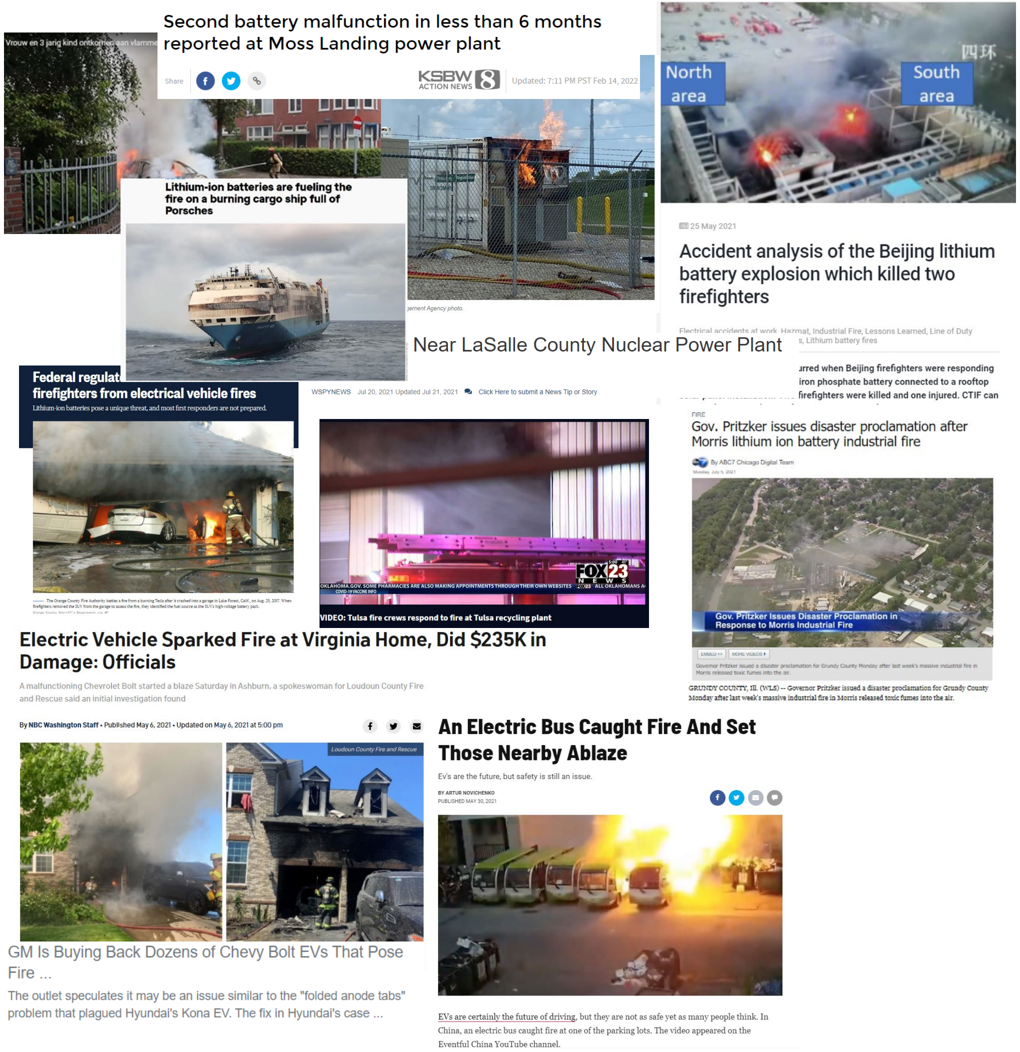

Li-ion Cell Venting Risks and Detection

Brian Engle

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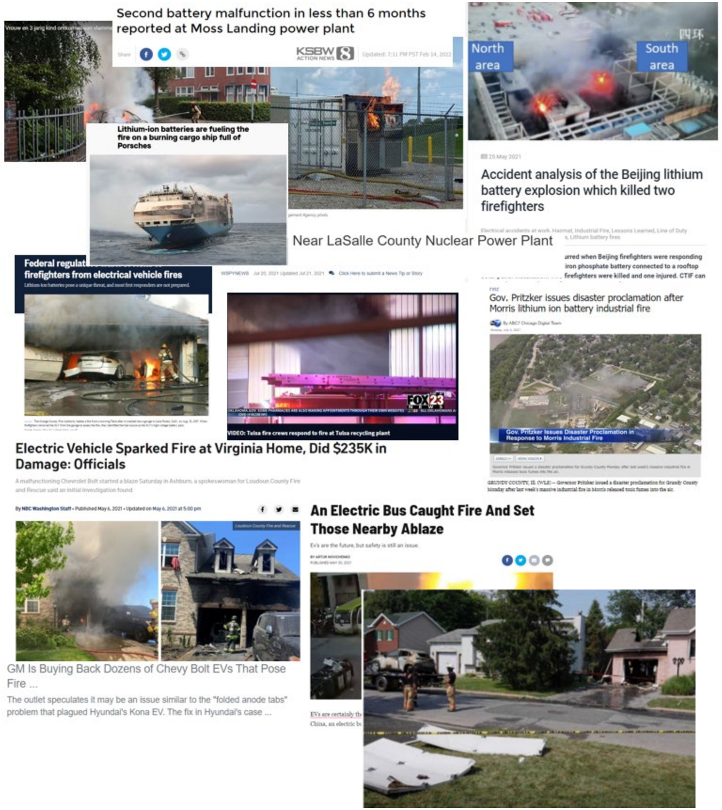
amphenol-sensors.com

Chair: SAE J2990 First/Second Responders Task Force

Vice President, NAATBATT

Facts:

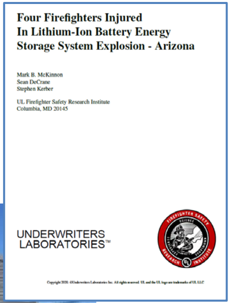
- Internal Combustion Engine (ICE) vehicle fires occur once every 3 minutes in the US - NFPA
- ~7000-9000 garage fires in the US/year
- 100 years of experience guide safety, tools, and SOP for ICE vehicles
- xEV's have ~***90% LOWER probability*** of experiencing a fire incident than ICE vehicles
- Many incidents in the headlines are from extreme (high speed) crashes
    - xEV's can put much more torque to the wheels than ICE vehicles



Challenges with xEV's / Lithium-ion Battery fires:

- Pack location is difficult to access
- Thermal Runaway temps >600 – 1000 C
- Hazardous and flammable gas release; explosive risk
- High Voltage (400 to 1.2kV) systems
- Gases, particulates and water vapor increase risk of arc discharge
- Lithium-ion batteries provide their own oxygen to support combustion
- Damaged cells/stranded energy can cause re-ignition
- Difficult to assess state of cell, pack and determine "end of event"
    - Events require hours of engagement and 1,000's of liters of water to extinguish
- ***New technology requires training, new processes, new tools***

Arizona Public Service McMicken April 19, 2019 – 4 firefighters seriously injured


Four Firefighters Injured
In Lithium-Ion Battery Energy
Storage System Explosion - Arizona

Mark B. McKinnon
Sean DeCrane
Stephen Kerber

UL Firefighter Safety Research Institute
Columbia, MD 20145

UNDERWRITERS LABORATORIES™

Summary Points:

- A call for smoke in the area of an electric substation came into Phoenix dispatch on April 19, 2019
- ***Four firefighters seriously injured in deflagration***
- Design of the ESS complied with the pertinent codes and standards active at the time of commissioning
- The fire and smoke detection systems did not include, and were not required to include, sensors that provided information about the presence of flammable gases. There were no means for the HAZMAT team to monitor toxic gas concentrations, LEL, or the conditions inside the ESS from a physically secure location.

Key Findings:

- Colwell's model indicates H2 concentration within enclosure was >7%, CO2> 9% before enclosure opened
- Lithium-ion battery ESSs should incorporate gas monitoring that can be accessed remotely.
- Research that includes multi-scale testing should be conducted to evaluate the effectiveness and limitations of stationary gas monitoring systems for lithium-ion battery ESSs.

Figure 6 Damage to the rear door and HVAC systems of the McMicken BESS

<u>There were five main contributing factors that led to the explosion:</u>

- Internal failure in a battery cell initiated thermal runaway
- The fire suppression system was incapable of stopping thermal runaway
- Lack of thermal barriers between cells led to cascading thermal runaway
- Flammable off-gases concentrated without a means to ventilate
- Emergency response plan did not have an extinguishing, ventilation, and entry procedure

Sacramento Tesla Incident

Jun 13, 2022 at 10:46am ET
By: **Steven Loveday**

According to reports issued by *Metro Fire of Sacramento*, firefighters from the unit recently experienced their first Tesla fire. Interestingly, it wasn't at the scene of an accident, but rather, at a wrecking yard.
As the story goes, the Tesla Model S was totaled in an accident, and it had been sitting at the Sacramento yard for about three weeks. Based on reports, despite the accident, the electric car had never caught fire prior to the incident at the yard, which makes this an interesting case.
As you can see from the brief video, the Tesla electric car is certainly not just sparking up or smoldering. This is a full-on fire engulfing the car, with clouds of thick black smoke clouding the air around the area.
The fire department shared that the firefighters were able to put out the flames, though the car kept re-igniting thanks to thermal runaway from the Tesla's battery pack. After turning the car over and learning that the battery pack was continuously re-igniting, the team went to great lengths in order to get the fire to go out and stay out. They dug a pit, placed the car inside, and filled the pit with water.
One Twitter user responded to the initial tweets saying that the firefighters should have finished putting the car out in the first place. It seems the person thought that perhaps the Model S had already been on fire after it recently crashed. However, Metro Fire of Sacramento responded that this was the car's first and only fire.
As far as the fire department was concerned, the car never caught fire at the scene of the crash, or for the three weeks prior to this incident unfolding.

“This was the 1st and only. The vehicle sat parked in a wrecking yard for 3 wks after a vehicle accident (not involving fire), and then caught fire in the yard. Our crews were dispatched and ensured the vehicle was extinguished after well over an hour of firefighting operations."

Fortunately, no one was injured at the wrecking yard. While Tesla has recently shared that fires are becoming less common among its vehicles, there have been a few other recent incidents that are concerning.

As we previously reported, a Tesla Model 3 caught fire in late May while parked (and not running or charging) in California City. Meanwhile, right around the same time, a Model Y started on fire while its owner was driving it in Canada, and NHTSA already requested information from Tesla. Check out the related stories below, and then leave us a comment.

https://insideevs.com/news/591794/tesla-fire-wreckage-yard-three-weeks-after-crash/

Tesla Goes Up In Flames Weeks After Crash That Didn't Involve Fire

The Tesla Model S was sitting in a wrecking yard in Sacramento for three weeks before it was suddenly ablaze.

Metro Fire of Sacramento
@metrofirepio

Photos of the pit the crews created...

5:57 AM · Jun 12, 2022

Hyundai Kona Garage Explosion - Montreal

Hyundai Kona Electric Blast: High Voltage Battery Area Had The Most Damage

That indicates where the issue began. Anyway, Transport Canada reinforces the cause is still under investigation.

Jul 28, 2019 at 2:16pm ET

Lithium has offered us the most efficient battery until now, but it is also very flammable. This is why any fire situation with a huge lithium-ion battery may be very difficult to extinguish. The newest such case comes from Canada. More specifically from Île-Bizard, Montreal. And it involves a vehicle that had not presented any similar problem until now, the Hyundai Kona Electric.

Piero Cosentino bought his last March. On July 26, he was about to have lunch when he heard ***an explosion and the fire alarm went off. Thick black smoke was coming from the door that leads to his garage.***
"As soon as I saw that, I immediately turned off the breaker," he told CBC. "My first instinct was to go out and run outside so I did not have to open doors and feed the fire." Cosentino then started to fight the fire with the help of a garden hose while he waited for the firefighters.

