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Managing fire safety of Battery Electric Vehicles (BEVs) in underground mines

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ABSTRACT

The use of Battery Electric Vehicles (BEVs) in underground mines offers a significant benefit than the traditional use of diesel machines: healthier working conditions by producing zero toxic gases & Diesel Particulate Matter (DPM) emissions and lowering heat & noise levels. Other benefits include potential reduction of ventilation and air conditioning costs and potential reduction of greenhouse gas emissions. Despite this, the use of BEVs in underground mines is still limited. One of many reasons is that the fire safety of BEVs is still not well understood. The fire risks of BEVs are different to the fire risks of diesel machines. BEVs do not carry large amounts of combustible liquids (diesel fuel and engine oil). They also do not have a hot exhaust system. However, a BEV fire is far more difficult to extinguish due to the possibility of the battery re-igniting after the initial fire is extinguished. Currently, there is insufficient data to suggest that BEV fires are more common or more dangerous than diesel fires in underground mines and there are no recorded fatalities related to BEV fires in underground mines. Despite this, a BEV fire has much higher consequences in an underground mine than a diesel fire because it is far more difficult to extinguish. Therefore, it is crucial that underground mines have adequate understanding of BEV fire safety. This paper outlines measures to prevent thermal runaway, the main cause of BEV fires, and how to manually extinguish a BEV fire and to manage battery charging bay fire safety in underground mines.

1. INTRODUCTION

The use of Battery Electric Vehicles (BEVs) in underground mines has gained significant interest in the past five years since it offers some benefits when compared to the use of traditional diesel machines. The benefits include creating better conditions by producing zero toxic gases and Diesel Particulate Matter (DPM) emissions and lowering heat and noise levels. Other benefits include potential reduction of ventilation and air conditioning costs and mine greenhouse gas emissions. Nevertheless, since the use of BEVs in underground mines is relatively new, its fire safety is yet to be fully understood. This is one factor that still limit its use in underground mines. Therefore, it is crucial that underground mines have adequate understanding of BEV fire safety. This paper outlines measures to prevent thermal runaway, the main cause of BEV fires, and how to extinguish a BEV fire in underground mines.

It must be noted that the types of BEVs covered in this paper use lithium-ion batteries (LIB); these batteries are used by the majority of the existing underground mines' BEVs.

2. FIRE RISKS OF BEV

The fire risks of BEVs are different from the fire risks associated with diesel machines and other Internal Combustion Engine Vehicles (ICEVs). BEVs do not carry large amounts of combustible liquids (diesel fuel and engine oil). They also do not have a hot exhaust system. However, their LIB has fire risks that are not present in diesel machines, which are thermal runaway and possible battery re-igniting after initial fire is extinguished. Thermal runaway is a phenomenon in which the lithium-ion cell inside the battery enters an uncontrollable, self-heating state. It occurs when a cell, or area within the cell, achieves elevated temperatures due to abuses (causes) such as thermal failure, mechanical failure, internal/external short circuiting, and electrochemical abuse. At elevated temperatures, exothermic decomposition of the cell materials begins. Eventually, the self-heating rate of the cell is greater than the rate at which heat can be dissipated to the surroundings, the cell temperature rises exponentially, and stability is ultimately lost. The loss in stability results in all remaining thermal and electrochemical energy being released to the surroundings. If sufficient heat is generated (typically 120°C to 150°C) the energy can spread to surrounding cells resulting in an eventual fire (Stewart, 2022). Thermal runaway can occur due to causes such as the degradation of lithium cells, internal or external short-circuits, physical damage on the battery, inadequate thermal management, over-charging, and over-discharging.

At the time of writing (January 2024), there was insufficient data to suggest that BEV fires are more common or more dangerous than ICEV fires and there are no recorded fatalities related to BEV fires in underground mines. It must be noted that several BEV fire incidents have happened in three north American underground mines (two in Canada and one in the USA) (Storm and Kumm, 2022; Stewart, 2022; Kuslap, 2022; Ontario Mine Rescue, 2021; Urcheck, 2022) and on the surface of two Canadian underground mines (Jacques, 2019; Ladouceur, 2024), which fortunately did not cause any fatalities. Nevertheless, any fire incident in underground mines has a potential to cause fatalities due to the confined nature of the underground mining environment. Therefore, it is critical that robust measures must be put in place to minimize fire risks of BEVs.

3. COMBUSTION PRODUCTS OF A BEV FIRE

The primary risks associated with a BEV fire is the release of toxic gases. Like an ICEV fire, a BEV fire produces carbon monoxide (CO). However, for BEV fires, the significant presence of hydrogen fluoride (HF) in combustion gases has sparked a major concern due to the toxicity and possible skin uptake of HF. HF is an irritant gas, which when dissolved in water forms hydrofluoric acid. Depending on the gas concentration and the duration of exposure, the health effect from skin exposure varies between skin irritation to tissue destruction, burns, and systematic effect. If it is inhaled, it may damage the respiratory tract, cause changes calcium, magnesium & potassium levels in the blood, and ultimately cause seizure, and death (Storm and Kumm, 2022). HF is released from combustion of battery electrolyte and non-battery combustibles such as plastics and air-conditioning (AC) refrigerant.

