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EVALUATION OF EPIROC'S BATTERY ELECTRIC VEHICLES IN THE SUSTAINABLE UNDERGROUND MINING PROJECT AT LKAB

Master's Thesis

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AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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ABBREVIATIONS

BEV	Battery Electric Vehicle
BMS	Battery Management System
CCS	Combined Charging System
DPM	Diesel particulate matter
GHG	Greenhouse gases
ICE	Internal combustion engine
LFP	Lithium-iron-phosphate (battery chemistry)
LIB	Lithium-ion battery
LKAB	Luossavaara-Kiirunavaara Aktiebolag
NMC	Nickel-manganese-cobalt (battery chemistry)
OEM	Original equipment manufacturer
PPE	Personal protective equipment
RISE	Research Institutes of Sweden AB
SOC	State of Charge
VCA	24-V battery of the Epiroc vehicle (Voltage Class A)
VCB	Main battery of the Epiroc vehicle (Voltage Class B)
VOD	Ventilation on Demand

ABSTRACT

As a part of the Sustainable Underground Mining project, Swedish iron ore mining company LKAB is testing out Epiroc's second generation battery electric mining vehicles (Scooptram ST14 Battery and Minetruck MT42 Battery) in Konsuln test mine. So far LKAB has used either diesel equipment or tethered electric loaders in the production but with stricter environmental regulations and societal demand, one way forward could be battery electric vehicles which combine benefits from both types of vehicles.

The first part of the thesis is focused on the theory of lithium-ion batteries and the specificity of battery electric vehicles compared to diesel vehicles that are mostly used in the mining industry – health aspects, environmental performance, and risks associated. In addition to the general insight into the topic, a more in-depth look at Epiroc's MT42 Battery truck and ST14 Battery loader was done to understand the specifics of those vehicles and what are the features of the new technology and how can it affect their performance in LKAB's Konsuln test mine. To assess the risks that BEVs present in underground mines, a bow-tie analysis was chosen as an outcome to visualise and present the findings of the risk analysis.

The most important aspect in implementing battery electric vehicles in Konsuln test mine and in the long run to LKAB other mines, is the safety of the change and to understand the risks that bringing big lithium-ion battery packs to an underground mine present, an in-depth risk analysis was done as part of the thesis. The three key lithium-ion battery abuse conditions are mechanical, electrical, and thermal abuse. Most commonly those abuse conditions are related to each other as being a cause or consequence for others. Most commonly cell or battery internal thermal abuse is the last step before thermal runaway is initiated so battery's thermal management and cooling are the most important countermeasures to prevent battery fire when using BEVs.

Based on the risk events and their causes and nature, possible control measures were discussed and proposed in the conditions of the Konsuln test mine. The most important one is the Battery Management System, but also regular maintenance of the vehicle and the main battery, various fire suppression systems (both battery internal, external, and availability for battery flooding), protective layers for battery (useful in case of mechanical abuse and with a thermal event), etc. One important aspect in managing the risks is the training of the operators, maintenance workers, and everybody working in a mine where BEVs are used, so they would know what it means to work with battery electric vehicles.

Based on the results of the risk analysis, in the Konsuln test mine, essential measures are already in place or have been decided to implement before starting the tests with Epiroc's MT42 Battery truck and ST14 Battery LHD. However, when the decision is made to replace ICE mining vehicles that are mostly used in LKAB mines with battery electric vehicles, significant changes need to be implemented to mine planning and development as working with BEVs requires additional infrastructure and connectivity.

ANNOTATSIOON

Rootsi suurim rauamaagi kaevandaja LKAB testib arendusprojekti “Sustainable Underground Mining” raames Konsulni proovikaevanduses masinatootja Epiroc teise generatsiooni akutoitelisi masinaid (allmaalaadur ST14 Battery ja allmaakallur MT42 Battery). Siiani on LKAB kasutanud kas diiselmasinaid või kaabelühendusega elektrilaadureid, aga heidetele kehtestatud üha rangemate regulatsioonide ja ühiskonna ootuse täitmiseks on üheks võimaluseks akutoiteliste elektrimasinate, mis ühendavad nii diiselmasinate kui ka kaabelühendusega elektrilaadurite kasulikud omadused ühes masinas, kasutuselevõtt.

Lõputöö esimene osa keskendub liitiumakude ja nende kasutamisega seotud teoreetilisele poolele ja aspektidele (mõju tervisele, keskkonnale, riskid), mis eristavad akutoitelisi elektrimasinaid diiselmasinatest. Lisaks üldisele ülevaatele, antakse lõputöös põhjalik ülevaade ST14 Battery ja MT42 Battery masinate kohta, et mõista konkreetsete testitavate masinate eripärasid ja kuidas need võivad mõjutada töötamist LKAB Konsulni proovikaevanduses.

Kuna kõige olulisem aspekt akutoiteliste elektrimasinate kasutusele võtul Konsulni proovikaevanduses ja pikas perspektiivis ka teistes LKAB kaevandustes, on ohutuse tagamine ja arusaam, mis riske võib liitiumakude kasutamine kaevandustes kaasa tuua, teostati lõputöö põhilise osana vastavasisuline riskianalüüs. Akutoiteliste elektrimasinate kasutamisega allmaakaevandamisel kaasnevate riskide analüüsi tulemuste visualiseerimiseks valiti “bow-tie” analüüsi meetod. Kolm põhilist rikke põhjust liitiumakudel on mehaaniline, elektriline ja termiline rike. Üldjuhul on need kolm põhjust omavahel tugevalt seotud, olles kas põhjus või tagajärg teistele riketele. Kõige sagedamini on viimane samm enne lõplikku soojuskadu sisemine termiline rike, mistõttu on aku termilise kontrolli süsteem ja aku jahutus kõige olulisemad kontrollmeetmed, et vältida liitiumaku süttimist.

Analüüsides põhilisi liitiumakudega seotud rikkeid ja nende põhjuseid ja iseloomu, pakuti lõputöös välja võimalikud kontrollmeetmed Konsulni proovikaevanduse tingimustes. Kõige olulisem ohutust tagav kontrollmeede on aku kontrollimise süsteem (Battery Management System), aga lisaks ka masina ja liitiumaku regulaarsed hooldustööd ja korrasoleku kontrollid, erinevad tulekustutamise süsteemid (nii akusisesed kui ka -välised, valmisolek aku veega uputamiseks), kaitsvad tugevduskihid aku moodulite kaitseks (kasulik nii mehaanilise kui ka termilise rikke korral) jne. Lisaks on ka oluline aspekt riskide maandamisel masinajuhtide, hooldustöötajate ja kõigi kaevanduses olevate töötajate asjakohane väljaõpe, et tagada vajalikud oskused ja teadmised akutoiteliste masinatega töötamiseks ja võimaliku rikke puhul toimimiseks.

Riskianalüüsi tulemustest lähtuvalt võib järeldada, et Konsulni proovikaevanduses on esmased vajalikud kontrollmeetmed juba rakendatud või võetud vastu otsused nende kasutusele võtuks enne ST14 Battery ja MT42 Battery masinate testimist. Kui LKAB otsustab asendada diiselmootoriga kaevandamismasinad akutoiteliste elektrimasinatega, tuleb kaevanduste edasisel projekteerimisel sisse viia küllaltki arvestatavad muudatused, kuna akutoiteliste masinate kasutamine eeldab nii täiendavat infrastruktuuri nt laasimisalade näol kui ka võimekamat elektrivõrku.

1. INTRODUCTION

As part of Luossavaara-Kiirunavaara Aktiebolag's (LKAB) strategic focus, a major industrial development project Sustainable Underground Mining was initiated in 2018. The Sustainable Underground Mining project (the Project) brings together LKAB, ABB, Epiroc, Combitech, and Sandvik and is one of Sweden's biggest-ever industrial investments. The Project has also received funding from the Swedish Energy Agency.

After 2030 LKAB must be ready to mine iron ore in Kiruna and Malmberget mines at depths approaching or exceeding 2 000 metres and one way to do it cost-effectively is developing the mine of the future that is safe, autonomous, electrified, digitalized, and CO_2-free. The Sustainable Underground Mining project was called to life to test new control systems, new and improved mining equipment, as well as complex and efficient management systems that meet future demands for a sustainable industry in Kiruna mine and in Konsuln test mine that was launched to validate the concept, methodology, and technology for mining at new depths. The project aims to find out how technologies and methodologies tested help to achieve three main goals set in the Sustainable Underground Mining project:

- Zero-harm
- 50% increased productivity
- CO_2 free production.

The Project is divided into four subprojects that are focused on:

- Mine, layout, and technology
- Autonomous, CO_2-free and smart equipment
- Management system and integration
- Human-centric change.

This thesis work is mostly related to subproject focused on autonomous, CO_2-free and smart equipment as the aim of the thesis is to analyse and assess the risks that introducing battery electric vehicles in LKAB mines present and work out possible risk control methods to be able to implement battery electric vehicles safely. An important part is to evaluate how using battery-electric vehicles contributes to achieving the main goals of the Sustainable Underground Mining project mentioned above.

Risk analysis in the thesis is based on alliance partner Epiroc's battery electric truck (MT42 Battery) and loader (ST14 Battery), that will be tested in Konsuln test mine as part of the Project. Epiroc AB (part of the Atlas Copco Group until 2018) is an equipment manufacturer that develops and provides equipment and tools for both surface and underground applications. The company has a long history of providing necessary equipment for mining and civil engineering and since 2014 Epiroc has had a strong focus on developing battery electric vehicles. As one of the original equipment manufacturers with a great offering of battery electric vehicles, Epiroc was chosen to be a partner in the Sustainable Underground Mining project.

As more and more mining companies are testing out battery electric vehicles as a resort to lower their operational costs, have a better work environment in their mines and contribute to environmental sustainability by reducing using fossil fuels in production, it is necessary to understand the differences in technologies and consider all possible outcomes with the change to battery electric vehicles. As the technology is new, the official safety standards and safety routines are yet not in place and so far, done on case by case by companies testing out battery electric vehicles. Therefore, my thesis aims to provide an in-depth analysis of risks that implementing BEVs to underground mines might present and what are the appropriate mitigation measures to ensure safe working conditions in the mines.

Although risk assessment in my thesis is also related to a specific company (LKAB) and Konsuln test mine, the aim is to discuss all the risk factors that battery electric vehicles could present when used in an underground mine with a broader perspective and by that allowing the findings in my thesis to be later applied for other mining operations or when working out industry-wide safety standards.

2. LITERATURE REVIEW

Compared to diesel machines used in mining, battery electric vehicles are a new development trend and therefore the first part of my thesis work was to familiarize myself with the theory and research on them and to get the knowledge what is the basis of possible issues and benefits of implementing battery electric vehicles in underground mines.

2.1 Iron ore mining and its impact

It is a well-known fact that mining affects the environment considerably but at the same time, it is important to understand that mining is necessary to satisfy our demand for materials and energy. As said by P.N. Martens and L. Rattmann (Martens & Rattmann, 2001), "*without mining there would be no future for anybody to look forward to*" as the materials being mined are used in every aspect of our lives. Iron ore is one of the most mined raw materials in the world not including mineral fuels (Federal Ministry of Agriculture, Regions and Tourism, 2020). 98% of mined iron ore is used in steel production (Government of Canada, 2020) which is one of the most important construction materials and is needed in almost every aspect of our lives if we want to continue and upgrade our living standards. Steel is mostly used in buildings and infrastructure, transportation, metal products, mechanical equipment, domestic appliances, and electrical equipment (World Steel Association, n.d.). As all the above-mentioned markets have boomed over the last decades, iron ore production has grown as well (*Figure 2.1*). One reason for the rapid drop in 2015 was China's reorientation of their growth strategy that led to substantial supply overhang (Löf & Ericsson, 2015). Since 2015 there was a slow but steady growth in iron ore production which started to decline in 2018.

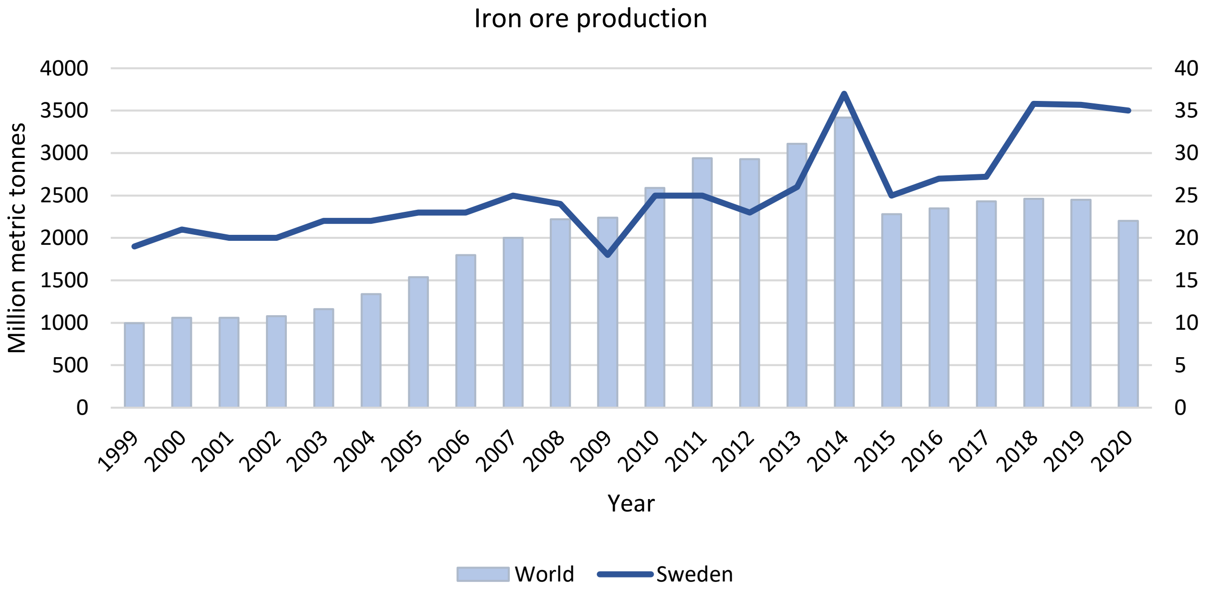


Figure 2.1 Iron ore production 1999 – 2020 (U.S. Geological Survey, 2021)

As mentioned before, mining has a great impact on the environment and therefore the reputation of the industry by the majority of stakeholders is broadly neutral or negative (World Gold Council, 2013).

Comparing different mining industries' reputations, according to the World Gold Council report, iron ore industry has the highest-ranking result overall in every stakeholder group analysed (government, civil society, media, and international organizations). As the conversation on climate change and what could be the necessary next step toward a more sustainable future is heating up, the mining industry including iron ore mining is under more pressure to change towards being more sustainable in a long run. Gold mining company Anglo American's CEO (Jamasmie, 2020) thinks that when talking about the future of mining, we must understand and connect it with next-generation societal values including responsible technological innovation and sustainability. To maintain or gain a social license to operate, radical steps must be taken by the mining companies to ensure sustainability in their production. Also related to the iron ore industry is steel making and in addition to the mining industry's environmental footprint, the steel industry accounts for 7% of CO_2 emissions globally (SSAB, n.d.) which makes it one of the highest CO_2 emitting industries.

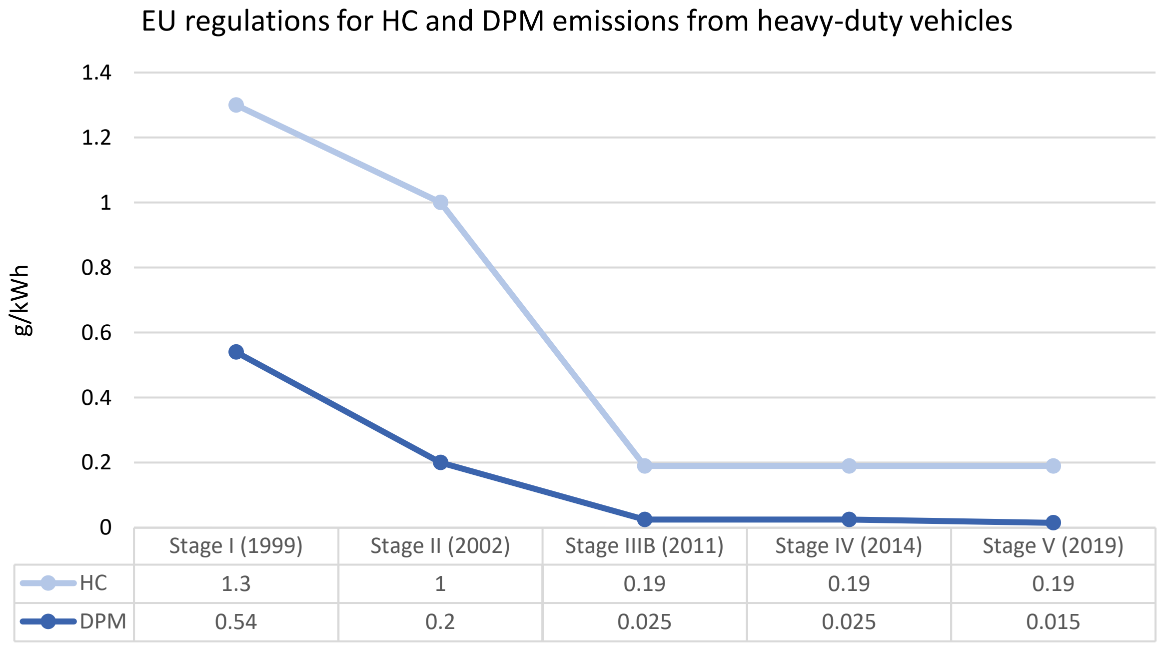
The Swedish government has set a goal in Sweden's Minerals Strategy (Swedish Ministry of Enterprise, Energy and Communication, 2013) to secure its leading position in the European mining industry. According to the mineral production statistics compiled by the Geological Survey of Sweden, mineral production levels have increased since 2009 with a little drop in 2015. Goals set in Sweden's Minerals Strategy will mean that mineral production, including iron ore production in Sweden, will continue to increase. As the biggest iron ore miner and pellet producer in Europe, LKAB has understood the responsibility they have as an iron ore company towards the stakeholders and has initiated projects like Sustainable Underground Mining and HYBRIT to determine how to make iron ore production more sustainable. The end-goal for the company is to have a CO_2-free value chain. In both projects, changing the source of energy used in the processes is vital – in the pelleting process replacing fossil fuels with hydrogen (LKAB, 2020) and in mining operations changing from diesel to electricity. In 2021 July the first patch of sponge iron was produced with 100% fossil-free hydrogen using the HYBRIT technology (HYBRIT, 2021). Both mentioned projects initiated by LKAB are supported by the Minerals Strategy as it also highlights the importance of research and innovation in the mining industry.

2.2 Regulations on diesel vehicles

So far, the mining industry has been mainly relying on equipment powered by internal combustion engines (ICE) that run on diesel. Next to many advantages of diesel-powered vehicles such as reliability, efficiency, durability, ease of maintenance, and necessary mobility for mining operations (Kurnia et al, 2014), diesel-powered vehicles have also considerable disadvantages like emitting diesel exhaust gases, diesel particulate matter (DPM), and heat.

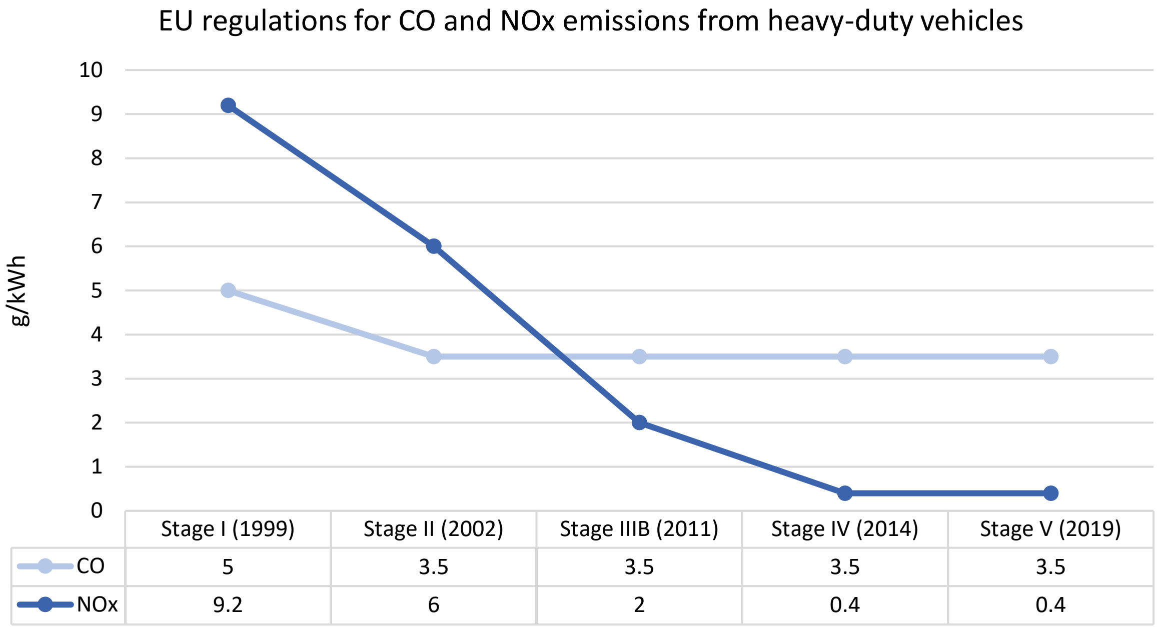
Stricter regulations on heavy-duty diesel engine emissions were adopted in the 1990s in Europe, Northern America, and as well in Japan. At first, the main emissions targeted with the regulations in all regions were CO, HC, NO_x, $NMHC+NO_x$ (in Northern America regulations), and DPM. Later additional regulations followed on greenhouse gas (GHG) emissions and fuel consumption. According to Jääskeläinen and Majewski (2014), regulations targeting emissions and fuel economy have been the main factors for improvements in engine technology. Market demand for lower fuel consumption and engine's high performance has also played an important part as the companies using diesel machines have acknowledged the need for change towards more sustainable production.