It was only there Cosentino could see the extent of the damage. The explosion ***set his garage door to the other side of the street. Part of the roof of the garage went down.***

Around 30 men managed to put out the fire. Louise Desrosiers, a Division Chief from the Montreal Fire Department, said they found no other possible cause to the fire apart from the Hyundai Kona.

"It was a fully electric vehicle, and there was nothing around that could have caused the explosion. We will be following up [...] closely with the owner to understand the problem in anticipation of other cases," she told Radio Canada, which also took the pictures in this article.

The story gets even weirder. Cosentino claims his Kona was not charging. And that is was not even connected to a socket.

Vancouver

NHTSA Requests Info From Tesla About Recent Car Fire In Canada

A Tesla Model Y in Canada recently caught fire while driving, and the NHTSA wants answers.

May 27, 2022 at 11:19am ET

By: Steven Loveday
There have been a few Tesla electric car fires in the news recently, and some media outlets and individuals seem to be getting confused about which is which. To be clear, the US National Highway Traffic Safety Administration (NHTSA) is now requesting information about the Model Y fire in Canada that happened while the car was in motion.

Another recent Tesla fire, which we also covered, happened in the States. It involved a Model 3 that was parked in California City. The Model 3 wasn't running or charging. We'll have to wait and see what comes of this related fire. NHTSA told Reuters it "is aware of the incident and has reached out to the manufacturer for information."

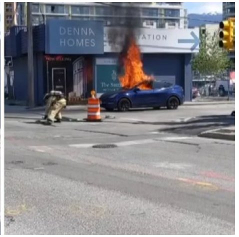
At any rate, as we previously reported, Tesla Model Y owner Jamil Jutha was driving his electric crossover when it alerted him of an error, powered down, started smoking, and suddenly caught fire. He ended up breaking the driver's side window to escape from the vehicle before it was in flames.

Tesla's cars have an emergency door release, which is often confused with an actual door-opening handle and can be used as such. However, Jutha said it was difficult to figure out amid the high-stress situation. He shared:

“The doors wouldn’t open. The windows wouldn’t go down. I kicked through the window, climbed out, and called 911 right away."

Just yesterday, May 26, 2022, the NHTSA explained that it had requested information from Tesla about the Model Y's spontaneous combustion that occurred in Vancouver, British Columbia. More specifically, the NHTSA provided that same comment to Reuters as it did about the Model 3 fire. The organization "is aware of the incident and has reached out to the manufacturer for information."

As of the time of writing, Tesla hadn't responded to a request for comment about the Model Y fire in Canada. The same appears to be true about the Model 3 fire in California City.



California City, CA incident

Tesla Model 3 Owner Provides Details On Recent EV Fire In California City

A Tesla Model 3 caught fire while parked, right after the owner canceled plans to drive it to a dinner party.

May 24, 2022 at 11:18am ET

By: Steven Loveday

As you may have heard, a Tesla Model 3 recently caught fire in California City. Thankfully, it was parked with no one inside, and there are no reports of anyone being hurt. However, the EV is clearly totaled, the owner won't get a new car until around October, and many of his belongings were destroyed.

According to Bakersfield Now, Ediel Ruiz was on a trip to visit his partner Edith Parker's family after she recently graduated from USC. Ruiz was inside a home, away from the Model 3 when he says he got a Tesla app notification about the car's alarm. When he headed out to see what was happening, the car was smoking.

Ruiz went on to share that he opened the rear door to find flames engulfing the interior. The fire was melting his infant's car seat. He also explained that all of his partner's "graduation stuff" was burned, as well as a stroller and some baby formula. The Tesla owner noted that the ***fire appeared to start beneath the car seat in the second row.***
The couple had plans to head to Bakersfield for dinner, but the plans were canceled at the last minute. Ruiz said:

"Luckily, it didn't happen while we were driving."

According to Bakersfield Now, HowItBroke.com founder Robert Swaim explained that EV fires are uncommon, but they're difficult to put out. This is especially true if the fire department hasn't had much experience with such fires. In addition, even after the fire appears to be successfully extinguished, a phenomenon called thermal runaway can cause it to reignite.

Swaim also suggested that Tesla has improved its models and battery chemistry over the years to make them less prone to fire. That said, he also said that "EVs within two years of being new seem to have more of a propensity to spontaneously ignite."
The California City Fire Department arrived on the scene, responding to the Model 3 owner's 911 call. The team was reportedly successful in putting out the fire quickly, though they've had training specific to dealing with EV fires. However, Tesla's Roadside Assistance wasn't able to move the car right away due to the severity of the damage. Ruiz also added that he had the car insured through Tesla's new in-house insurance program.

The fire department's public information officer David Orr shared that electric car fires aren't something he sees often. Andrew Freeborn of the Kent Country Fire Department agreed, but added that the statistics could change as more people begin to adopt electric vehicles.

Tesla Statement on Thermal Runaway

Statistically, Tesla Car Fires Are Less And Less Frequent

The company reports that fire incidents are 11x lower for Tesla vehicles than the average vehicle in the US.
May 09, 2022 at 2:25pm ET

By: Mark Kane

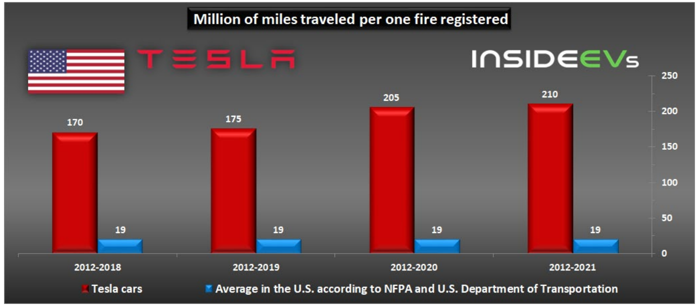
Tesla has recently revealed its latest Vehicle Fire Data provided for the period 2012-2021, which indicates another year of improvement in the reduction of fire incidents per driving distance.
According to the company, during the 2012-2021 period, there was roughly one Tesla vehicle fire for every 210 million miles traveled (compared to 205 million miles in 2012-2020 period).
It's great news. We also must remember that not all of the fires were caused by Tesla cars, as the manufacturer's data set includes instances of vehicle fires caused by structure fires, arson, and other things unrelated to the vehicle to make "an apt comparison" to the National Fire Protection Association (NFPA) data.

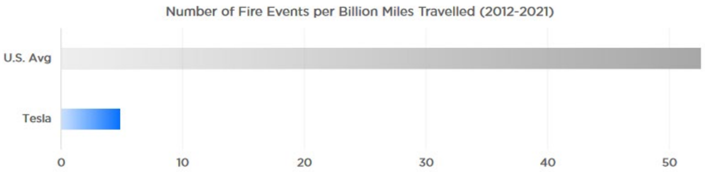
According to the NFPA, the national average for vehicle fires remains at the same level of ***one fire per 19 million miles traveled.***

The difference between Tesla and the average is 11:1, which is a big win not only for Tesla, but in general, for electric cars.

In the new 2021 Impact Report, Tesla revealed also the data in a different way, that from 202o to 2021, there were approximately five Tesla vehicle fires for every billion miles traveled, while the national average for all vehicles is 53.

The company notes that the media often reports on an EV fire, chasing clicks, while in reality, there are vastly fewer Tesla vehicle fires per distance unit.





Tesla Vehicle Fire Data – 2012-2021

> "From 2012 – 2021, there has been approximately one Tesla vehicle fire for every 210 million miles traveled. By comparison, data from the National Fire Protection Association (NFPA) and U.S. Department of Transportation shows that in the United States there is a vehicle fire for every 19 million miles traveled."

- Tesla data includes instances of vehicle fires caused by structure fires, arson, and other things unrelated to the vehicle
- NFPA average for the US includes all cars, also old

https://insideevs.com/news/584722/tesla-car-fires-statistic-2021/

“BlueBus” fleet in Paris: Solid State LMP cells

Paris Suspends 149 Bolloré Electric Buses After Two Fires

Two Bluebus 5SE electric buses were completely destroyed by fires in two separate incidents on April 4 and April 29.

May 02, 2022 at 3:16pm ET

By: Dan Mihalascu

RATP, the public transport operator in Paris, has temporarily withdrawn 149 electric buses made by Bolloré Group’s Bluebus brand from operation after two separate bus fires.

On April 29, a fire broke out on a Bluebus 5SE electric bus on line 71 in the 13th arrondissement of Paris, close to the French capital's national library. The driver immediately evacuated the passengers and no injuries were reported.

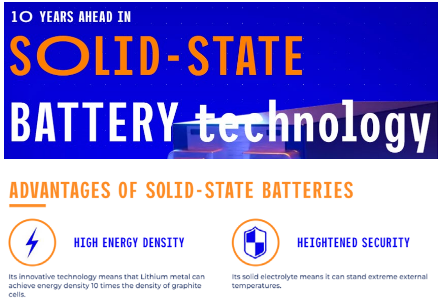
Fortunately, the fire department responded very quickly, with around 30 firefighters managing to put out the blaze. The François Mitterrand Library station, located nearby, was closed from 9 a.m. to 11 a.m. as a safety measure. The electric bus released thick clouds of black smoke and a strong smell of burning plastic, according to eyewitnesses interviewed by BFMTV.

The incident was caught on camera and shows the violent fire engulfing the roof of the electric bus where the battery packs are located. It certainly looks scary as burning debris were ejected from the roof, falling onto the sidewalk and the road like a rain of fire.
This was the second fire involving a Bolloré Bluebus in less than a month. On April 4, another Bluebus 5SE caught fire in central Paris on the Saint-Germain boulevard. That vehicle was also completely destroyed but no one was hurt. As a safety precaution, RATP has decided to temporarily suspend 149 electric buses belonging to the same Bluebus 5SE series as the two vehicles affected by fires.
Bolloré said that its Bluebus subsidiary was actively cooperating with the RATP and relevant authorities to determine the causes of the fires.

The state-owned public transport operator in Paris has 500 electric buses in its fleet of 4,700 vehicles. The electric buses are supplied by Bolloré, Alstom, and CNH's Heuliez Bus.

Bolloré's 12-meter (39-foot) long electric buses can transport up to 109 passengers and offers an estimated driving range of up to 320 kilometers (199 miles) from ***Lithium Metal Polymer (LMP) battery packs totaling 441 kWh*** of stored energy. On its website, Bluebus describes the batteries as "completely solid, with no liquid components, no nickel and no cobalt."

Since the Bluebus 5SE is a low-floor bus, the batteries are spread around the roof and rear of the vehicle.



Renault Zoe: Holland Dealership

Electric car burns out at car dealer in Velserbroek
Tuesday, January 18, 2022

An electric car spontaneously caught fire at the Renault dealer in Velserbroek on Tuesday morning.
The car fire was accompanied by a lot of smoke. As a precaution, many emergency services were present.

It is a brand new electric car that spontaneously started to burn.

Employees got the burning vehicle out of the showroom, after which the car burned out further outside.

Firefighters struggled to extinguish the fire. A number of those involved were treated at the scene by ambulance personnel. Two people have been taken to hospital for a check-up.

Renault ZOE Faces Battery Recall for Fire Risk

Home > News > Safety   5 Feb 2022, 21:56 UTC · by Gustavo Henrique Ruffo

The company warned European Union authorities that units produced between January 13, 2021, and February 22, 2021, present the risk of "an internal short circuit (..:) in the battery." According to Renault's own words, such an issue "will lead to increased risk of fire."

Renault did not disclose exactly which battery is involved with the problem. However, the information document suggests that it is related to the high-voltage battery pack, more specifically to the BT4 XLR (Extra Long Range). We suspect the French carmaker is talking about what it publicly refers to as the "E.V. 50 battery pack."