The best way (and the only way) to accurately quantifying HF emission rate from a BEV fire is by doing a full-scale vehicle fire test where a BEV is deliberately burned and the HF concentration within the combustion gases is measured until the fire go out by itself when all combustibles are burned. Unfortunately, at the time of writing, no such a test has yet been completed on an underground mine BEV. The only completed full-scale fire test on underground mine BEVs was undertaken on two Epiroc's drill rig battery sub- packs by the Research Institute of Sweden - RISE (Willstrand, 2021), as shown in Figure 1. This test investigated whether an external fire close to the battery, such as tyre fire, can cause a thermal runaway. The test assumed the worst-case scenario in which the fire cannot be extinguished. Therefore, both sub-packs, which had Lithium Nickel Manganese Cobalt Oxide (NMC) as the battery chemistry, were let to burn themselves out. The first sub-pack (SP1) had State of Charge (SOC) of 67% and was placed 1 m from the external fire. The second sub-pack (SP2) had SOC of about 53% (this was the mean value of the SOC of all eight modules within the sub-pack. Each module had different SOC, which varied between 7% and 82%), and was placed 0.6 m from the external fire to simulate higher heat radiation than that applied to the first sub-pack (it was theoretically 2.8 times higher). In both sub-pack tests, the external fire was simulated by a propane burner. The test found that it took significant time for the external fire to initiate thermal runaway in both sub-packs, which was around two hours for SP1 and 43 minutes for SP2. A secondary burner was required to initiate thermal runaway in SP1 since the primary burner was unable to do so. After the thermal runaway was initiated, SP1 burned for about 1 hour and SP2 burned for about 80 minutes. The HF emission rate was measured as 4.3 milligrams per watt-hour (mg/Wh) for SP1 and 3.2 mg/Wh for SP2. At the time of writing, they represent the only HF emission rate data measured from a full-scale fire test related to underground mine BEVs. It must be noted that these values do not include HF that is released from combustion of non-battery combustibles (plastics and AC refrigerant)

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Figure 1 Full-scale fire test on Epiroc's battery sub-packs (Willstrand, 2021).

Due to this limited data, we should look at the rate obtained from full-scale fire tests on non-mining BEVs (road BEVs). Literature search found only ten such tests that have been done by the time of writing of this paper. This is understandable since a full-scale vehicle fire test is very expensive and time-consuming. Only four of these ten tests measured and analyzed HF in detail. The first one was completed by RISE (Willstrand et al., 2020) in a fire test hall in Borås, Sweden. The tested vehicles were a 2019 full-size van that had 40 kWh pouch NMC cells (BEV1) and a 2016 small family car that had 24 kWh prismatic NMC cells (BEV2). Both vehicles had SOC of 80%. The fire was initiated by placing a propane burner underneath the battery pack of both vehicles to simulate thermal runaway caused by a fault inside the battery pack. The vehicles were let to burn themselves out to simulate the worst-case scenario where the fire cannot be extinguished. The HF emission rate was measured as 14.3 mg/Wh for BEV1 and 35.8 mg/Wh for BEV2.

The second test was completed by an Austrian team led by Technische Universität (TU) Graz (Sturm et al., 2021) in a tunnel inside Zentrum am Berg, an underground research and training facility owned by University of Leoben located near Eisenerz, Austria. It is the only full-scale BEV fire test that has been done in underground environment at the time of writing. The tested vehicles were a 2020 compact car (BV01) and a 2020 SUV (BV05). Both vehicles had 80 kWh NMC cells with SOC of 100%. Their cell packaging is not mentioned in the literature. The fire was initiated by flooding both vehicles' battery with Natrium Chloride (NaCl) to trigger short- circuit. Both vehicles were not allowed to burn themselves out due to the trialing of various firefighting techniques on their fire. Therefore, it was not possible to measure the HF emission rate since the whole battery energy was not released during the test. At the time of writing, this test is the only one that has trialed BEV firefighting techniques in underground environment. There was another BEV involved in this test (BV02), but it had Lithium Manganese Oxide (LMO) cells and therefore not relevant with this paper since this chemistry is not used in underground mine BEVs. More detail of this test is described later in this paper.

The third test was completed by the French National Institute for Industrial Environment and Risks (INERIS) in INERIS fire test gallery in Verneuil-en-Halatte, France (Lecocq et al., 2012). This test involved two BEVs, each was manufactured by different French car manufacturer. BEV1 had 16.5 kWh battery whilst BEV2 had 23.5 kWh battery. Both batteries had SOC of 100%. Their battery chemistry and cell packaging are not mentioned in the literature. It must be noted that fire in this test was initiated by igniting lacerated left front seat in both vehicles using a propane burner. The windows were opened before the test. This does not simulate thermal runaway caused by a fault inside the battery pack. Nevertheless, the HF release rate was measured as 93.3 mg/Wh and 62.5 mg/Wh respectively. Both vehicles burned themselves out to simulate the worst-case scenario where the fire cannot be extinguished.

The fourth test was completed by RISE (Hynynen et al., 2023) in a fire test hall in Borås, Sweden. This test involved a 2021 small SUV that had 50 kWh NMC cells. The SOC was 90%. The purpose of this test was to quantify toxicity of the used extinguishing water. The fire was extinguished ten minutes after it was initiated by a propane burner underneath the battery pack. Therefore, it was not possible to measure the HF emission rate since the whole battery energy was not released during the test.

The measured HF emission rates from the first and third tests are higher than those measured in the underground mine BEV battery sub-pack test. The difference is understandable since they include HF that is released from the combustion of non-battery combustibles and the different design of the road BEVs' battery and Epiroc's battery. The tested vehicles in the first test used pouch and prismatic cells whilst Epiroc's batteries use cylindrical cells. Each cell packaging has different plastic content, which contributes to different amount of HF released during a fire event.

4. FIRE SAFETY MEASURES OF UNDERGROUND MINE BEV

Due to many types of abuse that can cause thermal runaway, there is no single fire protection measure that can protect LIB from all types of abuse. Therefore, multiple layers of fire protection measure should be used. For example, the Battery Management System (BMS), which is the "brain and nervous system" of LIB, can only protect LIB from over-current/over-loading, over-charging, and over-discharging. It cannot protect LIB from external heating and mechanical abuse.

