# BATTERY ELECTRIC VEHICLES FIRES

## MODELLING AND DESIGN CONSIDERATIONS

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**Craig Stewart**

**Director, Minware**

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- Battery Electric Vehicles (BEVs) will inevitably dominate future mining.
- Carbon fueled internal combustion engine development stalled and will eventually be phased out.
- Legislators will introduce increasingly tough emission and atmospheric standards.


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## THE FUTURE HAS MANY UPSIDES....

- Zero emission, no DPM, no legislative vent demands, low heat release.
- Most major equipment manufactures now offer a line of BEVs using lithium batteries, although supply, performance and safety questions remain.



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# BUT ONE MAJOR DOWNSIDE…..

- Very limited research and investigation of lithium battery fires in underground environments.
- Many examples of surface EV fires show the potential for Lithium Battery fires underground is a real and foreseeable hazard that must be managed




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# BUT ONE MAJOR DOWNSIDE…..

*Five cars were destroyed by fire at Sydney airport. The battery that sparked the fire had been detached from the car and stored in the parking lot. Photograph: NSW Fire and Rescue/PR IMAGE Sept 2023*

**Very few real underground mining industry incidents and investigations have been made public to date.**

- Light vehicle Charging/parking bay in a Southern Districts Ontario mine (Ontario Mine Rescue, 2019)
  - Faulty charging cable started fire
  - Fire spread to three vehicles


## Onaping Depth (Craig Mine) BEV fire (Glencore, 2020)

- Electric Boom Truck fire from electrical faults
- Dark black smoke and extreme heat
- Fire burned for 4-5 hours

# RISK OF BEV FIRES

- Technology still in development / improvement phase for underground mining.
- Useful history of surface lithium powered electric vehicles (EVs) fires.
- In China, a major EV adopter - first 3 months of 2022 reported 680 electric car fires.
- But statistics show EVs are relatively safe
- An USA insurance company reported for every 100,000 cars sold…
  - Hybrid 3,475 fires
  - Gasoline 1,530 fires
  - EVs 25 fires

