency Response Guides (ERGs) into NCAP: open unacceptable response

- *NHTSA indicated work with responder community more effective*
- *NHTSA cited research in stranded energy before next steps*
- *NTSB incentive for manufacturers on difficult issues at the edge of design envelope*
- *NTSB feels pathway unclear*

2. Continue research on mitigating or de-energizing stranded energy

- *2015 NHTSA symposium and research of battery diagnostics/prognostics prior to onset of thermal runaway*
- *NTSB found issues after TR, with damaged battery and re-ignition*
- *NHTSA cited need for broader understanding of crash situations and vehicle design prior to planning research*
- *NTSB encouraging leadership position to focus a coalition of stakeholders*

To EV Manufacturers (NTSB H-20-32):

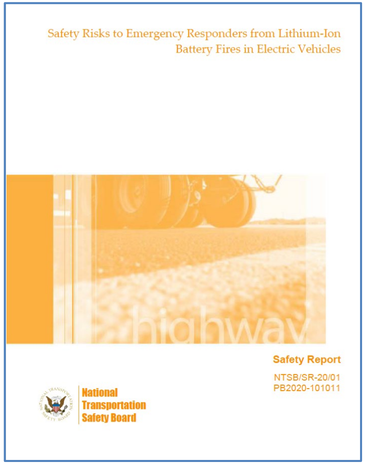
3. Model ERGs on ISO 17840 and SAE J2990

Vehicle specific information on fire fighting, stranded energy, safe storage
Several OEM's with ERG deficiencies identified in the study are actively engaged & improving ERG's

To responder associations (NTSB H-20-33):

4. Inform members of risks and available guidance

- *NFPA, IAFC: closed acceptable action*
- *AFTC, NVFC, TRAA: open awaiting response*
- *DOE grants*
- *May 2020: NFPA Distributed Energy Resources Training Program*
- *October 2020: NFPA Spurs the Safe Adoption of EVs Through Education and Outreach*


Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles

highway

Safety Report

NTSB/SR-20/01
PB2020-101011

National Transportation Safety Board

Thomas Barth, Ph.D.
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303.319.5774

Report number: SR2001
https://www.ntsb.gov/safety/safety-studies/Documents/SR2001.pdf

Summary Video on NTSB website
https://www.youtube.com/watch?v=J6eS6JzBn0k

Docket number: HWY19SP002
https://data.ntsb.gov/Docket/Forms/searchdocket

(put HWY19SP002 in search box)

Cooling cells, supressing fire, & relieving stranded energy

A driverless Tesla crashed and burned for four hours, police said, killing two passengers in Texas

Tesla Fire in Texas Crash Was Not How It Was Reported, Says Fire Chief

Persistent news reports that a battery fire of a crashed 2019 Model S couldn't be extinguished and stymied fire officials are wrong, he says.

By the time even the smallest embers were finally out, many hours after the crash, ***somewhere between 25,000 and 30,000 gallons were used***, Buck said. This was only possible because the incident happened in a residential area with a hydrant nearby. Had the crash happened on a highway, his department's trucks, which carry between 500 and 1000 gallons, would not have been able to keep on lightly soaking the car for that much time.

Response vehicles typically only have ~500 to 1500 gallons of water available on board -"lots of water" = multiple tankers

- First Responder research in EU providing new tools for Responders

Current
"Water Immersion"
& "Large amounts of water"

5,000 to 30,000 gallons

New Development:
AVL Water "spike" into pack substantially reduced water usage

First
Application Example

- Renault Zoe Q210
  - Nominal power: 46 kW
  - Max. power: 65 kW
  - Battery capacity: 22kWh
  - Pouch Zellen
- Battery ignited by penetration
- Max temperature after penetration: >600°C
- Water consumption: approx. 300l
- Extinguishing time: 20min
  ->15l/min water
- Temperature after extinguishing: <90°C
- After extinguishing the vehicle was transferred in a container with water

80 gallons

New field Tools for First Responders:
"Spike" systems from Murer, Rosenbauer

Press release — rosenbauer

October 7, 2021

New extinguishing system for burning traction batteries in electric vehicles

- **Safe deployment due to short deployment time on the burning vehicle and system activation with sufficient distance**
- **Efficient firefighting by cooling the modules and cells in the battery housing**
- **Lead users confirm the efficiency and ergonomics of the system**

Rosenbauer launches a new extinguishing system for burning traction batteries in electric vehicles. The system can be used to safely and efficiently extinguish lithium-ion based high-voltage batteries. It enables direct cooling of the battery modules, or the cells within the modules, and thus a quick stop to the propagation of the thermal runaway of the cells.