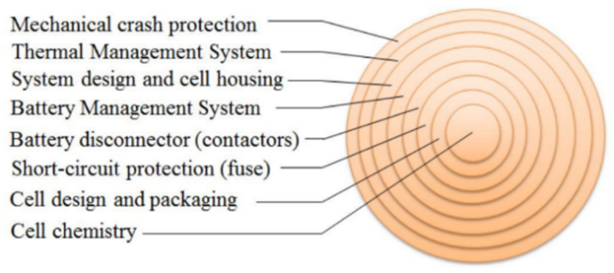

Figure 2 Safety Onion battery fire safety principle (Larsson, 2017).

Larsson (2017) proposed the Safety Onion guideline as shown in Figure 2. It is used by several underground mine BEV Original Equipment Manufacturers (OEMs). This guideline is about providing multiple layers of fire protection, starting from the innermost aspect, which is the cell chemistry, until the outermost aspect, which is protection against mechanical crash.

It must be ensured that these measures are maintained and operated properly. One outcome gained from a BEV trial program at the Kittilä mine in Finland (Halim et al., 2022) demonstrated the importance of keeping the battery thermal management system running throughout the operation of the BEV, since it is the only measure that can protect the battery from external heating. It was decided that the BEV should not be operated when the thermal management system is broken, even though the other components are working. In other words, the system is treated in a same way as the cooling system of electric motor and diesel engine. It is also important to ensure that machine operators and maintenance personnel are trained properly to implement this procedure. Figure 3 shows the extent of the thermal management system of the battery of Epiroc's ST14 battery LHD and MT42 battery truck.

Figure 3 The extent of the thermal management system of the battery of ST14 LHD (left) and MT42 truck (right) (courtesy of Epiroc).

The full-scale fire test on Epiroc's battery sub-packs described previously also aimed to test the fire safety measures on the sub-packs (from cell chemistry until system design & cell housing). The fact that it took significant time for the external fire to initiate thermal runaway in both sub-packs, which was around two hours for SP1 and 43 minutes for SP2, indicates that their fire safety measures are designed, constructed, and operated properly. In the event of a real BEV fire incident, the time is more than adequate to allow mine personnel to seek refuge in the nearest refuge chambers. In theory, by the time thermal runaway is initiated, all mine personnel should be inside the refuge chambers. Moreover, the subpacks are placed inside a battery pack so in a real BEV fire there is an additional protection barrier than what was available during the test.

One thermal runaway risk that should also be assessed is when a tunnel collapses during an operation of tele-remote or automated BEV and the falling rock crushes the mechanical crash protection and significantly damages the LIB. If this event triggers a thermal runaway and fire, it will hinder the recovery operation. At the time of writing of this paper, there is no assessment on this risk that has been done. This is one aspect that should be looked at in detail in the future.

4.1. LIB chemistries and their impact upon thermal runaway risk

The Safety Onion guideline starts the protection measure by selecting cell chemistry that has low fire risk. However, selecting this chemistry is not always optimal since it creates another issue, which is going to be discussed in this subsection.

There are many different chemistries available. In underground mine BEVs, currently Lithium Iron Phosphate (LFP) and Lithium Nickel Manganese Cobalt Oxide (NMC) are the chosen chemistries for large BEVs (LHDs, trucks, drill rigs). Ideally, the chosen chemistry should meet the following six criteria shown in Figure 4, namely high specific energy, high specific power, excellent safety, long lifetime, low cost, and excellent overall performance. However, like other things in life, none of these chemistries is perfect and therefore each only meets several of the six criteria, as shown in Figure 4. Therefore, choosing the chemistry must be based on acceptable balance between these six criteria. Afterwards, compromises must be made for the chosen chemistry. For example, an LFP battery has better safety than an NMC battery but has less specific energy, which means that it must be larger and heavier than an NMC battery to compensate its lower specific energy. This would create a handling issue when the battery pack is moved from the swapping & charging bay to the workshop or to the surface for maintenance. Conversely, an NMC battery has higher specific energy than an LFP battery but has poorer safety, which means that it can be smaller and lighter than an LFP battery but requires more fire protection measures than an LFP battery.

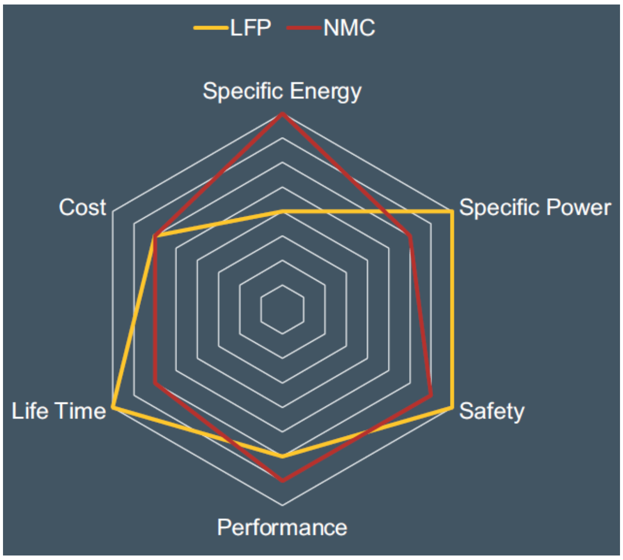

Figure 4 Comparison between LFP and NMC (source: www.lithiumhub.com).

It must be noted that there is a question about the use of NMC in underground mine BEVs due to its poorer safety than LFP. Abuse and emission tests carried out by Southwest Research Institute (SwRI) in USA on these two chemistries along with LMO found that NMC is the least safe chemistry among these three whilst LFP is the safest (Jones et al., 2021). Nevertheless, in the author's view, this does not negate the use of NMC for underground mine BEVs. It can be safely used providing that adequate fire protection measures are put in place. Epiroc uses NMC for its batteries and places multiple layers of fire protection measure. At the writing, Epiroc's BEVs had not had thermal runaway incident, which suggests that NMC can be used safely for underground mine BEVs providing that adequate fire protection measures are put in place. In other words, it is the design of the battery that really matters, not the cell chemistry. Since NMC batteries are smaller and lighter than LFP batteries for the same energy content, they have room for more fire protection measures such as placing insulating/fireproof dividers between cells.