European standards for nonroad heavy-duty vehicles have been divided into 5 stages (Stages I to V). The first EU standard on nonroad emissions is from 1997 (Directive 97/68/EC) which aimed at approximating the laws of the Member States relating to emission standards and type-approval procedures for engines to be installed in non-road mobile machinery. It aimed to contribute to the smooth functioning of the internal market while protecting human health and the environment. From 2004 stage III and IV emission standards were adopted (Directive 2004/26/EC), with stage III phased in 2006 – 2013 and stage IV entered into force in 2014. Stage V (Regulation 2016/1628) was phased in 2018 for new engine types and 2019 for all sales. For machines used in mining, usually, the net power of the vehicle is between 130 – 560 kW, which means that allowed CO emission has decreased from Stage I regulations from 5,0 to 3,5 g/kWh in Stage V regulations, HC from 1,3 to 0,19 g/kWh, NO_x from 9,2 to 0,4 g/kWh, and DPM from 0,54 to 0,015 g/kWh (Directive 97/68/EC; Directive 2004/26/EC; Regulation 2016/1628). Specific changes from Stages I to V are presented in *Figure 2.2* and *Figure 2.3*.



	Stage I (1999)	Stage II (2002)	Stage IIIB (2011)	Stage IV (2014)	Stage V (2019)
HC	1.3	1	0.19	0.19	0.19
DPM	0.54	0.2	0.025	0.025	0.015

Figure 2.2 EU regulations for HC and DPM emissions from heavy-duty vehicles (Directive 97/68/EC; Directive 2004/26/EC; Regulation 2016/1628)



	Stage I (1999)	Stage II (2002)	Stage IIIB (2011)	Stage IV (2014)	Stage V (2019)
CO	5	3.5	3.5	3.5	3.5
NOx	9.2	6	2	0.4	0.4

Figure 2.3 EU regulations for CO and NO_x emissions from heavy-duty vehicles (Directive 97/68/EC; Directive 2004/26/EC; Regulation 2016/1628)

In the USA and Canada, regulations on diesel heavy-duty vehicles have been divided into four stages. In 1994 first regulations were structured as three-tiered progress with Tier 1 taking effect in 1996 (Environmental Protection Agency, 1994), Tier 2 in 2001, and Tier 3 in 2006 (Environmental Protection Agency, 1998). Tier 4 was phased in from 2008 to 2015 with stricter regulations on NO_x and DPM emissions (Environmental Protection Agency, 2004). Specific changes in different regulation stages in Northern America are presented in appendix A.

Looking at the standards adopted over the years, it seems that CO emission has stayed the same from Stage 2 and Tier 2 which might imply that there is not much room left for improvements. Like CO emissions, HC regulations have stayed the same in European standards and other emissions reduction steps have decreased with time as well. Considering options to lower or eliminate emissions for vehicles used in mines, the next logical step would be looking at alternative energy solutions. Most commonly that would be electric machines that do not generate emissions targeted with regulations. When turning to electric vehicles for cleaner energy in the mining industry, it is necessary to look at the whole production cycle not just processes in mines as the electricity used for charging the vehicles should also be clean to have an actual impact on the operations.

2.3 Battery chemistries used in BEVs

Electric vehicles have been tested and used in the mining industry since the 1920s, becoming one of the major topics in industry development over the last decades. Most commonly, electric vehicles are used with three power solutions: vehicles with cables, vehicles with overhead catenary lines, and battery-electric vehicles. Looking more closely at LKAB, they have used tethered Sandvik loaders in Kiruna mine since mid-1980s (Gourley, 2021), and the results have been very successful. The only problem with electric loaders used so far has been vehicles' mobility and that is the reason LKAB is looking at battery electric vehicles to have the best features from electric and diesel vehicles – productivity and mobility, in one vehicle.

Replacing vehicles with ICE powered by diesel working in a mine with electric ones comes with many benefits associated with workers' health and safety, work environment, lower energy consumption, reductions to mine ventilation requirements, smaller heat generation, lower maintenance costs, etc (Global Mining Guidelines Group, 2018). Going for electric vehicles in mines can be done using either tethered equipment, vehicles with overhead catenary lines, or battery electric vehicles. All three have their challenges – tethered vehicles have limited mobility and still use diesel fuel for getting to the workplace, usage of vehicles with catenary lines is mostly limited by cost and mobility, and BEV's developed with the knowledge we have right now lack suitable batteries that would last for an entire shift.

Most BEVs run on lithium-ion batteries but exact battery chemistry varies between different original equipment manufacturers (OEMs). Lithium-ion batteries (LIBs) are currently the most suitable energy storage device for powering BEVs owing to their attractive properties including high energy efficiency, lack of memory effect, long cycle life, high energy density, and high-power density. These advantages allow them to be smaller and lighter than other conventional rechargeable batteries such as lead-acid batteries, nickel-cadmium batteries (Ni-Cd), and nickel-metal hydride batteries (Ni–MH). The importance of LIBs in future technologies is acknowledged by the fact that in 2019 Nobel Prize in Chemistry was awarded to Akira Yoshino, John B. Goodenough, and M. Stanley Whittingham for the development of lithium-ion batteries.

The most common LIB chemistries used for underground BEVs are lithium-iron-phosphate (LFP, used in Sandvik's BEVs batteries) and nickel-manganese-cobalt (NMC, used in Epiroc's BEVs batteries) which both have advantages and challenges when used. Another alternative is also lithium-titanate chemistry which right now is not in commercial usage in BEVs due to being more than three times more expensive than LFP (Gravelle, 2017). As a LIB chemistry with most kWh per volume of the cells, lithium-cobalt batteries are not used for underground mining BEVs due to being fire hazardous (Battery University, 2010).

One LIB chemistry widely used for underground mining BEVs is lithium-iron-phosphate chemistry which is the most common and well tested LIB chemistry. As a result of higher production rates, LFP batteries have a lower cost compared to the other LIB chemistries. The main reason for using LFP chemistry according to OEMs is that it is the safest chemistry for BEVs used in underground mining as the batteries do not catch fire or burn when punctured, they only produce smoke (Gravelle, 2017). However, they lack the energy density of NMC batteries. LFP chemistry may face a balancing issue with aging as it has a higher self-discharge rate than other LIBs (Ding et al., 2019) which can be mitigated by buying high-quality cells or using control electronics, but the solutions will increase the cost of the battery pack.

According to the OEMs using nickel-manganese-cobalt chemistry in their LIBs, the chemistry is very controllable, easy to steer, and is designed for energy density which allows the batteries to be more compact and lighter (Boudreault & Hedqvist, 2020). Another benefit of NMC chemistry is its lowest self-heating rate compared to other lithium-ion chemistries (Better World Solutions, 2016). NMC has also proved to have a higher cycle-life compared to other cathode materials. In a study conducted by Popp et al. (2014) it was determined that NMC batteries compared to LFP batteries can operate for a longer time before reaching the same retention rate of its initial capacity. According to the study NMC reaches 80% of its initial capacity with 455 cycles, while LFP reaches it with 377 cycles. Due to the high price of cobalt, many battery manufacturers are starting to move away from cobalt-based cathodes chemistries toward nickel cathodes (Frost&Sullivan, 2020). Nickel-based systems have a higher energy density, lower cost, and longer cycle life than cobalt-based cells but they have a slightly lower voltage. For example, Northvolt whose batteries are used in Epiroc's BEVs, have lowered their batteries cobalt content from 30% to 10% and according to the company continue developing the chemistry to get the best results (Plasgård, 2021).

An important aspect to consider while comparing different lithium-ion battery chemistries is the safety of the batteries. According to some OEMs, NMC batteries could be more fire hazardous than LFP batteries (Gravelle, 2017). However, according to Christina Lampe-Onnerud (Colthorpe, 2020), CEO and founder of Cadenza Innovation, neither the LFP nor the NMC cathode is what will burn due to thermal runaway but the organic electrolyte. The results of a study (Brand et al., 2013) where the safety of different lithium-ion cells was compared, indicated that LFP cells indeed have higher thermal stability but at the same time when overcharged are damaged earlier and LFP cells also showed some electrolyte leakage when short-circuited. The study also stated that apart from the chemistry, the design of each cell is key to its safety.

The overall safety of batteries used in Epiroc's BEVs is divided into various levels, stating with cell chemistry, and ending with mechanical crash protection (Boudreault & Hedqvist, 2020). Different levels of the safety onion for Epiroc's batteries are shown in *Figure 2.4*.

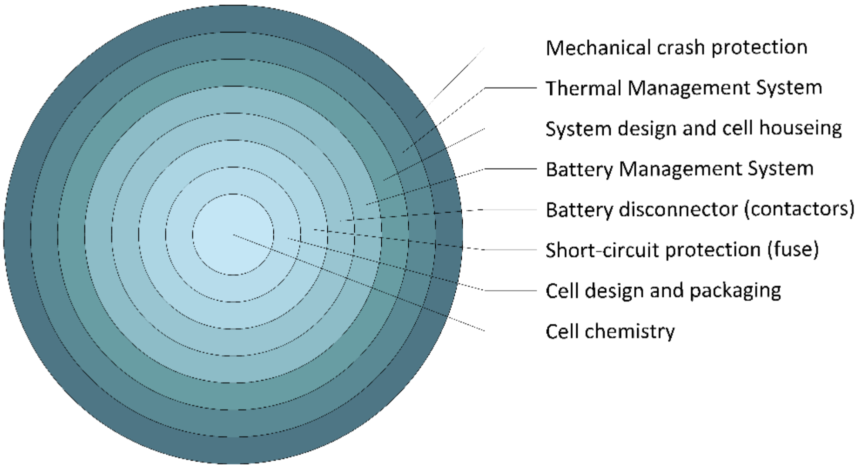


Figure 2.4 Safety onion of BEV batteries (based on Boudreault & Hedqvist(2020))

2.4 Benefits to using BEVs in underground mines

Many benefits of the BEV's mentioned above are related to the fact that BEVs do not generate diesel exhaust gases, diesel particulate matter, or greenhouse gases while working as they don't use fossil fuels for energy. While comparing two different types of vehicles and emissions that are related to them, it is important to look at the big picture – the whole life cycle of the vehicles, from production to the end of their life.

Looking at the GHG emissions for diesel cars and BEVs, studies have reached opposing results. Buchal et al. (2019, pp. 40-54) claim that while driving, BEV generates approximately 50% less GHGs than diesel car (73 g/km for BEV and 143 g/km for diesel car, calculations were done with based on energy mixture used in Germany consisting of fossil fuels, nuclear and renewable energy sources) but manufacturing of BEV generates up to 5 times more GHG than the manufacturing of diesel cars (100 – 125 g/km for BEV with battery manufacturing accounts for 75% and 27 g/km for diesel car) making the whole life cycle of a BEV generate more GHG than diesel vehicle. However, Hoekstra (2019) stated that earlier comparisons between GHG emissions from diesel vehicles and BEV have overestimated different parameters of BEVs like battery manufacturing, battery lifetime, etc and concluded in his study that BEVs generate 60% less GHGs over their life cycle than diesel vehicles (95 g/km for BEV and 244 g/km for diesel car). GHG emissions from BEVs can be even more reduced by running them on electricity generated from renewable energy sources. One great benefit while talking about replacing diesel vehicles for BEVs in LKAB, is the fact that about 97% of electrical energy in Norrbotten is generated from renewable sources (hydro, solar, and wind power) (Sardén et al., 2019) which according to Hoekstra (2019, pp. 1412-1414) would lower GHG emissions emitted while driving BEVs about 90% (from 55 g/km to 6 g/km).

Diesel vehicles are major contributors to diesel exhaust which can be separated into the gaseous phase and the particulate matter phase. Diesel exhaust, both gases (NO_x, CO, CO_2, SO_2, and HC), and diesel particulate matter are classified as carcinogenic to humans (group 1) (International Agency for Research on Cancer, 2012). As discussed earlier, because of strict regulations, diesel vehicles used in underground mines have developed greatly regarding diesel exhaust gas emissions. Lower emission levels have been achieved by in-cylinder technologies like exhaust gas recirculation, improving the efficiency of the combustion process, and various after-treatment technologies (Bugarski et al., 2011). Short-term exposure limits and threshold limit value-time weighted average of diesel exhaust gases such as NO_2, CO and NO are parameters that dictate the ventilation requirements in Sweden (Swedish Work Environment Authority, 2018) and by lowering or eliminating diesel exhaust gases from mining processes in addition to safer and healthier work environment it will be possible to implement considerable reductions to ventilation system (Halim & Kerai, 2013). The study (Gyamfi, 2020, p. 50) that was done on the ventilation on demand (VOD) concept in Konsuln test-mine showed that with battery electric vehicles cost savings can be up to 86,7% compared to using diesel vehicles.

DPM mostly consists of organic carbon and elemental carbon (Gaillard et al., 2019) with additions of particles from unburnt fuel, metallic additives, etc (Maximilien et al., 2017). Results of a study based on the Australian mining industry (Peters et al., 2017, pp. 282-289) indicate that on average miners working in underground conditions are exposed to 18 – 44 µg/m^3 elemental carbon for a 12-hour shift. Tests carried out in deep mines in Canada (Maximilien et al., 2017, p. 643) reported elemental carbon exposure for miners that exceeded Australian results by three times (elemental carbon exposure ranging from 31 µg/m^3 to 150 µg/m^3). Studies (Steenland et al., 1998; Attfield et al., 2012; Silverman et al., 2012; Boffetta et al., 2001) have found that long-term exposure to diesel particulate matter in high concentrations increase the risk for lung cancer. Silverman et al. (2012, p. 861) concluded that mineworkers who are exposed to over 1 005 µg/m^3 respirable elemental carbon a year, have a three times higher risk of lung cancer than workers with lower exposure.

Using different treatment technologies for diesel engines helps lower the emissions but in conventional diesel combustion, it might not be possible to lower all emissions simultaneously (Bugarski et al., 2011). By using in-cylinder methods for lowering NO_x emissions, DPM emissions will increase because NO_x emissions increase with higher combustion temperatures and lean conditions, but lower combustion temperatures and rich conditions will increase elemental carbon formation. One option is to use various after-treatment and in-cylinder methods combined but that will only lower the emissions. In addition to engine control technologies, Rojas-Mendoza et al. (2017, p. 1870) tested the possibility to use fog treatment to eliminate DPM from the airflow with results indicating that DPM removal using fog treatment ranged from 39,6 – 54,6%.

To eliminate the diesel exhaust gases and DPM emissions entirely from the production cycle, it is necessary to change the technology used in mining completely, and based on the knowledge we have right now, many mining companies have started testing out electric equipment and more specifically battery electric equipment (Gleeson, 2019; Vale News, 2020; International Mining and Resources Conference, 2020).

2.5 Risks associated with introducing BEVs to underground mining

Underground mines have limited entrances and exits, and the supply of oxygen is limited by the design of the ventilation system, therefore they can be listed as confined spaces. Although some undeniable benefits could be achieved with using BEVs in underground mining, research on battery electric vehicles and LIB packs suggest that there is a potential for safety hazards when using BEVs in confined spaces.

LIBs that are used to power battery electric vehicles regardless of its exact chemistry contain high energy and combustible materials which can pose a fire hazard under a critical failure event (Sturk et al., 2015). A failure within the vehicle or in a battery pack could in the worst-case lead to a fire and emission of toxic gases from the battery. A lot of research has been done on the issues regarding those risks and it has been concluded that even though ICE vehicles pose a fire hazard as well, fires related to BEVs have different nature and need to be handled differently from ICE fires – they need significantly more fire suppressant to fight the fire and putting out the fire take considerably more time (Bisschop, Willstrand, & Rosengren, 2020). With a fire incident involving LIBs, there is a chance of the fire reigniting after it has been put out, in some cases even several days after the initial fire (National Transportation Safety Board, 2019). That means with the introduction of battery electric vehicles into an underground mine, risks regarding battery technology must be analysed to evaluate if it is safe to use the vehicles and what measures should be taken to make the risk level acceptable for the mining environment.

As mentioned above, to put out a fire involving a lithium-ion battery, a great amount of suppressant is needed – fire tests done on batteries show that using water as a suppressant has a good cooling effect on the battery (DNV-GL, 2017; Willstrand et al., 2019; Kutschenreuter et al., 2020). Fire tests done by RISE (Research Institutes of Sweden) (Willstrand et al., 2019) found that having a fire suppression system inside a battery pack could lower the risk of thermal runaway propagation (which is the main cause for fire within the battery) compared to the outside suppression system which in the tests performed did not have a cooling effect for the battery. However, an outside suppression system is necessary to prevent the fire from spreading from the battery to the other parts of the vehicle (tyres, hydraulics, etc) and to surroundings especially in confined spaces. It is important to note that runoff water from extinguishing a fire can propose a separate hazard – the pH of runoff water has been measured to be between pH 6 – pH 11 (DNV-GL, 2017, p. 19) which indicates that the runoff water can be from slightly acidic to alkaline. Tests done in Switzerland (Federal Roads Office, 2020, p. 48) confirm also that water used for battery cooling is highly alkaline (pH 12). Therefore, with using BEVs in a mine there must be preparedness to treat the runoff water used in firefighting before its disposal.

Lithium-ion battery fires mostly emit toxic gases from combustion of the electrolyte (Willstrand et al., 2020). Tests done by RISE in 2020 (Willstrand et al., 2020, p. 6) measured the gas compounds that emitted during a battery pack fire – CO_2, CO, hydrocarbons, HF, HCl, HBr, HCN, SO_2, NO, NO_2 and polycyclic aromatic hydrocarbons. During the tests both ICEV and BEV fires were measured and the difference in amounts of anions sampled from ICE vehicles and BEV were compared. The results show that measured HCl levels are similar (1 720 g for ICE vehicle and 2 080 – 2 240 from BEV), measured levels of HF and HBr for BEVs were considerably higher (HF was measured 651 – 818 g from BEVs and 24 g from ICE vehicles). In addition to gases, various metal compounds were measured during the tests with BEVs having higher concentrations than ICE vehicles. One concern that might arise from the toxic gas emission during BEV fire is the fact that HF when inhaled or contacted can cause severe injuries which must be considered when evaluating risks associated with BEVs, especially in a mine. In a study where risks of HF were analysed (Swedish Civil Contingencies Agency, 2021) it was determined that for example to protect firefighters during extinguishing BEV fires a combination of base layers and firefighting clothing provides relatively good protection to avoid skin exposure of HF in gaseous form. This means that when introducing BEVs to mines, the suitability of existing personal protective equipment (PPE) must be evaluated and if necessary upgraded.

As seen from the literature review there is a great amount of research done on battery electric vehicles regarding their battery chemistries, their performance, and safety. As the pressure to make a change towards CO_2-free mining grows, implementing BEVs into mines is a great way to achieve that. It has been studied and analysed what it means on the mine design and ventilation requirements but conclusive studies on safety aspects of that change are still mostly missing or done case by case by companies testing out battery electric vehicles. Therefore, my thesis aims to provide an in-depth analysis of risks that implementing BEVs to underground mines might present and what are the appropriate mitigation measures to ensure safe working conditions in the mines.

3. MATERIALS AND METHODS

The thesis work consists of practical and theoretical parts. The practical part of the thesis was carried out over two months from October to November 2021 in Swedish state-owned mining company Luossavaara-Kiirunavaara AB (LKAB) which is operating the largest iron ore underground mine in the world in Kiruna and a mine in Malmberget and an open-pit in Svappavaara. As the thesis is part of the Sustainable Underground Mining project, the evaluation of the battery-electric vehicles was carried out with Epiroc's vehicles in Konsuln test-mine which is a separate part of the Kiruna mine (Figure 3.1).

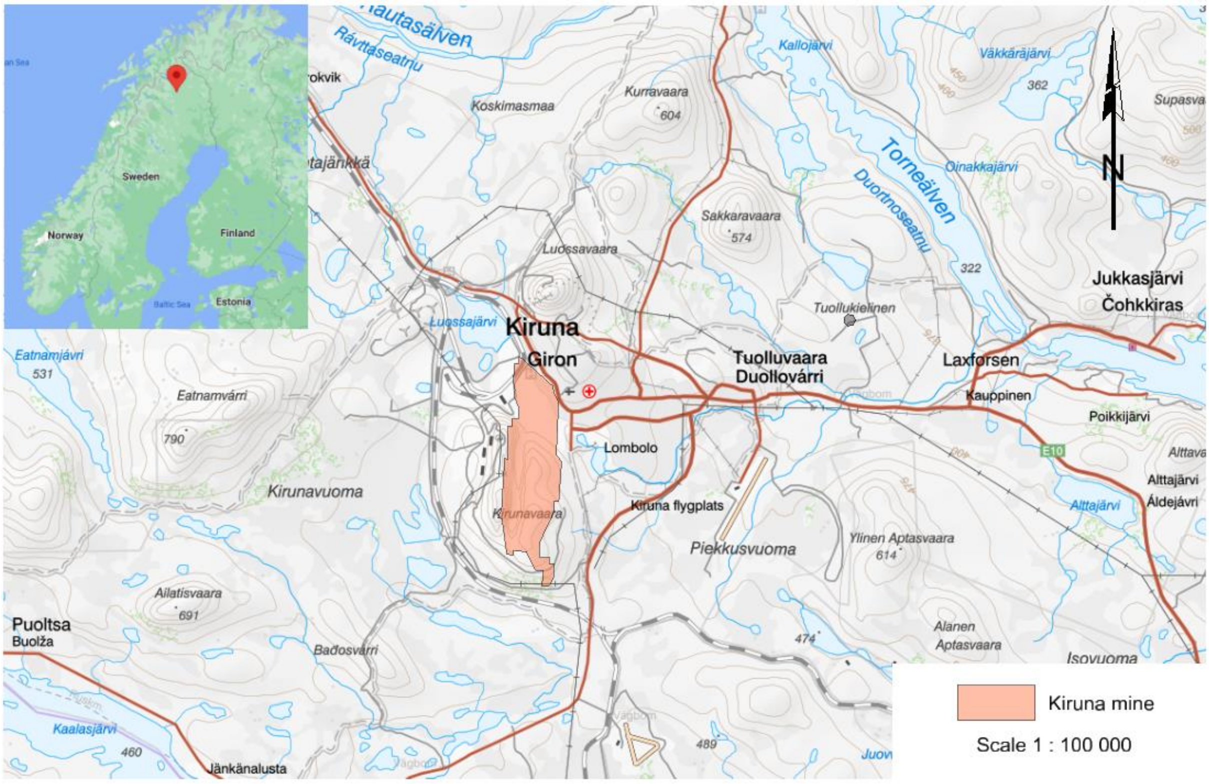


Figure 3.1 Location of the Kiruna mine

As one of the goals for the Project is zero-harm meaning that with the new technology tested, the first thing is that the changes must be as safe as possible – for workers, all stakeholders, for the environment, and the surroundings. The aim of the Project is to have zero accidents and no ill-health which also secures continuous production in the mine and helps to move towards increased production which is another goal of the Sustainable Underground Mining project. To understand what implementing BEVs to a working mine means from the safety aspect, my thesis focuses mainly on the risks that battery electric vehicles may present when introduced to an underground mine and what are the possible mitigation methods to ensure safe working conditions. As the battery electric vehicles within the Project are tested in the Konsuln test mine, Konsuln mine with its infrastructure and production processes is the basis of my evaluation. More thorough description of the Konsuln test mine is presented in section 3.2.