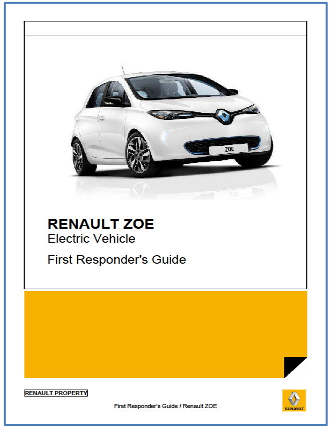
The safety of the firefighter was the top priority during the development and is achieved by the fact that the firefighter only being in the vicinity of the burning vehicle for a very short time and the system is activated from a safe distance. The extinguishing system applies the water exactly where it is needed: to cool the cells and modules in the battery housing. Extinguishing thus takes place in a very resource-efficient way and reduces the spread of flue gases to a minimum.

- ***Information on new tools/proposed processes needs to be reviewed by OEM's and J2990 team***
- ***New applications (eHVOR/eAero/ESS/e-Industrial) require review/evaluation of practices***
- ***Tie out between J2990 and NFPA855 recent revisions***

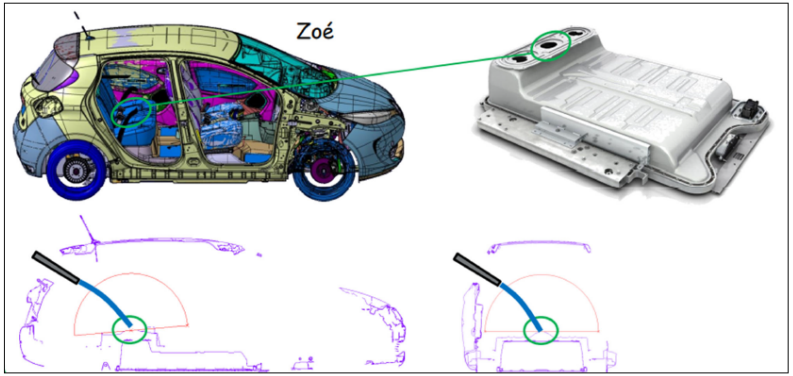
Benchmark: Renault Zoe “thermal plate”

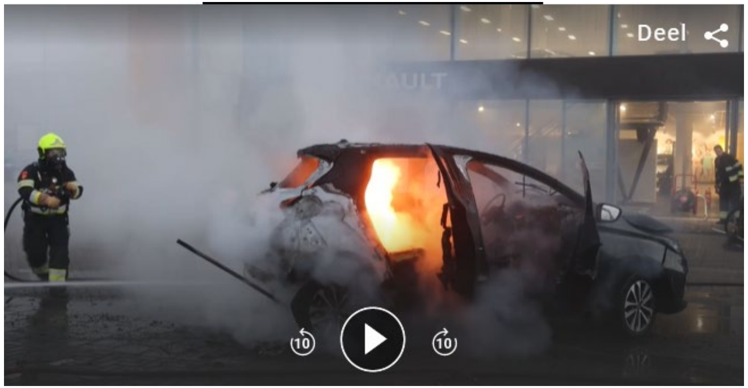
“Fire Hose Access” allows for direct battery immersion

- **Information on design is in Emergency Response Guide**
- **Incident at Dealership in Holland on 1/18 in showroom**
- 2 employees treated for smoke inhalation



Renault has developed a system whereby water can be introduced into the battery pack from the outside.
This is done by means of a thermal plate, which is mounted on top of the battery house and melts away in case of fire.
in case of fire and thus gives access to the high-voltage battery.