Renault Zoe [edit]

On October 4, 2020, a Renault Zoe caught fire in Karmøy, Norway. Local residents were evacuated from a nearby building as a precaution.[181]

On December 15, 2020, a Renault Zoe caught fire while parked in the Bjørndal suburb of Oslo, Norway.[182]

On December 30, 2020, a 2017 Renault Zoe caught fire in a parking garage in Sandvika, Norway.[183]

On January 3, 2021, a Renault Zoe caught fire while connected to a charging station in Illingen-Hüttigweiler, Germany. Parked next to the Zoe was another electric car, a Škoda Citigo e-iV, that also caught fire.[184]

On January 25, 2021, a Renault Zoe caught fire while travelling in Quimperlé, France. The driver and his daughter managed to exit the car without any injuries.[185]

On January 29, 2021, a Renault Zoe caught fire while charging at a public charging station in Teterow, Germany. The police suspected the cause to be arson.[186]

On February 16, 2021, a Renault Zoe caught fire while parked (and possibly charging) in Bamberg, Germany.[187]

On February 17, 2021, a Renault Zoe caught fire in the Amberg Tunnel near Feldkirch, Austria. The driver managed to exit the tunnel through the north entrance and stopped on the shoulder, where the firefighters subsequently extinguished the fire.[188]

On May 31, 2021, a Renault Zoe caught fire in a private parking lot in Mulhouse, France.[189]

On June 13, 2021, a Renault Zoe suddenly burst into flames while on the read near Villeneuve-lès-Béziers, France, injuring both occupants, one of whom suffered severe burns.[190]

On July 20, 2021, a Renault Zoe caught fire while charging at a public charging station in Stadskanaal, Netherlands.[191]

On August 14, 2021, a Renault Zoe caught fire in Stolberg, Germany.[192]

On November 11, 2021, a Renault Zoe caught fire in Vennesla, Norway. The driver had to rescue her baby from the burning car.[193]

https://en.wikipedia.org/wiki/Plug-in_electric_vehicle_fire_incidents#Renault_Zoe

Stationary Storage – Chandler, Az

Crews monitoring smoldering battery fire at SRP substation in Chandler
The facility is located within a Salt River Project substation near 54th Street and Pecos Road.
April 21, 2022

CHANDLER, Ariz. — Chandler firefighters are working to contain a battery fire burning at a Salt River substation near 54th Street and Pecos Road.

During a press conference Thursday night, Chandler Fire Battalion Chief Keith Welch said firefighters had taken ***a defensive posture against the fire given the hazardous materials inside the facility.***
Welch said robots were sent inside the building to open doors and ventilate the structure.

The Chandler Fire Department is working with businesses nearby and SRP to reduce the hazard potential at the site.

Officials said, as a precaution, businesses within roughly a quarter-mile area were asked to leave the area by 6 p.m. Thursday night.

An SRP spokesman said this is a 10-megawatt storage facility but that SRP has contingencies for situations like this and that customers should not be impacted by the temporary disruption at the substation.

A spokesman for the facility owner said it’s premature to speculate on the cause. He said the batteries are from LG Chem and there are 3,248 batteries inside. The facility is typically unmanned with periodic maintenance.

Officials said ***750,000 gallons of water have been used***, so far, to mitigate the fire. Chandler Fire is containing that water in the area and it will be tested to make sure it is not toxic. So far testing has not revealed any toxicity, officials said.

Welch said Chandler firefighters learned from an incident in Surprise in 2019 when 8 firefighters were injured trying to put out a fire at a similar Arizona Public Service facility.

The Interstate 10 ramps to eastbound Loop 202 and 56th Street between Frye and Allison were closed from 6 p.m. to 8 p.m.

Warehousing/Storage: Morris, Ill

Gov. Pritzker issues disaster proclamation after Morris lithium ion battery industrial fire
June 30, 2021

GRUNDY COUNTY, Ill. (WLS) -- Governor Pritzker issued a disaster proclamation for Grundy County Monday after last week's massive industrial fire in Morris released toxic fumes into the air.

That fire burned hundreds of thousands of pounds of lithium ion batteries, forcing nearly 5,000 people to evacuate their homes.
The blaze started just before 11:45 a.m. Tuesday at the old Federal Paper Board facility in the 900-block of East Benton Street.

Officials evacuated the southeast side of Morris after the fire broke out last Tuesday, as toxic fumes and smoke emanated from the building, stemming from as many as 200,000 lithium batteries exploding.

The EPA has placed air quality monitors around the town of Morris, including right at the entrance of the building. As of our last report, they had found any evidence of harmful contaminants getting into the air.

Morris Fire Chief Tracey Steffes said they have used 28 tons of Portland cement, an unconventional method, to smother the burning lithium batteries. Before using cement, ***firefighters tried using a dry chemical to extinguish the fire***.
The fire department said they plan to monitor the situation for at least the next couple of weeks.

The order allows the state to expedite additional resources to help Grundy County respond to the disaster.

Morris Mayor Chris Brown said the ***city was not aware of the batteries***.
"To our understanding, we were unaware of the batteries in the warehouse and only came upon it when the firemen started to do their work and push water onto the fire; they've been taking all the precautions necessary to make sure everything is safe and contained," he said last week.

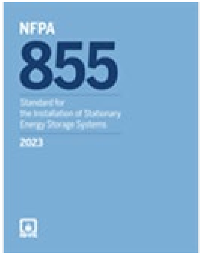
The building's owner Jin Zheng said he was on the scene minutes after the fire started, but he was unable to get inside. He said the thick black smoke coming from the building was fueled by explosions of thousands of lithium batteries he had inside.

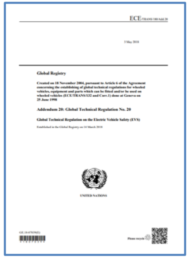
No clear regulation for storage that would compel owner to meet requirements

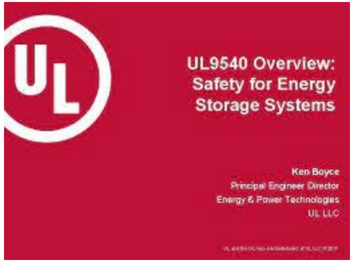
Regulations and Standards

Battery Regulations & Standards:

- NFPA 855: Standard for the Installation of Stationary Energy Storage Systems
- IFC: 2024; Chapter 3: Section 321 Rechargeable Battery Storage
- GTR-20: Electric Vehicle Safety
- UL 1973: Batteries for use in Stationary, Vehicle Aux Power and light rail apps
- UL9540: Safety for Energy Storage Systems
- NFPA 70: Electrical Safety
- ISO-17840: Road vehicles — Information for first and second responders
- SAE J2990: Hybrid and Electric Vehicle Safety Systems Information Report
- SAE 3235 (Draft) BEST- PRACTICES FOR THE STORAGE OF LITHIUM-ION BATTERIES







xEV Thermal Runaway Regulations

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

New regulation effective 1/1/2021.
AUTOMOTIVE THERMAL INCIDENT WARNING:

> 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
- Expected to extend beyond 5 minutes in 2026+

UN GTR 20 (EV Safety) cites requirement to protect occupants

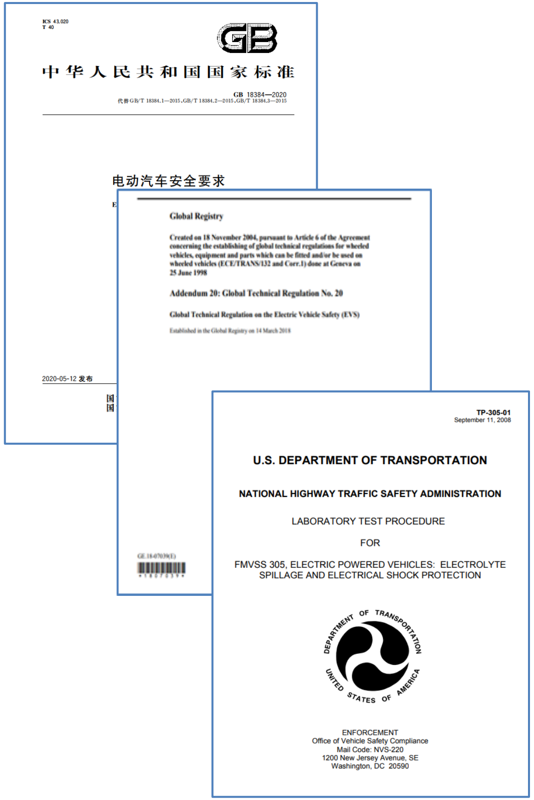
- Phase 2 to implement "vehicle off"/"full vehicle" test identifying gas release risk in cabin and proximate to vehicle

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

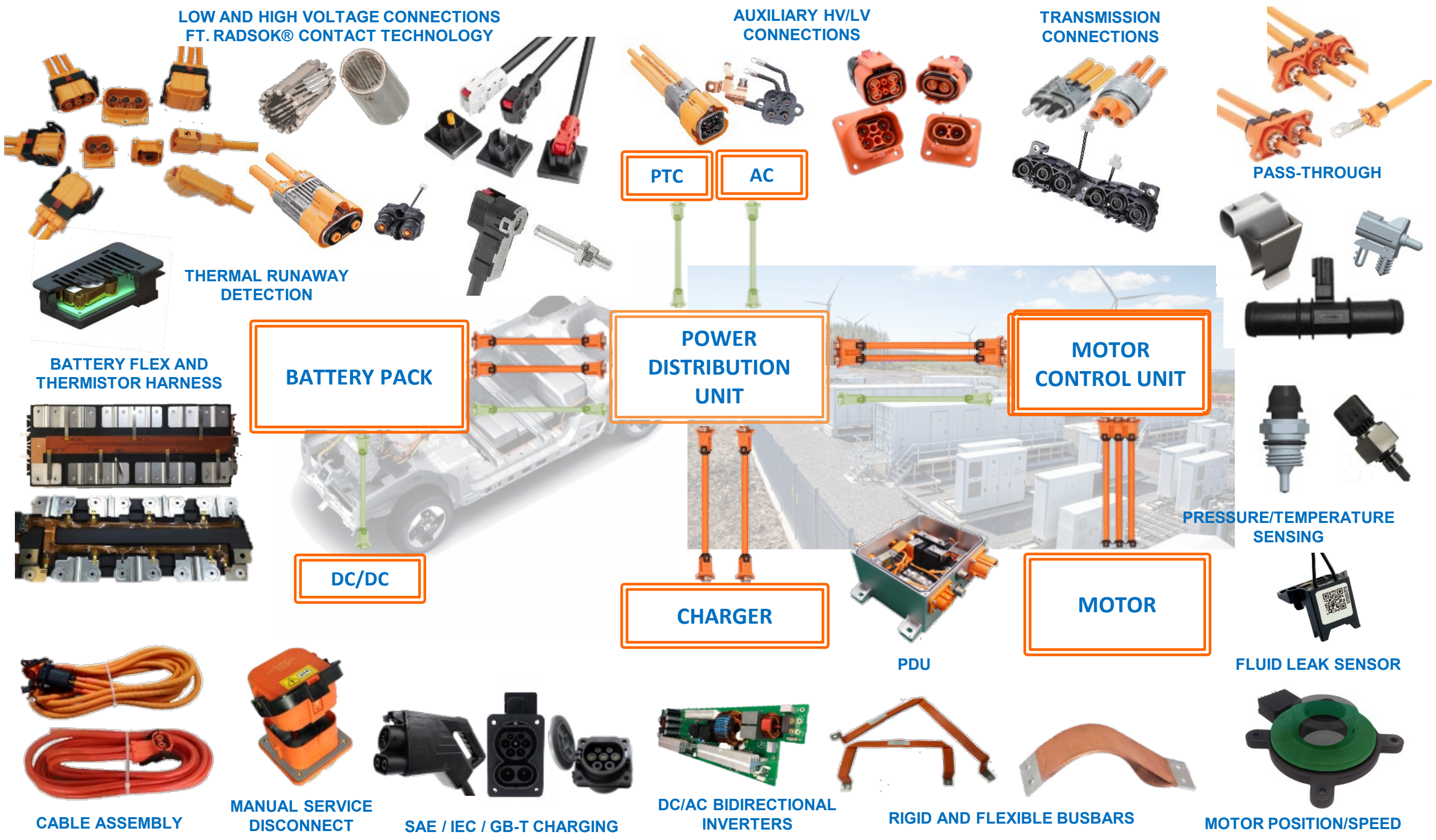
- Will change to reflect GTR-20

Amphenol working with Research and Industry Partners:

- Part of IWG for Global Technical Regulations (GTR)
- Amphenol support of SAE H/EV Committee, First Responders Task Force, Industry Consortia including NAATBATT
- R&D efforts at OEM's, Research laboratories across the globe focused on improving battery safety
- DoE / NREL/ JRC/ViV / NASA
- CDC/NIOSH (OSHA), UL , EPRI
- Universities and Research Institutions



Supporting Mobile and Stationary Sensing & Electrification Solutions



Sensing:

- *Temperature*
- *Pressure*
- *Fluid Level*
- *Concentration*
- *Speed*
- *Rotary/Linear Position*
- *Accoustic /ultrasonics*
- *Vibration / Acceleration*
- *Force*
- *Air Quality*
- *Gas concentration*
- *Particulates / Dust*
- *Moisture / Humidity*
- *Process Controls*
- *Validation Instruments*

Amphenol Battery Sensor Portfolio

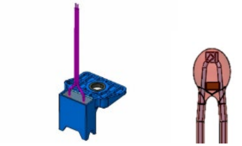
- **Robust Early Detection of Thermal Runaway (REDTR)**
  - **Mobile and Stationary applications**

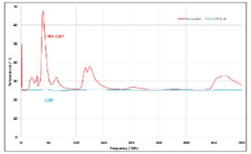
- **Cell & Pack Diagnostics**
  - **Coolant breach/water intrusion sensor**
  - **EMC immune Temperature sensors**

- **Battery / xEV Heat Pump / HX Sensors**
  - **Full suite of thermal management sensors**
  - **Pressure and Temperature**

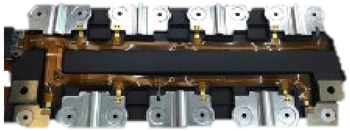
- **Cell Connection Systems**
  - **World’s largest supplier of Cell Connection Systems**

Working Together to Improve Battery Safety, Diagnostics, & Robustness



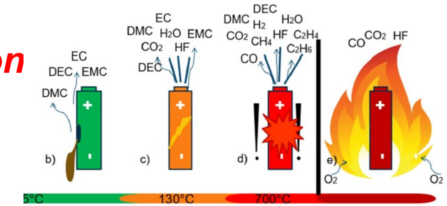


1	Sensor type	Assemby method	Main parameters	Sensor view
2	Water temp sensor	Thread M12	R25C=10K/100K/2.08K -40°C to 125°C	
3	Water temp sensor	Quick lock	R25C=10K/100K -40°C to 125°C	
4	Water temp sensor	Pipe surface 12/15 to18	R25C=10K/100K -40°C to 125°C	
5	Coolant medium temp s	Thread M12	R25C=10K/2.828K -40°C to 130/150°C	
6	PT sensor	Tread M14&M12	50-300KPa GE-2098 -1...10bar to -1...100bar -40°C to 125°C/130°C	



Why are lithium ion battery fires so pernicious?

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



Courtesy ViV

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

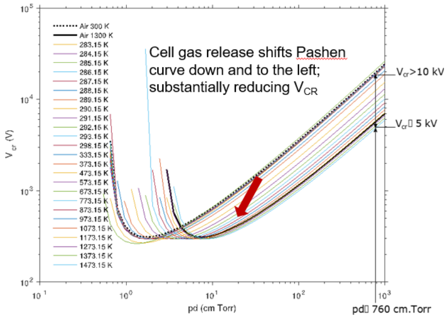
- Cells can achieve temperatures of >600C, transferring heat to adjacent cells
- Electrolyte can cause external fires on other cells
- ***Gas release increases potential for HV discharge***
- Once external oxygen is consumed, flammable gases can reignite with reintroduction of O2

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

Courtesy SWRI

3. 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 for First Responders to determine "End of Event"
- Stranded energy /damaged cells can generate reignition events

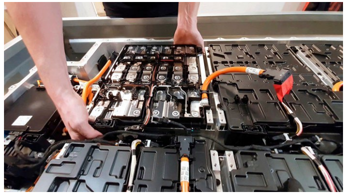


Courtesy Jeremy Riousset, FIT

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

Typical clearance standards – IEC 60664-1:2020

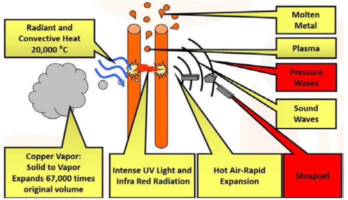
…and why they do not apply when lithium ion battery cells vent…



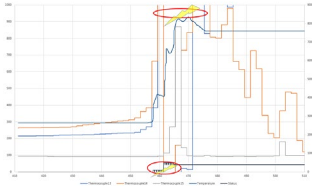
Lithium ion battery system design engineers generally use standards such as IEC 60664.

IEC 60664-1:2020 deals with insulation coordination for equipment having a rated voltage up to AC 1 000 V or DC 1 500 V connected to low-voltage supply systems. This document applies to frequencies up to 30 kHz. It applies to equipment for use up to 2 000 m above sea level and provides guidance for use at higher altitudes. It provides requirements for technical committees to determine clearances, creepage distances and criteria for solid insulation. It includes methods of electrical testing with respect to insulation coordination. The minimum clearances specified in this document do not apply where ionized gases are present. Special requirements for such situations can be specified at the discretion of the relevant technical committee. This document does not deal with distances:

- – through liquid insulation;
- – through gases other than air;
- – through compressed air.



- ➢ During cell venting, the cell ejects a highly conductive mixture containing hydrogen, carbon dioxide, hydrogen fluoride, VOC’s, water vapor, and conductive particulates. At ejecta temperatures of 1000 degrees C, this may even be considered a plasma.
- ➢ At least 4 major EV OEM’s have experienced HV discharge and arc damage (vaporized busbar materials and electromagnetic events)
- ➢ Scientific literature on the phenomenon is lacking



Incidents: Need for robust gas detection

Fire Industry Association Guidance (UK, Jan 2021)

Summary/Guidance:

- ***Systems that can detect off-gases in low concentrations can provide an early warning of an impending thermal runaway – and trigger shut down systems to electrically isolate the individual, or bank of, or rack of battery cells*** – and thus avoid thermal runaway occurring in a single cell. Such systems generally rely on a degree of enclosure around the batteries, such as an ESS container or a room housing large banks of batteries

- ***Note, the presence and build-up of significant quantities of H2 and Hydrocarbon gases may present an explosion hazard***. While such matters are beyond the scope of this document, it is worth noting that ventilation is an important feature in the mitigation of potentially explosive risks.

- Similar requests from NFPA, IFC, US DOT, FAA, FEMA, and others for detection of flammable and hazardous gases

6.3 Gas detection

Off-gassing occurs early in cell/battery failure. Some battery cells provide vents specifically intended to release the over-pressure that may develop within individual cells as a result for abuse or failure, others (such as pouches) may expand to accommodate a degree of off gassing but at some point these may burst – perhaps along a seam or pre-designed weak point. Systems that can detect off-gases in low concentrations can provide an early warning of an impending thermal runaway – and trigger shut down systems to electrically isolate the individual, or bank of, or rack of battery cells – and thus avoid thermal runaway occurring in a single cell. Such systems generally rely on a degree of enclosure around the batteries, such as an ESS container or a room housing large banks of batteries. It is not uncommon for effective off gassing detection, specifically tailored to be sensitive to the concoction of gases (predominately H_2, CO_2, CO, Hydrocarbon gases and battery electrolyte solvents) being generated by off gassing, to detect it within 30 seconds of it's initial release from the cell.

Note, the presence and build-up of significant quantities of H_2 and Hydrocarbon gases may present an explosion hazard. While such matters are beyond the scope of this document, it is worth noting that ventilation is an important feature in the mitigation of potentially explosive risks. Such hazards are traditionally associated with the slow accumulation of the gases given off during normal operation (e.g. charging of lead-acid batteries) but they may also occur relatively quickly as a result of the gases emitted during failure or thermal runaway of lithium-ion batteries. Thus, off gassing detection can play an important part in the control of ventilation systems.

It is also worth noting that early detection of off gassing is most effective when the ventilation is limited/minimal or at least fully understood. However, it is often the case that air movement is used to keep batteries cool during normal charging operations. Hence, off gassing sensors need to be strategically positioned and sensitive enough to detect the first signs of off gases before they become too diluted. Reference sensors are often used as well as off-gas sensors and are installed to monitor the ambient air conditions. Moreover, off gassing detection can provide situational awareness of the conditions within a facility; for example, providing information on where the incidence started to assist personnel responding to an event as well as more general information on any hazardous or toxic risks which may indicate that entering the facility is not appropriate.

6.4 Fire detection

As with all fires, a fire event in a lithium-ion cell/battery/installation is basically the rapid oxidation of the cell materials in an exothermic chemical process of combustion, releasing heat, light, and various reaction products, which can be gaseous or solid. Fire detection specialists have developed their products and systems to be capable of detecting one or several of these 'fire' phenomena.

A fire event starts long before flames are visible. Indeed, in certain circumstances a flame may not be produced at all i.e. if the combustible vapours and particles do not have the correct conditions, such as the equipment is contained within an inert gas atmosphere.

To detect the onset of a catastrophic fire event may require the use of several detection methods dependent on the number and layout of the cells and their positioning within their application.

Guidance Document – Guidance on Li Ion Battery Fires • Version 1 • December 2020 • Tel: +44 (0)20 3166 5002 • www.fia.uk.com

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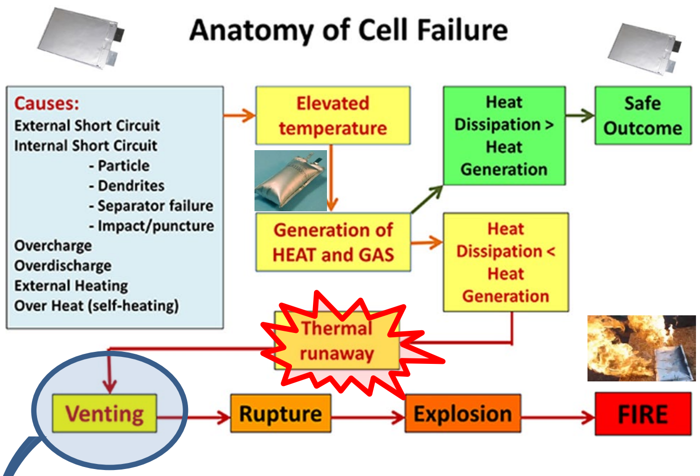
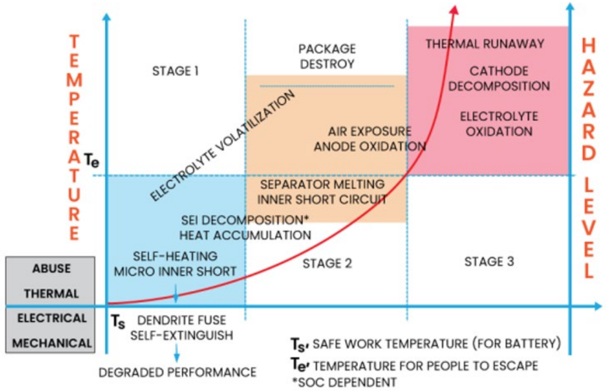
Anatomy of Cell Failure and available detection technology:





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

Requirements for Detection:

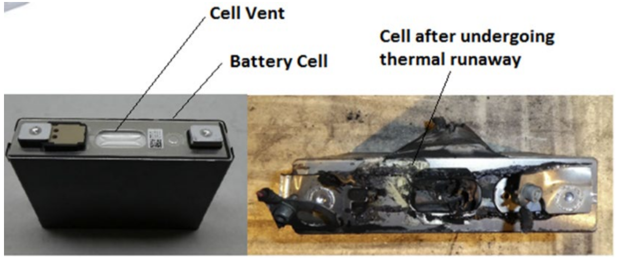
Challenges:

- Defining the threshold for failure generating a hazard: Electrolyte leakage, initial/soft venting, thermal runaway, fire

  Once a cell vents flammable gas, the hazard is present
- Do lab tests accurately represent real world Thermal Runaway? (soft vents, electrolyte leakage)

System Level Requirements:

- Stable Detection capability over entire pack service life (>20 years?)
- Continuous Lifetime operation, two operational states:
  - Vehicle driving/charging (fast response)
  - Vehicle parked for extended periods (low power consumption; < 5 mA @ 3V)
- TR venting can happen in seconds, requiring fast sampling
- Robust solution must be agnostic to:
  - Cell / module/ pack configuration
  - Electrochemistry
  - Cell size
- Must not exhibit Type 1 (Missed Detection) or Type 2 (False Positive) faults
- Meet ASIL (Safety Integrity Level) Requirements
- Value/Cost sensitive



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

No.	Cell	SOC (%)	θ_R (°C)	θ_m (°C)	Δm (g)	n_{exam}^{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.