3.1 Overview of Epiroc's battery electric vehicles

As part of the Sustainable Underground Mining project, both diesel-powered and battery electric Epiroc vehicles (LHDs and trucks) are studied. Loaders studied for sub-level caving operations are Scooptram ST18 (diesel-powered) and Scooptram ST14 Battery (battery electric) and the truck studied for haulage is the MT42 Battery (battery electric). This thesis will evaluate Epiroc's battery electric ST14 and MT42 performance in the mining environment.

Epiroc developed its first battery-driven machines for customers between 2014 - 2017 (scooptram, boomer, drill rig, and truck) (Swart, 2019). Second-generation battery-electric machines were put on the market in 2019 which included Scooptram ST14 Battery and MT 42 Battery that are tested as part of the Project. The machines were developed and first tested in the Sustainable Intelligent Mining Systems (SIMS) project within the EU's research and innovation program Horizon2020 (SIMS, 2017). The SIMS project's work package no. 6 aim was to demonstrate state-of-the-art mobile-mining technology in use in a mining environment and the tests for the vehicles were carried out in Kittilä gold mine in Northern Finland.

Epiroc's second-generation battery-electric vehicles have lithium-ion batteries with NMC chemistry which are designed and built by Northvolt (Swart, 2019). Batteries lay on a horizontal panel and the lifetime of one battery is about 10 000 hours. The driving time of a battery is 3 – 6 hours depending on the operation and specific conditions in the mine. One great possibility to extend the cycle length of the battery is using regenerative braking which according to the tests done in Kittilä gold mine gives a result even with minimal declines.

Minimum charging time for batteries used in the Epiroc's BEVS varies from 50 minutes for ST14 battery to 2 hours for MT42 battery (both estimations are for SOC 0 – 90%) (Svedlund, 2021). An alternative option to charging the battery on the vehicle is battery swapping which according to tests done by Epiroc takes about 10 – 15 minutes. As the battery on Epiroc's vehicles lies horizontally and needs to be lifted, an additional crane construction will be needed in the swapping station. During the tests done in Kittilä gold mine, mostly mobile charging unit was used for the ST14 Battery as it allowed to charge the battery at the loader's workplace.

As a charging interface, Epiroc uses the Combined Charging System (CCS) (Swart, 2019) which is also the recommended interface in the GMG Group guidelines for BEVs in underground mining. CCS's biggest advantages are that it is designed to allow robust and safe connection between the BEV and the charger, and it is capable of direct-current charging up to 1000 V compared to the other systems 500 V which is too low for mining BEVs (Global Mining Guidelines Group, 2018).

In the battery design, consideration of safety is a high priority for both Epiroc and Northvolt. According to Northvolt (Plasgård, 2021) safety of the battery lies more within the design not specifically in its chemistry. To protect the battery against fire in the battery cell, they have implemented many safety measures – using small and cylindrical cells, having fuse and overpressure vent in each cell, all cells are water-cooled and thermally insulated in several higher layers and three levels of Battery Management System (BMS). To protect the battery from the potential outside fire, Epiroc has implemented fire suppression on the machine and in a battery pack. One big concern when working in an underground mine is the durability of the machine to rock-falls. To mitigate that hazard, Epiroc has constructed the battery machines so that the battery has a thick top plate (Swart, 2019), but it must be determined if that is enough to protect the battery from damages like rock falls and avoid a potential fire as a result.

According to Epiroc, during benchmarking trials their battery electric vehicles have outperformed their diesel counterparts with the example of a truck on a ramp haulage application yielding 10 – 12% higher productivity (Gleeson, 2020, p. 14).

One of the biggest disadvantages of battery electric vehicles is being more expensive than their diesel counterparts resulting in higher capital costs for the mine. Including the cost of batteries in the BEV's price, it can be up to twice the price of a diesel vehicle with just the price of the BEV being up to 20% higher than the diesel machine. Although right now the capital costs with BEVs are considerably higher than with similar diesel ones, research (SRK Consulting, n.d.; Varaschin, 2016) has showed that with lower emissions and more sustainable performance, the operational costs are lower resulting in overall costs for diesel and battery electric vehicles being on-par. With the battery technology improvements, the capital costs of the vehicles are expected to decrease as well. Comparison of expected total cost of ownership of diesel and battery electric vehicles can be seen in *Figure 3.2* and is based on calculation from Gyamfi (2020), SRK Consulting (n.d.), Varaschin (2016) and Jacobs (2013). Furthermore, Jacobs (2013, p. 31) found in his research that considering all different components for a vehicle's capital and operating costs, the hourly cost per one unit of electric vehicle is about 30% lower than it is for a diesel vehicle.

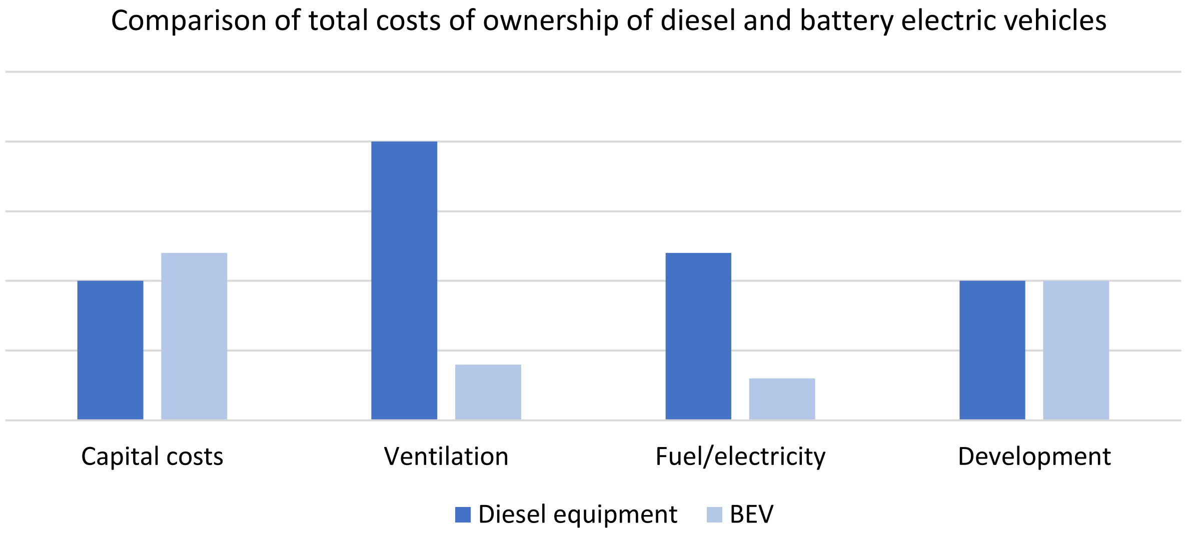


Figure 3.2 Comparison of expected life-cycle costs of diesel and battery electric vehicles (Gyamfi, 2020; SRK Consulting, n.d.; Varaschin, 2016; Jacobs, 2013)

3.1.1 MT42 Battery truck

The battery-electric truck evaluated in the Sustainable Underground Mining project and in this thesis is Epiroc's MT42 Battery (*Figure 3.3*) which is a fully battery-electric truck with a 42-tonne capacity

(*Table 3.1*). During the tests done in the SIMS project, the MT42 Battery truck's actual average productivity was ~20% lower than its theoretical productivity (Halim, A. , 2020, p. 16). The main reasons for the difference are delays caused by the traffic inside the mine and the truck not carrying its maximum payload with its payload varying from 37 to 41 tonnes during the tests. The truck's payload is directly related to the loader's bucket payload and in the tests done in the SIMS project, ST14 usually only filled its bucket to 80 – 90 % of its payload (Halim, A. ,2020).

Figure 3.3 Epiroc's MT42 Battery truck (photo by LKAB)

Table 3.1 Main technical specifications of MT42 Battery (Epiroc, n.d.a)

Parameter	**MT 42 Battery**
Max height (while dumping), width, weight	5 625 mm; 3 174 mm; 37,7 t
Tramming capacity	42 t
Battery run time	Depends on the terrain, up to 4 h
Battery charging time (SOC 0 – 90%)	120 min
Battery changing time	10-12 min
Battery energy	375 kWh

Comparing battery-electric MT42s theoretical productivity in the same conditions with a diesel-powered truck, diesel vehicle's productivity exceeds battery-electric vehicle by about 5%. The main reason for diesel-powered MT42s higher productivity is its higher speed on horizontal to 4% inclination tracks and while driving down the ramp. Although MT42 Battery is slower on the ramps, it regenerates the braking power and saves most of the energy back to the battery while the diesel machine's braking power only creates heat as waste.

Noise level inside the MT42 Battery cabin has been measured (Halim, 2020, p. 31) in Kittilä mine at 67,5 dB(A) and for diesel-powered MT42 75 dB(A). Noise level outside MT42 Battery has been measured at 101 dB(A) and 120,5 dB(A) for diesel-powered MT42 (Halim, 2020, p. 31).

Battery run-time for MT42 Battery while working was similar but a bit better than expected. After 200 minutes of work, the battery state of charge was at 30% (Halim, 2020, p. 22) while it was expected to be at 20% before testing the truck in a mining environment. Battery run-time is highly dependent on the working conditions, especially the terrain that the vehicle is driving whether it is constantly up the ramp or there are options for regenerative braking during the shift.

3.1.2 Scooptram ST14 Battery LHD

Figure 3.4 Epiroc's ST14 Battery loader (Epiroc, n.d.b)

The battery-electric loader evaluated in the Project and in this thesis is Epiroc's ST14 Battery (*Figure 3.4*) which is a fully battery-electric loader with a 14-tonne capacity (*Table 3.2*). ST14 Battery eliminates CO_2 and toxic gases (NO_x, HC, and CO) from the production cycle as it is a fossil-free loader. Tramming is provided by a traction motor connected to a high-efficiency driveline. Hydraulic functions are powered from a separate auxiliary motor that delivers hydraulic power-on-demand. As the ST14 Battery has a considerably lower number of service parts and moving parts compared to the diesel-powered ST14, the service intervals for the battery-electric vehicle are longer, consumption of parts and running costs are lower.

Table 3.2 Main technical specifications of ST14 Battery (Epiroc, n.d.b)

Parameter	**ST14 Battery**
Max height (while dumping), width, weight	5 586 mm, 2 788 mm, 42 t
Tramming capacity	14 t
Battery run time	4 – 6 h
Battery charging time (SOC 0 – 90%)	50 min
Battery changing time	10-12 min
Noise level	In a windowless cabin 80 dB
Battery energy	300 kWh

As mentioned before, ST14 Battery has been tested in a mining environment in Kittilä mine within the SIMS project. Testing out the loader showed that the average actual productivity of the machine is about 9% lower than its theoretical productivity (Halim, 2020, p. 18). The main reason for the difference is that the LHD was unable to fill its bucket to its theoretical payload, with actual payload during the tests varying from 11,7 t to 13,7 t. ST14 Battery diesel-powered counterpart ST14 loader was not tested in the same conditions but its theoretical productivity was calculated in the same conditions with it being a little bit lower than for the battery-electric one. As it is safe to assume that the same problem with bucket payload will be with a diesel LHD as well ST14 Battery faced in Kittilä mine, ST14 Battery on average exceeds its diesel counterpart's productivity.

Comparing vehicles' energy consumption, it is possible to compare Epiroc's first-generation battery electric loader ST7 with its diesel-powered counterpart. Experience shows that diesel-powered ST7 consumes about 16,5 l/h on average (Svedlund, 2018, p. 35). As one litre of diesel fuel contains about 10,7 kWh of energy ST7 consumes approximately 165 kWh in an hour. According to Epiroc, ST7 Battery consumes about 80% less (30 kWh/h), the same conclusion was done for the ST14 Battery in the SIMS project as well. As part of the Sustainable Underground Mining project, LKAB has been testing two Epiroc’s ST18 Diesel loader since the end on 2020 and looking at a six-month test period (May – October 2021) the average energy consumption per vehicle’s motor hour is 176,8 – 224,7 kWh.

Noise level inside the ST14 Battery cabin has been measured (Halim, 2020, p. 31) in Kittilä mine at 74 dB(A) and for diesel-powered ST14 78,1 dB(A). Noise level outside ST14 Battery has been measured (Halim, A. , 2020, p. 31) at 102 dB(A) and 119 dB(A) for diesel-powered ST14.

3.2 Konsuln test mine

Epiroc’s battery electric vehicles will be tested in the Konsuln test-mine (*Figure 3.5*) that is the most southern part of the Kiruna iron ore mine. Konsuln orebody has a dip of about 75° to the east, which is steeper than the main Kiruna orebody (a dip of about 60°). Konsuln orebody is thinner than the main Kiruna orebody with its thickness varying from 20 to 50 metres (Quinteiro, 2018). Konsuln is one of the testbeds for the Sustainable Underground Mining project where the battery-electric vehicles, a new type of layout (the fork layout), and an increase in the sublevel height from 27 metres up to 50 metres are tested. As Kiruna mine is classified as a seismically active mine, the main goal of the new type of layout and technological changes is to target disruptions in production due to rock falls in drifts and orepass instabilities (Quinteiro, 2018). An increase in the sublevel height is necessary to keep mining costs reasonable as using the fork layout requires more development work resulting in increased mining costs.

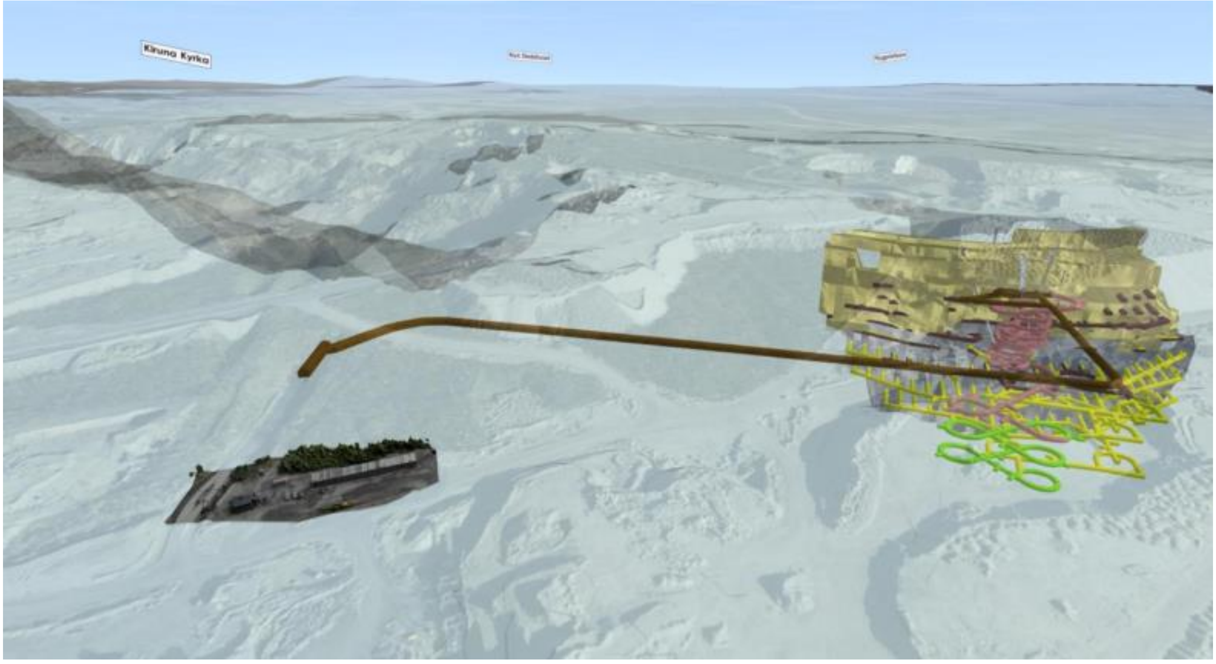


Figure 3.5 3D-model of Konsuln test mine (Gyamfi, 2020)

Work in Konsuln test-mine is carried out in two 10-hour shifts with 1 LHD and 4 – 5 trucks hauling the material. Usual expected production is 4 000 – 4 500 tonnes per day. Production cycle in Konsuln test-mine is determined on the basis that the LHD's cycle time is kept to a minimum or trucks waiting time will be too long. As the trucks used in Konsuln test-mine do not compile with ST14 battery LHD (trucks are too big for the LHD to load them), Epiroc's battery LHD and trucks will be tested as an addition to the usual production on the level, not as part of it. As a result of higher expected production rates from Konsuln test mine and due to the ramp dimensions and capacity, a new ramp is under construction to replace the spiral part of the old ramp. The new ramp is designed to handle 6 000 – 6 500 tonnes per day compared to 3 000 – 3 500 tonnes so it can handle the additional production.

Levels 436, 486, and 536 (*Figure 3.6, Figure 3.7, Figure 3.8*) in Konsuln test-mine are developed as part of the Sustainable Underground Mining project and the first trials of the Epiroc's battery-electric vehicles are carried out on level 436 which was completed in December 2019. Although the battery swapping station is in the southern part of the level, Epiroc's MT42 Battery and ST14 Battery will be tested in the northern part (Block 54) approximately 350 m from the Battery Bay no. 1. Battery Bay no. 1 is originally designed to service ST14 Battery loader but during the tests on level 436 it will be used for both the truck and the loader. Workshops for the vehicles are next to the footwall drift, Epiroc's workshop is the middle one (*Figure 3.6*).

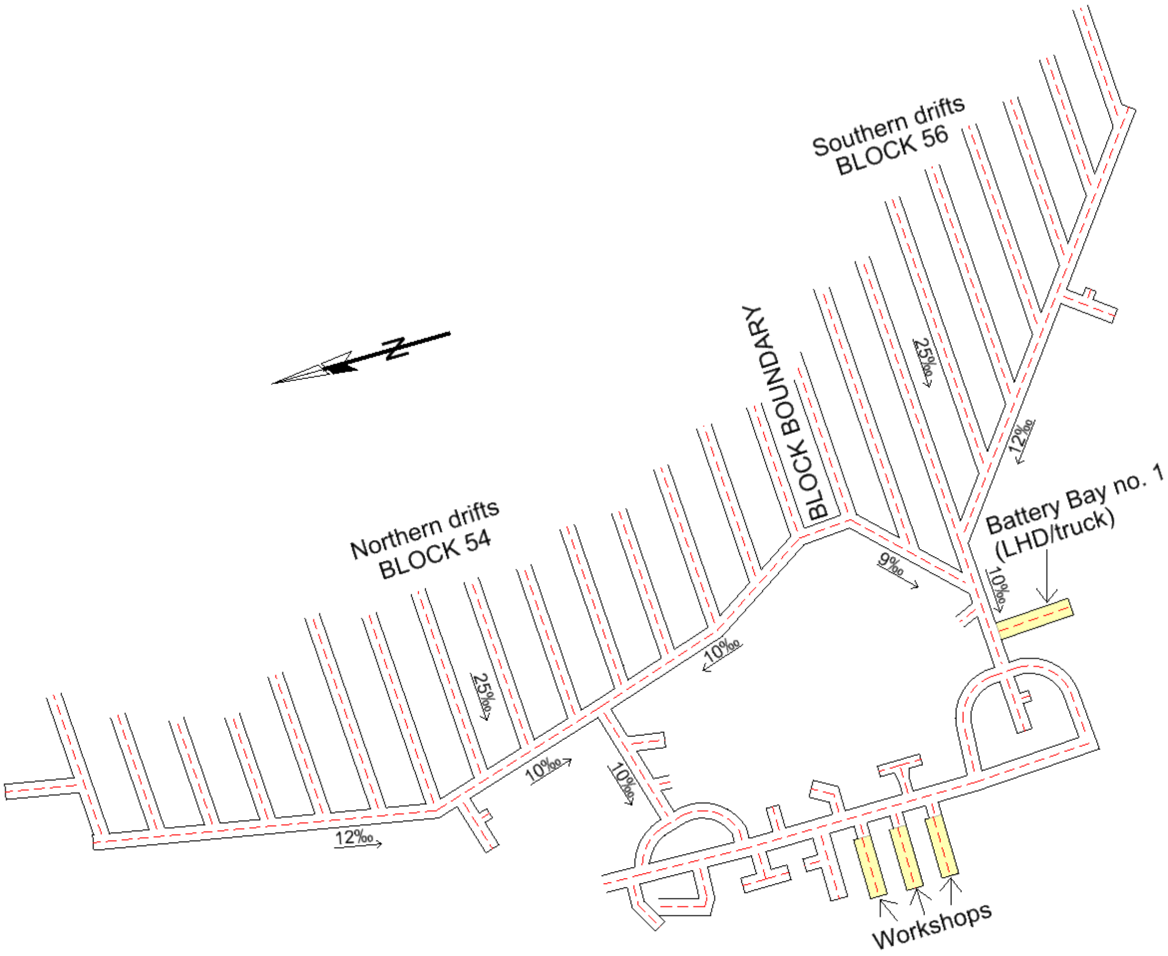


Figure 3.6 Layout of Konsuln test mine level 436

All production crosscuts on levels 436, 486 and 536 have a 2,5% decline towards the longitudinal drift which itself has a 0,9 – 1,3 % decline towards the transport drift. Transport drift has a 1,0% decline towards the footwall drift (*Figure 3.6, Figure 3.7, Figure 3.8*). Considering the decline of the drifts, when loaded, the LHD can benefit from the regenerative braking and hypothetically in an extended battery's run time as the LHD will only use its battery energy when driving back to the production drift with an empty bucket.