4.2. LIB cell packaging and its impact upon thermal management (Bisschop et al., 2019)

The second measure in the Safety Onion guideline is cell packaging. Packaging material is used to protect the electrochemical components of the LIB cell. This packaging can be of different materials and shapes. They are usually distinguished by the shape of the package. As such, LIB cells are thus sometimes referred to as being cylindrical, prismatic or pouch cells, as shown in Figure 5.

Figure 5 Packaging of LIB cells (Bisschop et al., 2019).

Cylindrical cells have a very high mechanical stability as their shape distributes forces, due to internal pressure increase, evenly over the circumference. However, their shape makes it harder to package them together in an efficient manner as a significant amount of space is lost when arranging them in a rectangular shape, as shown in Figure 6. This, however, makes it easier for air to flow freely around a group of cylindrical cells resulting in easier thermal management by reducing heat transfer between cells. In other words, the air gaps between cells allow some of the heat generated by a cell to be dissipated into the air and only a portion of it is dissipated onto the surrounding cells.

Prismatic cells are commonly used for automotive traction batteries. Their prismatic shape makes them easier to integrate in a battery pack than cylindrical cells. The contents of prismatic cells follow the principle for cylindrical cells. Instead of rolled up, several layers of current collector packages are put on top of each other. As a result, prismatic cells tend to be tightly packed, which results in relatively high mechanical stresses on the prismatic package. This can also make it more challenging to regulate their temperatures since there are no air gaps between each cell, as shown in Figure 6. In other words, virtually all heat generated by a cell is dissipated onto the surrounding cells.

Pouch cells store their content inside a flexible foil pouch rather than inside a rigid container. In this case, the current collector assembly is stacked inside the pouch package, rather than rolled. This allows most of the space inside the package to be used for electrochemical material and thus provides a high energy density per pouch cell. Their flat shape also allows for very high packaging efficiency of 90-95 % when it comes to integrating them in battery packs. As a result, temperature management also becomes more important for this cell type, as it is more difficult to dissipate heat. Their soft construction can also be a drawback as it makes them vulnerable to external mechanical damage. Furthermore, pouch cells require a support structure as they are not mechanically rigid. Due to this reason, pouch cells are not used in underground mine BEVs. The high risk of external mechanical damage caused by underground mining environment (falling rocks, collision between vehicle and the tunnel walls) warrants strong (rigid) cell construction and therefore disqualifies pouch cells from being used in underground mine BEVs.

Figure 6 Packing principle for cylindrical cells (left) and prismatic cells (right) (source: www.batteryfinds.com).

The author believes that cell chemistry and cell packaging should be two sides of a coin, to the extent that one influences another in term of minimizing thermal runaway risk. Epiroc chooses NMC as the cell chemistry and cylindrical as the cell packaging. This reduces thermal runaway risk by minimizing heat transfer between the cells due to the air gaps between them and due to the very high mechanical stability of cylindrical packaging.

5. EXTINGUISHING A BEV FIRE IN UNDERGROUND MINES (HALIM, 2024)

It was mentioned in Section 2 that there is insufficient data to suggest that BEV fires are more common or more dangerous than diesel machine fires in underground mines and there are no recorded fatalities related to BEV fires in underground mines. Nevertheless, BEV fires can still happen, as shown by several incidents in Canadian and American underground mines mentioned previously. Extinguishing a BEV fire is arguably more challenging than extinguishing a diesel fire since the battery fire can re-ignite itself after the initial fire is extinguished. In a confined space like an underground mine, this poses much greater risk to the firefighters than when they are trying to extinguish a diesel fire. During two Canadian underground mine BEV fire incidents described by Storm and Kumm

(2022), both mines were declared safe for 5.3 hours and 10.5 hours respectively after the fire started. A "safe" declaration in this case included fire extinguishing and clearance of combustion gases. In contrast, underground mine diesel fires are generally extinguished at a much faster rate. The author experienced three diesel truck fires when he was working at an underground gold mine in Australia in late 2000s and early 2010s. All of them were extinguished within 30 minutes and the mine was declared safe within one hour.

It must be noted that all modern underground mine BEVs are equipped with automatic internal fire extinguishers within their battery pack to extinguish fire within it and to prevent fire re-ignition. Nevertheless, things can go wrong in underground mines where for some reasons these automatic extinguishers fail to operate. Therefore, the mines must be prepared for this scenario; means that the fire must be extinguished manually. The best way to formulate the appropriate strategies to manually extinguish an underground mine BEV fire is by doing full-scale underground mine BEV fire tests in underground environment (inside a tunnel). It must be noted that numerous BEV fire tests have been done, but the majority were at laboratory-scale where they only tested battery cells and/or modules. A full-scale test produces significantly better results than a laboratory-scale test because it allows the following aspects to be investigated:

1. Investigation of the behavior of combustion of all combustibles within an underground mine BEV, not just within the LIB. This includes the overall vehicle's Heat Release Rate (HRR), the overall amount of vehicle's combustion products (gases, aerosols,) and the overall vehicle's burning time. All of these represent the most reliable input data for an underground mine BEV fire simulation.
2. Investigation of the overall release rate of HF. HF is also released by combustion of non-battery combustibles such as Air Conditioning (AC) refrigerant and plastics. Values of HF release rate has been obtained from some laboratory-scale LIB fire tests, but they only represent the rate from combustion of LIB, not from combustion of LIB and non-battery combustibles.
3. Investigation of the best manual firefighting techniques. Some techniques have been trialed during laboratory-scale LIB module fire tests, but they may not work in a real underground mine BEV fire since the LIB modules are placed in a thick casing inside the BEV, and it is usually difficult to be reached from outside the BEV.