Energy sufficient to generate fire/explosion

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)

- Typical pack dilution volumes from ~1l to 400L
- Testing has shown H_2 in pack > 4x LEL (~160 000ppm) from single cell
- CO_2 in high concentration has dilutive effect, displacing available O_2 in the enclosure

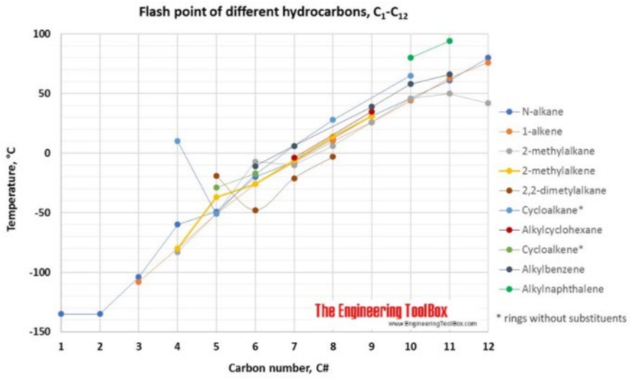
Cell Venting, even without fire, releases flammable gases into pack vapor space, where any ignition source can initiate fire/explosion

Thermal energy available for gas ignition

Cascading TR within enclosures:

Flash point - the lowest temperature at which vapor of a volatile material can be ignited with an ignition source present

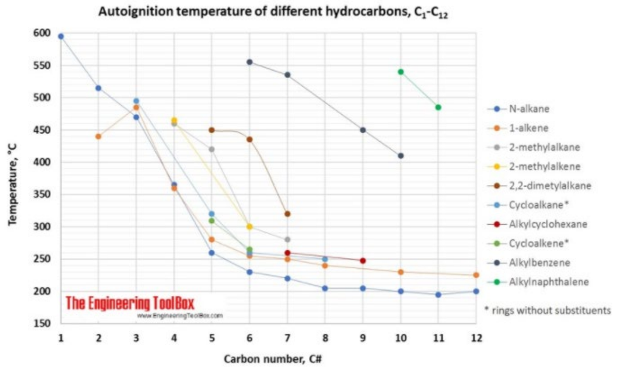
- H2 flash point: -253°C
- Ethylene flash point: −136 °C
- Methane flash point: −188 °C
- Ethane flash point: −135 °C



Autoignition temperature = kindling point

- is the temperature at which a material spontaneously ignites in a normal atmosphere without an external source of ignition.
- is the temperature required to supply the activation energy for combustion
- is usually applied to combustible fuel mixture

  - H2 autoignition temp: 585°C
  - Ethylene autoignition temp : 450°C
  - Methane autoignition temp: 580°C
  - Ethane autoignition temp: 472°C



Cell temps during venting/TR can approach 1000°C, providing ample thermal energy for gas autoignition provided sufficient reactants and oxygen are present between LEL and UFL

Hazardous Gas Release (Lebedeva, Prenmath, et al)

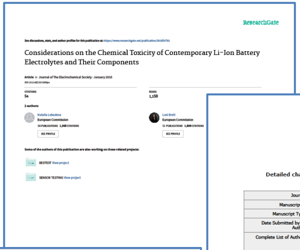
Solvent	Volume of evaporated solvent*, ml	
	PAC-2 level	PAC-3 level
Dimethyl carbonate (DMC), CAS # 616-38-6	25	149
Acetonitrile (AN), CAS # 75-05-8	6.6	19.2
	Volume of evaporated electrolyte*, ml	
	PAC-2 level	PAC-3 level
Hydrogen fluoride (HF), CAS # 7664-39-3	12.3 (20.5)**	22.1 (36.9)**

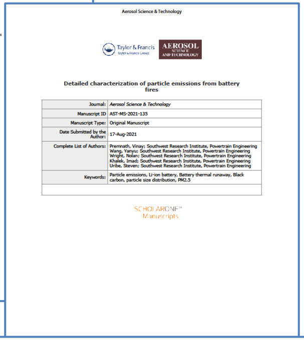
Can be achieved from **1 cell only**

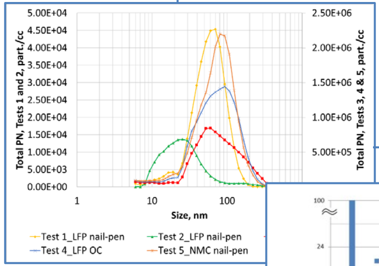
* Volume, solvent/electrolyte evaporates into, is defined as vehicle + 1-m clearance; 61.5 m^3 in this study
** Dependent on the stoichiometry of $LiPF_6$ hydrolysis – 1:5 (1:3)

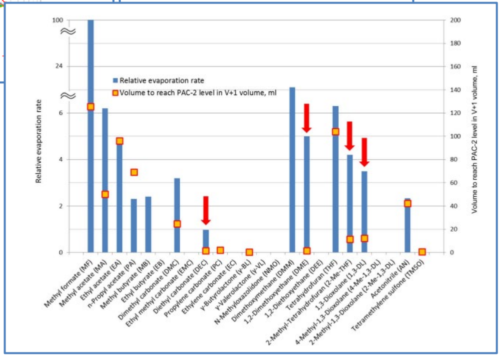
N.P. Lebedeva, L. Boon-Brett, Considerations on the Chemical Toxicity of Contemporary Li-Ion Battery Electrolytes and Their Components, Journal of the Electrochemical Society 163 (2016) A821

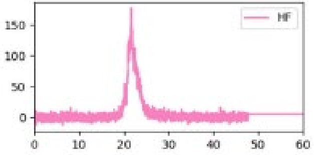
European Commission











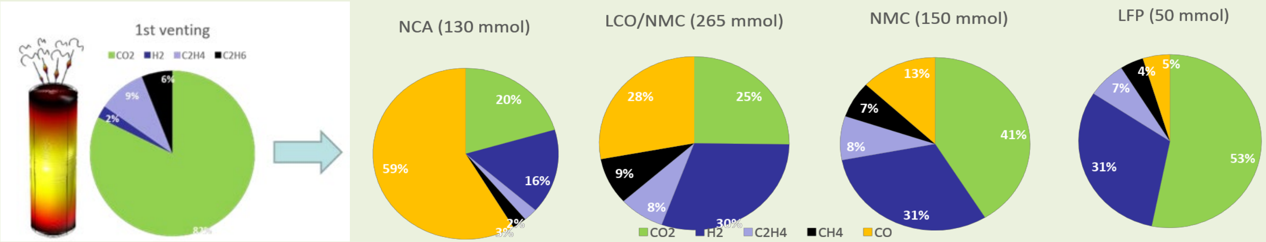
Summary Conclusions:

- (JRC) Li-ion cells contain enough free electrolyte in amounts sufficient for the formation of potentially toxic atmosphere in enclosed spaces from the electrolyte from a single cell
- Thermal Runaway vaporizes the electrolyte and creates hazardous decomposition products

  - A single EV pack can contain 100's of cells
  - Substantial amounts of HF gas have been found in independent studies as well as real world incidents (Morris, Il) (SWRi) Venting emission particulate rates are 5 to 6 orders of magnitude higher than those typically emitted from the exhaust of a modern heavy-duty diesel engine.
  - (SWRi) LFP overcharge tests yielded *HF that exceeded IDLH limits (30ppm) while the NMC nail penetration test yielded formaldehyde beyond IDLH limits (20 ppm).*

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 are CO_2, H_2
- Hydrogen release much higher than background concentration
- Gas concentration is 100 times background level; very strong signal:noise for detection
- Data has shown overall similar ratios of gas concentrations in testing

Gas sensor Selection Process

Electrolyte

Hydrogen

CO_2

Cross sensitivity/drift/aging effects

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 voltage	VOC's	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

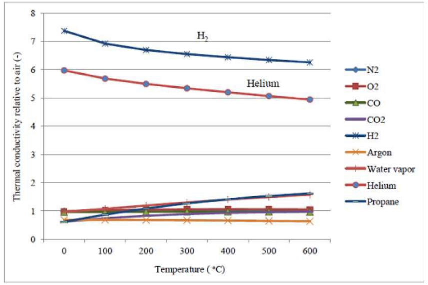
From the available technologies, it is critical to understand sensor response to analyte, cross sensitivity, signal to noise ratio as well as aging properties.

TC and Spectroscopy measure physics behavior, not chemical behavior

H2 Sensor: Principle of operation

OPERATING PRINCIPLE

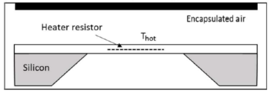
The elements operate on the thermal conductivity principle. The sensing element is open to the atmosphere under test and the reference element is supplied sealed in reference air in a second similar package. The response of the devices is dependent upon the difference between the thermal conductivity of the atmosphere under test and the reference air. When the atmosphere under test has a thermal conductivity higher than the reference air, the sensing element loses more heat to the surroundings than the reference element. This increased heat loss causes a cooling of the sensing element and a subsequent reduction in the resistance of the sensing element compared to the reference element. Two identical MEMS devices are glued on separated ceramic headers and wire bonded.



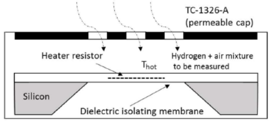
- Gas detection operates on the principal of thermal conductivity
- The sensing elements are made up of a micro machined diaphragm with intrinsically safe embedded planar heater resistor meander
- The typical maximum operating temperature of the heater is 450°C at 3Vdc
- A Wheatstone bridge circuit is used for monitoring the sensing elements
- The bridge circuit is supplied with 3Vdc and is pulsed on and off through an N-Channel MOSFET
- A microcontroller is used to control the MOSFET and subsequently the power consumption of the bridge
- Power consumption of the bridge circuit is approximately 150mW in continuous operation, but is cycled for 35msec “on time”/350 msec “off time”
- The bridge circuit provides a difference voltage between the reference leg and sensing leg reducing the affect of bridge supply voltage variation
- In the current configuration, gas detection uses an active and reference sensing element
- Using active and reference elements built on the same technology in a bridge circuit allows for temperature compensation
- In operation as the thermal conductivity of the atmosphere varies, the effective resistance of the heater varies causing a bridge output voltage differential change

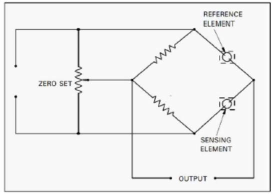
The reference element TC-1326-AS is covered with a sealed metal cap and encapsulated in reference air.