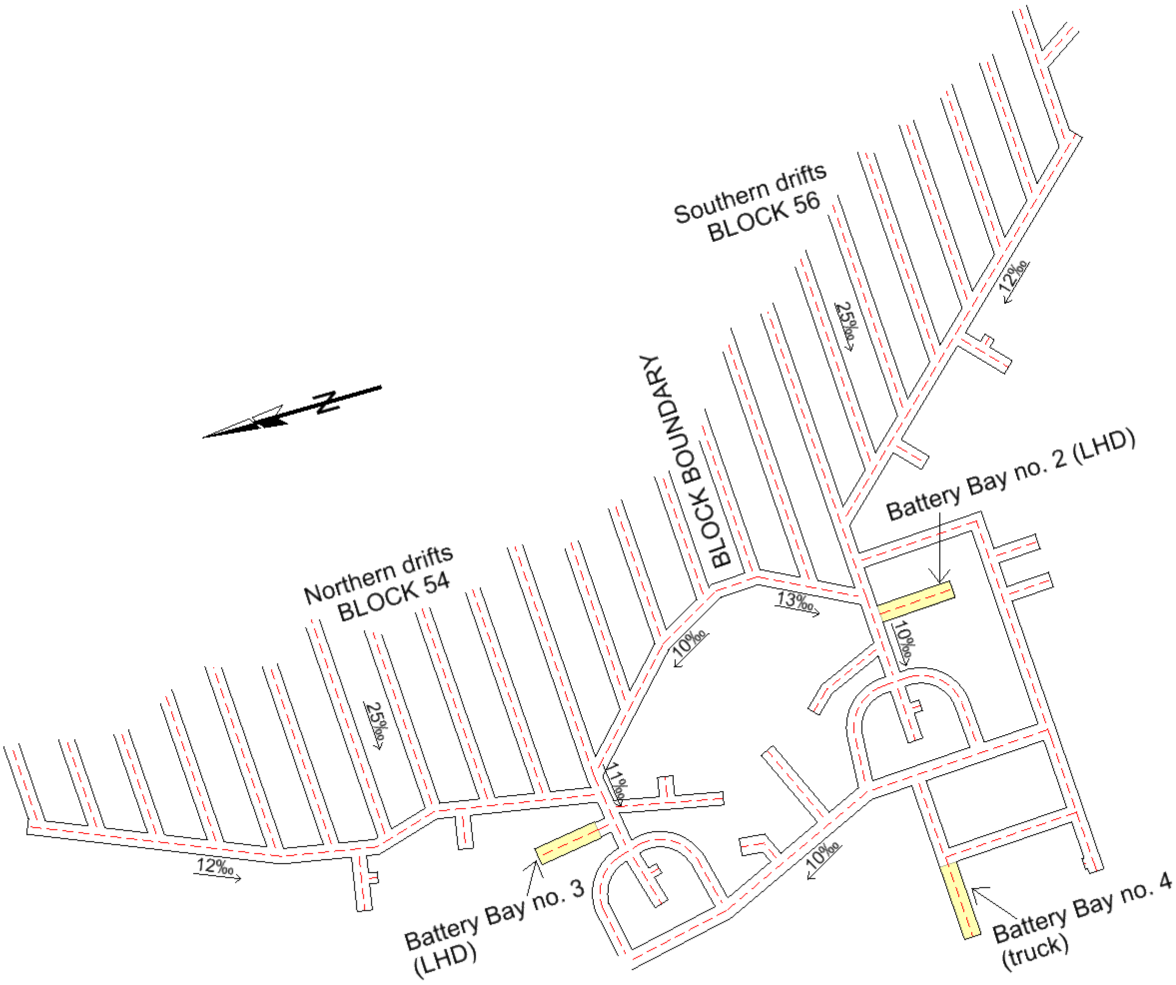


Figure 3.7 Layout of Konsuln test mine level 486

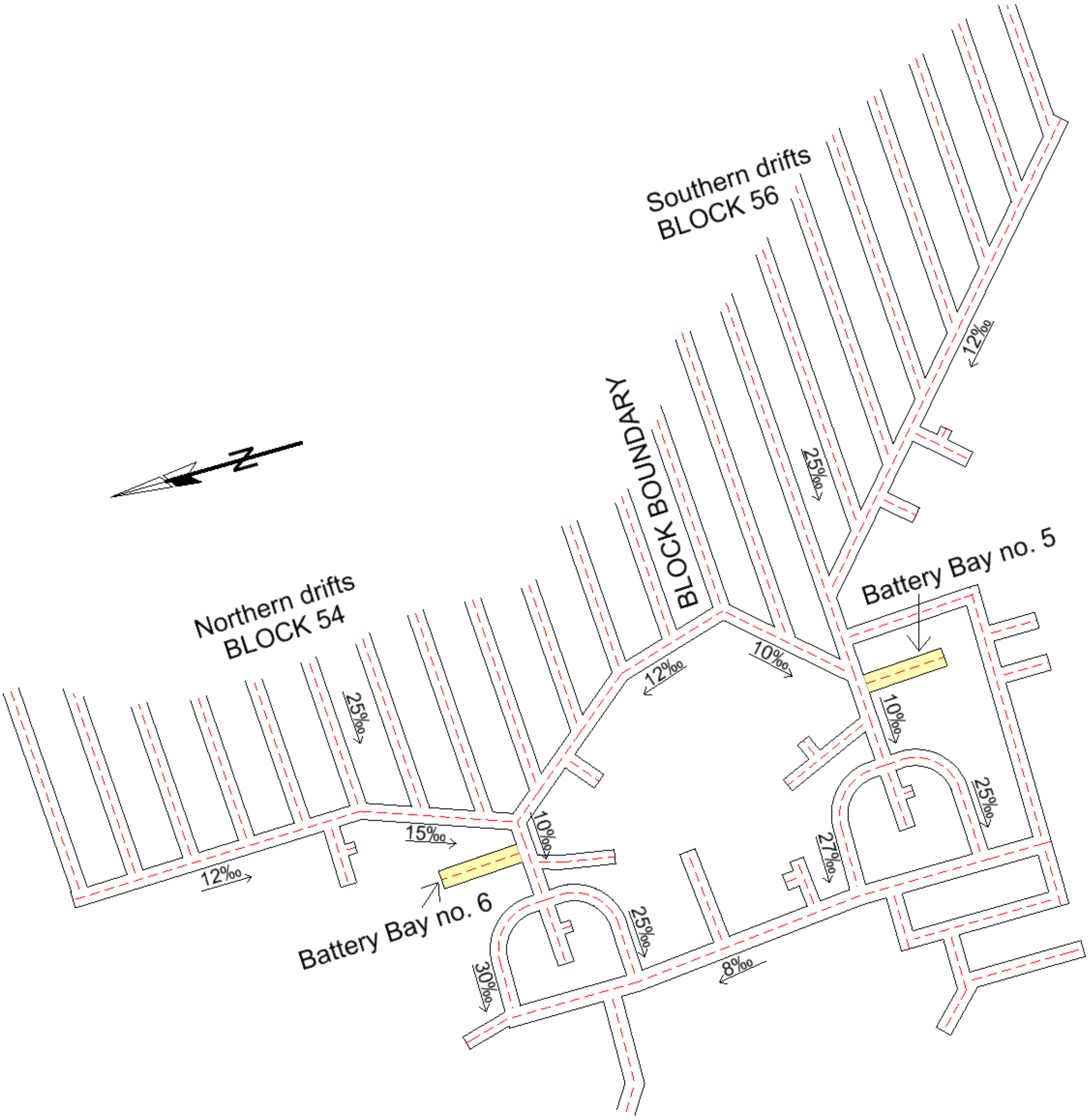


Figure 3.8 Layout of Konsuln test mine level 536

3.3 Risk assessment for implementing BEVs into a mine

Mining by its very nature is a hazardous operation where unsafe conditions can lead to accidents that can affect the whole mine. Safety should be the prime concern in every mine as it is the best way to ensure good working conditions and continuous production. With introducing new technologies, machinery, or procedures to the mine, it is vital to assess what are the risks that come with it and how can they be managed in the best way to minimize the possible risks they present.

Most common risk assessment method used by mining companies is a "layered risk assessment" or a variation of that (Hethmon, 2014). Changing the vehicles used in production in the Konsuln mine falls into the second layer of that method where projects, changes or serious incidents should be assessed. Risk analysis of implementing Epiroc's battery electric vehicles into Konsuln test mine was based on a particularly important question when undertaking a risk assessment – can a failure of a single vehicle or a human error result in a high-consequence event. As it concluded from the available research on the topic, a failure with BEV ignited either by a system or a human error can have serious consequences that may affect the whole mine if not managed appropriately.

Implementing BEVs into a mine means bringing a completely new vehicle type into the production and new procedures and ways of working that come with them. Main point of concern regarding battery electric vehicles is its lithium-ion battery and how it will work in a mining environment. One important aspect of assessing risks related to using BEVs in a mine is to understand if the concerns related to the battery are valid and what are the best methods to target them. By analysing risks and implementing necessary mitigation methods future production losses due to accidents can be minimised which will result in higher productivity which is one of the listed goals of Sustainable Underground Mining project.

BEVs have been introduced to mining operations only in a last couple of years so there is not one publication that addresses all areas that are affected by introducing BEVs to mining operations. Official instructions by mining industry associations cover the safety routines in conventional mines but don't cover using battery electric fleet in mines. The most inclusive publication on implementing BEVs in mining operations is compiled by Global Mining Guidelines Group in their report "Recommended Practices for Battery Electric Vehicles in Underground Mining" covering mine design, ventilation requirements, energy storage systems safety, etc. Unfortunately, the paper doesn't cover the behaviour of large battery systems in case of a fire or venting and therefor can't be used as an only basis for assessing risks related to using BEVs in underground mines. To understand all risks that BEVs present for a mine, a selection of publications and research articles on mine and fire safety, emergency routines in case of incidents with BEVs and lithium-ion batteries were studied. For specific parameters and technical information on ST14 Battery and MT42 Battery, technical documentation compiled by Epiroc was studied.

Based on the analysis of risks BEVs might present, a bow-tie risk model was generated that looks at threats as well as consequences that might follow if all control barriers in place should fail. Bow-tie analysis is based on the concept of layer of protection (which is also the theory behind the Swiss Cheese model) it and allows to have a structured approach on the causes and consequences analysis of the hazards that BEVs present (Hethmon, 2014) providing a way to combine all sides of the safety issues into one diagram. Bow-tie analysis was developed in 1970s, but it was adopted in the industry first by Royal Dutch/Shell Group in 1990s following the Piper Alpha oil platform explosion in 1988 (Sneddon, 2017).

One of the biggest limitations of bow-tie analysis is that they can be only used as a qualitative assessment method as the outcome doesn't provide numerical evaluation of the control measures and mitigation methods. Therefore, when using a bow-tie analysis to visualise the causes and consequences of a hazard, it is not obvious from the analysis which controls are the most important (Sneddon, 2017). If a bow-tie analysis is linked to another risk assessment method (for example fault tree analysis, HAZOP analysis, etc), the quantitative assessment method could be incorporated into a bow-tie analysis (Leveson, n.d.). Bow-tie analysis assumes that the causes leading to the main risk event have a linear chain of action and that assumption could lead to simplified analysis in case of a complex failure events.

The main hazard, that the bow-tie analysis in my thesis is centred on, is a battery failure with the top event being battery fire. Bow-tie model was chosen as an outcome as it provides a way of visualizing risk assessment and is useful to understand incident sequences and all credible scenarios regards the failure (Hitch, 2020). Constructed bow-tie model itself was used as a basis to understand what the best options are in implementing battery electric vehicles to Konsuln mine and how existing mine layout supports all necessary safety aspects presented in the risk analysis.

4. RISK ANALYSIS OF IMPLEMENTING BEVs IN KONSULN MINE

With battery electric vehicles being a fairly new technology to be implemented in mines, it is necessary to understand what possible risks are associated with them and what are potential prevention methods and solutions for risk mitigation. Swedish Association of Mines, Metal and Mineral Producers have worked out a fire safety guide (SveMin, 2009) for mines that provides safety routines and principles that should always be followed regardless of the exact technology used in the mine for example how to plan escape routes in case of a fire, how the rescue chambers should be designed, etc. As battery electric vehicles in mining is a new technology, there are not many official safety regulations in place regards having BEVs in the mines, so the risks must be assessed for every new operation separately.

The worst-case scenario for an underground mine is a fire as the space is confined and only designated routes can be used for evacuation. The most common reason for a fire in Swedish mines is vehicles, followed by electrical equipment (Hansen, 2015). Although vehicles with ICE used in mining present a fire risk that must be analysed, BEVs come with a lithium-ion battery pack which can be considered one of the biggest unknown factors with BEVs and a possible fire hazard. Within the tests of Epiroc's ST14 Battery and MT42 Battery done in the Kittilä mine, user experience and overall impressions of the workers on the vehicles were surveyed (Halim et al., 2021) and one of the concerns was the safety of the vehicles, especially concern about electrical-related accidents including battery fires. It shows that next to the benefits that BEVs can provide, possible risks are a concern for the workers, and they need to be addressed and analysed to provide a safe work environment in the mine.

Although there are no records of Epiroc battery electric vehicles being in an accident in a mine, there have been incidents with BEVs from other OEMs. That shows that implementing battery electric vehicles in underground mines presents a safety hazard. Looking at the information related to the accidents with BEVs in general and in the mines (Table 4.1), most of them are related to charging equipment or various issues with the battery.

Table 4.1 Examples of the BEV and LIB fires (Gillett, 2021; Holmik & Harris, 2021)

Where	BEV fire incident in a mine in Southern District, Canada	Sudbury Integrated Nickel Operations, Onaping Depth mine (Glencore)	Red Lake Gold mine (Newmont Goldcorp)
Year	2019	2020	2018
Overview of the accident, the reason for the fire	A total of 3 vehicles caught fire from one vehicle's faulty charging cable that fed the battery.	A vehicle was operated with no overcurrent protection in place as battery fuses were mistakenly removed and replaced with shunts resulting in a short circuit that lead to a tremendous amount of heat for a prolonged period leading eventually to the battery and front tyres ignition	A shelving unit containing batteries and a charging unit caught fire due to a failure in a charging station.

Where	BEV fire incident in a mine in Southern District, Canada	Sudbury Integrated Nickel Operations, Onaping Depth mine (Glencore)	Red Lake Gold mine (Newmont Goldcorp)
Time to put out the fire (h:mm)	1:45	2:40	1:00

One incident to look into regarding Epiroc's BEVs is a fire at Northvolt's factory in Västerås in November 2021 as Northvolt is the manufacturer of the batteries used by Epiroc. According to Northvolt, the fire started when two batteries came in contact with each other resulting in a short circuit (NyTeknik, 2021). The fire was extinguished with fire extinguishers on site but there was a release of toxic gases during the battery fire. Unfortunately, as the accident is fairly recent, there is no thorough information of the incident available yet.

Reasons for a potential failure in a battery can be divided into three main categories: mechanical and chemical, electrical, and thermal which all can lead to short circuit, extra heat generated in the battery, thermal runaway, cell ruptures, etc (AB Sturk Consulting, 2021). If the potential failure is not prevented with applicable countermeasures, the failure in a battery can result in a fire which must be always avoided. In the case where the preventive countermeasures fail, active countermeasures must be in place to prevent the fire from spreading and to ensure that no harm will come from the failure either to people, surroundings or to the production. As one of the main goals for the Sustainable Underground Mining project is achieving zero-harm, understanding, analysing, and managing risks related to introducing new technologies into the mine is a vital part of the project.

Risk analysis of implementing battery electric vehicles in a mine is based on a specific mining method and equipment used and work processed that will be carried out. LKAB uses a sublevel mining method in its mines but there are some differences in how the production is carried out – in the Kiruna mine only loaders are currently used in the production crosscuts and drifts and for ore haulage to the surface a combination of ore passes, trains on the main transportation level and hoists are used. Compared to Kiruna mine, the biggest difference in work processes in the Konsuln test mine is the usage of trucks to haul the ore to the surface, as described in Section 3.2, haulage is done using a spiral ramp. As more vehicles are working in the production area (both loaders and trucks), the risks related to vehicles are more likely to occur.

With time Kiruna mine will be expanded and reach new main levels and the development could mean implementing new work processes for ore haulage to ensure safety. One option can be implementing truck transportation in Kiruna mine similarly to Konsuln to transport the ore from new lower levels to a hoist that is on Level 1365 which is the current main level (ABB, 2021). That means similar work processes would be present in Kiruna mine as they are now in Konsuln test mine and the results of the risk analysis done for Konsuln test mine can be applied with some adjustments to Kiruna mine.

To work out the potential risks related to implementing battery electric vehicles to a mine and how to mitigate the risks, an in-depth risk assessment on BEVs was carried out within the Project. Based on the general risks with BEVs in underground mines, a more precise risk analysis for using BEVs in the Konsuln test mine was carried out. Risk assessment done in my thesis is based on the technical documentation by Epiroc on their MT42 Battery truck and ST14 Battery loader and various research done on BEVs and lithium-ion battery system safety. Based on the risk analysis, requirements for infrastructure both on the surface and in the mine and work routines when using BEVs in Konsuln are proposed.

4.1 Main risk events

Battery electric loader and truck that will be tested in Konsuln test mine have various process steps when used in production – loading/filling, hauling, dumping, battery swapping, and/or charging and maintenance. All the processes can be a source of risks and based on the processes and vehicles' location while completing those tasks, biggest risk events from battery vehicles are determined as followed:

1. Electrical failure of the battery
2. Mechanical damage to the battery
3. Thermal failure of the battery
4. Toxic gases emitting from the battery
5. Thermal runaway within the battery
6. Spillage of environmentally harmful substances to surroundings.

Many of the risk events are related to each other as being a cause or consequence for others. The worst-case scenario would be if a failure in a battery will escalate to a vehicle fire in an underground mine. Overview of the risk events is listed above, and overview of their causes and possible consequences are shown in *Table 4.2*. A more detailed analysis of the risk events, their causes and prevention methods, and consequences and mitigation measures are presented in the following sections.

Table 4.2 Main risk events with battery electric vehicles, their causes, and possible consequences

Risk event	**Causes of the risk event**	**Consequences of the risk event**
Mechanical damage to the battery	Mishandling of battery or vehicle	Electrical failure
		Thermal abuse
		Rupture of a cell/battery pack
	Rockfalls	Gas generation
		Thermal runaway
Thermal abuse	Failure of safeguard systems within the battery (Thermal Management System)	Gas generation
		Battery fire
	Mechanical rupture of a cell	Thermal runaway
	Electrical failure	
Damage to the thermal management system	Failure within the BMS	Thermal abuse
		Thermal runaway
Electrical failure of the battery	Mechanical damage	Thermal abuse
	Failure of BMS	Thermal runaway
	Faulty charging equipment	
	Error while doing maintenance	Gas generation

Risk event	Causes of the risk event	Consequences of the risk event
Toxic gases emitting from the battery	Venting	Ill-health of the workers
	Overcharge/over-discharge	
	External fire	In combination with water mist possibility to
	Thermal runaway	Toxic gases emitted to the environment through ventilation
	Mechanical damage	
Thermal runaway	Overcharging the battery	Ignition of battery cells
	Arc fault	
	Short circuit	
	High discharge rate	
	External heat	Battery fire
	Mechanical damage to the battery	
	External fire	
	Mechanical damage to the battery	
Vehicle fire	BEVs tyres, hydraulics, etc catching fire	Fire spreading to surroundings in the mine
		Fire spreading to the batter pack
Blockage on the ramp	BEV failure while driving up/down the ramp	Exit from Konsuln test mine is blocked
		Emergency exit from Kiruna mine is blocked
Spillage of environmentally harmful substances to surroundings	Water used for fire extinguishing turning acidic or alkaline	Contaminated runoff water spreading to the surroundings

The main battery systems of MT42 Battery (Figure 4.1) and ST14 Battery are electric-powered circuits with a nominal voltage of 697 V and the battery pack itself is made of 5 (MT42 Battery) or 4 (ST14 Battery) sub-packs that consist of ~ 5 400 cylindrical battery cells that are sealed in 8 modules (Swart, 2019). All the sub-packs have a nominal voltage of 697 V. The main battery pack powers the vehicle and has several functions:

- Thermal Management System that monitors the cells and heats or cools the battery when necessary
- High Voltage Interlock Loop which reduces the risk of exposure to hazardous voltage for the operator
- Battery Pack flooding function that allows connecting a water hose to battery in case of a battery failure
- VCA and VCB connectors connect the batteries to the power.

Figure 4.1 Main battery of the MT42 Battery truck

4.1.1 Electrical failure

Electrical failure of LIBs in essence is an abnormal operation of electrical components of the battery, usually meaning short circuit, overcharging or over-discharging, or arc fault. The most common reason for an electrical failure of a battery is the failure of the Battery Management System (BMS) which is designed to monitor, manage, and protect the main battery system of the vehicles. Additionally, electrical failure can be ignited by mechanical damage to a battery cell.

The Battery Management System is a safety control system within the battery that monitors and manages the state of the battery and its working conditions with a primary function to safeguard the battery pack, modules, and cells. BMS in essence is the only safeguard measure within the battery electric vehicle to prevent failure in the battery itself. The main functions of Epiroc's BMS for MT42 Battery and ST14 Battery include estimation of the state of health, state of function, the state of charge (SOC), depth of discharge, also protection from overheating, and data collection of the battery working parameters and emergency stop function. The BMS used in Epiroc's BEV batteries has been assigned a performance level D according to the ISO 13849-1 standard which means that the BMS provides safety even in case of single faults in the system and has a dangerous failure detection coverage of 90 – 99% (Epiroc, 2021a).

A short circuit can either be internally caused mainly by BMS failure, or externally caused by mechanical deformation of a cell, a contact with water, or for example by an electric shock while doing maintenance work on the battery. When a short circuit occurs, a lot of heat is generated as the conducting material is passed by an electric current resulting in a cell's energy discharge (Bisschop et al., 2019). The generated heat can trigger cell venting which can result in the emission of toxic or flammable gases, a thermal reaction, or thermal runaway within the battery cell (discussed in more detail in sections 4.1.4 and 4.1.5).

