Concerns with the Environmental Susceptibility of Mine Utility Vehicle and Rubber-tired Mantrip LITHIUM-ion Batteries

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ABSTRACT

The mining industry is beginning to implement lithium-ion batteries (LIBs) to power mine utility vehicles (MUVs) and rubber-tired mantrips (RTMs). However, the ability of LIBs to withstand the harsh conditions for these applications has not been rigorously evaluated. Concerns with the use of LIBs in the mining environment will be discussed including the effects of mechanical shock and vibration, temperature extremes, and moisture exposure. This paper will discuss adverse effects of the mining environment on LIBs and provide an overview of scientific gaps associated with the environmental susceptibility of LIBs used on MUVs and RTMs.

INTRODUCTION

Several mining vehicle manufacturers currently sell or plan to sell battery-electric vehicles (BEVs) powered by lithium-ion batteries (LIBs). Manufacturers of large BEVs that use LIBs and their battery suppliers have engineered LIB systems for such vehicles. After acquiring Artisan Vehicle Systems, Sandvik offers a truck and a few loaders powered by LIBs [1]. The model TH550B truck has a battery capacity of 354 kWh and the TH514BE and TH518B loaders have capacities of 74 kWh and 353 kWh, respectively. Each Sandvik vehicle uses lithium-iron-phosphate (LFP) LIBs [2]. Epiroc has partnered with Northvolt [3] to deliver several load-haul-dump vehicles. The ST7 model uses a 165-kWh Artisan LIB made with LFP cells [4]. The ST14SG and ST18SG models use Northvolt's proprietary Lingonberry NMC cells with capacities of 300 kWh and 450 kWh, respectively [5]. Komatsu sells several underground scoops including the 02ESV36 with a 158-kWh LIB, the 02ESV56 with a 214.8-kWh LIB, and the 02ESV60 with a 286-kWh LIB [6]. Caterpillar uses batteries from Lithos Energy, Inc.[7, 8]. Lithos Energy, Inc. does not explicitly state the battery chemistry it uses, but due to claims of higher energy density of 170 Wh/kg and lower cycle life of 500–1,500 cycles, it is likely that the company uses NMC chemistry [9]. Recently, Siemens has patented a mobile mining truck that utilizes LTO cells [10].

Recently, a group of NIOSH researchers have had multiple discussions with various mining industry personnel regarding LIB-powered mine utility vehicles (MUVs) and rubber-tired mantrips (RTMs). While large LIB-powered BEVs have been engineered specifically for the application, the lead-acid batteries on smaller vehicles such as MUVs and RTMs could be swapped out for commercially available LIBs that are not designed to withstand the harsh mining environment. Some underground coal mines have been switching their outby MUVs from traditional batteries to LIBs. Some of these vehicles use 6V or 12V automotive-type batteries. Other mines have reportedly begun working with RTM manufacturers on LIB-powered vehicles. One of the concerns with using LIBs in these applications is that there are currently no guidelines for installing LIBs in these vehicles. Even though these are outby vehicles, a LIB thermal runaway (TR) in the outby area of an underground coal mine would be problematic because the surrounding coal could catch on fire. Mines from other sectors also use these types of vehicles. Because off-the-shelf automotive-type LIBs can be easily retrofitted into such vehicles, MUV and RTM manufacturers and mines could easily swap out lead-acid batteries for LIBs. Therefore, research on implementing LIBs on these vehicles is warranted. This paper will describe the effects of mine environmental conditions on LIBs and outline a new NIOSH research project examining the environmental susceptibility of MUV and RTM LIBs.