# LITHIUM BATTERY TYPES

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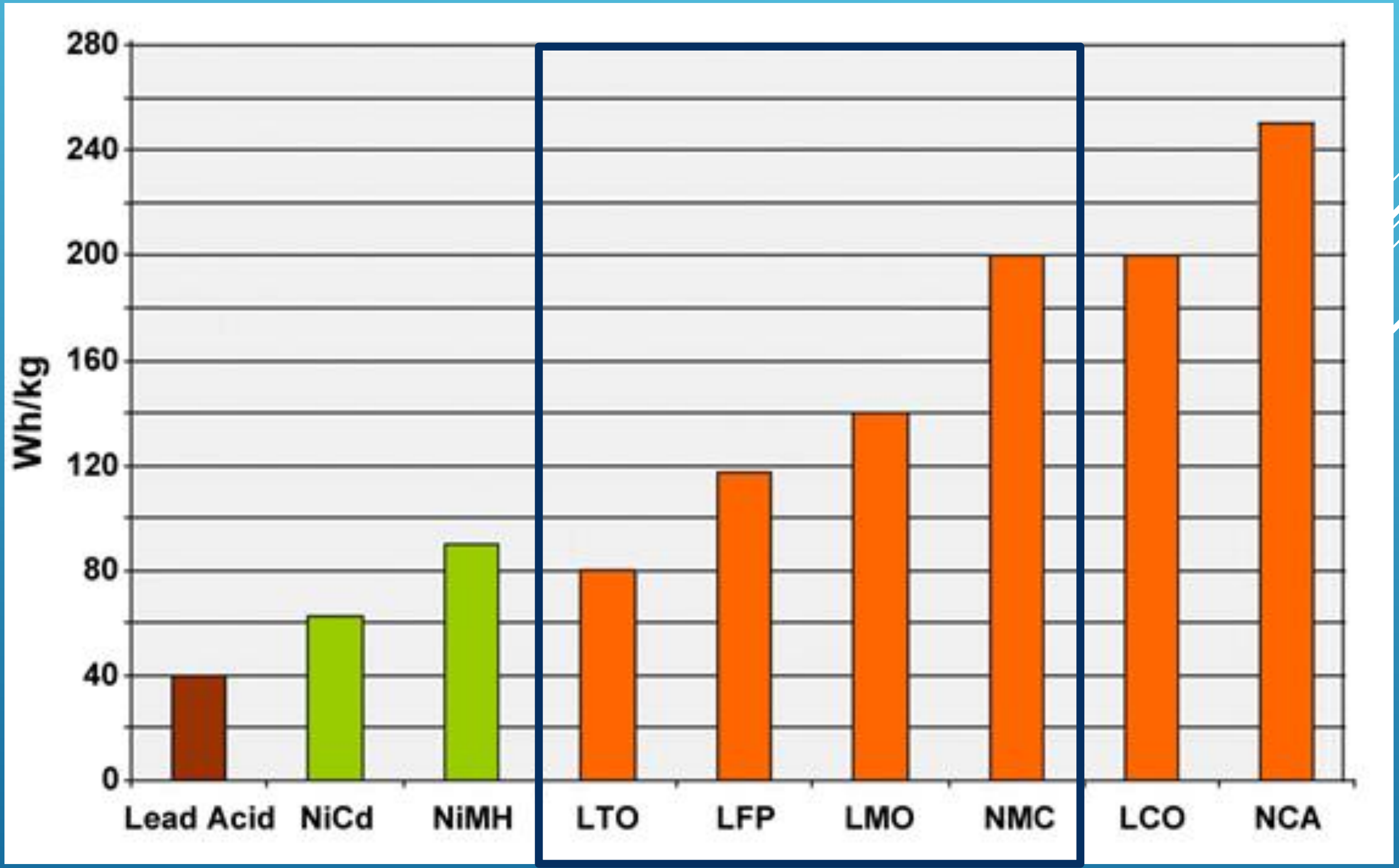
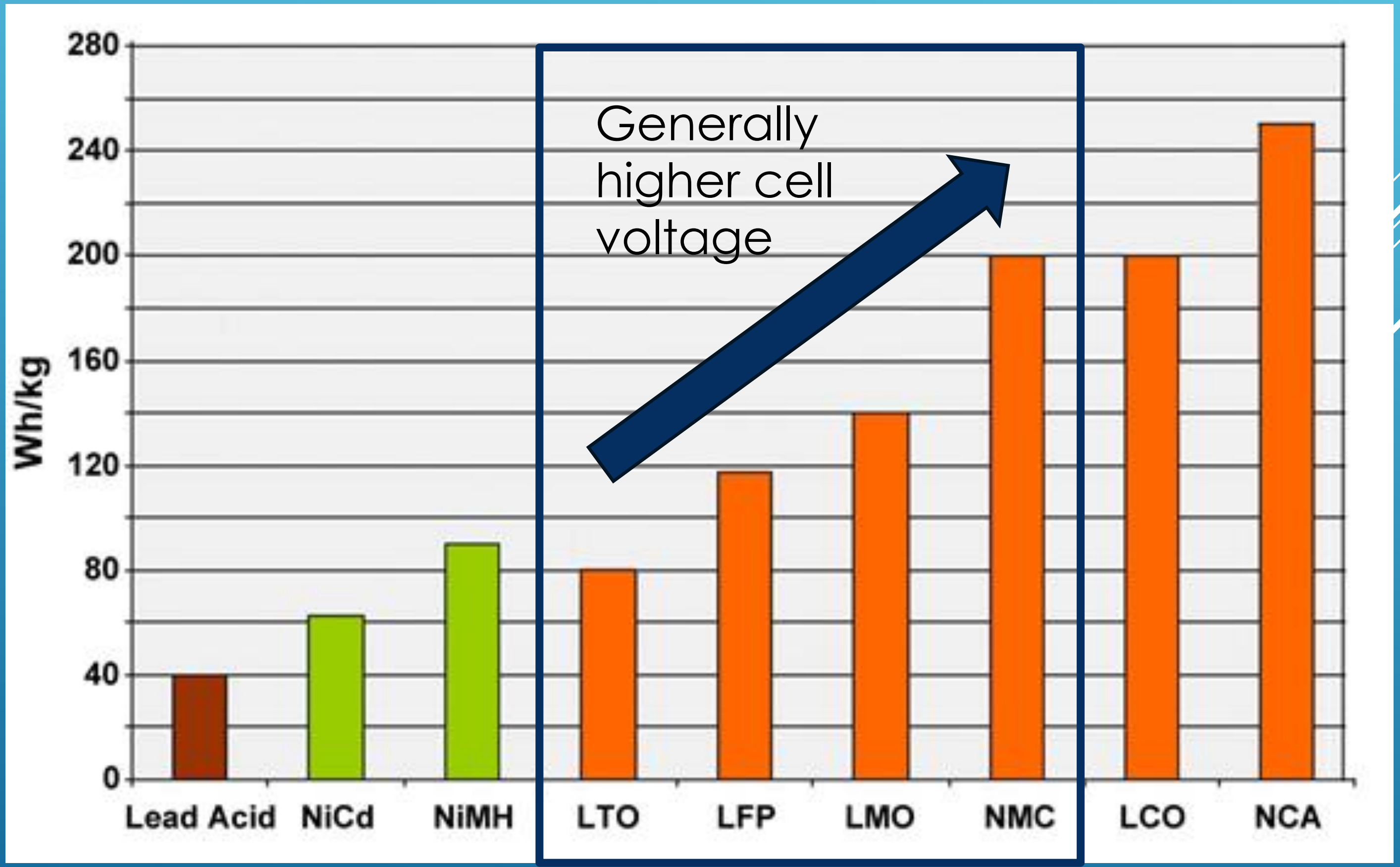
## Many types of lithium battery chemistries.

- The most stable/safest lithium battery technologies are the lowest energy density / highest weight.
- NMC, LFP with LTO being considered for underground.
- High energy density batteries often used for surface vehicles (NMC, NCA), although LFP becoming more popular due to safety, cost and cycle life.