Batteries in Epiroc's vehicles have an internal fire suppression system, which is automatically started if a fire is detected in the battery by BMS (Epiroc, 2021c). The system can however be useful to control the external short circuit of modules inside the battery pack. With an external short circuit, the internal fire suppression system must be activated manually which also switches off electrical power to VCB. Therefore, before activating the internal fire suppression system, it is preferred to move the vehicle to a safe location in the mine where are necessary amenities for handling a vehicle with a failed battery. As the battery packs have multiple layers of casing, there is no imminent risk for a short circuit when battery packs are stored together. However, when the batteries are under maintenance and taken apart, it must be considered that battery pack components separately could pose a risk for an electrical failure.

Lithium-ion batteries' charge level is defined by the SOC ranging from 0% to 100% where 100% SOC represents a fully charged battery regarding its rated capacity. When looking at the battery performance and its safety risks, it is important to consider that usually, the actual full capacity of the battery exceeds the defined SOC levels. As BMS is set to manage and control charging and discharging of the battery, a failure in the BMS could mean incorrect detection of cell voltage by the control system resulting in overcharging or over-discharging the battery. Additionally, overcharging and over-discharging can also be caused by a fault in charging equipment or when using a charger not designed for specific vehicles or conditions.

If not controlled and managed, overcharging and over-discharging of a battery can lead to a short circuit and thermal event in a battery. To prevent electrical failure from escalating, there are possible control measures to prevent that: controlled current load, regular inspections of the battery (both digital and manual), failure detection system for gas and heat generation.

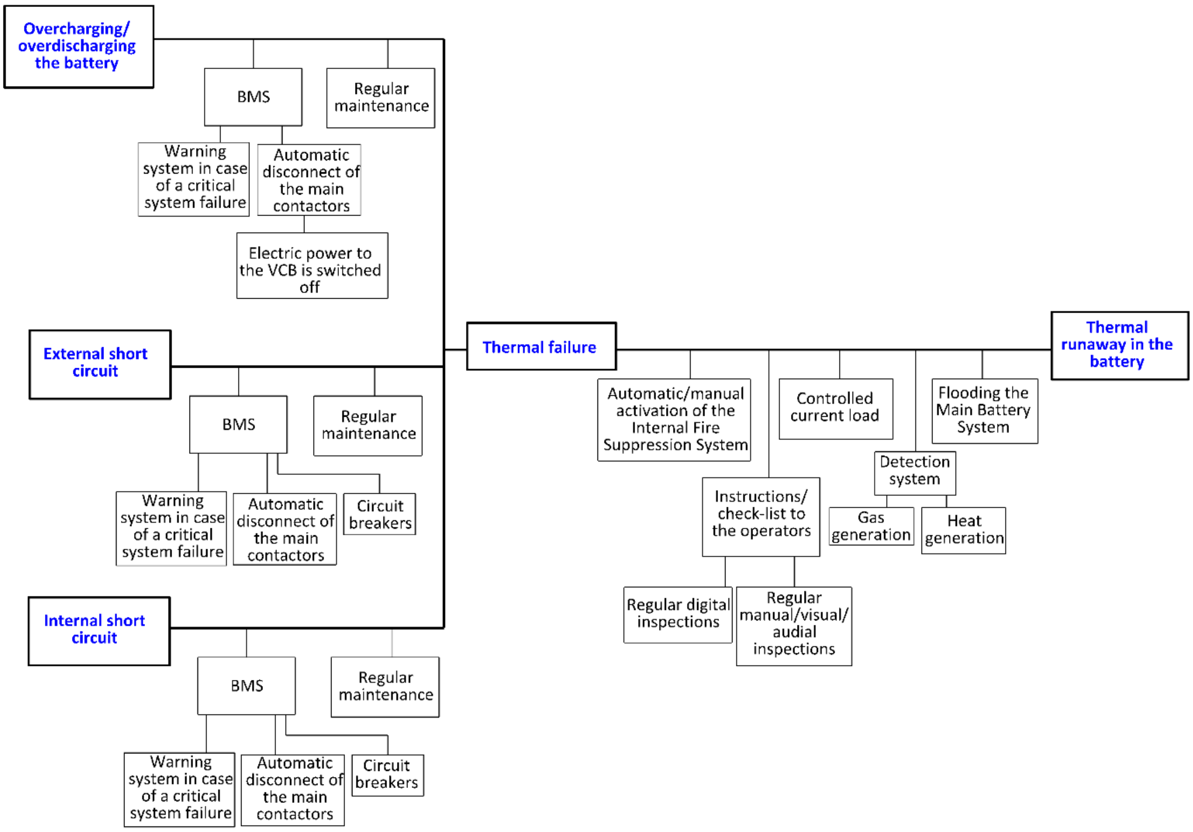


Figure 4.2 Possible control measures in case of an electrical failure in the battery (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

To prevent an electric failure from happening, essentially the only available protection measure is the Battery Management System (*Figure 4.2*). Effective and working BMS is the key control measure to protect the battery from electrical failure – a warning system will notify the user in case there is a failure or an abnormal event that could ignite a critical system failure and the main contactors will be disconnected.

One important question that needs to be answered before the testing of BEVs will start in the Konsuln test mine is what the instructions for an operator are, to make sure and control if the BMS is working as designed. As the issue needs further investigation, it is not included as a control measure for an electric failure.

4.1.2 Damage to the battery

Mechanical damage to the MT42 Battery truck's and ST14 Battery loader's battery is a potential cause for their failure. Mechanical damage of the BEV's battery could result in electrical damage (most commonly short circuit) within the main battery system (VCB) impacting the Battery Management System (BMS) or individual battery cells, the release of toxic gases, and thermal failure which are discussed in sections 4.1.1, 4.1.4, and 4.1.5.

An underground mine is a confined space with many controllable but also uncontrollable hazards that can cause mechanical damage to the battery. Kiruna mine (including Konsuln test-mine) is a seismically active mine which means that there is a risk for a seismic event that can cause rockfalls and uncontrolled rock bursts that present risks for workers, mining equipment, and to the production. The same goes for LKAB's Malmberget mine. The last big seismic event in the Kiruna mine occurred in May 2020 with a measured magnitude of 3.3 on the local magnitude scale (LKAB, 2020), and a magnitude of 4.2 on the regional scale, which resulted in the closure of the Kiruna mine for longer than a month. Therefore, possible rockfalls in the Kiruna mine could present a risk to the battery electric vehicle and could damage the battery pack either while being parked or while used in production.

With an uncontrolled rockfall in the production area, the battery might be crushed, ruptured, or penetrated in a way that affects the battery cells inside the battery pack. Several tests have been done on the consequences of mechanical abuse on a battery cell (Kitoh & Nemoto, 1999; Mao et al., 2018). When the battery cell's body is affected by an outside force, electrode materials and current collectors inside the battery cell are connected resulting in an increased heat generation either at the penetration or internal short circuit site propagating through the whole cell leading to thermal runaway of the battery cell (Wang et al., 2019). To avoid uncontrollable rockfalls, other mining companies testing battery electric vehicles have limited the working areas to mitigate the risks possible rockfalls could present to the battery electric vehicle (Hansson, 2021).

Another more BEV-specific hazard that can present a risk for mechanical damage to the battery is mishandling of the battery either when swapping the batteries, charging, or doing maintenance work on them. An important aspect is also the consideration of where to store spare batteries so there is no risk present to mechanically damage them.

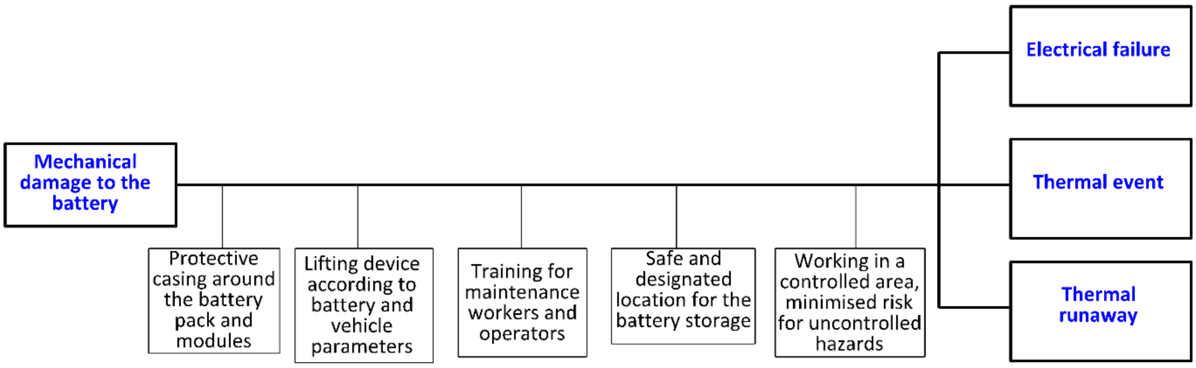


Figure 4.3 Control measures to avoid mechanical damage to the battery (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

To protect batteries from mechanical damage, control measures both from OEM and the user of the vehicles are applicable (*Figure 4.3*). The most elementary control measure to prevent mechanical damage to the battery or battery cells is to have a protective structure around the battery and well thought through location for the battery. The battery pack on Epiroc's vehicles is on a horizontal plate and is protected by a steel casing and additional thick top plate. Additionally, modules making up the battery pack are lined with several layers of steel and ceramic casings.

Figure 4.4 Battery Bay no. 1 on level 436 in Konsuln test mine

Besides ensuring no damage to the battery when connected to the vehicle, handling of the batteries must be carried out according to instructions by the manufacturer and in locations where it is possible to handle and store the batteries safely. Epiroc has worked out recommendations within the Sustainable Underground Mining project for battery bays and workshops designs to minimize possible hazards that could result in mechanical damage to the batteries while swapping or charging the batteries. The dimensions of the battery bay and the workshop and capability of the overhead crane used in both must allow safe working conditions when swapping or charging the batteries or doing maintenance work on them. Epiroc as an OEM has determined that the minimum lifting height for ST14 Battery is 4 315 mm and for MT42 Battery 3 841 mm to the top of the lifting fixture. The suggested width of a battey bay is 8 m, and the suggested lifting capacity of the overhead crane is 10 tonnes (ST14 Battery loaders battery weights 4,1 tonnes (Epiroc, 2021b, p. 15) and MT42 Battery trucks battery weights 4,9 tonnes (Epiroc, 2021c, p. 15)). Battery Bay no. 1 is shown in *Figure 4.4*.

To improve the safety of handling the batteries in a battery bay and in the workshop, designated locations for batteries should be worked out and marked on the floor. This allows avoiding batteries being placed in an area where the conditions are not safe for battery handling. Placing crash protection barriers in between the vehicles and batteries designated locations makes it easier to avoid causing mechanical damage to the batteries by hitting them by accident. When writing the thesis, there was an issue with extra water coming in through the rocks in Battery Bay no. 1, making the conditions unsuitable for handling batteries without any additional measures. If the issue continues, it will be necessary to install a base construction at the designated battery location to avoid the battery being in contact with water and mud. The layout of the Battery Bay no. 1 on level 436 is shown in *Figure 4.5*.

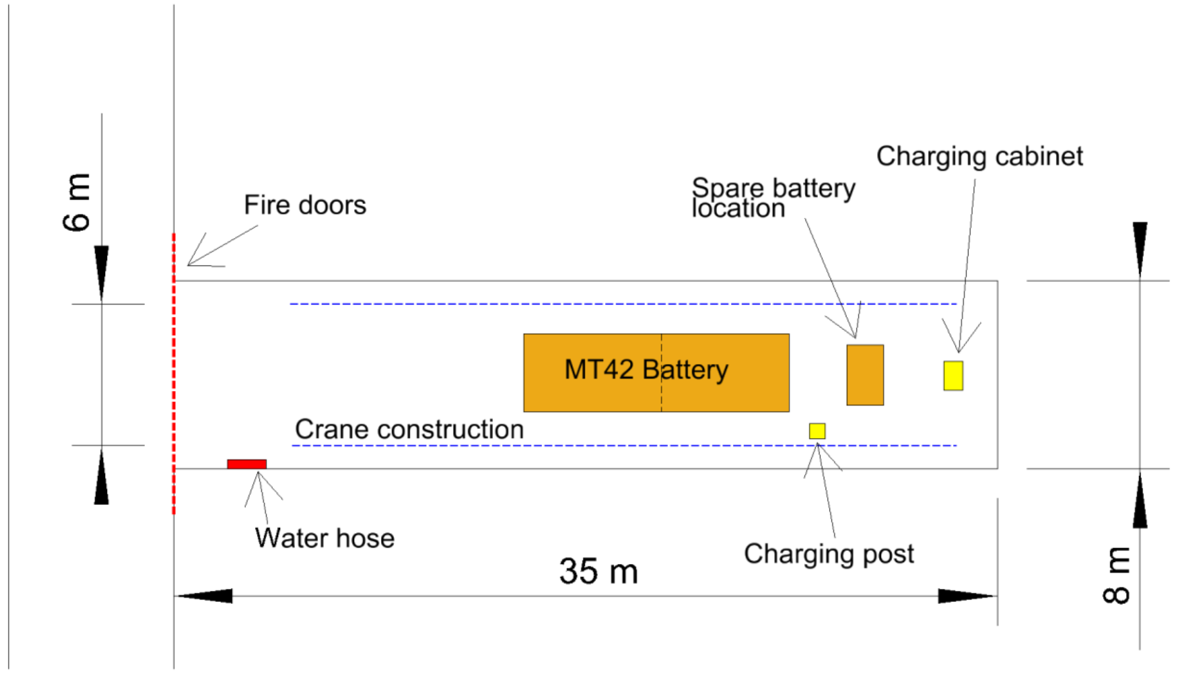


Figure 4.5 Layout of the Battery Bay no. 1 in Konsuln test mine level 436

An important safety aspect of a damaged battery is its right handling after an accident to prevent possible consequences that might follow the initial incident. Both damaged batteries and battery electric vehicles should not be stored in an unventilated and enclosed space which an underground mine is by its very nature. If transportation of a damaged battery to a safe location on the surface is not possible, it is necessary to handle them in a way that minimizes the risks in case of a delayed failure within the battery. National Fire Protection Agency (2018, p. 20) has recommended that a damaged battery should not be stored closer than 15 metres to combustible materials and other vehicles until it has been discharged as there is a risk for a delayed electrical or thermal failure within the battery. A good safety measure to monitor a damaged battery is constant thermal surveillance to be able to register any thermal changes that could occur in a damaged battery. GMG has advised in their guidelines for mining BEVs that OEM or battery system manufacturers should provide procedures manual and specific instruction on how to handle battery system or its components that have been damaged (Global Mining Guidelines Group, 2018). That applies to all possible abuse conditions for a battery.

4.1.3 Thermal failure

Thermal failure of a battery cell can be a result of its previous mechanical or electrical abuse or be initiated by exposure to external high temperatures. Thermal abuse of the battery could lead to thermal runaway or initiate a breakdown and pressure build-up inside the cell skipping thermal runaway. Without mitigation or control measures in place, both can lead to a battery fire. As one possible result of thermal abuse, the emission of toxic gases must be considered. Part of the main battery BMS is the Thermal Management System that is responsible for monitoring and maintaining the optimal thermal conditions in the battery pack and therefore preventing thermal abuse of the battery. It is important to note that the Thermal Management System cannot be considered as a separate safety layer of the battery as it is part of battery functions.

Internal thermal exposure to the battery cells can be a result of a previous mechanical or electrical failure within the battery that will cause a local heat up. Internal thermal abuse can be ignited by malfunctioning of the battery management system and other safety electronics or by an unpredictable failure within a battery cell for example to due faulty battery manufacturing. Mechanical abuse of a battery cell or module can result in heat generation at the disturbed location.

External heat can cause a thermal reaction within the battery and therefore present a risk for a battery failure (*Figure 4.6*). External factors could be a fire fuelled by other components of the vehicle (tyres, hydraulics, etc), fire in the proximity of the vehicle, or long-term exposure to high temperatures. This goes both for when BEVs are working and when the batteries are stored for a longer period. For the MT42 Battery truck and ST14 Battery loader, Epiroc has limited optimum operating temperatures from -20°C to +40 °C. In Konsuln, the temperature is about +6 – +8 degrees, in Kiruna mine, it is warmer, about +18 degrees. So, in normal conditions temperature in the mines is in the limits of optimal operating temperatures for Epiroc's BEVs.

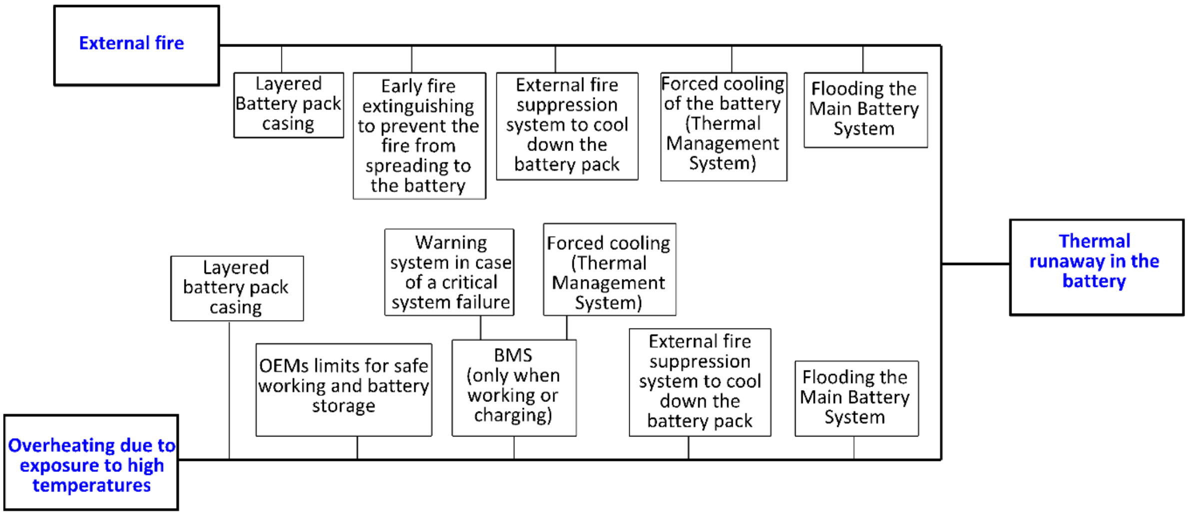


Figure 4.6 Control measures to avoid battery failure in case of an external temperature change close to a BEV or a spare battery (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

Usual temperatures in Konsuln and Kiruna mine don’t pose a hazard for overheating the BEV’s battery, therefore the biggest external risk affecting the battery thermal conditions is an accidental failure that produces a lot of heat – fire with or close to the BEV. Epiroc has provided safety measures to protect the battery pack used for MT42 Battery and ST14 Battery in case of an external fire – the layered casing of the battery pack plus additional layering of the sub-packs within the battery which acts as an isolator between the external heat and the battery cells. The key with an external fire is early detection of the incident and fast extinguishing to prevent the fire from spreading to the battery and initiating a thermal failure. If there is a chance that the external heat has affected the battery pack, Thermal Management System can be activated to cool down the battery, if the battery that has been affected is stored, the system has to be activated manually.

In 2021 RISE (Research Institutes of Sweden) did tests on lithium-ion battery sub-packs used for Epiroc’s BEVs. Tests were set up so that the battery sub-pack was affected by an external fire with the parameters that a tyre fire could have, as a result, the time for the battery to go into a thermal runaway was recorded. Test results (Willstrand, 2021, p. 9) showed that with exposure to external fire gas ventilation started after 46 minutes and thermal runaway was initiated after 48 minutes when peak heat release rate was recorded. These test results imply that if a battery electric vehicle catches fire or there is an external fire close to the battery, there are about 45 minutes before the battery will fail. As the tests by RISE were done on a sub-pack, not with the entire battery pack used for MT42 Battery and ST14 Battery, it is expected that the time for a battery failure is even longer as there are layers of casing that provide even better isolation from the external influences. In the report, it was assessed to be in a range from 45 minutes to several hours (Willstrand, 2021, p. 18).

If spare batteries are stored in the mine, it is necessary to ensure optimum conditions for battery storage so the risk for battery failure would be minimized. GMG has suggested for OEMs of battery electric vehicles to have a defined storage condition for battery packs including suitable temperature range, maintenance intervals, and procedures, necessary equipment to maintain battery components while storing the battery (Global Mining Guidelines Group, 2018). Epiroc has determined that the temperature in an area where batteries are stored should be room temperature, approximately +18 – +25 °C, with low humidity, below 60%. Batteries with higher SOC have appeared to be more prone to failure than batteries with lower SOC. Therefore, Epiroc has suggested that when a battery is stored, its SOC should be between 23% - 65% (Epiroc, 2021c).

Although the temperature in the Konsuln test mine is in the range of optimal operational temperature for the BEVs, recommended storage temperature for the batteries is more limited and long-term storage of the batteries in Konsuln test mine should be avoided. However, if spare batteries are stored in Konsuln below 15 degrees, they must be brought into a warm environment before their usage at least one day (Epiroc, 2021c), in Kiruna mine, the temperature for battery storage is within a recommended limit. Tests done in Boliden's Kristineberg mine, where the temperature is similar to the Kiruna mine (approximately +15°C – +20°C) proved no problems regards to vehicle and battery operations (Hansson, 2021).

4.1.4 Emission of toxic gases

Any kind of failure within the lithium-ion battery cells may lead to gas generation which increases pressure in the battery cell. In 2019, study done by Det Norske Veritas AS (DNV GL AS Maritime, 2019) found that release of the gases can occur either with thermal runaway or before it during a failure leading to thermal runaway. There are also toxic gases emitted with a battery fire. Epiroc's battery packs have vents that should prevent pressure build-up and potential swelling. However, it is necessary to consider that the gases emitted from the battery are toxic and flammable and can when ignited can cause serious damage to the battery and surroundings (*Table 4.3*). Gases emitted during a battery cell failure or battery fire that have the highest quantities compared to the set health limits are CO, CO_2, NO, SO_2, HF, HCl, HCN, and PAHs. Measured emissions from various fire tests with lithium-ion batteries are listed in Table 4.3.