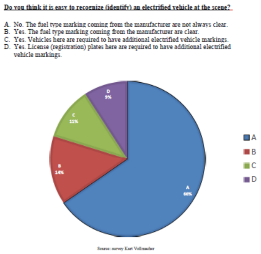


First & Second Responders Survey 2021

"First" survey on EV response of its kind

Survey issued in 2020/21: >500 respondents, ~30% experienced xEV incidents

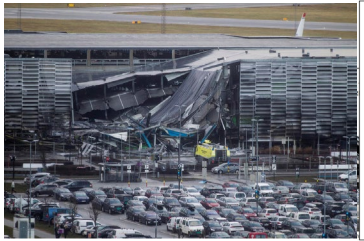
Kurt Vollmacher, ISO17840 Author

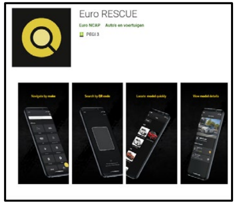


https://us01.z.antigena.com/l/EgGN4kdmCCZAjTVohChpvdEd8gr8rL8A5fDDYuXdpS-aujUzR3KNiF6RPFxJkQ-WJw7KBPCTXLtzNludWQGnX0A5r1nK-Wh35RvWgxi-IylPSpfL-8il0zp6j0W2FasFE1fKhAR3rCGCIh7zO5HmqBHwA1mVA0orVpaKM4sQSSUCEYOAkgULMsCC47XXent1Vd3xT1BaF~y2M1V-vvHqOKrolAg~

Key Findings & First Responder Requests:

- Additional training needed in all regions
- Need for clear recognition of xEV's
  - Belgium: proposed ISO icon on plate; Germany "E" at end of plate
- Uniform, globally available information per ISO 17840
- Uniform disconnect system design and placement
- Uniform procedures for extrication and firefighting
- System to make it easy to extinguish HV batteries
- Safety systems to deal with HV stranded energy
- Handling of xEV's in car parks requires research/recommendations





- ➢ J2990 team evaluating recommendations from survey
  - ➢ Investigate equivalent of free EuroRescue app for US / non Automotive applications
  - ➢ Additional First Responder Training needed

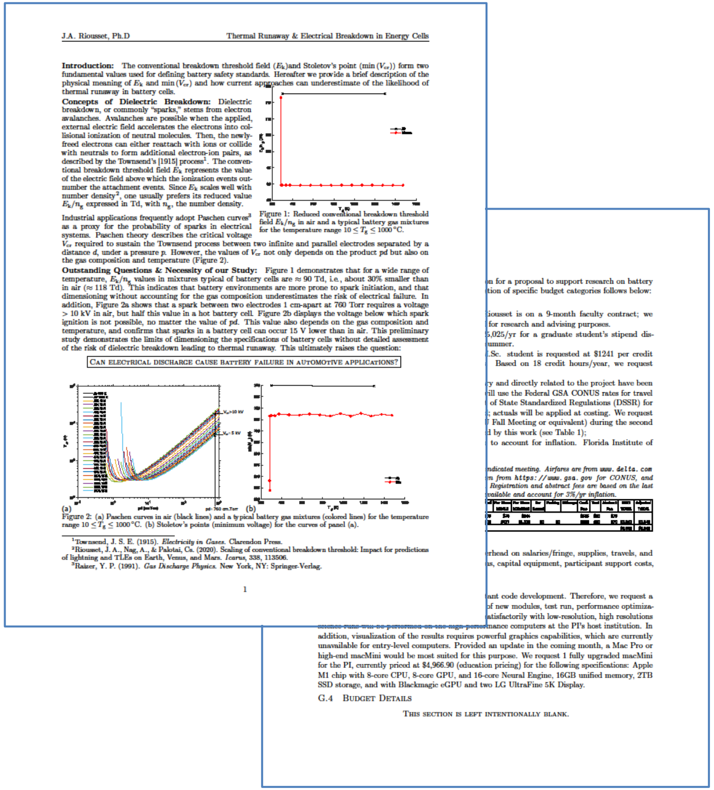
Venting Physics: Ad Hoc Group investigating HV Discharge w/ venting

B. Engle (Amphenol), Dr. Riousset, NASA/Florida Institute of Technology, T. Wilcox(VW), Dr. Harenbrock (M+H), Vinay Prenmath (SWRI), Dr. Essl (ViV), A Thaler (ViV), T. Bohn (ANL)