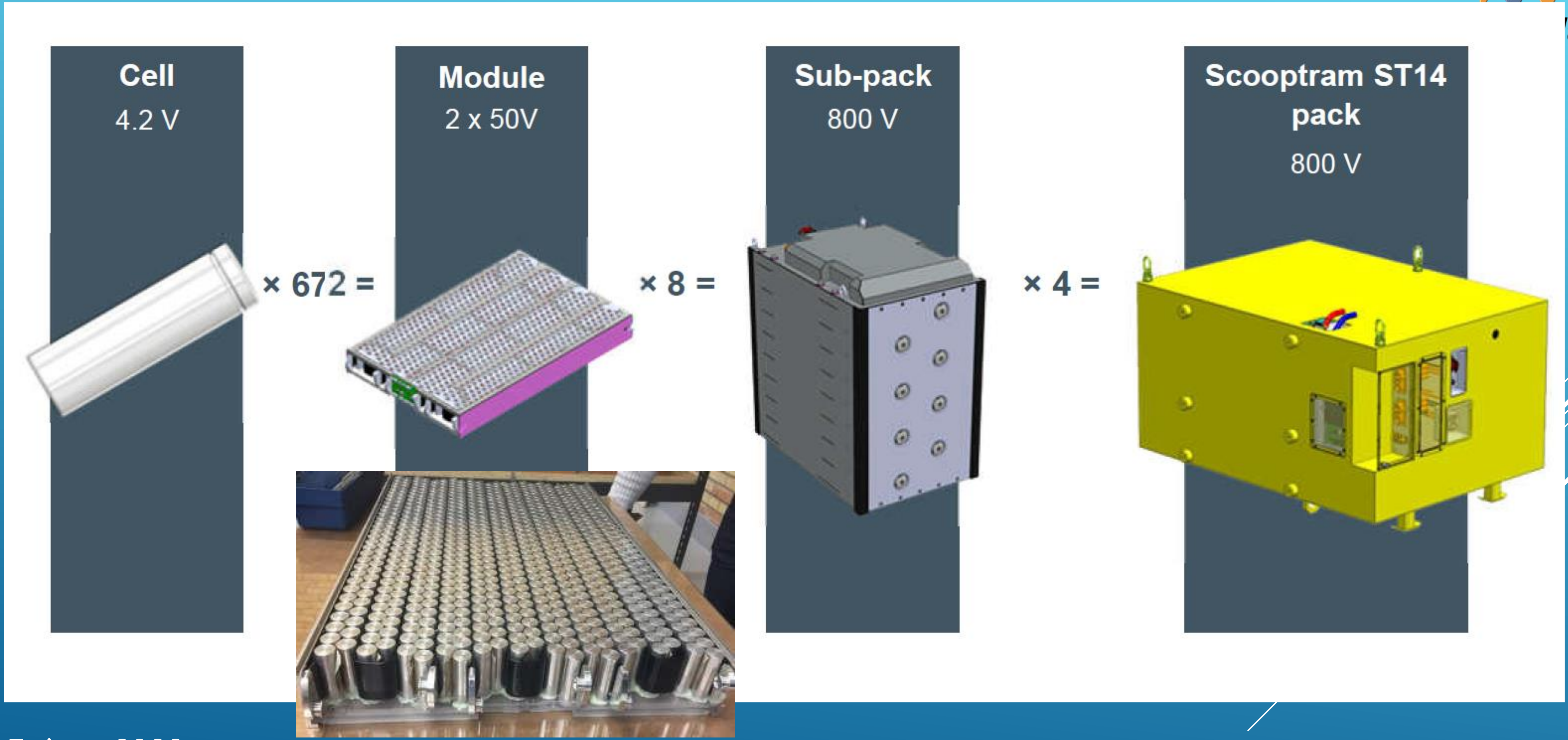


# LITHIUM BATTERY TYPES

- Battery packs are made of many small cylindrical, prismatic or pouch cells (2.8V - 4.2V) wired in parallel and series and packaged securely.
- A battery monitoring system (BMS) monitors and balances all cell recharge and discharge and shuts down the battery in the event of faults, overcharging or over-discharging.
- Underground designs have internal cooling - liquid or refrigerant to maintain optimum working temperature ($35^0$C)