TC-1326-AS (sealed cap) – used as reference

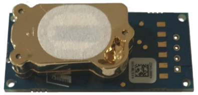


The sensing element TC-1326-A is covered with a perforated metal cap allowing air/gas mixture access (here below).



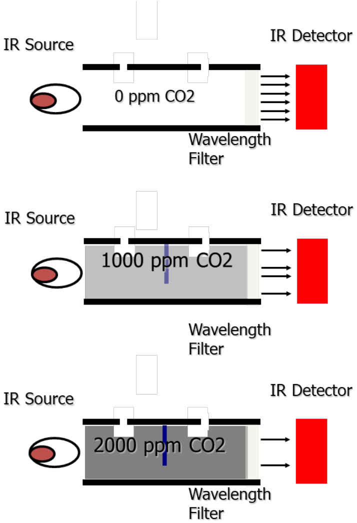


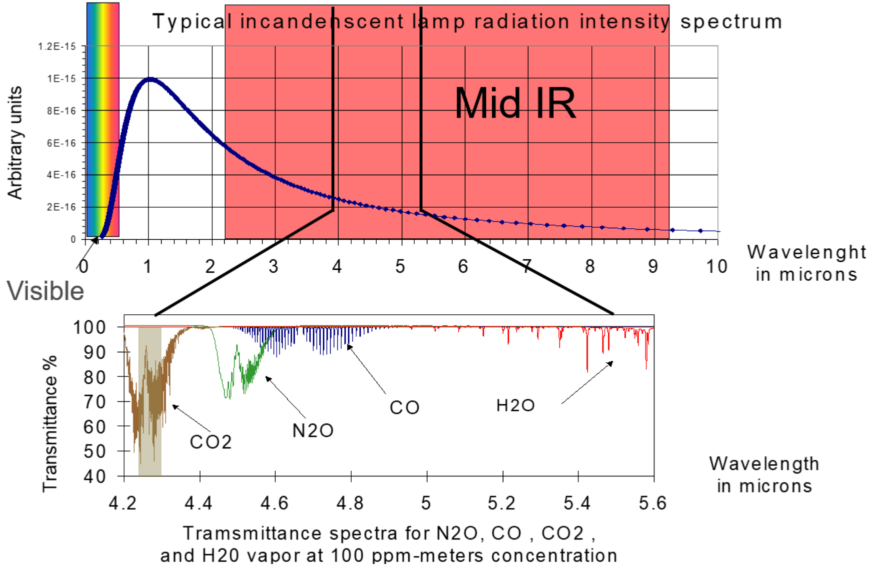
CO2 Sensor: Principle of Operation



Gas molecules have a number of vibration-rotation resonant frequencies. These frequencies are fundamental characteristics of the molecule. For most of gases these frequencies are located in IR spectral band of EM radiation in 2-10 micron wavelength. Absorption of infrared radiation leaves gas molecules in an excited state, which de-excites by colliding with other molecules, raising gas temperature and/or pressure.

- Target gas absorbs radiation at signature wavelength
- Filter isolates wavelength that reaches detector
- More gas in chamber leads to lower signal to detector
- NDIR – non dispersive IR relates to the method of selecting the signature wavelength – with narrow bandwidth IR filter

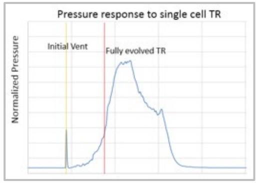




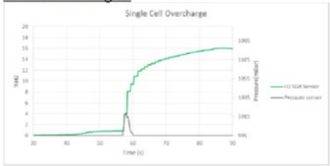
Auto OEM testing observations:

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***



Cell Overcharge:

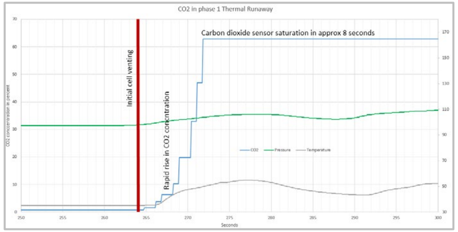


Cell Re-Overcharge:

Fails to detect slow venting

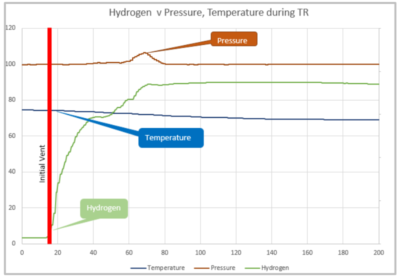
CO_2 IR Spectroscopy Sensor: consistent performance

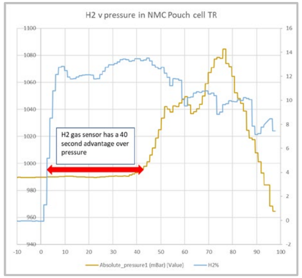
- ✓ 5 to 8 second response time
- ✓ Durable, stable in long term applications
- ✓ No cross sensitivity issues
- ✓ Strong signal to noise ratio
- ✓ Low risk of Type 1/Type 2 faults
- - Higher power consumption
- - Larger sensor footprint
- ➢ ***Useful for larger enclosure spaces for asphyxiation hazard***



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

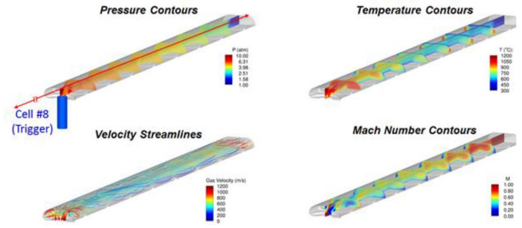
TR plasma plume velocity:

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

Velocity flow field within pack

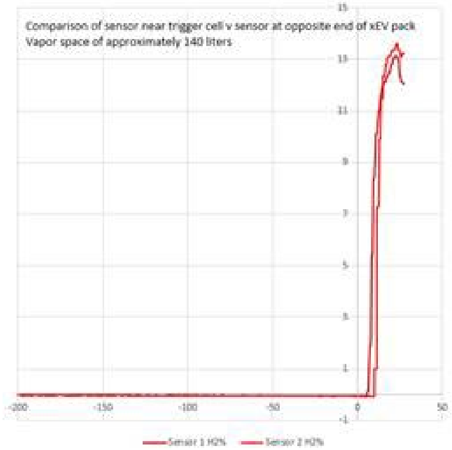


Supplementary Figure S5. Ejecta flow along the vent channels as predicted by CFD simulation.

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

H2 sensor location not critical



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

Gas evolution and cascading TR

Relationship between signals and environment:

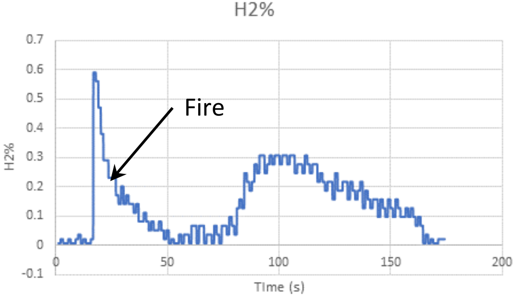
- Ratio of cell SOC/SOH(thermal capacity) to free air volume will drive sensor location, response characteristics (ie, smaller cells with lower SOC's venting will generate less gas to detect in large dilution volumes
- Current approach has been generally insensitive to dilution volumes
    - Superheated 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:

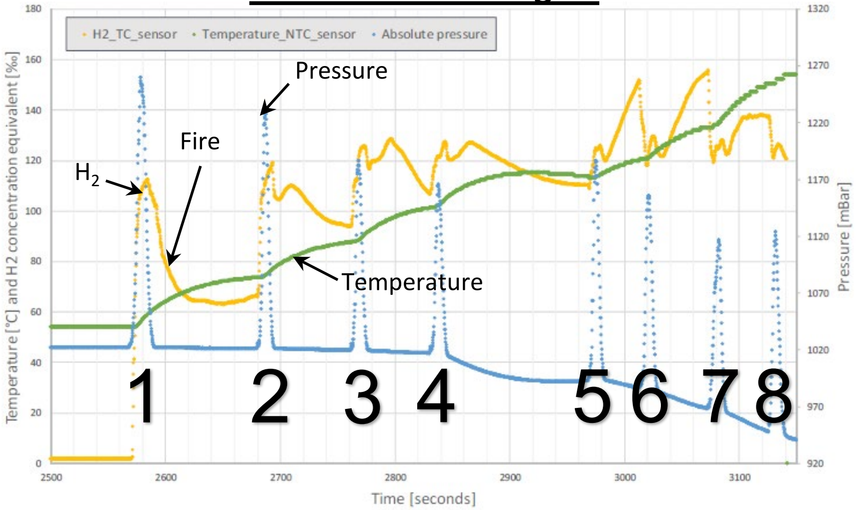
- Shown at right, prismatic cells in cascading TR in traction pack of ~150L dilution volume
- Concentration of H_2 (yellow) continues to rise after consuming available oxygen in the pack with each incremental cell venting
- Gas temperatures throughout the pack increase and sensor data limited by electronics 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

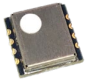


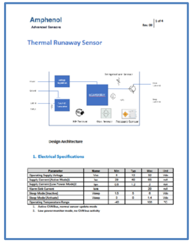
Multiphysics sensors with high concentration calibrations can track performance of TR countermeasures

Surface Mount REDTR MiniModules for BMS mounting:

Components for BMS or assembly:

- H_2,CO_2 sensors for surface mount
- Auxiliary P, RH, T sensors
- Analog/CAN/I2C/SPI/LIN communications
- Power management on board
- Can operate independent of BMS with «wakeup»
- Small package size
- >20 year design life
- Can detect single v cascade TR
- AEC Q
- In production with multiple OEM’s





Components to surface Mount on BMS, or as “sentinel” standalone device with CAN BMS wakeup

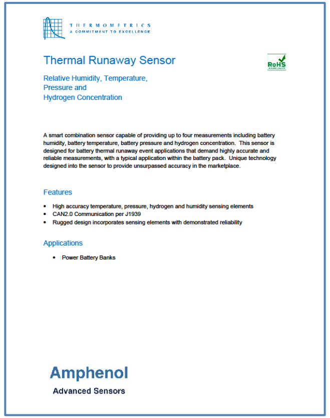
RedCAN: Plug and Play fully compensated detection capabilities

Content and Features:

- H2/Rh/T/P Sensor
- CAN communications
- Fully compensated gas sensor assembly
- >20 year design life
- Can detect single v cascade TR
- Plastic enclosure with integrated mounting features
- Designed to meet ASIL requirements

Ideal for:

- ***Applications with remote or “off shelf” BMS***
- ***Aerospace eVTOL, eAero, applications***
- ***Mobile energy storage***


THERMOMETRICS
A COMMITMENT TO EXCELLENCE

Thermal Runaway Sensor

RoHS

Relative Humidity, Temperature,
Pressure and
Hydrogen Concentration

A smart combination sensor capable of providing up to four measurements including battery humidity, battery temperature, battery pressure and hydrogen concentration. This sensor is designed for battery thermal runaway event applications that demand highly accurate and reliable measurements, with a typical application within the battery pack. Unique technology designed into the sensor to provide unsurpassed accuracy in the marketplace.