Background: Empirical evidence suggests vented gases create environment prone to HV discharge and EMI events. Damage inconsistent with flame temperatures and EM events have been witnessed

- Initial model shows 30% reduction in E_k required for electron avalanche w/ dry gas (in the 100's of volts)
- Paschen curves move down and left
- Need to add to model:
  - Relative humidity
  - Particulates
- Testing:
  - Parallel plate proveout with gases
  - Parallel plate in situ during TR

➢ **SAE Cooperative Research Project in process**


J.A. Riousset, Ph.D — Thermal Runaway & Electrical Breakdown in Energy Cells

Introduction: The conventional breakdown threshold field (E_k)and Stoletov's point (min (V_{cr})) form two fundamental values used for defining battery safety standards. Hereafter we provide a brief description of the physical meaning of E_k and min (V_{cr}) and how current approaches can underestimate of the likelihood of thermal runaway in battery cells.

Concepts of Dielectric Breakdown: Dielectric breakdown, or commonly "sparks," stems from electron avalanches. Avalanches are possible when the applied, external electric field accelerates the electrons into collisional ionization of neutral molecules. Then, the newly-freed electrons can either reattach with ions or collide with neutrals to form additional electron-ion pairs, as described by the Townsend's [1915] process[1]. The conventional breakdown threshold field E_k represents the value of the electric field above which the ionization events outnumber the attachment events. Since E_k scales well with number density[2], one usually prefers its reduced value E_k/n_g expressed in Td, with n_g, the number density.

Figure 1: Reduced conventional breakdown threshold field E_k/n_g in air and a typical battery gas mixtures for the temperature range $10 \leq T_g \leq 1000\,°C$.

Industrial applications frequently adopt Paschen curves[3] as a proxy for the probability of sparks in electrical systems. Paschen theory describes the critical voltage V_{cr} required to sustain the Townsend process between two infinite and parallel electrodes separated by a distance d, under a pressure p. However, the values of V_{cr} not only depends on the product pd but also on the gas composition and temperature (Figure 2).

Outstanding Questions & Necessity of our Study: Figure 1 demonstrates that for a wide range of temperature, E_k/n_g values in mixtures typical of battery cells are ≈ 90 Td, i.e., about 30% smaller than in air (≈ 118 Td). This indicates that battery environments are more prone to spark initiation, and that dimensioning without accounting for the gas composition underestimates the risk of electrical failure. In addition, Figure 2a shows that a spark between two electrodes 1 cm-apart at 760 Torr requires a voltage > 10 kV in air, but half this value in a hot battery cell. Figure 2b displays the voltage below which spark ignition is not possible, no matter the value of pd. This value also depends on the gas composition and temperature, and confirms that sparks in a battery cell can occur 15 V lower than in air. This preliminary study demonstrates the limits of dimensioning the specifications of battery cells without detailed assessment of the risk of dielectric breakdown leading to thermal runaway. This ultimately raises the question:

CAN ELECTRICAL DISCHARGE CAUSE BATTERY FAILURE IN AUTOMOTIVE APPLICATIONS?

Figure 2: (a) Paschen curves in air (black lines) and a typical battery gas mixtures (colored lines) for the temperature range $10 \leq T_g \leq 1000\,°C$. (b) Stoletov's points (minimum voltage) for the curves of panel (a).

[1] Townsend, J. S. E. (1915). *Electricity in Gases.* Clarendon Press.
[2] Riousset, J. A., Nag, A., & Palotai, Cs. (2020). Scaling of conventional breakdown threshold: Impact for predictions of lightning and TLEs on Earth, Venus, and Mars. *Icarus*, 338, 113506.
[3] Raizer, Y. P. (1991). *Gas Discharge Physics.* New York, NY: Springer-Verlag.

1

addition, visualization of the results requires powerful graphics capabilities, which are currently unavailable for entry-level computers. Provided an update in the coming month, a Mac Pro or high-end macMini would be most suited for this purpose. We request 1 fully upgraded macMini for the PI, currently priced at $4,966.90 (education pricing) for the following specifications: Apple M1 chip with 8-core CPU, 8-core GPU, and 16-core Neural Engine, 16GB unified memory, 2TB SSD storage, and with Blackmagic eGPU and two LG UltraFine 5K Display.