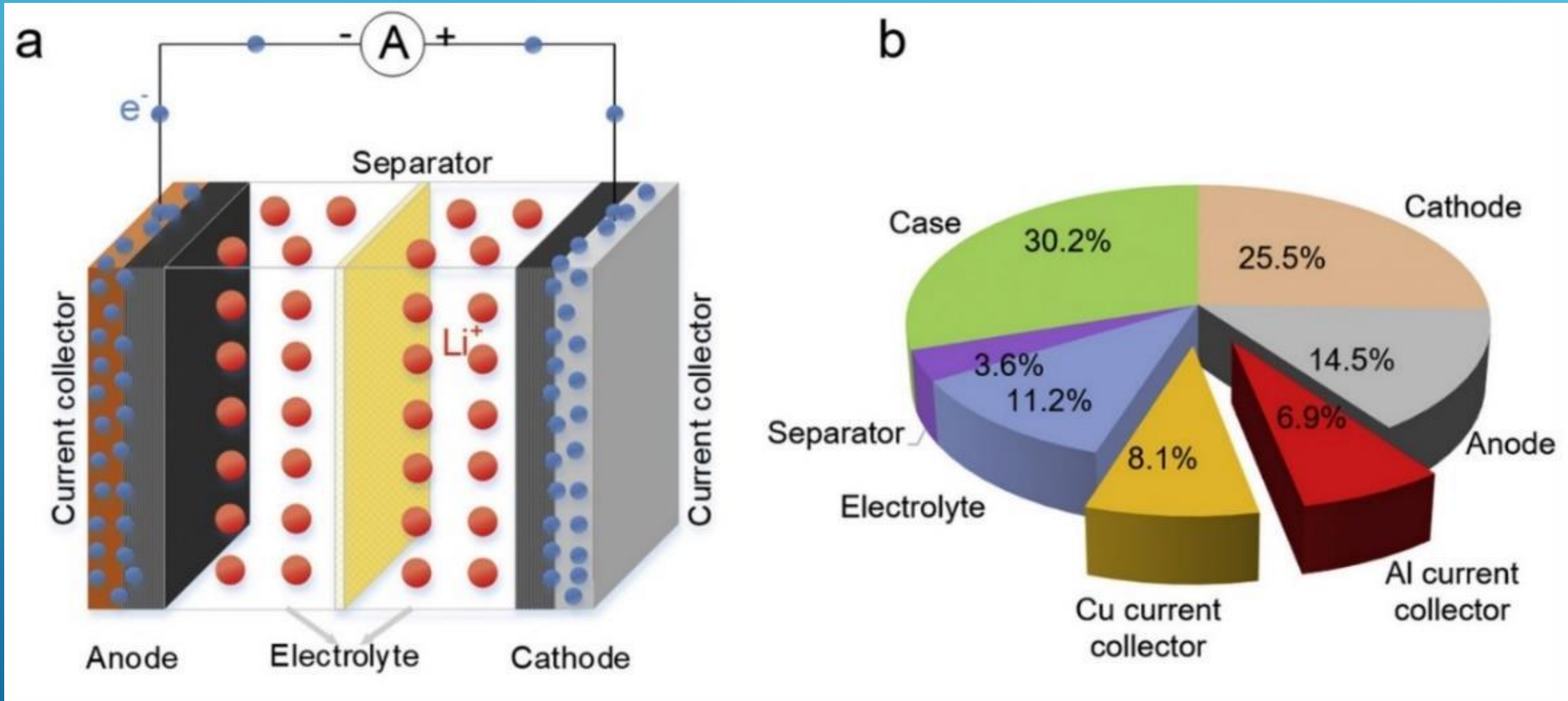
# LITHIUM BATTERY TYPES




Epiroc 2022

# COMBUSTION OF LITHIUM BATTERIES

- Combustible materials includes the carbonate electrolyte solvents, anode (graphite), casing and oxidizing metals.
- Under heat, the solvent can break down into hydrogen, methane and other flammable hydrocarbons.



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# IGNITION OF LITHIUM BATTERIES

- External non-electrical fires or heat that spreads into the battery packs.
- Electrical fires from short circuits, bridged fuses, faulty switches etc.
- Internal battery thermal runaway and combustion from cell failure / damage / overcharging.

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# IGNITION OF LITHIUM BATTERIES

- Cell thermal run-away caused by internal chain reaction
- If heat reaches 120$^0$C - 150$^0$C, electro-chemical & exothermic reactions become self-sustaining and spread to all cells.
- Risk is increased in highly charged cells.
- Internal thermal run-away does not require oxygen, although the burning of released gas products does.
- External heat of burning gases can accelerate internal thermal run-away.

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# WHAT IS THE RISK ?

- Beware of misleading reports (such as nail penetration tests)
- ALL current lithium batteries containing liquid electrolytes have a fire risk.
- Actual fire risk depends on many factors beyond battery types – packaging, BMS, cooling, armoured protection

NAIL PENETRATION FTIR EMISSIONS COMPARISON (PPM)

| Exhaust compound | LFP | LMO | NMC |
|---|---|---|---|
| $CO_2$ | 0 | 0 | 85,959 |
| $CH_4$ | 0 | 43 | 28 |
| CO | 4 | 230 | 4,235 |
| NO | 0 | 0 | 632 |
| $NO_2$ | 0 | 0 | 5 |
| $NH_3$ | 0 | 8 | 0 |
| $C_2H_6$ | 0 | 25 | 0 |
| $C_2H_4$ | 0 | 62 | 53 |
| $C_3H_6$ | 0 | 63 | 280 |
| HCL | 0 | 0 | 459 |
| $CH_2O$ | 0 | 19 | 10 |
| HF | 0 | 0 | 26,698 |

*A misleading comparison which only tells part of the story.*

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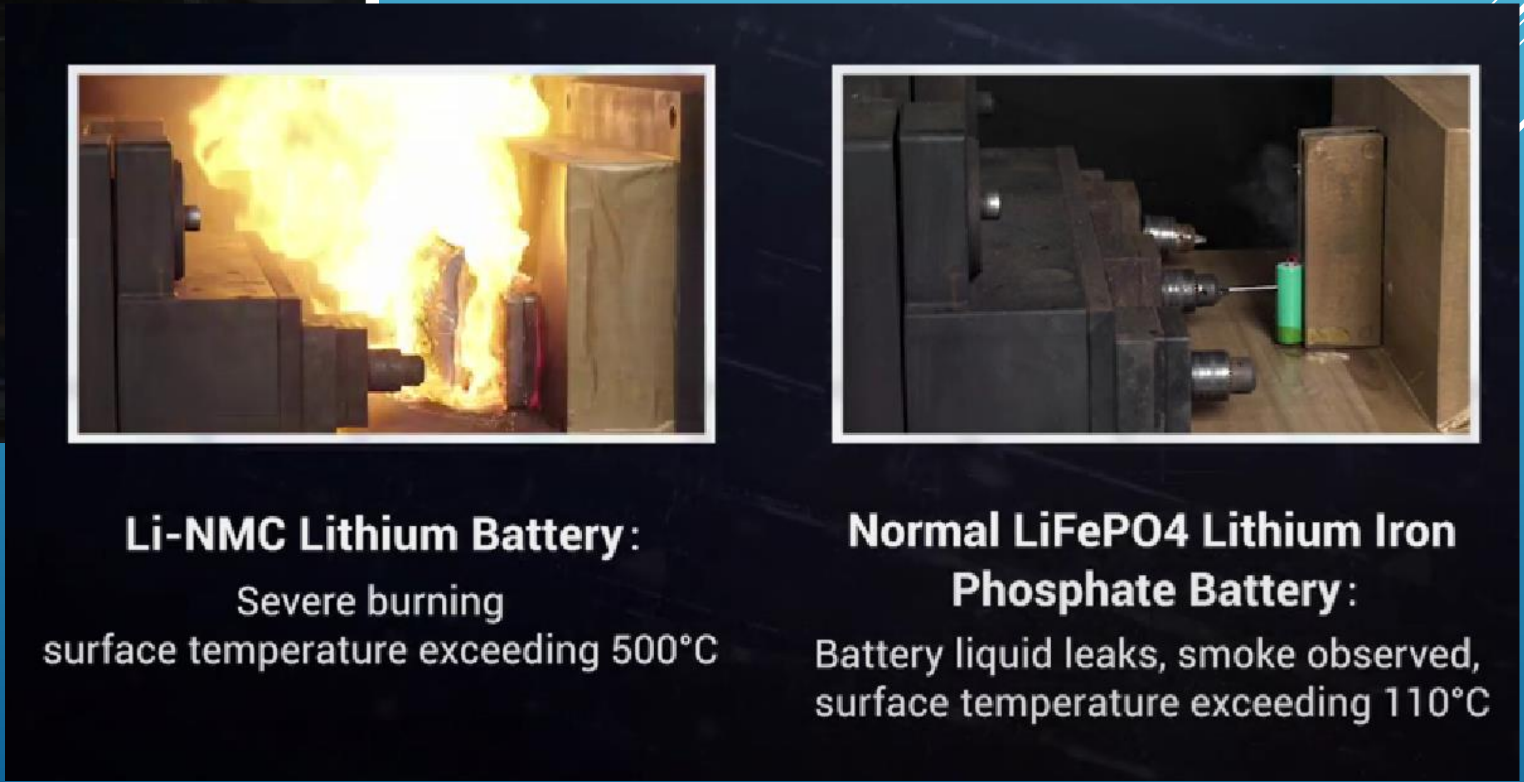
# BURNING BEHAVIOUR OF LFP BATTERIES