Table 4.3 Measured emissions during a lithium-ion battery pack fire

Gas	**Toxicity/flammability**	**Measured gas emission, max ppm (Willstrand, 2021)**	**Short-term (15 minutes) value, ppm (Swedish Work Environment Authority, 2018)**	**SOC influence on emission (DNV GL AS Maritime, 2019)**
CO	Toxic, flammable	56	100	Emissions grow with higher SOC
CO_2	At higher concentrations can be toxic	8000	10 000	Emission value constant, not dependant on SOC
SO_2	Toxic, forms an irritating acid when in contact with water	2,1	1	Emissions grow with higher SOC
NO	Toxic, flammable	16	25	No correlation

Gas	Toxicity/flammability	Measured gas emission, max ppm (Willstrand, 2021)	Short-term (15 minutes) value, ppm (Swedish Work Environment Authority, 2018)	SOC influence on emission (DNV GL AS Maritime, 2019)
NO_2	Toxic, not flammable	0,9	1	No correlation, highest value from the tests with 75% SOC
NH_3	Toxic, flammable	11	50 (Ceiling limit value)	No info
HF	Toxic	6	2 (Ceiling limit value)	Emissions grow with lower SOC, tests done by Larsson suggest that the peak is at 50% SOC
HCl	Toxic, in contact with water forms an acid that can cause burns	0,2	4 (Ceiling limit value)	No correlation
HCN	Toxic, flammable	28	3,6	Emission value constant
PAH	Toxic, flammable	-	0,02 mg/m^3	Emissions grow with higher SOC

Differences in amounts of gases released between ICE vehicle and BEV are not significant (Willstrand et al., 2020) with one exception – generation of HF during a BEV fire has been tested to be up to 80 times more than during an ICE vehicle fire. As HF is highly toxic and in contact with skin cause irritation or breathing it in can cause damage to the lungs and heart, a lot of research has been done on HF emissions from lithium-ion battery fires. With batteries used in Epiroc's battery electric vehicles, the expected HF emission is 20 – 200 mg/Wh (Epiroc, 2021c, p. 79) which means 7 – 70 kg in case of a fire with an ST14 Battery and 7,5 – 75 kg in case of a fire with MT42 Battery.

In 2021, RISE (Willstrand, 2021) run external fire tests on Epiroc's vehicles batteries sub-packs. Tested sub-packs had nominal energy of 60 kWh and 93 kWh. During the fire tests $CO_2$and CO emissions were recorded, with one of the sub-packs low concentrations of HF was measured and with another one low concentrations of NO and NH_3. The test setup was calibrated to detect also HCl, HCN, HBr, SO_2, and NO_2 emissions but these were not recorded in quantifiable amounts.

From research and tests done on gas release in case of a lithium-ion battery fire, SOC can affect the amount of specific gas generation and it also affects how fast the gas release will occur. Overheating tests done (DNV GL AS Maritime, 2019, pp. 14-15) found that the higher the battery's SOC, the faster the gas release will take place in case of a thermal runaway. With 100% SOC, it took about 16 minutes, and in comparison, with 50% SOC, it took approximately 28 minutes. These results support the guidelines from Epiroc that MT42 Battery truck or ST14 Battery loader batteries should not be stored with high SOC. As mentioned before, per Epiroc's recommendation when batteries are stored the SOC should be between 23% - 65%.

To avoid dangerous consequences of toxic gas release from the battery in case of a failure, it is necessary to monitor and if needed apply measures to control the gas emission. One key aspect is early detection of gas release or notices if there is a potential for a gas release from the lithium-ion battery. To prevent fire in battery bays, gas sensors should be installed and if possible, also in the area where BEVs will be working. As mentioned before, tests have shown that there is a possibility for a gas release before thermal runaway within the battery, so early detection of a gas release can predict a possibility for a battery failure.

4.1.5 Thermal runaway

All the above-discussed failure mechanisms – mechanical, electrical, thermal – are in most cases related to each other, for example, mechanical rupture of a cell leads to electrical failure which prompts heat-up in a battery cell. In case mechanical and electrical abuse of the lithium-ion battery cannot be avoided or controlled, following thermal failure is the main condition that could push the battery into thermal runaway which itself is the lead event to a battery fire (AB Sturk Consulting, 2021).

Thermal runaway is initiated when the chemical reactions between electrolyte and cathode material are generating more heat than is transferred to the battery cell surroundings (Bisschop et al., 2019). If the battery cell under thermal runaway is not isolated from other battery parts, the additional heat is dissipated to other cells resulting in a battery-wide thermal runaway. Epiroc’s MT42 Battery truck’s and ST14 Battery loader’s batteries’ modules are each separated by multi-layer protective casings consisting of steel and ceramics. Isolation capabilities of the protective casings of battery modules used in the truck and loader were tested with cold conditions and the inside temperature of the battery module lowered about 4 °C during the test. With good isolation, it takes a longer time to affect the module temperature in case of external high temperatures and that also limits possible thermal reactions in between different battery modules within the battery pack.

Thermal runaway is the main lead event to a fire within the battery and therefore it is necessary to have control measures present within the battery and in the mine site to prevent a fire or detect a possibility for a failure within the battery to be able to ensure safe exits for all workers from the mine. When a vehicle is working the responsibility to notify the operator of a possible failure event lays on the Battery Management System. Epiroc’s vehicles batteries have an internal suppression system that is designed to detect a fire in the main battery system and uses gas as a suppression medium, system will be activated automatically when a fire is detected within the battery. The internal battery suppression system does not activate the vehicle’s external fire suppression system. When the suppression system is activated, power to the VCB is switched off. However, it might be too late to control the failure in the battery if the system is activated only when a fire is detected, the best solution is to react as early as possible to a potential failure. It is important to note and consider when planning battery storage that the fire suppression system in the battery is only active while battery is turned on or when charging.

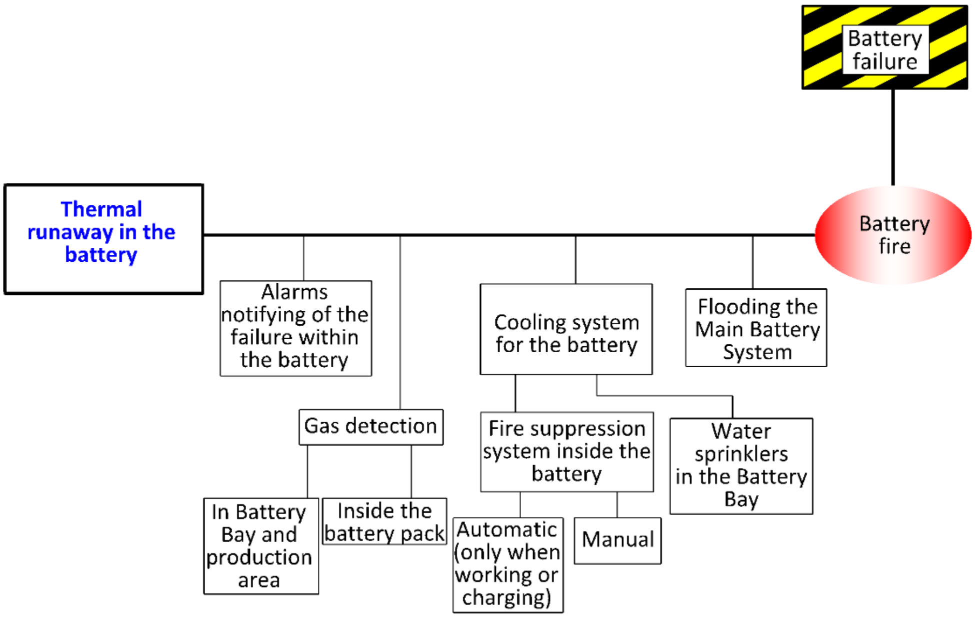


Figure 4.7 Prevention measures to avoid battery fire in case of a thermal runaway (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

The batteries of MT42 Battery and ST14 Battery have an option for flooding the Main Battery System by using an external water supply via the flooding port located on the side of the battery. Epiroc has suggested in the technical description of the batteries that the flooding should only be used in case of fire as the internal components will be irreversibly damaged after the flooding. However, flooding the battery system is the only option that the operator has to manage a thermal event or thermal runaway in the battery so it has to be determined what are the indicators when the decision to flood the battery should be made by the operator. With flooding the battery before a thermal runaway happens in a battery, there is a risk for delayed thermal runaway (Willstrand, 2021). Therefore, damaged battery must be monitored to detect any later reactions, i.e., thermal changes.

Detecting heat-up within the battery that could lead to thermal runaway can be difficult with the casings around the battery pack and sub-packs as the signs of a temperature change would not be able to reach outside of the battery pack. For example, during fire tests with smaller batteries, thermal imaging has been used for detecting temperature changes within the battery (The Fire Protection Research Foundation, 2013). Even though detecting temperature differences within the battery compared to the outside would prove to be not possible, it could be helpful when monitoring the battery after a fire to assess the risk of the battery reigniting. According to Bisschop et al. (2019) any local high temperature might be an indication of a cell failure leading to reignition. It is stated in the technical documentation on the Epiroc's batteries that the batteries can reignite up to one day. However, there have been cases where a BEV caught fire, reignited on the same day but after 5 days reignited again. Therefore, it would be suggested to monitor the failed battery for a longer period than one day after the failure.

4.1.6 Spillage of toxic water

As mentioned above, gases that can be both toxic and flammable are generated and vented before and with the thermal runaway in a lithium-ion battery. In addition to battery failure, toxic gases are emitted with a BEV fire. The most effective method to cool down the battery is flooding which requires a lot of water and to limit the spread of a battery fire, an external water suppression system must be installed in battery bays.

Toxic gases emitted during a battery failure or BEV fire can dissolve in water used for firefighting and battery flooding and make it contaminated, especially high with lithium and some heavy metals (Co, Ni, and Mn). Tests done by Swish Federal Roads Office (Federal Roads Office, 2020) showed that cooling water used for direct battery treatment has a higher level of impurities than firefighting water but compared to the water used both can be highly contaminated. In the tests done, cooling water had considerably higher levels of chloride, fluoride, sulphate, lithium, ammonium, potassium, and sodium in it compared to firefighting water. When compared to the initial water, a considerable amount of cobalt, nickel, and manganese were present both in cooling water and firefighting water.

Cooling water from the tests previously mentioned had a pH value of 12, making the water highly alkaline, at the same time firefighting water was almost neutral with a pH value of 8 (Federal Roads Office, 2020, pp. 47-48). Therefore, runoff water from putting out a BEV fire needs to be treated before releasing it into the environment. In the Konsuln test mine, there is a water treatment system in place for wastewater collection and disposal from production areas. On every level, there is a filter for collecting oil from the water, and on the lowest level, there is a water treatment system before the water is pumped on the surface. All battery bays in the Konsuln test mine have a decline towards the transportation drifts and the water used in them will be diverted into the general water collection system used in the mine.

According to the Fire Protection Research Foundation, up to 12 000 litres of water was needed to put out a 16-kWh battery pack fire(The Fire Protection Research Foundation, 2013, p. 190). That could mean that the overall level of additives in the runoff water will likely not be very high.

4.2 Possible consequences of a lithium-ion battery fire in a mine

Risk events related to BEVs battery failure discussed in previous sections can result in a battery fire if control measures in place fail or prove to be not sufficient to ensure safe working conditions. With a fire in an underground mine, several high-risk consequences might occur depending on the location of the battery fire and if people are present in the mine during the accident. As one of the goals of the Sustainable Underground Mining project is zero-harm, all possible accidents must be prevented, and necessary mitigation methods must be implemented to ensure the safety of the workers, equipment, and continuous production.

Battery fire in Konsuln test mine might result in mine drifts and/or exits being blocked if the incident happens while the vehicles are working. Blockages in the mine could result in safe passage to the surface or the refuge chambers being affected. With a battery failure and battery fire, there is a likely possibility for toxic and flammable gas emissions, and if in contact with the toxic gases it could present ill-health and danger to the people present in the mine. If battery fire is not detected early and put out within a timely manner, the fire could spread from battery to the vehicle igniting for example tyres or the hydraulics system and in addition, could spread to an adjacent structure close to the initial burning battery or battery electric vehicle.

The best option to avoid harm is early detection of a battery failure/fire by the BMS or the operator and immediately notifying everybody in the mine of the danger and then evacuating from the mine. If the failure or fire is occurring in the vehicle outside the battery system, then, if possible, both external and internal battery fire suppression systems should be activated to limit the spread of the fire and cool down the battery.

Everybody who works in Konsuln test mine when BEVs are present must be instructed and trained on how to act and what is the right sequence to activate fire mitigation measures if there is either a failure in the battery or a fire close to a BEV. Specific instructions and training provide assistance to workers and ensure that if an accident should occur, there are sufficient measures taken to provide a safe exit from the location of the incident to the surface or to a refuge chamber. As mentioned before, to successfully implement BEVs in an underground mine, the acceptance of workers is a key aspect.

4.2.1 Blocked mine exits

Layout in the Konsuln test mine is divided into two areas – the north side and the south side with both having a loading drift connecting the production crosscuts to the footwall drive. Konsuln test mine has one exit to the surface – the main ramp that is spiral in design until level 415 and following the shape of eight after that to the production levels 436, 486, and 536. Konsuln's main ramp is the emergency exit for the Kiruna mine as the mines are connected via a drift. Therefore, in case of an incident in Kiruna mine, a blockage on the Konsuln ramp could lead to no safe exits to the surface from both mines.

Failure with a BEV, either a truck or a loader, can additionally affect the transportation flow in the mine drifts leading to blockages in the production area and possible production delays. The average width of the drifts and production crosscuts in the Konsuln test mine is about 7 metres meaning that if the MT42 Battery is to fail in the production area, passing the truck to access the area might be an issue. Compared to the Scania R500 and Volvo trucks that are used in daily production in the Konsuln test mine for ore haulage, Epiroc's MT42 Battery mining truck is about 0,7 metre wider. If the BEV is to fail in a loading drift that connects the production area and footwall drift, exit from the production area is cut off. If the blockage is on the main ramp or in the footwall drift so that the exit the surface is blocked, it is necessary to use the refuge chambers in the Konsuln test mine to avoid harm to workers in case of a further failure with the BEV.

In the Konsuln test mine, there are 10 refuge chambers and rooms with two on every production level (Levels 436, 486, and 536) and four located on the main ramp (on road 54) on levels 253, 338, 415, and 506. More detailed info of the refuge chambers in the Konsuln test mine is presented in *Table 4.4*, refuge chamber locations on production levels are shown in *Figure 4.8, Figure 4.9, and Figure 4.10*. As the maximum number of people in the Konsuln test-mine is currently limited to 58, the available capacity of refuge chambers (96 persons) is enough to fit everybody in the mine in case of an emergency.

Table 4.4 Refuge chambers in Konsuln test mine

Refuge Chamber	**Location**	**Capacity**	
		People	**Maximum operating hours**
RK13	Ramp 253, road 54	6	72
RK43	Ramp 338, road 54	8	72
Räddningsrum	Ramp 415, road 54	8	72
RK42	Level 436, footwall drift	14	72
RK36	Level 436, transportation drift	8	72
RK38	Level 486, northern fork	14	72
RK23	Level 486, southern fork	8	72
RK18	Ramp 506, road 54	8	72
RK39	Level 536, southern fork	8	72
RK40	Level 536, northern fork	14	72
Total		**96**	

As seen from the level layouts of the Konsuln test mine, if one of the forks on the production level is cut off due to a BEV failure, it is possible to exit the production area using the other one as the crosscuts on the northern side and southern side are connected via the main transportation drift.

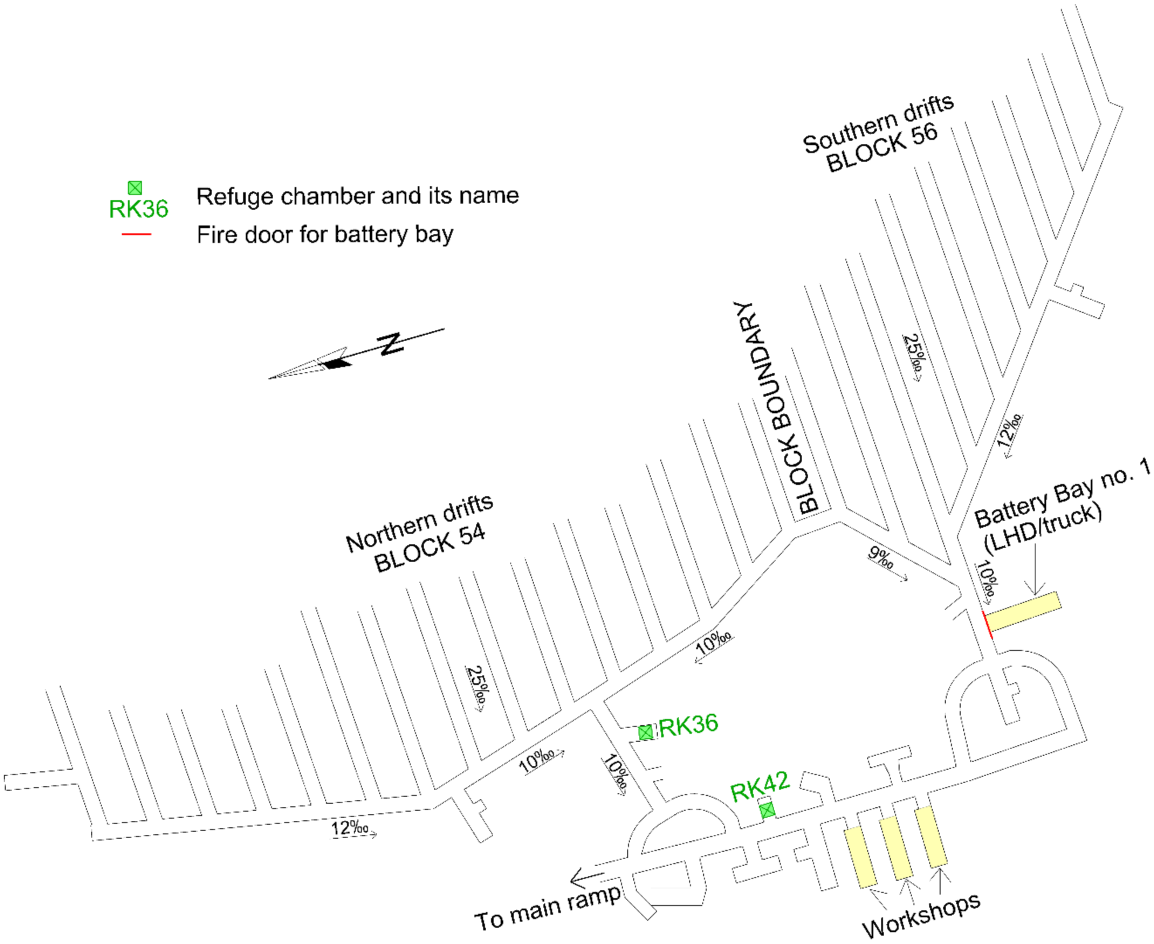


Figure 4.8 Location of the refuge chambers on level 436

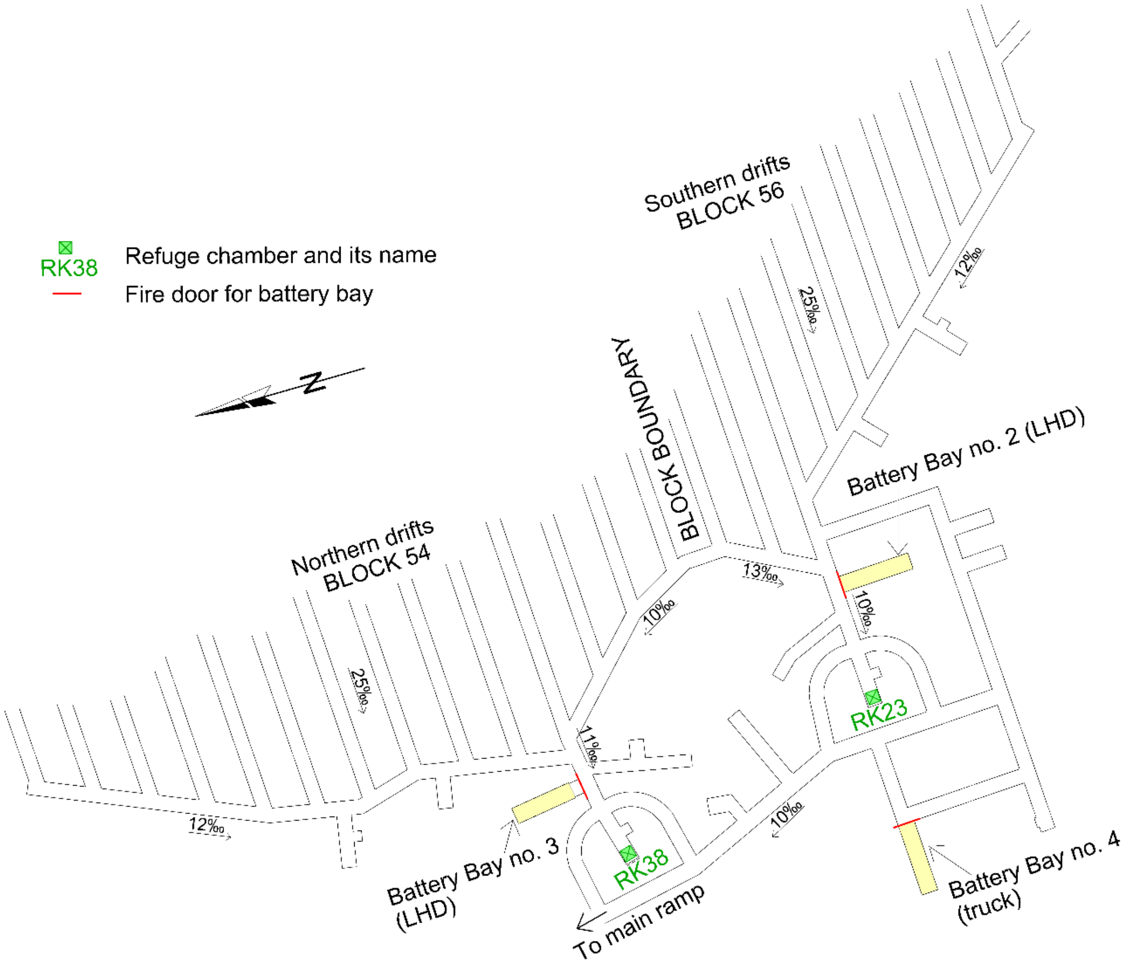


Figure 4.9 Location of the refuge chambers on level 486

As seen from *Figure 4.9* and *Figure 4.10*, refuge chambers are in the "fork" part of the levels both on the northern and southern sides of the mine. Battery Bays no. 2 and no. 3 are connected to the loading drift that connects the fork to the production drift meaning that if there is a failure of a battery or a BEV in a battery bay, exit to the ramp, and to the refuge chambers from the production crosscuts could be affected or cut off. To be able to separate the battery bays from the mine drifts and allow workers to exit the production area, fire doors must be installed to the battery bays. Even though fire doors have a limited time they can isolate the area, it is necessary to add time for evacuation. Usually, fire doors last about 2 – 3 hours depending on the application.