LITHIUM-ION BATTERY BACKGROUND

Lithium-ion Battery Chemistries

Lithium-ion battery is an umbrella term for a group of batteries with components that vary in chemical composition. Most LIBs are named by the elemental makeup of their cathode, while others are named using the makeup of their anode. During discharge, the anode releases stored lithium ions and the cathode accepts lithium ions [11]. The cathode is normally made up of a lithium metal oxide such as lithium-nickel-manganese-cobalt-oxide (NMC) or a lithium metal phosphate such as lithium-iron-phosphate (LFP) [12]. The anode is typically made of carbon in the form of graphene or graphite. LFP cells are used nearly exclusively with a carbon-based anode material. In some cases, the anode is made with lithium titanate or lithium-titanium-oxide (LTO). NMC, LFP, and LTO LIBs are the most common chemistries in mining battery-electric vehicles (BEVs)[13].

Before selecting the types of LIB cells to use, BEV manufacturers have to consider several design parameters: energy density requirements, safe operating temperatures, cost/capacity ($/Wh), unit weight, and others. NMC cells have high specific energy and voltage and low cost per kWh. LFP cells have increased safety and better cycling characteristics, but lower specific energy and slightly higher cost per kWh. LTO cells also offer increased safety and better cycling characteristics along with very fast charging times [12]. However, LTO cells have lower specific energy and higher overall cost. To keep the voltage within a practical range, LTO cells are normally paired with a lithium-metal-oxide cathode.

Lithium-Ion Battery Form Factors

LIBs can be categorized into four form factors or shapes: coin, cylindrical, prismatic, and pouch. Coin batteries are not commonly used in BEVs. Cylindrical, prismatic, or pouch cells are used to form BEV LIB modules by wiring numerous cells in series, parallel, or a combination of series and parallel. LIB packs are built using multiple modules. Large BEV LIB packs can weigh a few thousand pounds.

Cylindrical cells are popular because they are well-suited to automated manufacturing and are available in standard sizes, both of which bring down manufacturing costs. The most common cylindrical cell is the 18650 cell that is 18 mm in diameter and 65 mm in length. Cylindrical cells are also available in larger cells, such as 22650 and 21700 cells. The cylindrical shape provides mechanical stability and helps resist deformation. In some cylindrical cells, built-in safety vents or gaskets can be used to prevent high internal pressures. Cylindrical cells have lower packing density than other cell types but allow easier thermal management [14].

Prismatic cells are built by layering or folding the cathode, separator, and anode, and compressing them into a firm enclosure, which offers mechanical stability. The folding of the layers can lead to stresses at the corners. The size and shape of prismatic cells are highly customizable and allow for a thinner battery pack, if needed. Prismatic cells have higher packing efficiencies but cost more, and they have thermal management challenges [15].

Pouch cells allow for a simple, low-cost construction by placing the battery components in a flexible foil pouch. This thin exterior allows for the lowest weight and highest packing efficiency, but this reduces protection from mechanical deformation, punctures, etc. Another drawback is that pouch cells are prone to swelling [16].

LITHIUM-ION BATTERY ENVIRONMENT-RELATED RESEARCH, STANDARDS, AND REGULATIONS

Limited research has been published regarding environmental effects on LIBs. Some researchers have examined the effects of temperature on LIB aging and dendrite growth, while others have studied the effects of mechanical shock and vibration on LIBs. These mechanical shock and vibration studies have examined performance degradation, mechanical damage, or change in dynamic response. Dendrite growth coupled with mechanical shock and vibration could result in an internal short circuit if dendrites pierce an LIB's separator. Numerous standards exist that involve LIB environmental testing. These standards cover testing such as mechanical shock, vibration, extreme temperatures, thermal shock, humidity, and immersion. Several publications on temperature effects, mechanical shock and vibration, and standards are discussed below.

Waldmann et al. [17] studied temperature-related aging of 18650 LIBs across a temperature range of -20°C to 70°C. The LIBs were cycled at a charge/discharge rate of 1C. Ageing followed an Arrhenius plot with 25°C dividing ageing into two regions. Below 25°C, the ageing rate increased with decreasing temperature and was caused by lithium plating during charging. Above 25°C, the ageing rate increased with increasing temperature and was caused by solid-electrolyte interphase growth on the anode and degradation of the cathode.