Unfortunately, at the time of writing, no such tests have been completed. This is due to the very high cost, significant amount of time and resources, and the availability of an underground mine BEV to be tested. The price of an underground mine BEV is more than US$ 1 million so it is very unlikely that any OEM or mining company will be willing to donate a brand new mine BEV to be burned in a fire test in foreseeable future. Therefore, for time being we should look at full-scale fire tests on road BEVs to find some clues. As mentioned previously, literature search found only ten such tests that have been done by the time of writing. This is understandable since a full-scale road BEVs fire test is still expensive and time & resource consuming, even though it is relatively cheaper than a full-scale underground mine BEV fire test due to the much cheaper price of a road BEVs than an underground mine BEV.

As mentioned in Section 3, among the ten full-scale tests that were found in literature search, the test done by a team led by Graz University of Technology in a tunnel inside an underground research facility *Zentrum am Berg* in Austria is the only full-scale road BEVs fire test that was done in underground environment and the only one that trialed manual firefighting techniques. The test was a part of a project funded by the Austrian government to investigate the safety aspects of road BEVs in public road tunnels (Sturm et al., 2021)

The test found that ensuring water penetration into the battery pack is the key to extinguish a

BEV fire in an underground environment. The researchers found that the fire extinguishing lance (E-Löschlanze in German), as shown in Figure 7, is a promising device to manually extinguish a BEV fire in underground environment. The device pierces the areas that are difficult to access like inside the battery pack, then allows water to be sprayed into them. Previous research show that water appears to be the best extinguishing agent in fighting a LIB fire because it provides great and lasting cooling effect and therefore can prevent fire re-ignition within the battery (Willstrand et al, 2019; Tang et al, 2023). Sturm et al found that the lance could be used effectively only after the initial fire intensity was reduced by hose spraying 300 litres of water. They also looked at the effect of additives in the extinguishing water. They found that doing so generally helps but it appears not to have significant effect upon the extinguishing ability. They concluded that the main key is to ensure water, with or without additives, can penetrate the battery pack, in which the fire extinguishing lance could be the best device to do so. They also found that the firefighters must have comprehensive knowledge of the structure of the battery and possible hazards during the insertion of the device to use it effectively and safely. During the trial, one firefighter touched an insulated surface of the vehicle and received a minor electric shock; fortunately, the person was not injured.

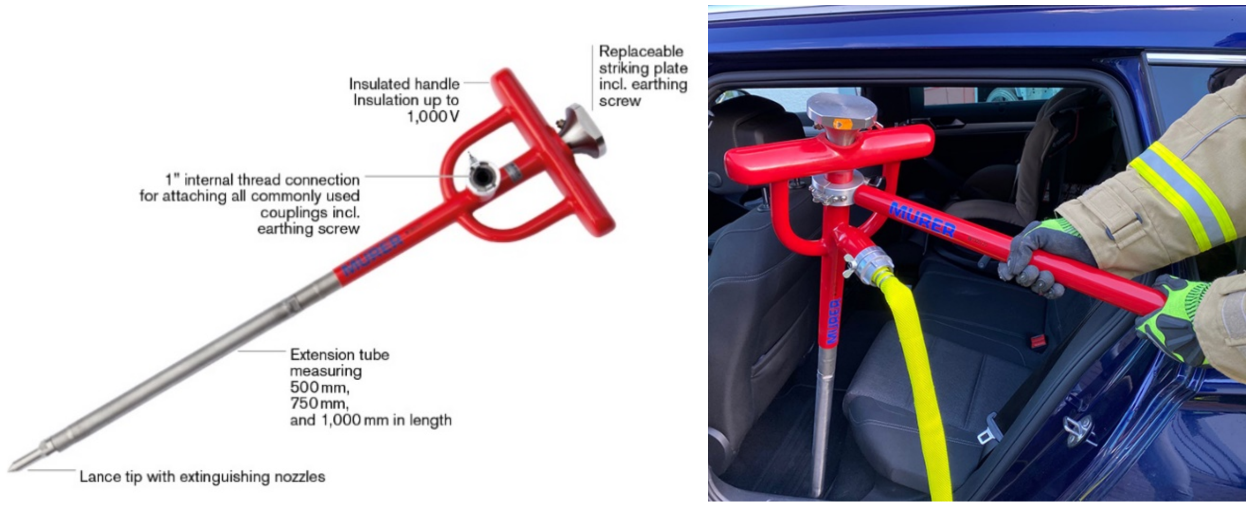

Figure 7 Fire extinguishing lance (https://www.murer-feuerschutz.de/e-loeschlanze/).

Based on this trial, it appears that the fire extinguishing lance is promising as the device to extinguish an underground mine BEV fire. However, given the larger size of underground mine BEVs and the thicker casing of underground mine BEVs' battery pack (which is designed to protect the pack from rock falls), the underground mine lance must be larger and stronger than the one used in this trial. Moreover, the larger size of underground mine BEVs means that their fires are more intense than road BEV fires thus they produce more heat than road BEV fires. This might prevent firefighters to get close enough to jam the lance into the battery pack, particularly in a confined space like an underground mine. Nevertheless, the effectiveness of extinguishing lance as the main manual extinguishing device for underground mine BEV fires can only be confirmed by full-scale underground mine BEV fire tests.

There are two other potential techniques to manually extinguish an underground BEV fire, which are placing a quenching port on the sides of the battery pack and the use of large water pools. The quenching port, as shown in Figure 8, could be used as another way to ensure water penetration into the battery pack. After the initial fire intensity is reduced by conventional water hosing, the water hose is attached to the quenching port to spray water into the battery pack.