G.4 BUDGET DETAILS

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Hazardous Gas Release (Lebedeva, et al)

Solvent	Volume of evaporated solvent*, ml	
	PAC-2 level	PAC-3 level
Dimethyl carbonate (DMC), CAS # 616-38-6	25	149
Acetonitrile (AN), CAS # 75-05-8	6.6	19.2
	Volume of evaporated electrolyte*, ml	
	PAC-2 level	PAC-3 level
Hydrogen fluoride (HF), CAS # 7664-39-3	12.3 (20.5)**	22.1 (36.9)**

Can be achieved from **1 cell only**

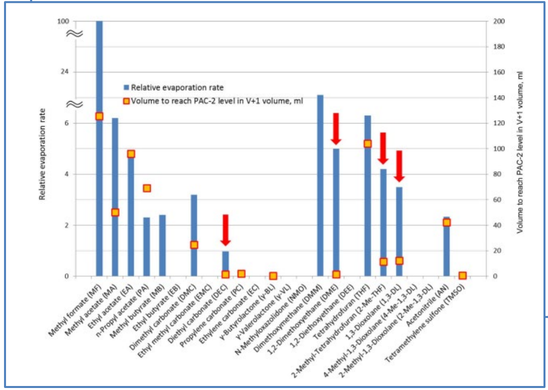
* *Volume, solvent/electrolyte evaporates into, is defined as vehicle + 1-m clearance; 61.5 m³ in this study*
** *Dependent on the stoichiometry of $LiPF_6$ hydrolysis – 1:5 (1:3)*

N.P. Lebedeva, L. Boon-Brett, Considerations on the Chemical Toxicity of Contemporary Li-Ion Battery Electrolytes and Their Components, Journal of the Electrochemical Society 163 (2016) A821

European Commission

Considerations on the Chemical Toxicity of Contemporary Li-Ion Battery Electrolytes and Their Components

Article in Journal of The Electrochemical Society · January 2016

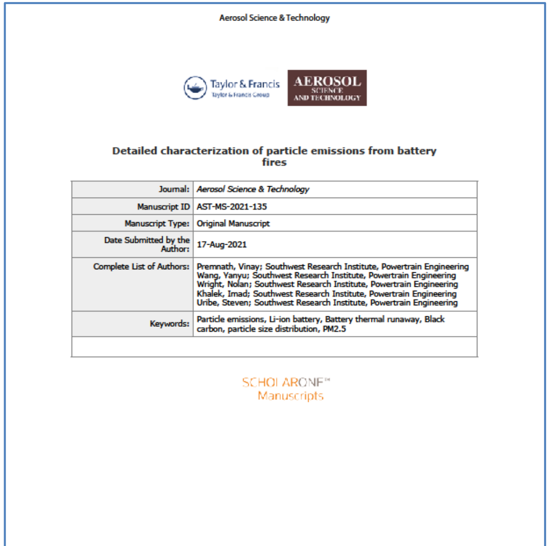


Summary Conclusions:

- Li-ion battery cells can contain free liquid electrolyte in amounts sufficient for the formation of potentially toxic atmosphere in enclosed spaces after a release of electrolyte from a single battery cell.
- Li-ion cells containing appreciable amount of free liquid electrolyte are used in mass-production PHEVs and BEVs, which are on the EU market since 2013 and 2010, and which belong to the top-10 most sold electric vehicle models in the EU.
- Release of the contained free liquid electrolyte represents the best case scenario as its amount corresponds to the minimum amount of electrolyte that can be released from a battery cell when the integrity of the cell casing is compromised.