Lithium dendrite growth is a significant concern with LIBs. Dendrite formation can cause internal short circuits leading to TR [18]. During charging, these metallic microstructures develop when extra lithium ions accumulate on the anode surface. Dendrites can pierce the battery separator and cause an internal short circuit. Dendrite growth during charging is a function of temperature. Love et al. [19] investigated lithium dendrite growth at -10°C, 5°C, and 20°C. At -10°C, dendrite growth was the fastest as more than twice the number of dendrites formed compared to 5°C and 20°C. However, internal shorting occurred the fastest at 5°C due to the needle-like shape of the dendrites produced at this temperature. Needle-like dendrites are more likely to pierce a LIB's separator. If the separator is pierced by dendrites, an internal short circuit could occur possibly leading to TR.

The separator is a critical component of LIBs [20]. As a safety feature, separators exhibit a large increase in impedance that occurs just below the separator's melting temperature. The purpose of this feature—referred to as shutdown—is to prevent TR. In BEV applications, the separator is roughly 40-mm thick. Due to the thinness of the separator, high puncture strength is required, especially in wound cells such as the cylindrical 18650. If electrode material penetrates the separator, possibly from mechanical abuse, an internal electrical short could be created that might lead to TR.

Mechanical shock and vibration are important environmental concerns for LIBs as vehicles in mining drive over rough terrain and underground vehicles may regularly bump into the rib or other vehicles. The state of charge (SOC) of LIBs affects their vibration response. Pham et al. [21] studied the vibration response of LIB pouch cells as a function of SOC from 0% to 80% SOC in 10% increments. The researchers found that the frequency response of the cells shifted to higher frequencies as SOC increased, indicating a stiffening effect.

Brand et al. [22] studied mechanical shock and vibration effects on pouch-type and cylindrical 18650 lithium-ion cells. The researchers subjected the cells to 300·shocks with a peak amplitude of 150 g and a duration of 6 ms, following the UN 38.3 T4 standard. In addition, sinusoidal vibration was applied to the cells according to the UN 38.3 T3 standard with 10 logarithmic sweeps from 7 Hz to 200 Hz over a period of 3 hours with a peak acceleration of 1 g from 7 Hz to 18 Hz, a peak displacement of 0.8 mm from 18 Hz to 50 Hz, and a peak acceleration of 8 g from 50 Hz to 200 Hz. In addition, a six-month-long sine sweep vibration test was conducted on the cells at a root-mean-square (RMS) acceleration of 1.9 g and frequencies from 4 Hz to 20 Hz. The tests did not harm the pouch cells, but they damaged the 18650 cells. The mechanical shocks caused the 18650 cells to have loose mandrels—center pins—and movement of the current interrupt device (CID). According to the authors, "The CID as well as the connection to the jelly roll are already turned upward. Thus, the CID is likely to be deactivated and therefore might not be able to prevent any dangerous incident anymore." In addition, the jelly roll–so named because of the appearance of the cross section of the battery–had scorch marks where the mandrel contacted the separator. Scanning electron microscope (SEM) inspection confirmed that the separator had melted at the scorch marks. Upon disassembly, the 18650 cells subjected to the UN 38.3 sine sweep test exhibited loose mandrels. After the six-month-long vibration tests, the mandrels of the 18650 cells moved enough to strike against the terminals. The mandrel damaged the separator causing internal short circuits that were confirmed with SEM analysis.

Hooper and Marco [23, 24, 25] investigated the vibration levels and frequencies experienced by passenger car BEVs, hybrid vehicles (HVs), and internal combustion engine (ICE) vehicles. The vehicles were driven across various surfaces at various speeds to compare the resulting vibration across a variety of road input conditions. The researchers found that significant vibration occurs at frequencies below 7 Hz because the vehicle suspension vibration modes are in this frequency range. For automobiles, LIB pack mounting could be an integral part of a vehicle's frame stiffness which affects its vibration response in the 20 Hz to 40 Hz region where torsional vibration modes are important. The researchers compared the results of their vehicle vibration data to recommended vibration test profiles from SAE J2380, USABC Procedure 10, ECE Regulation 100, and BS EN 62660-2:2011. The authors concluded that electric vehicles (EVs) may be exposed to vibration levels outside the range of existing standards. Further, they used the measured vibration data to develop a durability profile for EV testing using HBK nCode software. The nCode-developed profile allows 100,000 mi of vehicle life—a full lifetime of vibration—to be simulated in a short time, for example, fewer than 100 hours.