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# MODELLING OF UNDERGROUND FIRES

As with any fire, modelling of BEV fires requires the following information

- Total Heat Released (THR)
- Heat Release Rate (HRR)
- Products of Combustion

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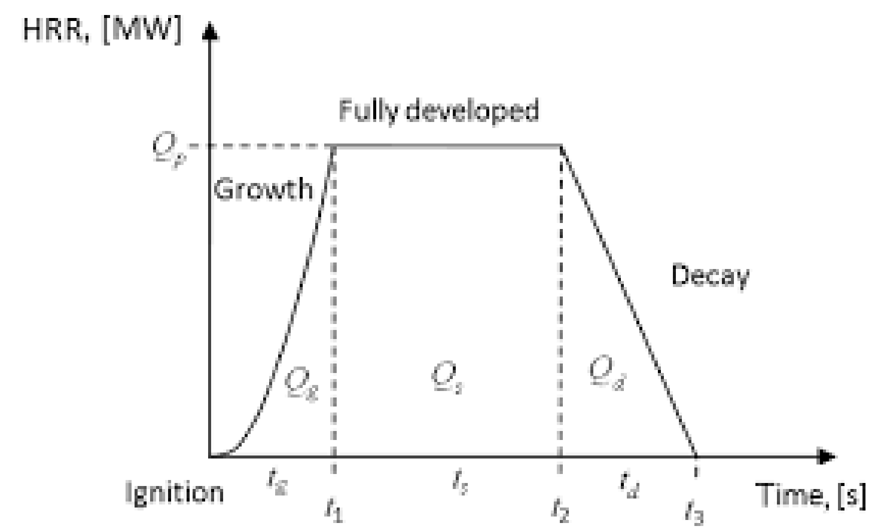
# BURNING BEHAVIOUR OF LITHIUM BATTERIES

- Typically follows a T-Square burning heat release rate
  - Rapid growth
  - Sustained period of constant combustion
  - Gradual decay

- Highly charged batteries (high SOC) have a more volatile behaviour (flaring and gas jetting) with a more rapid burn rate.



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# BURNING BEHAVIOUR OF LITHIUM BATTERIES

- Similar overall combustion heat output over time regardless of whether high SOC or low SOC.
- Low oxygen will retard open flame, but not stop thermal runaway and flammable gas venting.
- Most underground vehicles fires are considered to occur in oxygen rich environments.

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# HEAT RELEASE OF LITHIUM BATTERIES

*Refresher…..*

HRR Heat Release Rate (MW) = THR Total Heat Release energy (MJ) / Time (Sec)

For example

- A fuel source mass contains 100,000 MJ of thermal energy
- The fuel source is burned at a consistent rate over 1 hour (3600 seconds)

- Therefore, heat release rate (HRR) = 100000 / 3600 = 27.8 MW

# HEAT RELEASE OF LITHIUM BATTERIES


Sandvik 518B Loader

# HEAT RELEASE OF LITHIUM BATTERIES

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- The battery mass on a BEV is likely to be 10X or more than the equivalent diesel fuel mass.
- Diesel fuel has a total heat release (THR) of up to 47 MJ/kg in a fire.
- Lithium (LFP) battery combustible components have a TMR of 28 MJ/kg in a fire.
  - However, not all of a battery pack is combustible, depending on packaging etc.
  - Typically total battery pack mass heat release is only around 7 MJ/kg.
  - Mining equipment may be as low as 2 – 3 MJ/kg because of extra armoured housing / cooling etc.
  - The actual heat release per manufactured mass is difficult to estimate.