Swedish Work Environment Authority (2010) provisions state that a suitable distance for refuge chambers is 200 – 300 m from the working face. In Konsuln test mine level 436 one refuge chamber is in the northern loading drift and the other is next to the footwall drift. Distance from the production crosscuts to the nearest refuge chambers varies from 100 m to 475 m. On levels 486 and 536 the distance from production crosscuts to the nearest refuge chamber is 150 – 370 m. As the distance from the southern crosscuts on level 436 to the refuge chamber in the footwall drift is up to 475 m, it is advised to use the same logic on level 436 as on level 486 and 536 and move the refuge chamber RK42 to the southern fork. Distance from the furthest production crosscut would then be 340 m, making the distance of the rescue route 135 m shorter.

Figure 4.10 Location of the refuge chambers on level 536

If a BEV battery fails while the vehicle is working and BMS is still working, the main battery system is automatically disconnected from the vehicle making it impossible to move the BEV without additional assistance, i.e., towing. That makes it harder to control where the vehicle is located at the time of a failure leading to the disconnection and how it will affect the evacuation plan. As a result, if the failure is happening in a not controlled environment, the whole area has to be shut down to ensure everybody's safety. One additional option is to separate the production area from the "forks" and footwall drift with fire doors so when a failure occurs in the production area, it is possible to isolate the area and provide longer time for evacuation.

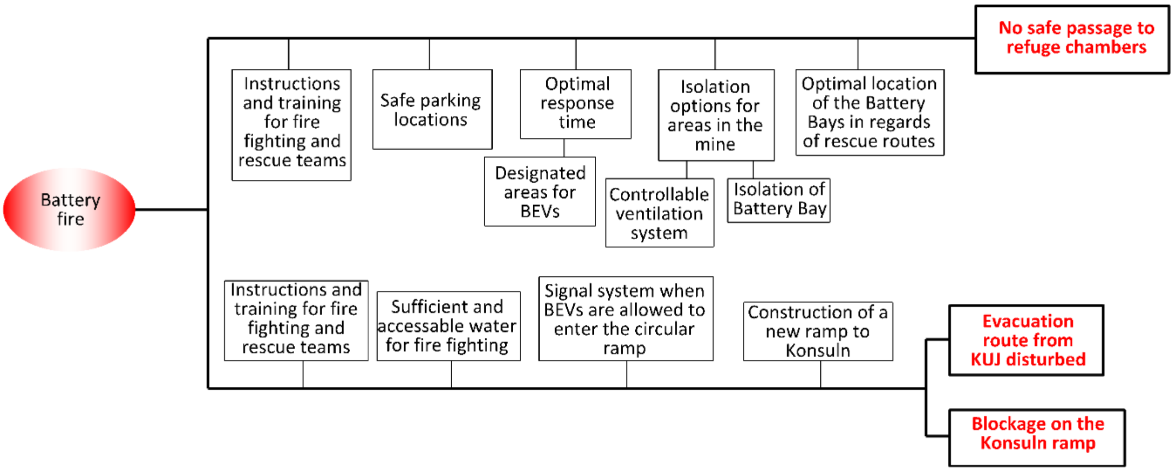


Figure 4.11 Possible mitigation measures for safe evacuation in case of a battery fire (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

As mentioned before, LKAB is constructing a new ramp for the Konsuln test mine to replace the old ramp's spiral part until level 415. The new ramp will be wider than the old one, 8 metres compared to 6 – 6,5 metres (Quinteiro, 2021), allowing trucks to pass each other when meeting on the ramp. The wider ramp also means that when the MT42 Battery trucks are tested in the Konsuln test mine, they wouldn't affect the actual production cycle as the Scania trucks used don't need to stop on the ramp to let the MT42 Battery trucks pass them. However, as the new ramp is expected to be ready to use at the end of March 2022, it might be necessary to implement traffic control methods for MT42 Battery trucks before that. One possible option is to control the battery truck's movements and have a signal system in place to be able to control when the trucks are allowed to enter the ramp so the disturbance and risk to the production would be minimal.

4.2.2 People in contact with toxic gases

Gases generated during a battery or BEV fire are toxic and pose a health risk for people present in the mine during a battery failure. If a fire has occurred, it is necessary to ensure the well-being of everybody and make sure that risk mitigation methods are sufficient for that. As said before, if a failure with a battery is detected, everybody should be evacuated from the mine. However, toxic gas generation can happen before a thermal runaway in a battery, so there must be measures in place that protect people in the mine if toxic gases are generated.

To be able to monitor the environment in the mine, gas sensors have been installed in the Konsuln test mine with a measuring capacity of O_2, CO, NO_2, NH_3. During the test period for BEVs in the Sustainable Underground Mining project, sensors should be installed on the level where BEVs are currently working. If the decision is made to implement only battery electric vehicles in the Konsuln test mine after the tests within the Project, gas sensors should be installed on all levels to provide a good overview of the conditions. In addition to already installed sensors, an option to measure HF should be implemented as various fire tests on lithium-ion batteries show that during a battery fire, the amount of HF exceeds set health exposure limits, so a higher concentration of HF can be a signal that there is a failure within the battery.

It is also important to provide sufficient ventilation in the battery bays in case of a battery fire. During lithium-ion battery fire, there is a possibility of H_2 generation, which even though is not a toxic gas, is extremely flammable if concentrated in a big amount in a confined space which a closed battery bay is. As ventilation is an integral part of a safer environment for evacuation and rescue works, the ventilation plan requires updating and readjusting with the implementation of battery electric vehicles. Calculating the necessary airflow requirements is not in the scope of this thesis and requires further work. However, a specific procedure for emergency ventilation that is based on experience and simulations of various battery fire scenarios should be established in the mines where BEVs will be implemented and tested.

To limit the spread of gas emissions in the mine, it is important that there is a possibility to isolate parts of the mine so that in case of an accident, the area where the vehicle with a failure is located can be separated. In the Konsuln test mine, block 54 and block 56 ventilation systems are separated and therefore provide a good option to control the airflow in case of a battery or BEV fire in one of the blocks. If a failure with a battery electric vehicle is to occur, it is preferred the vehicle in question be transported to the battery bay where more measures are in place to control the failure and if necessary to separate the BEV from the mine.

Similarly to what was discussed in the previous section, with the release of toxic gases in case of a failure with a battery electric vehicle, a safe exit from the mine has to be provided and it not possible, refuge chambers must be accessible to ensure the safety of the people present in the mine.

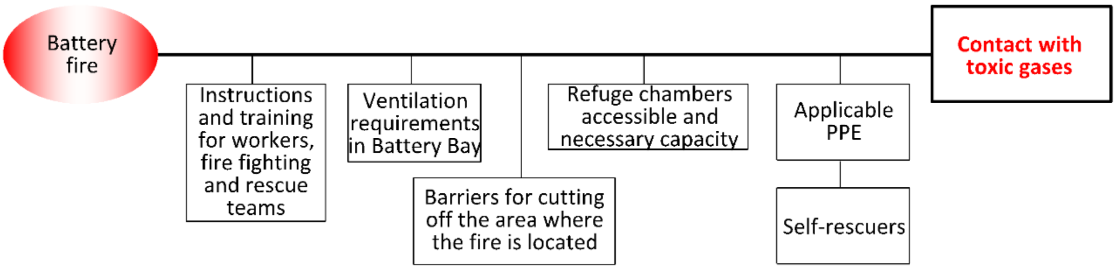


Figure 4.12 Possible mitigation measures to avoid contact with toxic gases in case of a battery fire (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

Compared to most mining jurisdictions, in Sweden it is not mandatory for people working in a mine to carry a self-contained self-rescue device (self-rescuer) which is a portable device designed to provide clean air for example if the O_2 level in the mine is too low or there are toxic gases present in the mine that are harmful to people. Depending on the specific model of the self-rescuer, it can provide respiratory assistance for more than four hours, most commonly for 30 – 40 minutes. This additional time can be extremely valuable in case of a failure with a battery to be able to evacuate people from the mine or provide safe passage to the refuge chambers.

4.2.3 Adjacent structure fire

Battery or BEV failure can happen while the vehicle is working, charging in a battery bay, or while parked. Depending on the location of the failure and the surrounding structures, if not put out timely, battery fire can spread to the vehicle and adjacent structures. If the fire starts within the battery, flooding the battery with water can help to cool down the inside of the battery and mitigate or at least delay escalation of the fire. A good solution to prevent the fire from spreading from the battery to the vehicle or adjacent structures is to have a water sprinkler system in the battery bays and in the workshop. As the batteries will be charged and possibly stored in the battery bays and maintenanced in the designated workshop, there are various possible risk events present for the batteries (mechanical damage, charging fault, etc.) that could lead to a battery fire. It suggests that having a water sprinkler system installed in the battery bays in the Konsuln test mine is justified and could prove helpful in case of a battery failure to stop the spread of a possible fire.

However, if the battery failure that leads to a battery fire happens in the production area or on the ramp, sprinkler systems will not be applicable. In that case, the spread of the fire must be controlled by the firefighting teams. Therefore, it is necessary to ensure that there is enough available water for firefighting the battery fire and limit its spread to the vehicle or adjacent structures in the mine. As mentioned before, a battery fire needs large amounts of water to be put out but this is also the case for large ICE vehicle fires if the whole vehicle is ignited.

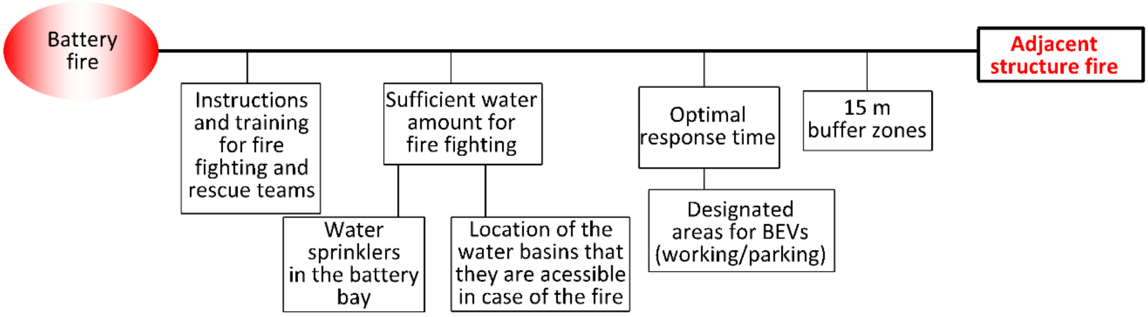


Figure 4.13 Possible mitigation measures to prevent adjacent structure fire in case of a battery fire (extract from APPENDIX 2 – Bow-tie analysis of Lithium-ion battery fire)

Extra consideration is needed to ensure the safety of the batteries that are not used for BEV operations and are stored in the mine in a battery bay or on the surface in a storage facility. As various other structures in a battery bay can pose a fire hazard when contacted fire, a specific storage location has to be determined to prevent incidents escalation in case of a battery failure. As per a recommendation by National Fire Protection Agency, damaged batteries should be stored with a buffer zone of 15 metres from other vehicles and adjacent structures, it would be the best practice to implement it while storing spare batteries as well. Looking at the dimensions of the batterie bays in the Konsuln test mine, it is not possible to archive the suggested buffer zone as the battery bay itself is only 8 metres wide. However, one solution to minimize the risk of a large-scale fire in a battery bay is to have a suggested safety buffer at least with other structures and parked vehicles in the battery bay.

4.2.4 Safety of the fire-fighters

Introducing new technology to an underground mine means that the mine rescue plan and rescue team's action plan has to be reviewed in light of battery electric vehicles. Global Mining Guidelines Group (2018) has suggested that the OEMs must provide fire-fighting information specific to each battery electric vehicle model. This information can be the basis for putting together a mine specific instructions and training programs for operators, maintenance workers, and fire-fighters.

Epiroc has provided some guidelines in the technical information of the battery pack on firefighting in case of a BEV fire (Epiroc, 2021c). The main pointers are that LIBs can burn for hours despite attempts to extinguish it, a large quantity of water will be needed to put out the fire, cooling down the battery by flooding it, and Epiroc has also stated the risk for the reignition of the battery after extinguishing the fire. However, there should be more precise instructions in place from the OEMs to assist with updating mines emergency response plans. In addition to guidelines on firefighting, the rescue teams need to have as accurate as possible description of the failure site and its surroundings (Gillett, 2021). For that, it is necessary to know the exact locations of all the vehicles in proximity to the failed vehicle (both other BEVs and diesel-powered vehicles) and locations of battery bays and storage areas with exact quantities of batteries that are present in those. One possible option for determining vehicle locations in the mine is vehicle tracking which in some production areas has already been implemented in LKAB including the Konsuln test mine.

To provide acceptable working conditions for rescue teams, all the above-discussed points are applicable – ventilation requirements in the battery bays and in the mine that compile with the specifics of battery fires, sufficient water supply for BEV fire, etc. Additionally, firefighter PPE used in a mine where battery electric vehicles are present must protect rescue team members from toxic gases generated with a LIB and BEV fire.

5. DISCUSSIONS

Thinking of all the benefits that working with battery electric vehicles in an underground mine can provide, it is a fair question to be asked if the risks of a failure with a machine are worth the consideration as the chances for a failure with a battery electric vehicle have been estimated to be the same or even less likely than with a diesel vehicle. That could imply that if a risk assessment on having diesel vehicles in a mine and working with them has been done, implementing BEVs wouldn’t change the overall risk levels of the operations. However, as the battery electric vehicles have a new power technology and reliable data on its risks severeness and probability of occurrence in underground mines is yet to be determined, it is essential to analyse the results of even the smallest changes and determine what could be the worst-case scenarios, so it is possible to use those as a basis for the safety requirements and implementing safety systems in the mine. Therefore, the risk analysis in the previous section assumed that all the risk levels for the failure mechanisms discussed were the same and would occur at some point when operating BEVs.

The next step in the risk analysis for implementing battery electric vehicles to Konsuln test mine should be determining possible risk events' possibility for occurrence and the severity of the consequences. By grading both factors it is possible to build up a matrix for the risks with specific scores for each of them. That gives a good overview of the actual severity of the risks related to battery electric vehicles present and after including planned and possible control measures to prevent failures and mitigation methods for possible consequences to the risk matrix, it can be determined if the risks of implementing BEVs to Konsuln test mine but also to any LKAB mine, has an acceptable risk level. If not, it must be analysed if it is necessary to have additional safety measures next to the ones that the OEMs provide and what are implemented by LKAB and operators to lower the risk grades even further or if there are some limitations in the implementation of BEVs.

Levels 436, 486 and 536 of Konsuln test mine were developed for the Sustainable Underground Mining project which means that the layout of the levels was planned with the requirements for battery electric vehicles kept in mind – construction of the battery bays, designated workshops for BEV maintenance, the electrical power system in the mine, etc. In the test phase of implementing BEVs to the Konsuln test mine, only one ST14 Battery loader and two MT42 Battery trucks will be working in the mine, meaning that to get the production volume defined for Konsuln, diesel equipment will be working parallel to the new battery electric vehicles. Assuming that the BEVs have similar productivity to diesel equipment used, it would mean that when replacing all diesel vehicles with battery electric ones, there would be 8 – 10 trucks and 2 loaders in use. One issue with the battery electric loader to be tested in the Sustainable Underground Mining project is the fact that the Epiroc ST14 Battery loader has a smaller capacity than the loaders used right now in the Konsuln test mine (17 tonnes loaders) which could mean that more pieces of equipment would be needed with today’s battery electric vehicle offering leading to issues with vehicle and battery charging and storage.

Using only battery electric vehicles in the Konsuln test mine requires a large area for charging the batteries and storing them. As Epiroc’s battery electric vehicles require additional crane construction for battery swapping, the design for a bigger battery bay has to be reconsidered. As the development costs for a battery bay are high, a more economical solution bearing in mind all the safety hazards that battery electric vehicles could present should be worked out to cater to all BEVs used in the mine. The reality is that large scale tests of battery swapping both for ST14 Battery and MT42 Battery have not been performed yet as in the tests in Kristineberg mine ST14 Battery loader was mostly charged on-board over lunch breaks and in Kittilä the vehicles were tested just for a couple of days and not as part of actual production but as a trial. Therefore, the actual safety aspects of the battery swapping, and battery bays are yet to be determined in the tests planned in the Konsuln test mine by LKAB which will provide important input to designing battery bays for more BEVs.

If a decision is made to replace diesel mining vehicles with battery electric ones, either just in Konsuln or in all LKAB mines, level layouts must also be redesigned with BEV requirements kept in mind – charging and swapping areas for battery electric vehicles must be implemented into the design. As part of the Sustainable Underground Mining project, battery bays are designed to service one BEV at a time (*Figure 4.5*). The total length of the battery bays constructed in the Konsuln test mine is 35 m, meaning that it should be able to fit two trucks in a row (*Figure 5.1*) but there is not enough space to swap two vehicles' batteries parked in the battery bay at the same time. However, as the charging post can be as far as 100 m from the charging cabinet and one can serve two charging posts, there is a possibility to install two charging posts to one battery bay to provide an option to charge the second truck on-board if it is necessary.

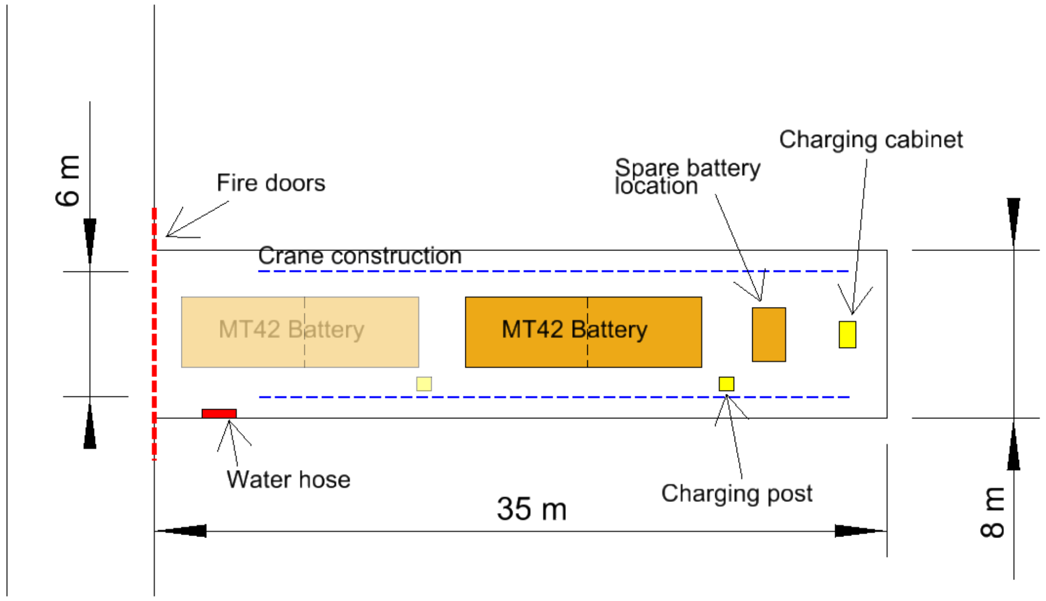


Figure 5.1 Battery Bay layout with two MT42 Battery trucks parked for charging

One option for battery bay design to lower development costs when implementing battery electric vehicles on a large-scale is to have one battery bay being able to hold multiple vehicles at the same time with the capability for battery swapping as well. One possible layout option for a multiple vehicle battery bay is shown in *Figure 5.2*. However, with bigger battery bays holding more batteries and BEVs, it is necessary to consider the safety aspects of the construction, both from the mine planning side and also what risks would large-scale lithium-ion battery storage and charging site present in an underground mine. Having several batteries stored together could be increasing the risk factor for BEV implementation as the power that is stored in a battery bay which by nature is a confined space could be multiplied several times compared to the battery bay design used now in Konsuln test mine; therefore, in case of a battery failure the possibility for an escalation in more likely.

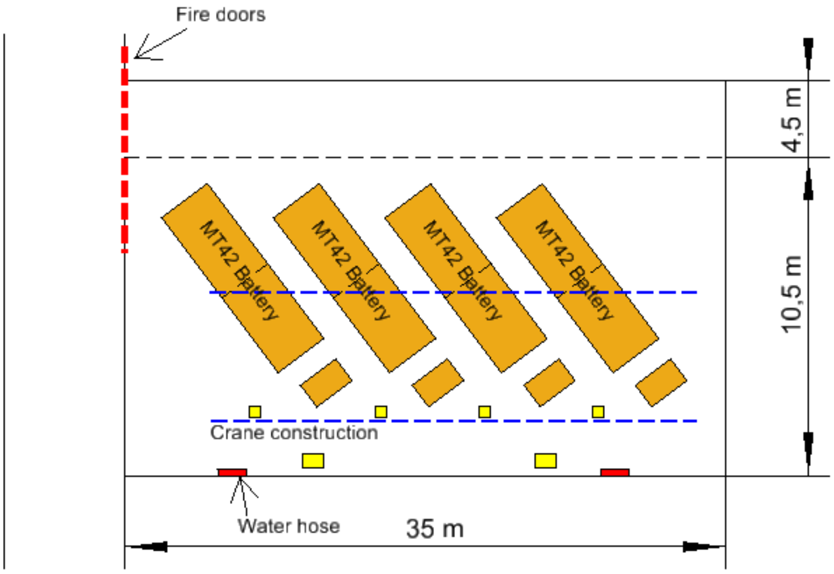


Figure 5.2 Battery bay layout concept for multiple MT42 Battery trucks

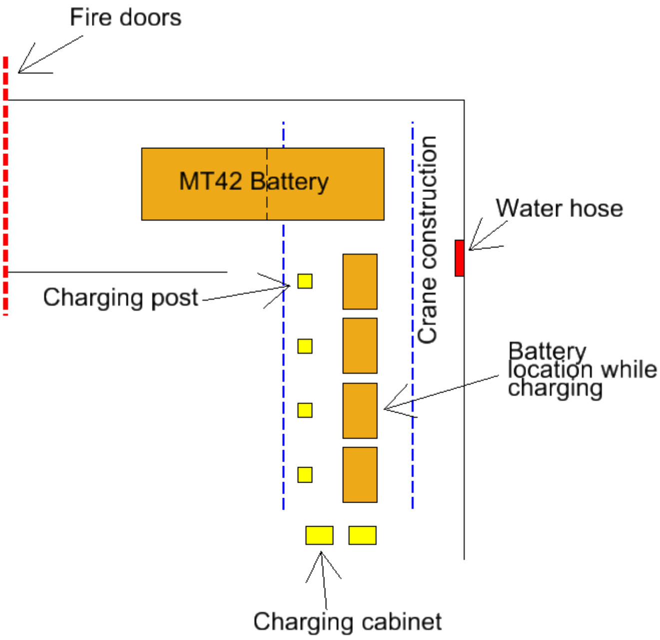


Figure 5.3 Charging area layout concept for multiple batteries (modified from ABB (2021))

Another option for battery charging and swapping when more battery electric vehicles are working in the mine is to have a charging area for batteries. The charging area layout concept in *Figure 5.3* is accessible for one vehicle at a time and the empty battery that was used can be replaced by a charged battery using a crane construction. One benefit for that option compared to the one in *Figure 5.2* is less development work as it requires a smaller area. However, from the safety viewpoint, the situation is similar – multiple LIBs are stored at narrow conditions making it a safety hazard. In addition to the charging area, locations for battery electric vehicle parking are required while they are not used in production.