Hooper et al. [26] also tested the vibration durability of nickel manganese cobalt oxide (NMC) lithium-ion 18650 cells. The researchers subjected groups of NMC cells to vibration that represented 100,000 miles of vehicle life according to either SAE J2380 or the authors' own test profile as developed by Hooper and Marco [23]. Individual cells were charged to 25%, 50%, or 75% SOC. For each profile, a cell was subjected to vibration in one direction—X, Y, or Z. All testing was conducted at a fixed temperature of 21°C. Both vibration profiles resulted in changes in electrical performance and mechanical properties. The electrical performance of the cells subjected to the SAE J2380 profile had the most degradation at 75% SOC, while the cells subjected to the author's test profile had the most degradation at 25% SOC.

In a similar study, Hooper et al. [27] investigated the effect of cell orientation on degradation of nickel-cobalt-aluminum-oxide (NCA) 18650 cells subjected to road-induced vibration using SAE J2380 vibration profiles. For this study, the NCA cells were charged to 75% SOC and all tests were conducted at 21°C. The authors did not observe significant electrical or mechanical degradation.

Lang and Kjell [28] compared triaxial vibration data measured in an EV to several proposed vibration test standards: IEC 62660-2, ISO 12405-1, SAE J2380, SANDIA2005-3123, ECE R100-2, and UN38.3. The measured vibration levels were highest below 100 Hz. Above 1 kHz, the vibration levels were low. Between 200 Hz and 1 kHz, the vibration levels were lower than the sub-100 Hz levels but high enough to be important. The vibrations in all three directions had similar levels, but the frequency spectra of each direction exhibited peaks at different frequencies due to component resonances. When comparing measured vibration to the vibration specified in the standards, the authors found that "Overall, these results are not consistent with existing standards." The main issues are that most of the standards do not go low enough in frequency, as IEC 62660-2, ISO 12405-1, SAE J2380, and SANDIA2005-3123 begin at 10 Hz. Further, most of the standards do not test at frequencies above 200 Hz as SAEJ2380, SANDIA2005-3123, and UN 38.3 stop at 200 Hz, and ECE R100 stops at only 50 Hz.

Ruiza et al. [29] reviewed 12 vehicle LIB standards and regulations that deal with mechanical, electrical, environmental, and chemical abuse. Mechanical abuse tests include drop, mechanical shock, vibration, penetration, immersion, crush/crash, and rollover. Depending on the standard or regulation, the mechanical tests can be applied to LIB cells, modules, or packs, and some apply to the whole vehicle. Pass/fail conditions for individual tests are specified as no fire, no explosion, no rupture, and no leakage. Only the drop, mechanical shock, and vibration tests will be discussed here. Environmental tests include thermal stability, thermal shock and cycling, overheating, extreme cold temperature, and fire exposure. Only the extreme cold temperature test will be discussed here.

Drop tests are recommended to guard against damage during battery removal or installation [29]. The standards/regulations specify battery pack drop tests with heights from 1 m to 10 m and surfaces that include 20-mm-thick hardwood floor, concrete floor, flat surface, and a cylindrical steel object with a 150-mm radius. The SOC for the drop tests ranges from 80% to 100%, depending on the standard/regulation.

Mechanical shock tests subject LIBs to impulsive loading that results from events such as hitting a pothole with a vehicle. The mechanical shock tests vary significantly amongst the standards/regulations [29]. For mechanical shock tests applied to cells, modules, or packs, the standards/regulations specify peak acceleration levels from 20 g to 150 g with durations from 6 ms to 110 ms. During these tests, the SOC is 50%, 80%, or 100%, depending on the standard or regulation. Each standard/regulation has different requirements with respect to the direction of the shock. Some standards apply shocks in all three axes, while some require only one or two directions.