*E.g. a 3000 kg LFP battery module may release between 5000 - 20000 MJ depending on module application design.*

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# HEAT RELEASE OF LITHIUM BATTERIES

- Heat release estimates are more consistent when considering electrical capacity of an LFP battery, rather than the quoted manufacturer battery module mass.
- Testing shows LFP batteries typically have up to 14X the potential heat release of the rated electrical capacity (kWh).

$$THR = \frac{14 \times 3600 \times C_b}{1000} = 50.4 \times C_b$$ **(For LFP batteries only)**

Where $C_b$ is the battery capacity (in kWh) and THR is total heat release (in MJ)

For diesel comparison

$THR = 39.5 \times C_d \; (for\ diesel\ fuel)$ **where $C_d$ = number of litres of diesel**

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# EXAMPLE OF TOTAL HEAT RELEASE

Heat Release of a Sandvik* Loader Diesel vs LFP Battery (fuel source only)

- **LH518B (BEV) loader with a 353kW battery THR =** $\mathbf{50.4 \times 353 = 17,791\ MJ}$

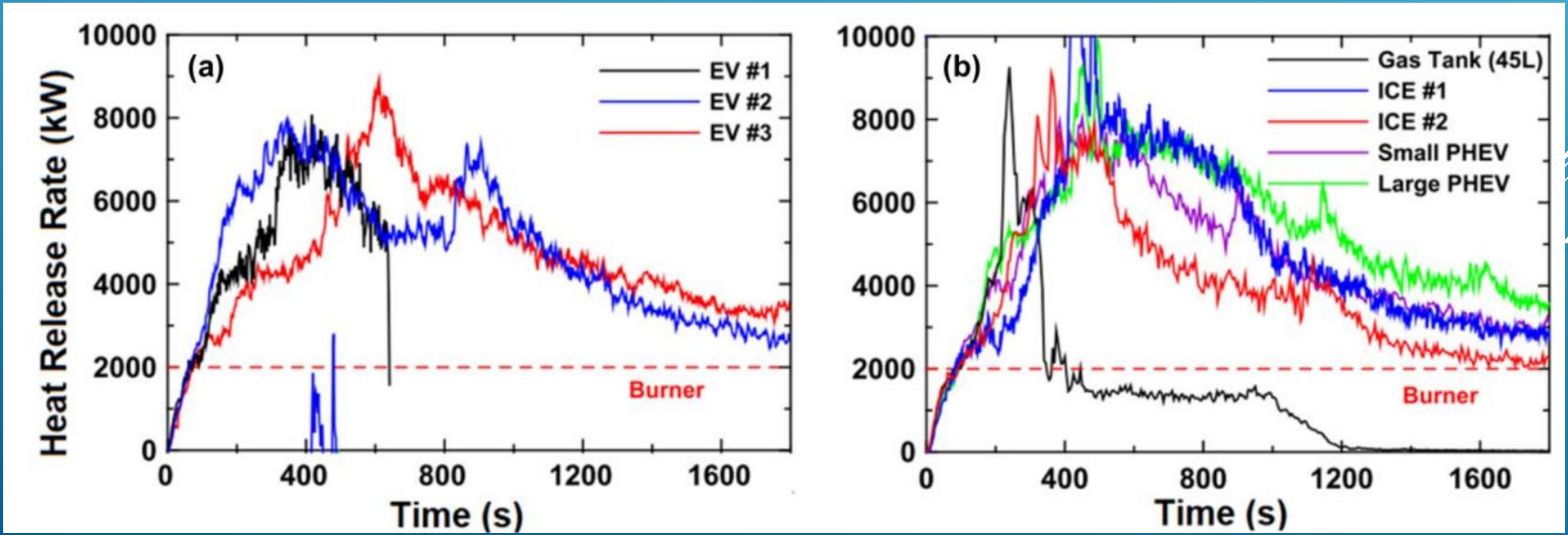
- **TH517i (IC) loader with a 580L 100% fuel tank THR =**$\mathbf{39.5 \times 580 = 22,910\ MJ}$
- **TH517i (IC) loader with a 580L 50% fuel tank THR =**$\mathbf{39.5 \times 290 = 11,455\ MJ}$