However, there are potential issues of this technique:

1. The port may be damaged by the initial fire. The intense heat might deform the cap, making it unable to be removed, and might damage the hose docking mechanism. This could be mitigated by making the cap pierceable so another device like fire extinguishing lance is used to deliver water into the battery pack.
2. The firefighters might be unable to get close to the vehicle to attach the hose due to the heat produced by the initial fire, particularly in a confined space like an underground mine.

Figure 8 A quenching port on an underground mine BEV LIB pack (courtesy of Mr. Tim Paquin).

Large water pools could be used to extinguish the initial fire and to cool the vehicle and the battery pack, and subsequently allowing firefighters to use extinguishing lance or quenching port. The burning BEV should be driven into the pool and keep it submerged for several hours. However, there are still unknown aspects of this technique, such as how big the pools should be, how many pools are required, where to place the pools, and how to manage the used water. The latter is also important since a study done by Hynynen et al. (2023) found that the water used to extinguish a road BEV fire contains toxic substances.

Nevertheless, like the fire extinguishing lance, the only way to confirm the feasibility of these other techniques is by doing full-scale underground BEV fire tests. These tests are crucial to develop strategies to manually extinguish an underground mine BEV fire and to test the automatic internal fire extinguishers. This is an important topic for future research on the use of BEVs in underground mines. The research should investigate other manual extinguishing techniques than the ones described above.

6. FIRE SAFETY OF BATTERY SWAPPING & CHARGING BAYS

Another fire risk when operating BEVs in underground mines is the risk in battery charging and swapping bays. The current large underground mine BEVs, manufactured by Epiroc and Sandvik, the two largest underground mine BEV OEMs in the world, use battery swapping to operate continuously. A BEV that has battery with low SOC travels to the nearest charging and swapping bay to replace its battery with a fully charged one. The used battery is then recharged using a slow charger similar to the one used by road BEVs. The vehicle can select to do onboard charging in this bay instead of swapping the battery.

The fire risk in the bays increases during the charging process. Causes such as faulty BMS, faulty fuses, and excessive air temperatures inside the bay may initiate thermal runaway. Since a LIB fire can re-ignite itself after the initial fire is extinguished, fire safety measures of battery charging & swapping bays should be different than that for other electrical infrastructures such as substations. There is a suggestion that the best measure to mitigate fire risk at the charging & swapping bays is to place the bays in the access to primary exhaust airway. Theoretically this would prevent combustion products (smoke and toxic gases) to spread to the other parts of the mine since they will be directly sucked into the exhaust airway. However, there are several issues with this suggestion:

1. The severe consequences of rollback. Rollback is where natural pressure buoyancy, which is resulted from the fire

heat, causes combustion products to travel along the tunnel roof in the opposite direction to the airflow for some distance back from the fire. It may blow the combustion products back to fresh air areas and reverse the airflow direction in the exhaust airway. The latter may adversely affect ventilation in the other areas/levels within the mine.

2. The fire may receive continuous supply of oxygen, even when rollback occurs, due to the continuous airflow to the exhaust airway. This makes extinguishing fire extremely difficult. Placing a fire door that closes automatically is not an option since doing so will cut ventilation to the area/level where the bay is located and may adversely affect ventilation in the other areas/levels within the mine.
3. Under normal operation (no fires), the charger and the LIB are exposed to dirty airflow that carries dust and oil mist. Accumulation of these substances may damage the charger and the LIB.
4. The location of the bays also depends on maximizing BEV's productivity; means that they may have to be placed close to production areas that are far from the accesses to primary exhaust airway.
5. For brownfield mines that want to replace their diesel fleet with BEVs, it is not always possible to place the bay in the existing accesses to primary exhaust airway. For example, in narrow vein mines, the accesses to primary exhaust airway are usually short drives from the ramp/decline. They are not large enough to house charging & swapping infrastructures.

The possible "best" option to mitigate fire risk at the charging & swapping bays is by placing the bay inside a dead-end heading that is equipped with a fire door (with man access), temperature & gas sensors, and a fire suppression system (e.g. fire sprinklers). The bay shall be fitted with a small auxiliary ventilation system with a rigid & fire-resistant duct (e.g. metal or fiberglass duct) and a fan with a self-closing valve (e.g. butterfly valve). When a fire occurs, the temperature & gas sensors should activate automatic closure of the fire door, automatic shutdown of the auxiliary fan, and the sealing of the ventilation duct by the fan's self-closing valve. This should cut the airflow (oxygen) supply into the bay. Then the fire sprinkler system is automatically activated. The fire should be extinguished quickly due to the lack of oxygen. Rigid duct should be used instead of lay-flat duct because it is more resistant to cuts and punctures. Figure 9 shows a schematic of this concept. The automated activation system should be linked to a system that detects the presence of personnel inside the bay so that the fire door will not be closed until all personnel leave the bay. Epiroc's Mobilaris Situational Awareness system, https://www.epiroc.com/en-uk/products/digital-solutions/safety-solutions/mobilaris-situational-awareness, is an example of the personnel detection system that can be used for this purpose.

However, there are some aspects of this concept that must be investigated further, which are:

1. How to release combustion products from the bay? This could be done by doing the following:
   a. Placing a valve on the fire door to allow the combustion products to escape the bay and then flow to the nearest primary exhaust airway. In this situation, the airway between the bay and the primary exhaust airway must be isolated during the clearance of the combustion products.
   b. Excavating a direct connection to the nearest primary exhaust airway, such as a small tunnel that is closed during normal operation. This connection is opened after the fire is extinguished. This option is theoretically better than the first one since it ensures that the combustion products will flow directly into the exhaust airway. However, it may not be economically feasible to do it.

2. How to drain water that is used to extinguish fire from the bay? As mentioned previously, a study done by Hynynen et al. (2023) found that the water used to extinguish a road BEV fire contains toxic substances found that the water used to extinguish a road BEV fire contains toxic substances. Based on this finding, it is likely that the water used to extinguish a LIB or a charger fire will also contain toxic substances.
3. How to activate the system if there are personnel who are unable to exit the bay (e.g. trapped behind the fire or knocked unconscious)?