Vibration tests are applied to cells, modules, or packs using either sinusoidal inputs to search for resonances or random input to simulate road-induced vibration during operation [29]. Depending on the standard/regulation, the lowest vibration frequency is 5 Hz, 7 Hz, or 10 Hz; and the highest vibration frequency is 50 Hz, 55 Hz, 150 Hz, 190 Hz, 200 Hz, or 2 kHz. Each standard/regulation specifies vibration in either the vertical direction, the vertical and horizontal directions, or all three directions. The SOC for vibration testing is one of either 20%, 50%, 60%, 80%, 95%, or 100%, depending on the standard/regulation. Two of the standards/regulations use a different SOC for each direction of vibration.

Each of the standards/regulations includes immersion tests to examine the effect of flooding [29]. Immersion tests consist of immersing a cell, module, or pack in a 25°C saltwater bath. Depending on the standard/regulation, the SOC is specified as 50%, 80%, 95%–100%, or maximum operating SOC. Of the standards/regulations, two specify the fluid as "clear or salty water" and "nominal composition of sea water," one calls for 0.6 M sodium chloride, and two specify 5% sodium chloride by weight. The immersion time varies from 1 to 2 hours or until "visible reactions have stopped."

Immersion tests could be particularly important in mining applications. Considering that some mines have water dripping from their roofs, an LIB could be exposed to flooding due to water dripping onto a piece of equipment for an extended period. In addition, some underground mines have pools of water throughout, and water could be splashed onto an LIB as the operator drives through the water. In late 2022, flooding associated with Hurricane Ian led to LIB-powered golf cart fires [30, 31]. As flood waters receded, numerous golf carts caught fire due to internal shorting or reactions caused by saltwater entering the golf cart batteries. Fires were observed on October 16, 2022 and November 19, 2022, destroying 71 of 72 LIB-powered golf carts.

Extreme cold temperature tests subject the cell, module, or pack to conditions that could lead to dendrite formation [29]. Only U.S. Advanced Battery Consortium standard SAND99-0497 calls for an extreme cold temperature test. In this test, an LIB is charged at its normal charge rate and subsequently discharged to 80%, 50%, 40%, 20%, and 0% SOC at temperatures of -40°C (-40°F), -20°C (-4°F), 0°C (32°F), and 25°C (77°F). The test is stopped if damage is observed.

The research discussed above highlights several mining-environment-related concerns for LIBs. LIBs are prone to dendrite growth during charging, and dendrite growth rate and morphology depend on charging temperature. The presence of dendrites combined with high mechanical shock and vibration levels could result in damage to the separator, possibly leading to an internal short circuit and TR. LIB vibration response is affected by SOC. Therefore, the damage caused by mechanical shock and vibration depends on SOC. Over time, mechanical shock and vibration could cause microscopic cracks that might allow mine water to enter an LIB housing. Further, condensation on an LIB in a cold, high relative humidity (RH) environment might cause water droplets to form, and cracks in an LIB case could allow dripping water to enter. In addition, an LIB could be dropped when it is being installed or swapped out. The shock and impact loading due to dropping the battery pack could immediately damage internal components or cause microscopic cracks in the LIB case. Based on these concerns, LIBs intended for use in mine vehicles should be subjected to a comprehensive test procedure that includes a drop test; mechanical shock and vibration tests across ranges of SOC, temperature, and RH, and, possibly, an immersion test. The immersion test should be applied to an LIB after it has undergone the drop test and mechanical shock and vibration tests because these tests could cause cracks in a battery case that might allow water to enter.