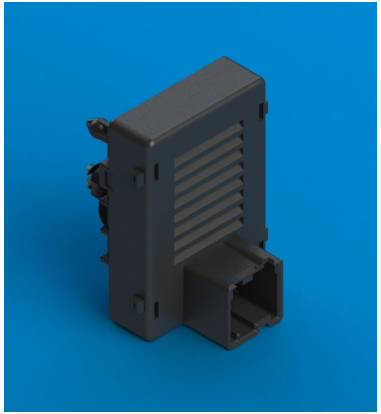
Features

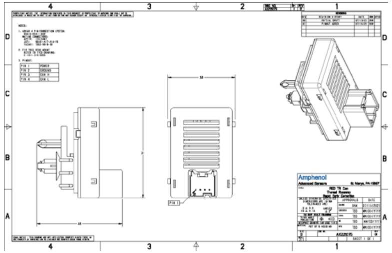
- High accuracy temperature, pressure, hydrogen and humidity sensing elements
- CAN2.0 Communication per J1939
- Rugged design incorporates sensing elements with demonstrated reliability

Applications

- Power Battery Banks

Amphenol
Advanced Sensors



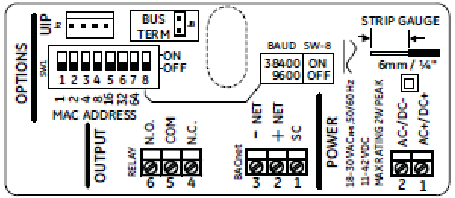


ESS Applications:
Expansion of Ventostat product line: T8200TR

CO2 sensor/ H2 / RhT sensor suite :

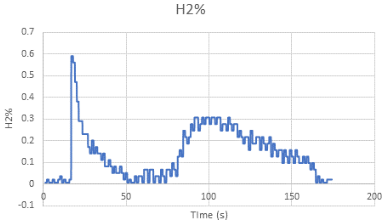
Designed to give early warning of battery failure in industrial energy storage systems.
The Ventostat TR allows the continuous monitoring of the environment and connection to automation systems as well as local control of ventilation equipment using the on-board relay.

Part number T8200-HD-50P-H2MOD



Features:

Carbon Dioxide, Hydrogen, Relative Humidity and Temperature Measument
· CO_2—Patented, Absorption Infrared Gas sensing engine provides high accuracy in a compact low-cost package.
· Hydrogen— Precalibrated, cutting edge technology
· Mounting plate with two-piece terminal blocks provide quick, easy wiring.
· Standard Modbus output enables local and remote monitoring.
· H2 and CO2 Relays-output with customizable factory settings
· Sensors are shipped factory-calibrated.
· Two-piece design allows unit to be replaced without the need for rewiring.
. MS/TP RS485 Output (TCP IP is to be included in future generation releases)



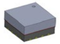
Cylindrical cell TR in 20 000 liter ISO container

Amphenol TR family









System/ Configuration	Amphenol Development Tool AX220054 Engineering Tool	Amphenol TRDU5 Production	Amphenol RedCAN Fully packaged H2/RhT assembly w/ CAN AX221075 Production	Amphenol CO2 Detection select solder or module assembly AX221087 Production	Amphenol Gen 2.0 H2 miniPCB Surface AX221058 Production	Amphenol T8200 AX221042 In Development	Amphenol NPB surface mount pressure sensor In validation	Amphenol BLD1 Fully packaged H2 w/ CAN Production	Amphenol BLD2 Fully packaged H2 & CO w/ CAN Production
Pressure Range	260 to 1260 mBar	20mbar to 2500mbar	50 to 200 kPa	260 to 1260 mBar	Optional	260 to 1260 mBar	260 to 1260 mBar or 50 to 300 kPa (other pressure ranges available)	N/A	N/A
Pressure accuracy	± 1% FSO	± 0.1 mBar	± 1.5% FSO	± 0.1 mBar			± 0.1 mBar	N/A	N/A
Gas	**H2 / CO2 / P/ RhT**	**H2/P/CO/NH3 with RhT compensation**	**H2/P/Rh/T**	**CO2**	**H2 w/ RhT compensation**	**Co2 / H2/ Rh/T**	**Press only**	**H2 with RhT compensation**	**H2/CO with RhT compensation**
Temperature (-40 to 150C ; <±2 °C)	Y	-40°C to 85°C	-55 to 105C	Y	Y	Y	Optional	-40 to 85C	-40 to 85C
Relative Humidity (0 to 100%; <±4%)	Y	5% - 95% ± 3% RH	Y	N/A	Optional	Y	N/A	0 to 95% RH	0 to 95% RH
Power Supply	10 to 32V DC max	9-18V	12V / 24V	6 to 12V, 32V DC max	3V to 5V	6 to 12V, 32V DC max	1.7V~3.6V	9 V to 18V	9V to 18V
Power mode	single	single	variable	variable	single	single mode/ relay	single	single	single
Q Current (µA)	30mA	<80mA	10 mA / < 25uA* *sensor not active	10 mA / < 25uA* *sensor not active	12mA / <0.1mA *	18-30 VAC RMS, 50/60 Hz, or 10.8 to 42 VDC, polarity protected 0.50 A at 125 VAC, 1A 24 VDC	35uA	<25mA / <100uA sleep mode	<25mA / <100uA sleep mode *sensor not active
Interfaces	CAN 2.0A ISO 11898 SAE J2284	LIN 2.1	CAN 2.0A ISO 11898 SAE J2284	LIN 2.1	Ratiometric	MS/TP RS485 TCP IP	18 bit DSP I2C & SPI	HS CAN	HS CAN
Wake up BECM	Yes	No* *BMS continuous powered	Optional	Yes	No	Relays on H2 nd Co2 sensors	N/A* *(capable if CANFD xceiver chip is used)	No	No
Physical Dimension (module)	66 x 42x 12mm	35 x 39 x 37mm	38 x 51 x 48mm	47 x 2 x 10mm	25 x 20 x 1.5 mm surface mount	116 x 81 x 27mm	4 x 4mm QFN surface mount	35 x 39 x 37mm	35 x 39 x 37mm
Automotive	UL94 Planned	AEC Q104	N/A	AEC Q100	AEC Q104	N/A	AEC Q100	AECQ-104	AECQ-104
Additional features	IP5K0, w/ hsg; optional coolant breach/water intrusion detection	IP6K7 w/ hsg	IP6K7	IP6K7	IP6K4K	UL94 5VA; CE and RoHS, REACH, and WEEE compliant	IP5K0	IP6K7	IP6K7
Samples	4 wks ARO	4 wks ARO	4 wks ARO	4 wks ARO	4 wks ARO	4 wks ARO	4 wks ARO	4 wks ARO	4 wks ARO
Available	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

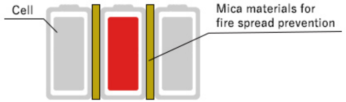
**** Note: Any Amphenol variant can be installed in custom plastic housing as needed**

Good News: State of the Industry for Thermal Propagation countermeasures

- **On vehicle:**
  - “Livestream” data to secure server
  - Aggressive HX
    - Coolant
    - refrigerant
  - load dump from affected modules (as with MegaPack)
  - Phase change materials that absorb heat
  - Disable regen braking contribution to pack charging
  - Disable charging
  - Thermal isolation (Mica, aerogels)
  - On board extinguishing agents (busses)
  - Dielectric coolant
  - Access port

- **Off vehicle**:
  - ISO bath (ISO 17840 / SAE J2990)
  - E lance
  - Lots of water
  - See First Responder Survey Recommendations

Lithium-ion batteries with mica materials for fire spread prevention



Mica materials for fire spread prevention prevent an ignited cell from affecting adjacent cells.

Background

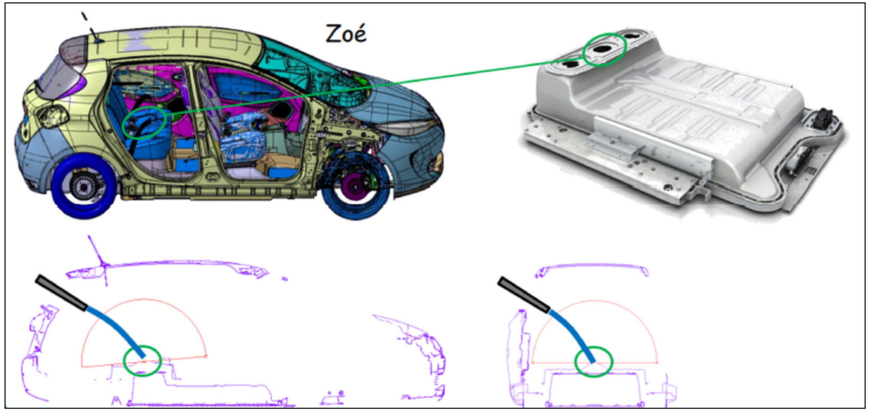
OEM / Amphenol Dialog on Battery Cell Venting
October 2021
Countermeasures and Field Experiences

Benchmarks: Renault Zoe

“Fire Hose Access” allows for direct battery immersion

Information on design is in Emergency Response Guide

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.



b. Action procedure to extinguish the vehicle

The action procedure for an electric vehicle is the same than a thermic vehicle. Water is recommended to extinguish the fire on the vehicle.

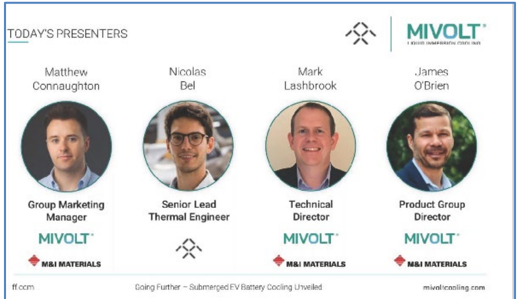
- **Spray the vehicle with very large amounts of water until the complete battery's extinguishing.**
- **To extinguish the traction battery, swamp it through the vents located behind the rear passenger bench seat.**
- **Keep a suitable distance, taking into account the risk of flames from the combustion of electrolyte.**
- **Do not insert the fire hose directly into the traction battery's compartment. RISK OF SERIOUS INJURY OR LECTRIC SHOCKS WHICH MAY LOAD TO DEATH.**
- **Fully ventilate if in a confined space.**

Picture 1

RENAULT PROPERTY

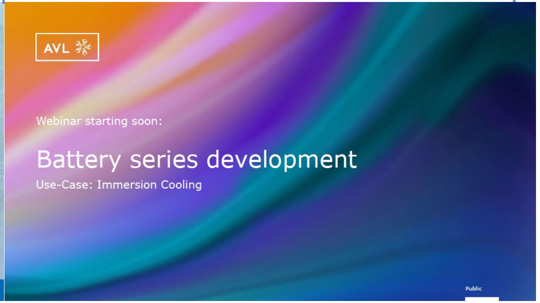
First Responder's Guide / Renault ZOE

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

NTSB Report – Jan 2021 (T. Barth)

Safety Issues:

• Inadequacy of emergency response guides for minimizing risks to first and secondary responders from Li-ion battery fires

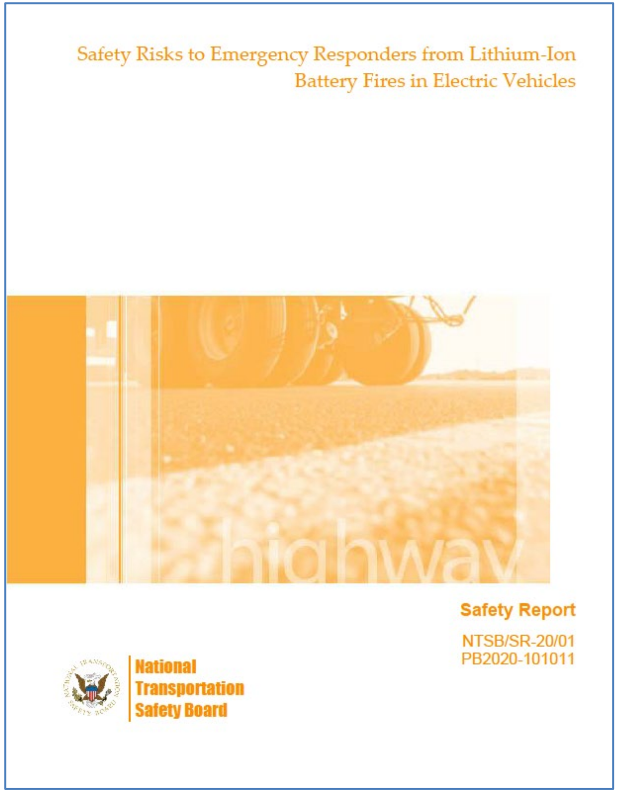
• Gaps in safety standards for high-speed, high-severity crashes involving Li-ion battery vehicles