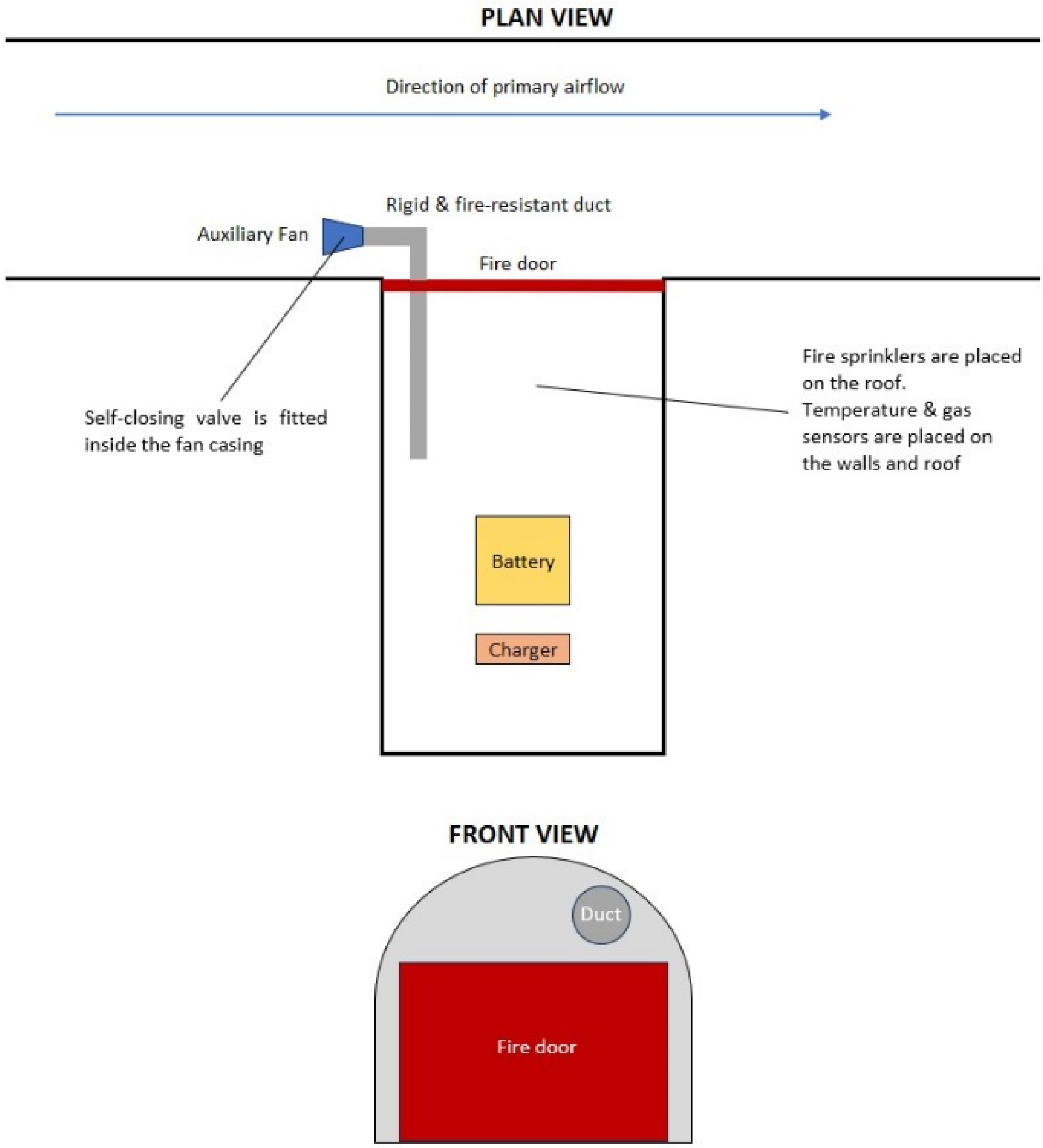

Figure 9 **A conceptual fire safety measures for a LIB charging & swapping bay. Note that the fire door is opened during normal operation.**

Another possible "best" option is by placing the bay in a dead-end heading connected to a primary exhaust airway. The connection drive to the exhaust airway is fitted with a fire louvre. The bay is equipped with a fire door (with man access), temperature & gas sensors, and a fire suppression system (e.g. fire sprinklers). The louvre is opened during normal operation to provide ventilation to the bay. When a fire occurs, the temperature & gas sensors should activate automatic closure of the fire louvre and the fire door few minutes after the fire is detected. This is to allow initial fumes to escape to the exhaust airway before the airflow (oxygen) supply into the bay is cut. Then the fire sprinkler system is automatically activated. After the fire is extinguished, the fire louvre is opened to clear the combustion products. Like in the dead-end heading option, the automated activation system should be linked to a system that detects the presence of personnel inside the bay so that the fire door will not be closed until all personnel leave the bay, such as Epiroc's Mobilaris Situational Awareness system.

The advantage of this option is that the clearance of the combustion products would be better than the dead-end heading option due to the presence of the connection drive. However, to make it economically feasible, the bay must be placed near a primary exhaust airway to minimize the cost of excavating the connection drive. This may not be possible in brownfield mines but is possible in greenfield mines. Moreover, this option still shares the last two unknown aspects with the dead-end heading option (draining the extinguishing water and dealing with personnel who are unable to exit the bay).

It is obvious that more research is required to test these two concepts. Full-scale tests should be integral parts of the research.