ENVIRONMENTAL SUSCEPTIBILITY OF MINE UTILITY VEHICLE AND RUBBER-TIRED MANTRIP LITHIUM-ION BATTERIES

Due to the potential widespread use of LIBs in MUVs and RTMs in the near future and concerns with adverse mine-related effects on LIBs, the National Institute for Occupational Safety and Health (NIOSH) is launching a project to examine these concerns. The project is planned as a four-year effort that started on October 1, 2023. The objective of the project is to determine the susceptibility of MUV and RTM LIBs to environmental factors associated with mining, such as mechanical shock, vibration, temperature, moisture, and immersion, and to provide information related to protecting LIBs from these environmental factors.

The MUV/RTM LIB project has five specific aims:

1. To characterize the environmental conditions that LIBs would be exposed to while in use on MUVs and RTMs
2. To identify existing environmental test standards for LIBs that could be applied to LIBs used on MUVs and RTMs
3. To develop an environmental test procedure to evaluate LIBs used on MUVs and RTMs
4. To determine the susceptibility of MUV and RTM LIBs to environmental conditions associated with mining
5. To determine how to protect MUV and RTM LIBs from the environmental factors associated with the mining environment.

Each of the above will be discussed below.

Characterize MUV/RTM Environmental Conditions

Knowledge of the operating conditions for MUVs and RTMs is critical to assessing LIBs' ability to withstand mining environment conditions. The project team will work with collaborating mines, equipment manufacturers, and battery suppliers to collect operating data in surface and underground mines across all commodities. Collecting data at mines across the country ensures that all mining conditions are represented.

Environmental data recorders and rugged data acquisition equipment will be used to collect operating data. The main parameters of interest are mechanical shock and vibration, temperature, and relative humidity. In addition, parameters such as travel speed and incline angle will also be acquired. After installing the data acquisition equipment, one or more days of data will be acquired from the instrumented MUVs/RTMs under normal operating conditions.

The measured data will be used for developing a robust laboratory test standard for MUV/RTM LIBs and to develop a "torture track" within the NIOSH Experimental Mine. The measured mechanical shock and vibration data will be used to develop an accelerated life test so that multiple years of LIB use can be represented in a few months of time using laboratory vibration testing on an electromechanical shaker. The temperature and relative humidity will be used as thermal conditions for the laboratory testing.

Identify Existing Environmental Standards/Regulations and Develop a Comprehensive Environmental Test Procedure

As discussed in the literature review above, numerous test standards for LIBs already exist. However, these are not necessarily based on real-world operating conditions, especially the conditions encountered in mining. We plan to thoroughly review existing LIB standards/regulations to ensure all potential environmental concerns are addressed in our test procedure. The anticipated components of the test include the following:

1. A drop test to account for unintentional mishandling of an LIB prior to installation
2. Shock and vibration applied to LIBs at ranges of temperature and SOC
3. Immersion of the LIB in electrically conductive "mine water."

The drop test will specify the drop height, orientation, and surface. The drop height will likely be roughly 1 m, as this is reasonably representative of the height at which a person would carry an object. The battery could be dropped so that it lands on a corner, or it could be dropped to land flat on its bottom surface. The surface could range from pea-sized gravel to concrete. The drop test is important because it could cause cracks in the case that would subsequently allow moisture to enter.

The mechanical shock and vibration tests will be conducted across a range of temperatures that encompasses the minimum and maximum temperatures observed in field conditions at regularly spaced intervals, for example every 10°C. The relative humidity for these tests will also be based on field measurements. Because LIB vibration response depends on SOC, the SOC will be varied from 20% to 100%, for example. At each combination of conditions, the device under test will be tested for a set number of hours before moving on to the next combination of conditions. Once a complete "cycle" of shock and vibration tests is complete for all combinations of temperature, relative humidity, and SOC, an immersion test will be conducted.

The immersion test will be conducted by placing the LIB into a tank of "mine water" which will contain contaminants that are representative of mining. The purpose of this is to ensure that the liquid is electrically conductive. Once the LIB is lowered into the liquid, the LIB will be kept in the liquid until air bubbles are not observed. After the battery is lifted out of the tank, it will be observed for enough time to ensure no adverse events will occur, 24 hours for example.