*note: LFP Battery figures not ratified by Sandvik

*note: other battery chemistries such as NMC may have different rates

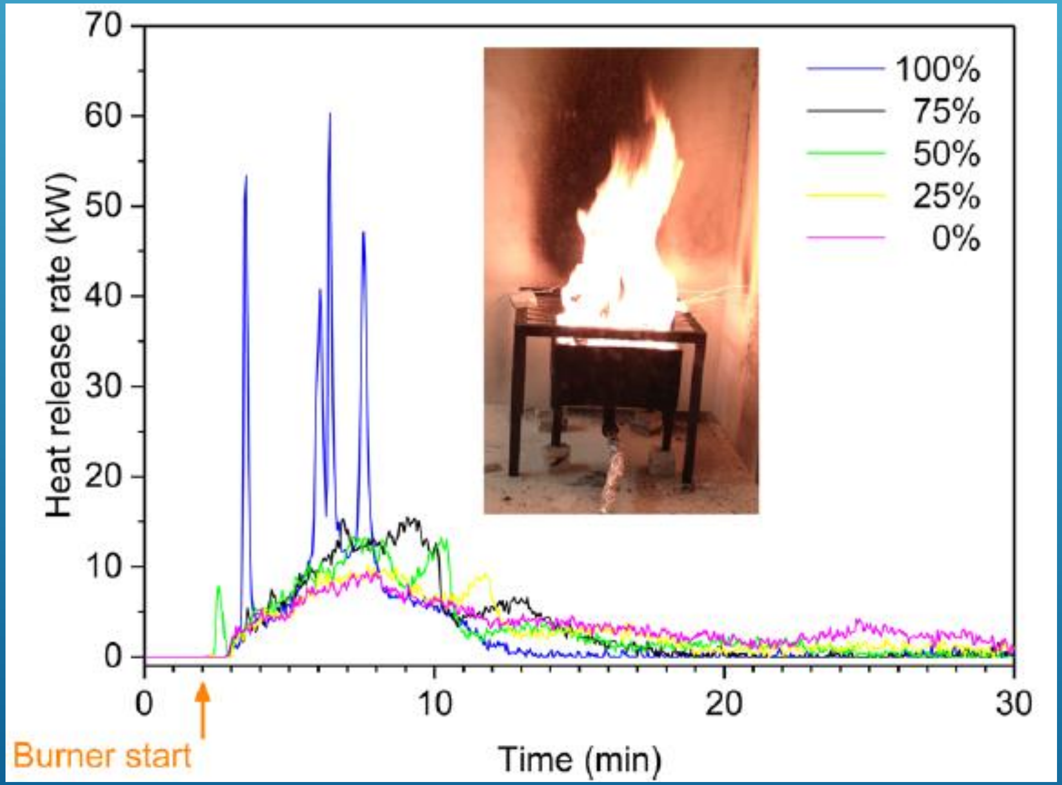
# HEAT RELEASE RATE OF LFP BATTERIES

- Independent Full-Scale EV (surface) vehicle testing (including tyres, plastics etc.) suggests HRR curves similar to fuel / hybrid vehicles.
- Smaller vehicles < 1 hour, Larger vehicles longer



# HEAT RELEASE RATE OF LFP BATTERIES

- State of Charge (SOC) of battery impacts early burning rates (HRR) but has little effect on the total heat released (THR).



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# PRODUCTS OF COMBUSTION

Main products of concern for BEV fire are:

- Carbon Monoxide (IDLH 1200 ppm - 10 min toxicity 1700ppm)
- Hydrogen Fluoride (IDLH 30 ppm - 10 min toxicity 170 ppm)

- STEL (15 minutes) 200 ppm CO and 2-3 ppm for HF

# PRODUCTS OF COMBUSTION

How are the IDLH values derived?

*IDLH or Immediately dangerous to life or health means an atmospheric concentration of any toxic, corrosive or asphyxiant substance that poses an immediate threat to life or would cause irreversible or delayed adverse health effects or would interfere with an individual's ability to escape from a dangerous atmosphere. (OSHA)*

Huge historical research and medical history for CO exposure and fatalities, but very limited research on HF.

- NIOSH limits stem from animal testing in the 1960s
- Testing performed on monkeys, rats, guinee pigs and rabbits suggested 30ppm for 40 hours was tolerated without fatality.  300 ppm for 2 hours was fatal.
- IDLH HF 30 ppm appears to be a conservative limit due to backing of real human statistics and data.

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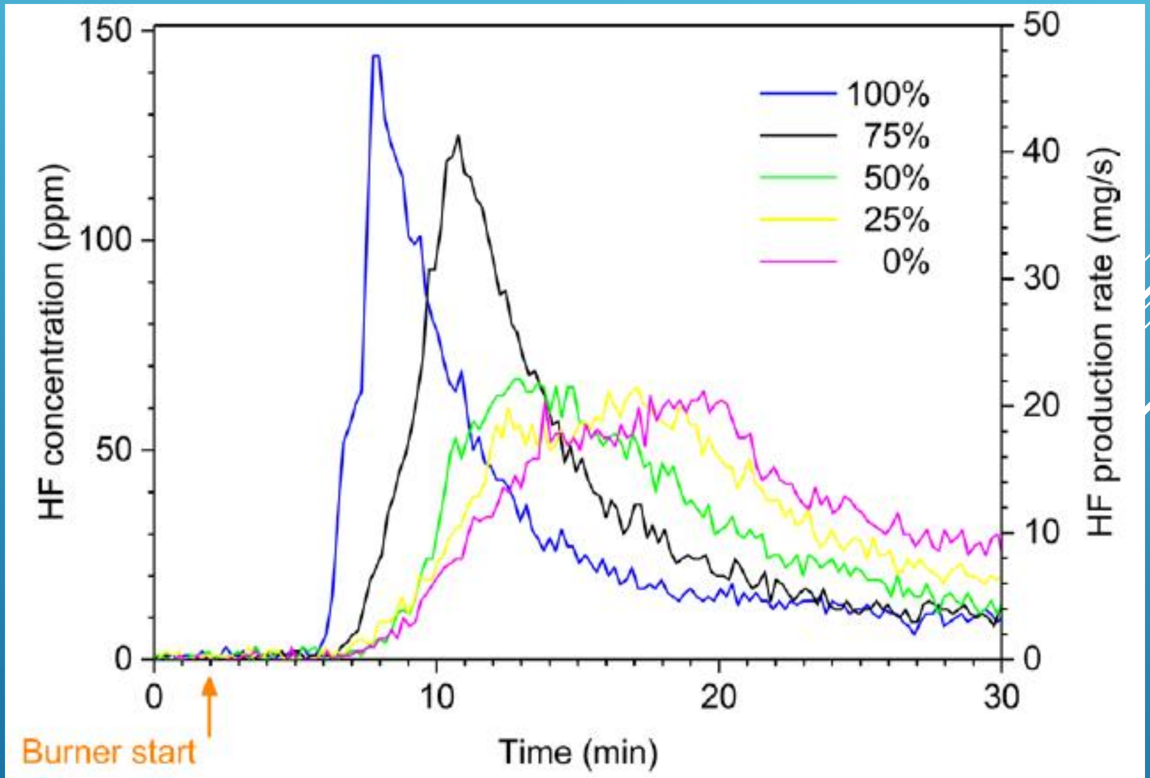
# PRODUCTS OF COMBUSTION