For further risk analysis for BEVs implementation in a mine, a large-scale LIB and BEV storage option in underground mine should be addressed as the problem will be faced after the first trials with BEVs and assessment of the risks that will be raised when replacing all diesel mining vehicles with BEVs will help to decide if the change supports the goals set in the Sustainable Underground Mining project.

One of the key benefits of using battery electric vehicles in underground mines is the reduction of emissions from production that reduces the requirements for the ventilation system and therefore lowers the operational costs. As mentioned before, cost-saving when using BEVs in the Konsuln test mine instead of ICE vehicles can according to (Gyamfi, 2020) be up to 80%. However, even though the gas emissions will be reduced, as it turned out when analysing the risks associated with BEVs, there is a risk of toxic gas generation with battery failure. So, it is suggested to continue with gas concentration monitoring in mines even after replacing diesel vehicles with BEVs and based on the research done on battery failure events even add measuring capability for specific gases.

One idea that was discussed as an option for detecting potential failure with BEV battery was monitoring gas concentrations in the mine and if higher levels of gases are generated due to a battery failure, preventative measures could be activated, such as the evacuation of people and ventilation system adjustments to stop the spread of generated toxic gases. RISE carried out various fire tests with lithium-ion batteries (Willstrand et al., 2020) that included both tests with the whole battery pack and tests for separate battery modules. Gas measurements that were recorded during the fire tests are shown in Figure 5.4 and Figure 5.5.

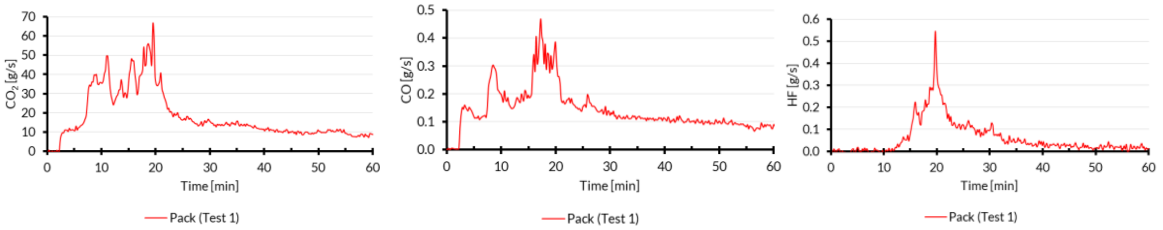


Figure 5.4 Gas measurement results from RISE 2020 tests with a battery pack (Willstrand et al., 2020), from left: CO_2, CO, HF

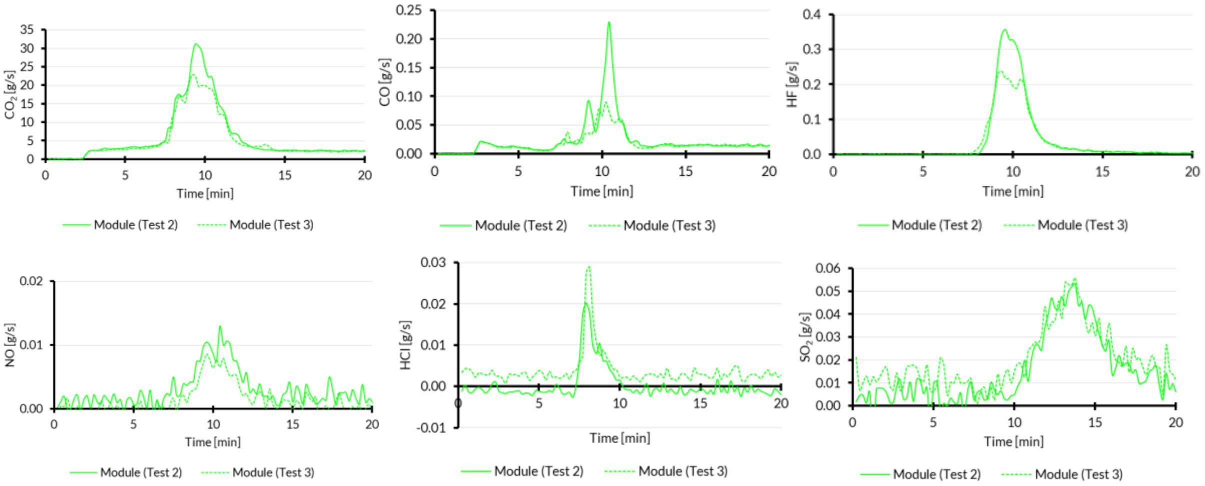


Figure 5.5 Gas measurement results from RISE 2020 tests with battery modules (Willstrand et al., 2020), from left: CO_2, CO, HF (first row); NO, HCl, SO_2 (second row)

Peak gas emissions are generated during thermal runaway within the battery, so based on the results from (Willstrand et al., 2020), with the battery pack tested thermal runaway occurred around 15 – 20 minutes and with the battery modules around 10 minutes. From the battery pack test results it appears that an increase in CO and CO_2 generation can be fixed before thermal runaway when the emissions reach their peak value, however, HF generation starts to rise only when thermal runaway occurs. Therefore, monitoring CO and CO_2 concentrations in the mine can prove helpful in detecting battery failure but as the time for thermal runaway after a battery failure can be rather short, the potential additional time from detecting the thermal event by the gas sensors might be minimal.

From the tests with battery modules, there is not as noticeable rise in CO and CO_2 generation before thermal runaway as there is with the battery pack tests results. However, a slight rise was detected about 7 – 8 minutes before the peak gas generation. From the measured gases, HCl can have an earlier peak time compared to other gases, in the RISE tests about 2 – 3 minutes. One additional aspect that can be noticed from the test results with battery modules is the SO_2 gas generation peak time which is somewhat later than other gases peak times measured in the RISE tests. With that in mind, SO_2 concentration detection in the mine could be helpful to provide information about the status of the thermal runaway and could be used as an indicator for the rescue teams and firefighters.

Combining the results discussed above and fire tests results with Epiroc battery sub-packs done also by RISE (Willstrand, 2021), the time it takes for a battery to start thermal runaway can be in the range of hours meaning that the build-up to thermal runaway takes longer than measured in the 2020 fire tests by RISE where the batteries tested were with a smaller capacity than the ones in Epiroc's BEVs. That could mean using data from gas sensors to detect potential failure with a battery of the BEV might be helpful in the early detection of a problem and add valuable time to activate control measures to prevent escalation of the failure.

As discussed in section 4.1.4. there are gas sensors in the Konsuln test mine that can measure concentrations of O_2, CO, NO_2, NH_3. Right now, the sensors are installed on level 486 in block 54 to the transportation drift connecting production drifts (green marks in Figure 5.6). Additional CO sensors are also installed in block 56 (grey marks in Figure 5.6). The first suggestion is to reinstall the gas sensors to level 438 where the first tests with battery electric vehicles will be carried out. If production will be carried out parallel on all levels, additional gas sensors should be installed to all levels in the Konsuln test mine.

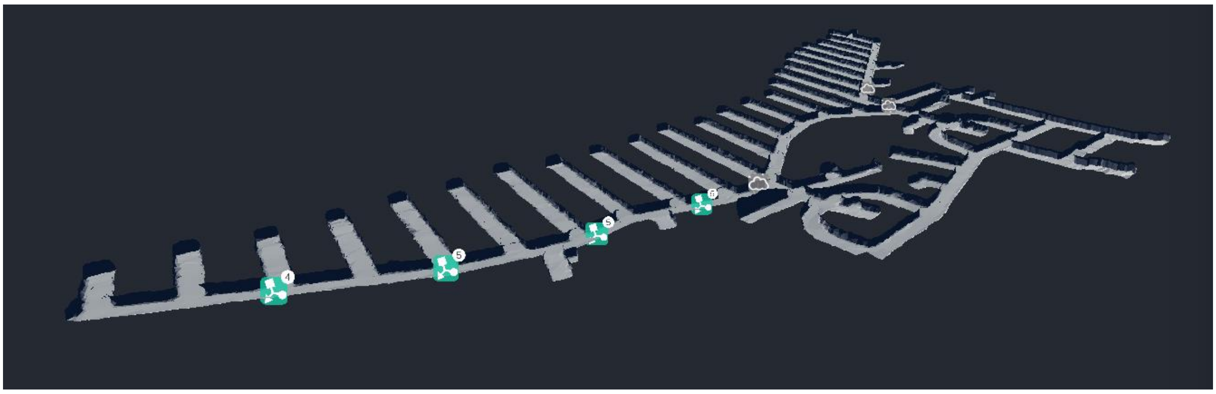


Figure 5.6 Gas sensors on level 486 in Konsuln test mine by LKAB

In addition to the measuring capacity of O_2, CO, NO_2, NH_3, it could prove to be helpful to have gas sensors for the detection of HF and SO_2 concentrations in the mine. It can be seen from *Table 4.3* that HF and SO_2 emissions during a battery failure exceed the limits set by the Swedish Work Environment

Authority. Those can provide valuable insight into the local conditions in case of a battery failure for rescue teams.

Based on the tests done so far with lithium-ion battery packs and modules, there are some early detection options for thermal runaway within the battery (higher concentrations of CO, CO_2, and HCl) that can be used to activate applicable control measures and ensure the safety of the people in the mine. One issue that was raised during the thesis work was the fact that carrying self-rescuers with you while working underground is not mandatory in Sweden and it is not a common practice to have them in LKAB. However, self-rescuers can assist people while evacuating in case of a BEV failure either to the surface or to a refuge chamber. As there are still many unpredictable factors with a LIB fire in an underground mine, it is worth considering introducing the use of self-rescuers in the Konsuln test mine while battery electric vehicles are tested. If a decision should be made to replace diesel vehicles with battery electric ones, general safety requirements regarding self-rescuers have to be reviewed.

However, there have not been full-scale fire tests with battery electric mining vehicles, so further research is needed to draw conclusive conclusions on BEV failure mechanisms while used in underground mining. In 2013 (Hansen & Ingason, 2013) carried out full-scale fire experiments with a wheel loader and a drilling rig in an underground mine, similar study is recommended to do with battery electric vehicles in an underground mine setting to get a better understanding of a BEV fire specificity.

A potential way forward with the risk analysis on battery electric vehicles and implementing them in LKAB mines is using digital solutions for safety system analysis which allows to test out various BEV failure scenarios and control the effectiveness of the mitigation methods to prevent the escalation of the failure. Safety simulations can further be combined with real-time mine control systems that provide accurate base information for specific scenarios and test cases. One of the most important issues that should be looked into is the evacuation plan in case of a battery failure and assessing the mine layout suitability for using battery electric vehicles. That way it could be determined whether there are certain mine areas where the risk level is too high for the well-being of workers, and usage of BEVs should be limited. Furthermore, it would be a good exercise to run through the risk scenarios with diesel equipment to compare the result to understand the differences with the technology and how to address the potential change from diesel to battery electric vehicles.

6. CONCLUSIONS

My thesis aimed to evaluate the battery electric vehicles tested by LKAB in the Sustainable Underground Mining project that are provided by Epiroc who is one of the partners in the Project. Vehicles that are the basis of the evaluation are 14 tonne loader ST14 Battery and 42 tonne truck MT42 Battery. The focus of the evaluation was the safety aspect when introducing battery electric vehicles to an underground mine – what risks are present when using lithium-ion batteries in a confined space, what are possible control measures to prevent failures, what could be the consequences, and what can be done to mitigate them. As the battery electric vehicles provided by Epiroc will be tested in the Konsuln test mine, which is a separate part of the Kiruna iron ore mine, the analysis is based on the conditions of the Konsuln test mine.

Using battery electric vehicles in mining and especially in underground mining is a fairly new thing so the first part of the thesis is focused on the theory of lithium-ion batteries and the specificity of battery electric vehicles compared to diesel vehicles that are mostly used in the mining industry – health aspects, environmental performance, and risks associated. In addition to the general insight into the topic, a more in-depth look at Epiroc's MT42 Battery truck and ST14 Battery loader was done to understand the specifics of those vehicles and what are the features of the new technology and how can it affect their performance in LKAB's Konsuln test mine.

As the biggest unknown factor in BEVs is their lithium-ion battery, the risk analysis part of the thesis focused on uncertainties that it could present. The three key lithium-ion battery abuse conditions are mechanical, electrical, and thermal abuse. Most commonly those abuse conditions are related to each other as being a cause or consequence for others. Most commonly cell or battery internal thermal abuse is the last step before thermal runaway is initiated so battery's thermal management and cooling are the most important countermeasures to prevent battery fire when using BEVs.

The first link in the overall battery safety is the Battery Management System which is part of the main battery system and monitors and manages its working conditions. BMS used in the batteries in Epiroc's BEV have been assigned a performance level D according to the ISO 13849-1 standard which means that the BMS provides safety even in case of single faults in the system and has a dangerous failure detection coverage of 90 – 99%. If the BMS is to fail or it is not working for some reason, failure with the battery will happen and then only external control measures can be applied to stop the event from reaching thermal runaway leading to a battery fire.

Even though battery electric vehicles are becoming more common as everyday light-duty vehicles, implementing them in underground mines that are confined spaces, additional safety measures have to be in place to ensure everybody's well-being. LKAB has set a goal to archive zero-harm with the possible changes being tested in the Sustainable Underground Mining project so, with a risk for a battery electric vehicle failure present, all possible consequences must be evaluated, and necessary mitigation measures implemented to prevent them from occurring.

Assessing risks related to using battery electric vehicles in an underground mine showed that there are a lot of risk aspects to using BEVs and if not managed, could have serious consequences. Main risk events for battery electric vehicles were stated as:

1. Electrical failure of the battery that can be short circuit, overcharging and over-discharging
2. Mechanical damage to the battery meaning the battery being crushed, ruptured or penetrated in a way that affects the battery cells
3. Thermal failure of the battery initiated by electrical or mechanical abuse or external heat
4. Toxic gases emitting from the battery prior or with thermal runaway
5. Thermal runaway within the battery as the main event leading to a battery fire
6. Spillage of environmentally harmful substances to surroundings.

Based on the risk events and their causes and nature, possible control measures were discussed and proposed in the conditions of the Konsuln test mine. As mentioned before the most important one is the Battery Management System, but also regular maintenance of the vehicle and the main battery, various fire suppression systems (both battery internal, external, and availability for battery flooding), protective layers for battery (useful in case of mechanical abuse and with a thermal event), etc. One important aspect in managing the risks with implementing battery electric vehicles in Konsuln or any other underground mine is the training of the operators, maintenance workers, and everybody working in a mine where BEVs are used, so they would know what it means to work with battery electric vehicles. Effective risk management implies that control measures for preventing risks are in place and working and if a failure should happen, there have to be instructions for what are the mitigation methods and what is the right sequence to activate them.

Based on the results of the risk analysis, in the Konsuln test mine, essential measures are already in place or have been decided to implement before starting the tests with Epiroc’s MT42 Battery truck and ST14 Battery loader – a water supply for flooding the battery, fire doors for the battery bays, refuge chambers with a capacity that will facilitate all people present in the mine at the time of the accident, adjustable ventilation system. When the decision is made to replace ICE mining vehicles that are mostly used in LKAB mines with battery electric vehicles, significant changes need to be implemented to mine planning and development as working with BEVs requires additional infrastructure and connectivity.

To summarise, battery electric vehicles provide many benefits when used in underground mining and based on the risk assessment done in this thesis, the risks that BEVs present are controllable and the worst-case consequences avoidable with appropriate mitigation measures. Therefore, large-scale testing of Epiroc’s ST14 Battery loader and MT42 Battery mining truck in the Sustainable Underground Mining project can provide valuable information on both the performance of the vehicles and safety aspects while used in an underground mine which can be used to build up more precise analysis of replacing diesel vehicles with battery electric ones.

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Epp Kuslap
December 2021
Tallinn, Estonia

8. PERSONAL EXPERIENCE

The process of writing my Master’s thesis took me longer than expected but at the same time gave me the experience that was worth the extra time. When reaching out to LKAB to get my thesis work started in December 2019, I thought it would be good to have a head start to avoid any mishaps and finish my studies on time. Little did I know that almost everything that could go wrong would go wrong. The experience of the thesis work was enriched by the global pandemic, several travel restrictions, multiple delays in the Project, changing the topic for the thesis, etc. However, as it turned out in the end, it all was good for being able to write the thesis I have now and get the most from the whole process.

My thesis work culminated for me when I was able to do my work in LKAB in Kiruna, Sweden for two months from the beginning of October 2021 till the end of November 2021. As the visit had been postponed a countless number of times, first it felt unreal to actually be there but quickly it seemed like a place where I was supposed to be all along, and the help and care everybody showed made the transition feel natural.

Working on my thesis in LKAB was my first experience being part of a big mining and minerals group and it made me understand how important it is for a student but also for an engineer to broaden their horizons and gain new experiences and knowledge in an unfamiliar environment outside one’s comfort zone. Being able to learn and see how iron ore is mined in the largest underground iron ore mine, get an insight into the processing of the ore, and familiarize myself with the geology of new development projects, showed what possibilities can lie within one company and what has been missing from my professional baggage.

Both my Master’s studies and my thesis work presented a great opportunity for me to grow as a person and to learn not to choose the easy way out if the situation is complicated or it feels like the end goal is starting to fade away. With all the uncertainty that the pandemic caused, the decision to postpone my Master’s graduation to be able to do the thesis project the way it was first planned and to get the outcomes from the experience that would be beneficial for my personal development, was the right thing to do. The encouragement from both of my supervisors to make the decision helped to keep the motivation that in the end resulted in getting everything I could have wanted from the experience and for that I will be forever grateful.

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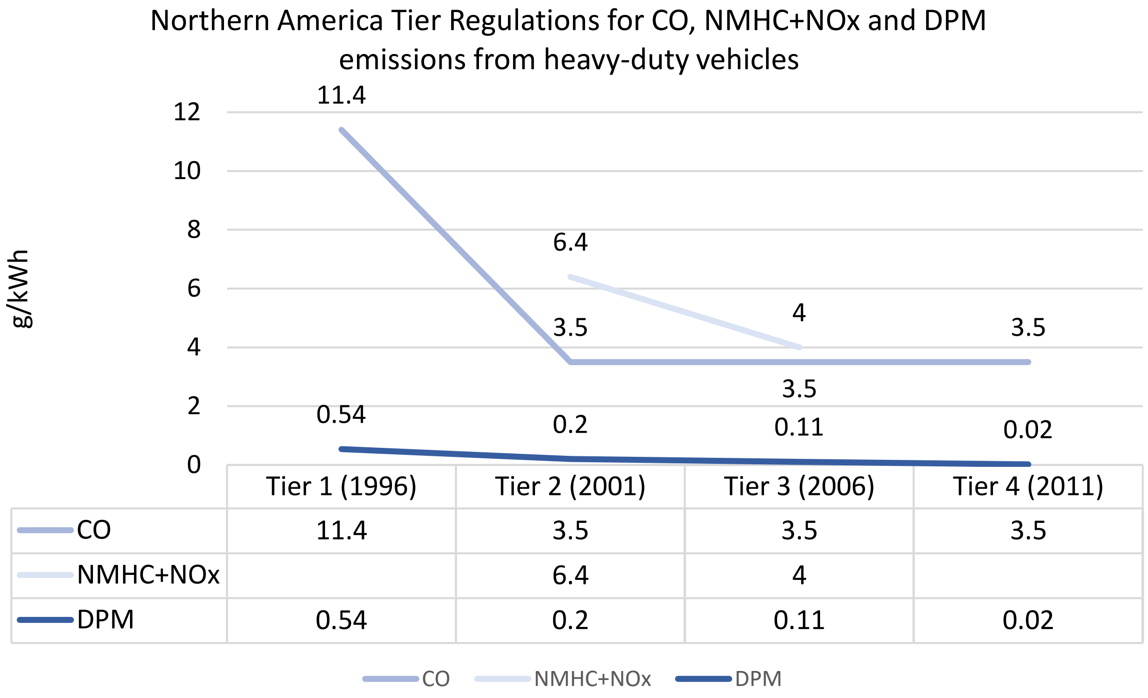
APPENDICIES

APPENDIX 1 –Northern American regulations for emissions from heavy-duty vehicles



	Tier 1 (1996)	Tier 2 (2001)	Tier 3 (2006)	Tier 4 (2011)
CO	11.4	3.5	3.5	3.5
NMHC+NOx		6.4	4	
DPM	0.54	0.2	0.11	0.02

Figure 1. Northern American Tier Regulations for CO, NMHC+NO$_x$ and DPM emissions from heavy-duty vehicles (Environmental Protection Agency, 1994, 1998, 2004)

APPENDIX 2.
BOW-TIE ANALYSIS OF A LITHIUM-ION BATTERY FIRE

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