The details of each of the aforementioned tests will be determined after completing our review of applicable standards/regulations. The individual tests will follow the standards when they are appropriate for the mining application. However, modifications will be made to the procedures to improve the tests' representations of mining conditions.

Determine the Environmental Susceptibility of Mine Utility Vehicle and Rubber-tired Mantrip Lithium-ion Batteries

In order to determine MUV/RTM LIB environmental susceptibility, the test procedure described above will be applied in a laboratory setting. These tests may be conducted internally at NIOSH or at an outside laboratory. However, because it is expected that the cost associated with conducting the above tests at an outside laboratory will be cost prohibitive, we expect to conduct these tests at NIOSH Pittsburgh Mining Research Division. Tests will first be conducted at mechanical shock and vibration levels that represent field conditions. If these tests do not result in adverse LIB events, such as a voltage drop, visible damage, or indication of thermal runaway, the mechanical shock and vibration levels will be increased incrementally in an attempt to establish the levels that would cause adverse events.

To conduct these tests internally, specialized test facilities and apparatuses will be developed within the NIOSH Experimental Mine which has controllable fresh air flow and multiple boreholes to the surface. In addition, the Experimental Mine stays at a consistent temperature of roughly 13°C to 16°C (55°F to 60°F) year-round. This is expected to be roughly halfway between the minimum and maximum temperatures at which the LIBs will be tested.

The primary apparatuses that would be developed or purchased include a drop test machine, a temperature/relative humidity chamber, and an immersion test apparatus. The drop test machine will lift the tested battery to the necessary height and release it so that it free falls onto the test surface. To subject LIBs to shock and vibration, a commercially available hydraulic or electromechanical shaker and a suitable controller will be purchased. The temperature/relative humidity chamber will be designed to encapsulate the moving portion of the shaker. The immersion test apparatus will consist of a platform that lowers the tested LIB into a suitably sized container of liquid.

During testing, the LIB will be monitored to examine surface and, possibly, internal temperatures. A thermal imaging camera will be used for surface temperature measurement. Multiple thermocouples will also be attached to the battery case and, if possible, to cells within the battery case. Pressure sensors may also be used inside the case because any venting of LIB cells inside is expected to increase the internal pressure of the case. At this time, we expect to conduct the tests with the battery management system activated.

Numerous safety measures will be taken to protect researchers and test equipment. The facility will use a video monitoring system so that researchers can remain outside the test chamber during tests. A ventilation system will be installed to allow fresh air to flow into the test chamber and contaminated air to flow out through an existing borehole. Gas monitoring equipment will be installed within the test chamber to ensure the atmosphere is safe for researchers to enter.

Mine Utility Vehicle/Rubber-tired Mantrip Battery Protection

To protect LIBs on MUVs/RTMs from excessive mechanical shock and vibration, vibration isolation systems will be designed. For this effort, dynamic simulation models of the vehicles will be developed to predict the vibration response at the LIB on the machine with and without vibration isolators in place. Simulations will be conducted to determine appropriate isolator parameters such as spring rate and damping. Tire and suspension characteristics and vehicle weight will be obtained from cooperating manufacturers or determined via testing and measurement.

For the simulations, the approximate road inputs will be derived from field conditions using measurements of speed and resulting vibration response. In addition to the shock and vibration recorded using the environmental data recorders, on selected MUVs/RTMs additional accelerometers will be mounted at the corners of the vehicles to determine the predominant vibration directions of the tested vehicles. This data will allow us to determine the contributions of vertical, pitch, and roll suspension modes of vibration.

The road inputs determined from test data will also be used to construct a "torture course" within the Experimental Mine. It is expected that this test track will consist of coarse gravel, fine gravel, 2x4s, speed bumps, and curbs. The 2x4s, speed bumps, and curbs will be arranged to elicit the vehicle motion observed in the field. NIOSH will instrument one or more of its MUVs to conduct in-house testing on the test track. To verify that the vibration isolation designs reduce LIB vibration, vehicle vibration tests will be conducted using the test track.