7. CONCLUSIONS AND RECOMMENDATIONS

Fire is the most hazardous safety risk in an underground mine. Even though there is insufficient data to suggest that BEV fires are more common or more dangerous than diesel machine fires in underground mines and there are no recorded fatalities related to BEV fires in underground mines, a BEV fire is far more difficult to extinguish than a diesel fire due to the possibility of fire re-ignition inside the LIB pack. Therefore, it is critical to understand the behavior of underground mine BEV fires, to develop adequate techniques to manually extinguish an underground mine BEV fire, particularly ensuring the penetration of water or other suitable extinguishing agents into the battery pack and to manage fire risk in charging & swapping bays.

Since fire safety of underground mine BEVs is still not well understood, more research should be done in the future to investigate fire safety of BEVs. Conducting full-scale fire tests is paramount in this research.

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REFERENCES

Bisschop, R., Willstrand, O., Amon, F. & Rosengren, M. (2019). Fire safety of lithium-ion batteries in road vehicles. Research Institute of Sweden (RISE) report 2019:50. http://ri.diva-portal.org/smash/get/diva2:1317419/FULLTEXT02.pdf

Halim, A. (2024). Field trials and fire safety of Battery Electric Vehicles in underground mines. *IEEE Electrification Magazine*, 12(1), 56-65. https://ieeexplore.ieee.org/document/10453311

Halim, A., Lööw, J., Johansson, J., Gustafsson, J., van Wageningen, A. & Kocsis, K. (2022). Improvement of working conditions and opinions of mine workers when Battery Electric Vehicles (BEVs) are used instead of diesel machines – Results of field trial at the Kittilä mine, Finland. *Mining, Metallurgy & Exploration, 39*(2), 203-219. https://doi.org/10.1007/s42461-021-00506-8

Hynynen, J., Willstrand, O., Blomqvist, P. & Quant, M. (2023). Investigation of extinguishing water and combustion gases from vehicle fires. Research Institute of Sweden (RISE) report 2023.22. https://www.diva-portal.org/smash/get/diva2:1744894/FULLTEXT01.pdf

Jacques, D. (2019). BEV pioneering partnership at Borden - celebrate the wins, face the challenges together. A presentation at Mining Diesel Emission Council (MDEC) conference 2019. https://mdec.ca/2019/S6P3_David_Jacques.pdf

Jones, K., Bhattacharya, S. & Surampudi, B., (2021). Safety enhancing technologies for usage of multi-cell battery power systems in underground equipment. Southwest Research Institute report 03.24852.

Kuslap, E. (2022). Evaluation of Epiroc's Battery Electric Vehicles in the Sustainable Underground Mining project at LKAB (Master thesis, Tallinn University of Technology, Estonia). https://digikogu.taltech.ee/et/Download/7703fcb7-110a-4d3b-a131-31764a37cbf6/

Ladouceur, N. (2024). Macassa mine battery fire summary. A presentation at Symposium on Battery Electric Vehicle Safety in Mines 2024. https://www.workplacesafetynorth.ca/sites/default/files/2024-02/Agnico-Eagle-BEV-Equipment-Fires-Case-Studies-2024.pdf

Larsson, F. (2017). Lithium-ion battery safety - Assessment by abuse testing, fluoride gas emissions and fire propagation (PhD thesis, Chalmers University of Technology, Sweden). https://publications.lib.chalmers.se/records/fulltext/251352/251352.pdf

Lecocq, A., Bertana, M., Truchot, B. & Marlair, G. (2012). Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle. In Proceedings of 2nd International Conference on Fires in Vehicles – FIVE 2012 (pp 183- 194). https://hal-ineris.archives-ouvertes.fr/ineris-00973680/document

Ontario Mine Rescue (2021). BEV Emergency Response Incident Review and Best Practices. A presentation at Virtual Symposium on Battery Electric Vehicle Safety in Mines. https://www.workplacesafetynorth.ca/sites/default/files/resources/Ontario-Mine-Rescue-BEV-Emergency-Response-Incident-Review-and-Best-Practices.pdf

Stewart, C. (2022). Ventilation considerations and modelling of lithium battery fires in underground mining. In Proceedings of The Australian Mine Ventilation Conference 2022 (pp. 267-276). The Australasian Institute of Mining and Metallurgy (AuIMM), Melbourne, Australia

Storm, A. & Kumm, M. (2022). Fire safety of battery electric mining vehicles, WP3 report: Fire and rescue operations. Research Institute of Sweden (RISE) confidential report P111657

Sturm, P., Fößleitner, P., Fruhwirth, D., Heindl, S., Kohl, B, Heger, O., Galler, R., Wenighofer, R. & Krausbar, S. (2021). Report of project BRAFA - Brandauswirkungen von Fahrzeugen mit alternativen Antriebssystemen, ein Projekt finanziert im Rahmen der Verkehrsinfrastrukturforschung 2018 (in German). https://www.itna.tugraz.at/assets/files/areas/vuu/BRAFA_Ergebnisbericht_v1.0.pdf

Tang, W., Yuan, L, Thomas, R. & Soles, J. (2023). Comparison of fire suppression techniques on lithium-ion battery pack fires. *Mining, Metallurgy & Exploration 40(4)*, 1081-1087. https://doi.org/10.1007/s42461-023-00765-7

Urcheck, J. (2022). BEV truck commissioning at Nevada Gold Mines - operational and safety considerations. A presentation at BEV Fire Safety Workshop, Missouri University of Science & Technology. Rolla. https://drive.google.com/file/d/1uioU_pt_3JWLbX0qV2tB9qmB_UF8zo5N/view

Willstrand, O., Bisshop, R., Blomqvist, P., Temple, A. & Andersson, J. (2020). Toxic gases from fire in electric vehicles. Research Institute of Sweden (RISE) report 2020.90. http://ri.diva-portal.org/smash/get/diva2:1522149/FULLTEXT01.pdf

Willstrand, O. (2021). Battery fire tests. Research Institute of Sweden (RISE) confidential report P110675