Recommendations:

NHTSA:
• Incorporate Emergency Response Guides (ERGs) into NCAP
• Continue research on mitigating or de-energizing stranded Energy

EV Manufacturers (cars, trucks, buses in USA)
• Model ERGs on ISO 17840 and SAE J2990
• Vehicle specific information on fire fighting, stranded energy, safe storage

Responder Associations (NFPA, IAFC, IAFF, AFTC, NVFC, TRAA
• Inform members of risks and available guidance



https://youtu.be/J6eS6JzBn0k

Benchmarks:

Stranded Energy & Immersion:
“Fire Hose Access” allows for direct battery immersion

Firefighters in Leuven, Belgium posted photos of their approach to cooling battery cells after a hybrid vehicle.&
When crews were called to the car fire, they "found a strong smoke development, which pointed to the battery's thermal runaway" which caused the battery cell temperatures to rise. Shortly after, the smoke turned to fire and the crew knocked down the fire.
The department posted the next steps to cool the battery cells on their Facebook page: they "refrigerated the vehicle abundantly and placed it in a special #waterdipping container."
They loaded the vehicle into a special container with filled with water using a crane.
The container was placed in a remote parking lot. As soon as the vehicle has completely cooled down, a branch service will remove it from the container and transport it towards scrap dealer. Not for the sake of immersion, but because a car like this is completely destroyed when the battery catches on fire anyway," the department posted on Facebook.
The contaminated water from the container was collected to be examined after the vehicle was removed and hauled off to a scrap yard.

Belgium FFs Submerge Burning Hybrid Car in Container

Firefighters in Leuven, Belgium used a crane to put the burning hybrid vehicle into a water-filled container to keep its battery cells cool.
Source Firehouse.com News
Aug. 27, 2021

Surface vehicle standard practice to supress fire and relieve stranded energy

Response vehicles typically only have ~500 to 1500 gallons of water available on board

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

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

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

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

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.

5,000 to 30,000 gallons → **80 gallons**

- "Spike systems" need identified locations for piercing to avoid striking HV bussing & cables
- Pouch cells will self discharge when exposed to water, CID's in prismatic and cylindrical cells may prevent discharge

Stranded Energy and Second Responder safety need to be addressed

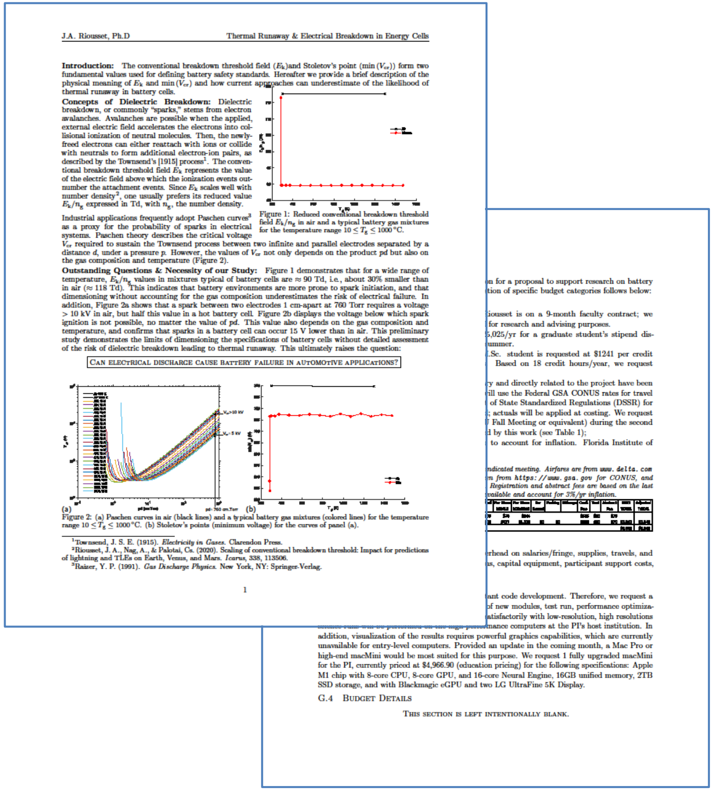
Venting Physics: Ad Hoc Group investigating HV Discharge w/ venting

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:
  - In situ battery cell testing with electrodes
  - Model verification with dry/wet gas samples

Need budget to further develop model and test


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 $10 \le T_g \le 1000\,°C$.

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 $10 \le T_g \le 1000\,°C$. (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

...n for a proposal to support research on battery
...tion of specific budget categories follows below:

...iousset is on a 9-month faculty contract; we
... for research and advising purposes.
...5,025/yr for a graduate student's stipend dis-
...ummer.
...Sc. student is requested at $1241 per credit
... Based on 18 credit hours/year, we request

...y and directly related to the project have been
...ill use the Federal GSA CONUS rates for travel
... of State Standardized Regulations (DSSR) for
...; actuals will be applied at costing. We request
... Fall Meeting or equivalent) during the second
...d by this work (see Table 1);
... to account for inflation. Florida Institute of

...ndicated meeting. Airfares are from www.delta.com
...n from https://www.gsa.gov for CONUS, and
... Registration and abstract fees are based on the last
...vailable and account for 3%/yr inflation.

...rhead on salaries/fringe, supplies, travels, and
...s, capital equipment, participant support costs,

...ant code development. Therefore, we request a
...of new modules, test run, performance optimiza-
...atisfactorily with low-resolution, high resolutions
...ance computers at the PI's host institution. In 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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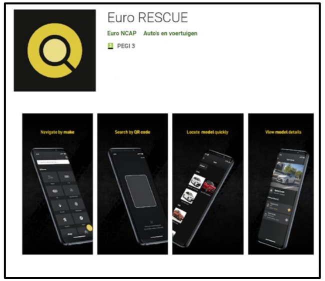
First & Second Responders Survey 2021

Survey issued in 2020/21: >500 respondents,
~30% experienced xEV incidents
Kurt Vollmacher, ISO17840



- 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


PROPOSALS
TO IMPROVE SAFETY FOR
FIRST AND SECOND
RESPONDERS

PASSENGER CARS
AND LIGHT COMMERCIAL
VEHICLES

Kurt Vollmacher
AUGUST 1 2021

J2990 Group soliciting training support from SAE (Elizabeth Melville), DoE/FCAB (David Howell), DOT (Martin Koubek)

First Responder Training

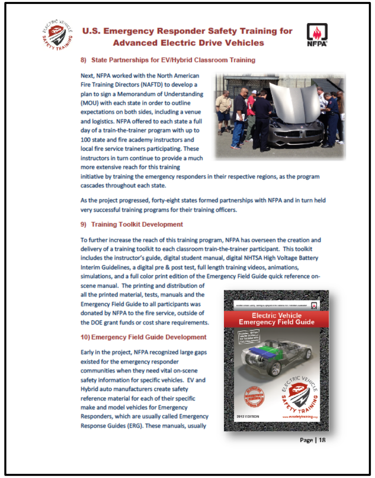
Andrew Klock, NFPA

- **In US, 300k trained; >800k need training**
- **Interest from NA OEM to support training**

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, free interactive 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.



U.S. Emergency Responder Safety Training for Advanced Electric Drive Vehicles

8) State Partnerships for EV/Hybrid Classroom Training

Next, NFPA worked with the North American Fire Training Directors (NAFTD) to develop a plan to sign a Memorandum of Understanding (MOU) with each state in order to outline expectations on both sides, including a venue and logistics. NFPA offered to each state a full day of a train-the-trainer program with up to 100 state and fire academy instructors and local fire service trainers participating. These instructors in turn continue to provide a much more extensive reach for this training initiative by training the emergency responders in their respective regions, as the program cascades throughout each state.

As the project progressed, forty-eight states formed partnerships with NFPA and in turn held very successful training programs for their training officers.

9) Training Toolkit Development

To further increase the reach of this training program, NFPA has overseen the creation and delivery of a training toolkit to each classroom train-the-trainer participant. This toolkit includes the instructor's guide, digital student manual, digital NHTSA High Voltage Battery Interim Guidelines, a digital pre & post test, full length training videos, animations, simulations, and a full color print edition of the Emergency Field Guide quick reference on-scene manual. The printing and distribution of all the printed material, tests, manuals and the Emergency Field Guide to all participants was donated by NFPA to the fire service, outside of the DOE grant funds or cost share requirements.

10) Emergency Field Guide Development

Early in the project, NFPA recognized large gaps existed for the emergency responder communities when they need vital on-scene safety information for specific vehicles. EV and Hybrid auto manufacturers create safety reference material for each of their specific make and model vehicles for Emergency Responders, which are usually called Emergency Response Guides (ERG). These manuals, usually

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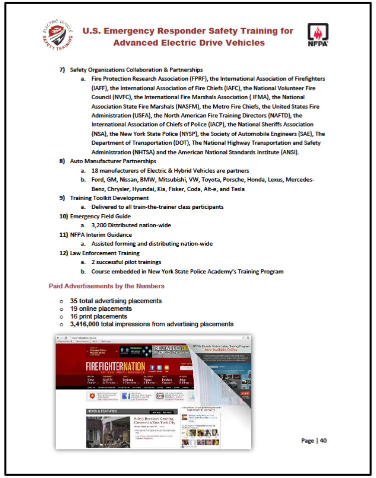

U.S. Emergency Responder Safety Training for Advanced Electric Drive Vehicles

7) Safety Organizations Collaboration & Partnerships
   a. Fire Protection Research Association (FPRF), the International Association of Firefighters (IAFF), the International Association of Fire Chiefs (IAFC), the National Volunteer Fire Council (NVFC), the International Fire Marshals Association (IFMA), the National Association State Fire Marshals (NASFM), the Metro Fire Chiefs, the United States Fire Administration (USFA), the North American Fire Training Directors (NAFTD), the International Association of Chiefs of Police (IACP), the National Sheriffs Association (NSA), the New York State Police (NYSP), the Society of Automobile Engineers (SAE), The Department of Transportation (DOT), The National Highway Transportation and Safety Administration (NHTSA) and the American National Standards Institute (ANSI).
8) Auto Manufacturer Partnerships
   a. 18 manufacturers of Electric & Hybrid Vehicles are partners
   b. Ford, GM, Nissan, BMW, Mitsubishi, VW, Toyota, Porsche, Honda, Lexus, Mercedes-Benz, Chrysler, Hyundai, Kia, Fisker, Coda, Alt-e, and Tesla
9) Training Toolkit Development
   a. Delivered to all train-the-trainer class participants
10) Emergency Field Guide
   a. 3,200 Distributed nation-wide
11) NFPA Interim Guidance
   a. Assisted forming and distributing nation-wide
12) Law Enforcement Training
   a. 2 successful pilot trainings
   b. Course embedded in New York State Police Academy's Training Program

Paid Advertisements by the Numbers

- 35 total advertising placements
- 19 online placements
- 16 print placements
- 3,416,000 total impressions from advertising placements

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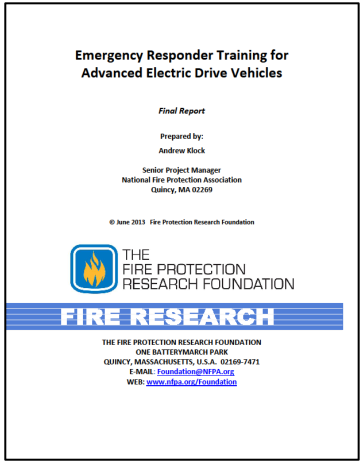

Emergency Responder Training for Advanced Electric Drive Vehicles

Final Report

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