CONCLUSIONS

LIBs are being implemented in the mining industry on MUVs and RTMs. Because the mining environment is severe in terms of mechanical shock and vibration, temperature range, and relative humidity, research must be performed to examine the environmental susceptibility of LIBs used on these vehicles. Existing standards/regulations may not be representative of field conditions. Therefore, field testing must be performed to determine actual operating mechanical shock and vibration levels, temperatures, and relative humidity values for tests. By subjecting LIBs to a comprehensive environmental test, the environmental susceptibility of LIBs can be assessed. LIB isolation systems can be installed on MUVs/RTMs, if necessary. The information resulting from this effort can be used by mines, equipment manufacturers, and battery suppliers to improve LIB designs and to reduce the likelihood of adverse LIB events.

LIMITATIONS

The research project described above will not necessarily prevent all adverse LIB events. Manufacturing defects will not be addressed. In addition, field testing will be conducted at a small number of mines relative to the entire population of mines. Through laboratory testing, this research intends to evaluate only the environmental effects that are expected to be most critical, such as mechanical shock and vibration, temperature extremes, and moisture exposure, and only within a range of each of these parameters. Therefore, the worst-case conditions may not be identified.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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24-021

Corrosion Strategies at the Resolution Copper Project, Arizona

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INTRODUCTION

Corrosion has long been identified as a potential risk to the long-term ground support stability due to degradation of internal ground support elements such as rock bolts but also to surface support from mesh, straps, bolt plates, and ancillary support of utilities such as hangers. The emphasis is to understand the corrosion mechanisms on the primary ground support elements and any supplemental steel or arch sets. The water and chemical processes from oxidation(rust), stress corrosion cracking, and even the electrical charge created during these reactions contribute to the corrosion of the steel support elements. The main goals are to mitigate the effects of corrosion and to be able to predict those areas of high water or high sulphide for potential rehab maps. It is also essential to identify and classify the visible corrosion as part of damage mapping and provide bolt testing to those areas of suspected internal damage from corrosion. This is important to get an estimate of the support longevity or expected life before rehab to minimize the overall cost of the operation.

Fully encapsulated bolts using resin provide the best protection from the low pH acids generated from oxidation of pyrite as well as alkaline waters with high particulate solids and higher salinity that can lead to corrosion. In addition, it can be demonstrated that pumpable resins using hollow bolts or rebar are more effective in ensuring the complete encapsulation of bolts than the partial encapsulation from resin-epoxy cartridges that must be placed in the holes manually and bolts spun to break the cartridges to complete the mixing. This is especially important in high water prone areas.

Resolution Copper completed the sinking of the No 10 shaft to a depth of 6,943' below the surface and was ultimately connected to the number 9 shaft. The deepest development at the mine is the second transfer pumping station (TPL2) or 68 level at 6,780 feet below the surface. The current 68 level and subsequent 58 level development and lower caving levels and shafts will be dependent on the long-term viability of the ground support given the high sulfide environment if coupled by the presence of hot water and associated high humidity (>60%).

WATER CHEMISTRY RESEARCH

Water sampling of the #9 and #10 shaft and of the TPL2 or 68L were collected and summarized in several reports. In a more recent study by Logsdon (2022), the kinds of water collected from deep water flows include Montgomery (2012) and are summarized in Table 1. The chemical concentrations of typical water collected vary in the number of dissolved solids and show that underground waters at Resolution are neutral pH and do not show evidence in total dissolved solids or high sulfate concentrations of high acid generation. The conceptual model is that native groundwater is not corrosive (neutral pH, very low oxygen), but where the groundwater becomes oxygenated (in mine voids, fractured rock around excavation development aided by ventilation), and passes through high sulfide rock, the water becomes corrosive. The suggestion is that if these were typical of most of the water and geology low in sulfides, the environment of rock bolts, mesh, and other steel-based infrastructure, there would be little or no risk of corrosion. However, the presence of abundant hot water