| Gas types | Mass yield LFP | | Energy yield LFP | |
|---|---|---|---|---|
| | Low kg/kg | High kg/kg | Low kg/kWh | High kg/kWh |
| $O_2$ | -0.3975 | -0.3375 | -3.8813 | -4.5713 |
| $CO_2$ | 0.4500 | 0.5300 | 5.1750 | 6.0950 |
| CO | 0.0038 | 0.0133 | 0.0431 | 0.1524 |
| NO | 0.0021 | 0.0021 | 0.0242 | 0.0242 |
| $SO_2$ | 0.0023 | 0.0023 | 0.0265 | 0.0265 |
| HCL | 0.0003 | 0.0003 | 0.0035 | 0.0035 |
| HF | 0.0017 | 0.0174 | 0.0200 | 0.2000 |

*Maximum and Minimum experimental results



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# FIRE MODELLING OF BEVS

**Lithium Battery Total Heat Released (including other equipment items)**

**+**

**Heat Release Rate typical of diesel equipment fires.**

**+**

**Gas Yield Rates and Oxygen Consumption**

**=**

**Simulation prediction of temperature, gases and natural ventilation changes**

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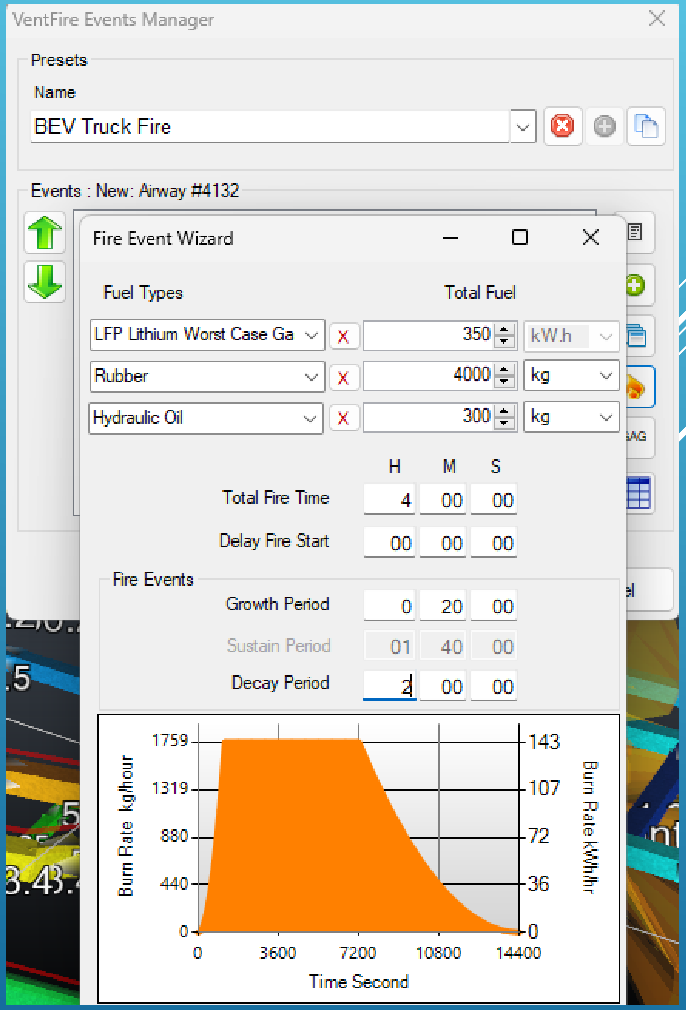
# BEV FIRE MODELLING IN VENTSIM 6

- Define Battery Combustion Parameters
- Include Battery in BEV Equipment Fuel Types

| Name | Description | Heat of Combustion MJ/kWh | O2 Consume | y CO2 kg/kWh | y CO kg/kWh | y NO kg/kWh | y SO2 kg/kWh | y HF kg/kWh | y HCL kg/kWh | y Soot kg/kWh |
|---|---|---|---|---|---|---|---|---|---|---|
| LFP Lithium Worst Case Gas | | 50.4 | 4.5713 | 6.095 | 0.1524 | 0.0242... | 0.0265 | 0.2 | 0.0035 | 0.05 |



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# CONCLUSIONS

- Lithium Battery Fires can be modelled with mine fire simulation software.
- Inputs should be modified to consider heat output as a function of battery capacity (kWh), not battery mass (kg).
- Similar heat release rates expected for BEV fires compared to diesel fires.
- Due to HF gas, BEV fires are at least equally or potentially more hazardous than ICEV (diesel) fires.

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# CONCLUSIONS

- Lithium Batteries in BEV fires must be still considered as part of a total fire mass, including other combustibles such as tires, hydraulics etc.
- HF gas output should be considered in BEV fires – may be as toxic, or more toxic than CO gas released.
- HF gas output consideration essential for battery only fires (e.g. charging bays or storage areas) – can be up to 10-40X more toxic than the CO gas released

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# CONCLUSIONS

- The hazards of lithium battery use must be separately considered in any mine (protection, mine design, refuge, fire suppression, emergency response, training etc.)
- Ventilation infrastructure is recommended to have independent exhaust for storage and charging of lithium batteries. Extra caution must be taken for faulty or damaged batteries which may enter thermal runaway hours or days later.
- Special techniques and considerations for fire fighting, mine refuge and mine rescue, including effectiveness of refuge, scrubbers or PPE against HF gas.
- The likelihood of underground BEV fires vs Diesel equipment fires is undetermined. More testing (including full scale) and incident statistics required.

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# THANK YOU