Particulate release with TR (Premnath Sept 2021)

- **<u>The results from this work highlight the following:</u>**
- Battery fires emanating from thermal runaway events can result in significant particle and gaseous emissions. Both overcharge tests of LFP modules, and the nail penetration test of the NMC module resulted in PM2.5 emissions exceeding 370 g/hour and total PN emissions of the order of 2E+17 part./hour. These emission rates are 5 to 6 orders of magnitude higher than those typically emitted from the exhaust of a modern heavy-duty diesel engine. It is to be noted that the aforementioned statement is primarily to provide a contextual comparison with a well-documented particle emitter.
- Initiation mechanism could play an important role in the scale of the thermal runaway event. Within a module, it is possible that there may be a localized impact with some cells experiencing runaway without further propagation. This was observed during nail penetration tests of LFP modules where no cell-to-cell propagation occurred.
- Physical dimensions and arrangement of cells within a module could also influence the severity of the runaway event, particularly if the triggering mechanism is mechanical in nature.
- Battery chemistry coupled with the thermal runaway initiation mechanism influences the magnitude of particle and gaseous emissions, along with release profile. The overcharge LFP tests resulted in a single continuous release event till peak levels were reached after which a gradual decrease was observed. The NMC nail penetration test resulted in multiple peak events that corresponded with propagation of thermal runaway from one cell to the next.
- Particle emissions from thermal runaway events of identical modules induced into runaway via the same mechanism could be highly variable.
- Battery chemistry including the type of electrolyte solvent/salt can influence the nature of hazardous gaseous emissions. ***The LFP overcharge tests yielded HF that exceeded IDLH limits (30ppm) while the NMC nail penetration test yielded formaldehyde beyond IDLH limits (20 ppm).***


Aerosol Science & Technology

Taylor & Francis — AEROSOL SCIENCE AND TECHNOLOGY

Detailed characterization of particle emissions from battery fires

Journal:	*Aerosol Science & Technology*
Manuscript ID	AST-MS-2021-135
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	17-Aug-2021
Complete List of Authors:	Premnath, Vinay; Southwest Research Institute, Powertrain Engineering Wang, Yanyu; Southwest Research Institute, Powertrain Engineering Wright, Nolan; Southwest Research Institute, Powertrain Engineering Khalek, Imad; Southwest Research Institute, Powertrain Engineering Uribe, Steven; Southwest Research Institute, Powertrain Engineering
Keywords:	Particle emissions, Li-ion battery, Battery thermal runaway, Black carbon, particle size distribution, PM2.5

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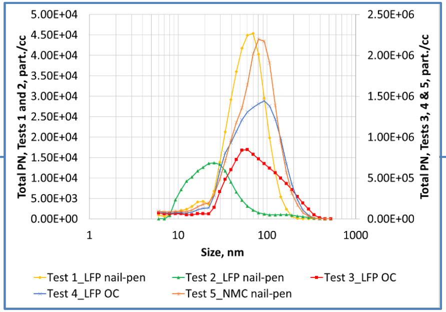


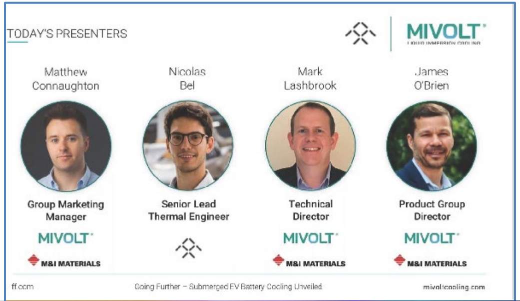
Benchmarks: Immersion Cooling

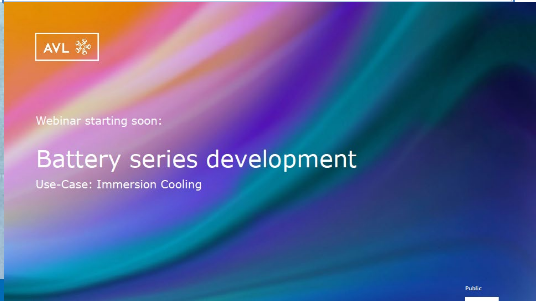
Faraday Future, new xEV Co.

- Dielectric immersion cooling

Investigations by:

- AVL
- Ricardo
- University of Warwick
- M&I Materials/ MiVolt





- ✓ Current data shows substantial promise for improved, more uniform cooling, especially in high c rate charging
- ✓ Ricardo data cites improvement in system weight due to direct cooling of busbars, elimination of convective cooling h'ware
- ✓ Reduced risk / containment of TR
- × Current price of mineral oils, esters based on existing market requires improvement for passenger car use