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Injury Surveillance and Safety Considerations for Large-Format Lead-Acid Batteries Used in Mining Applications

Miguel Angel Reyes and
Office of Mine Safety and Health Research, National Institute for Occupational Safety and Health, Pittsburgh, PA 15216 USA

Thomas Novak [Fellow, IEEE]
Department of Mining Engineering, University of Kentucky, Lexington, KY 40506 USA

Miguel Angel Reyes: MAReyes@cdc.gov; Thomas Novak: Thomas.Novak@uky.edu

Abstract

Large lead-acid batteries are predominantly used throughout the mining industry to power haulage, utility, and personnel-carrier vehicles. Without proper operation and maintenance, the use of these batteries can introduce mechanical and electrical hazards, particularly in the confined, and potentially dangerous, environment of an underground coal mine. A review of the Mine Safety and Health Administration accident/illness/injury database reveals that a significant number of injuries occur during the maintenance and repair of lead-acid batteries. These injuries include burns from electrical arcing and acid exposure, as well as strained muscles and crushed hands. The National Institute for Occupational Safety and Health investigated the design and implementation of these batteries to identify safety interventions that can mitigate these inherent hazards. This paper promotes practical design modifications, such as reducing the size and weight of battery assembly lids in conjunction with lift assists, as well as using five-pole cable connectors to improve safety.

Index Terms

Coal mining; lead-acid battery safety; mining industry; occupational health; occupational safety

I. Introduction

In 2001, two sequential explosions inside the Jim Walter Resources Mine No. 5 in Alabama claimed the lives of 13 mine workers. The Mine Safety and Health Administration (MSHA) postdisaster investigation identified the ignition source of the initial explosion as a scoop tractor battery, which was damaged from a roof fall. The battery arced and ignited an explosive mixture of methane and air [1]. Fig. 1 shows how the metal battery assembly came in contact with a battery terminal after the enclosure was damaged. The initial explosion severely injured one person and destroyed numerous ventilation controls, which led to a subsequent and larger explosion. Dubaniewicz [2] subsequently recommended a

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reevaluation of the Code of Federal Regulations (CFR) Title 30, Part 7 requirements for battery assemblies, with regard to insulation between a battery enclosure and cells to prevent shorting.

The ignition of an explosive methane and air mixture from arcing may be the most extreme example of a hazard posed by batteries, but a variety of additional hazards exist. Other safety-related hazards include fire, flash, and burn hazards attributed to the extremely high energy dissipated during short circuits. In addition to the electrical dangers, musculoskeletal hazards exist in the form of muscle strains and overexertion from performing recurring tasks such as lifting heavy lids on battery assemblies or lifting the battery cells themselves. Environmental hazards also exist. Potentially explosive hydrogen gases may be emitted and battery acid spillage may occur as a result of improper maintenance and charging practices.

Whether batteries are identified as the cause of an incident, or implicated as a compounding factor in the severity of an incident, accident reports reveal some of the inherent vulnerabilities of lead-acid batteries commonly used in underground coal mines. To address these problems, researchers at the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research investigated the applications of lead-acid batteries through a multifaceted approach designed to identify root causes of problems and develop safety considerations based on the findings. The main objective was to investigate the use of these batteries with respect to hazards resulting from routine operations. The investigation included analyses of MSHA injury statistics and observations about the safety practices and considerations being explored by battery and machine manufacturers.

II. Methodology

The design, application, maintenance, and operation of lead-acid batteries used in mining were investigated. This effort consisted of analyzing injury statistics, conducting literature reviews on safety considerations, and performing site visits and interviews with engineers and safety personnel.

A. Investigation of MSHA Accident/Illness/Injury Statistics

The initial phase of the investigation was to identify the primary sources of injury. The MSHA Accident, Illness and Injury database was reviewed to obtain accident statistics involving large-format batteries from 2008 to 2012. The analysis emphasized nonfatal, days lost (NFDL) injuries [4].

The cases were selected by filtering the incident records using a keyword search to focus specifically on cases that mentioned the word “battery” in the accident narratives. This approach yielded a total of 324 reports. Of the 324 reports, 128 incidents could be attributed to the maintenance and repair of lead-acid batteries. The remainder of the incident narratives containing the word “battery” described incidents involving battery-powered vehicles or other battery formats (e.g., cap lamp batteries), which were outside the scope of this investigation. The applicable reports were then reviewed and categorized to gain insights into the root causes.

B. Literature Review

In addition to those cited earlier, other resources used included a review of battery safety prevention program tips found at MSHA's Accident Prevention Program webpage (http://www.msha.gov/Accident_Prevention/minetype/ugcoal.htm) [5] and manufacturers' installation and maintenance manuals [6]. This review focused on large-format lead-acid batteries typically used in underground mining equipment.

C. Site Visits and Interviews

Site visits and informal interviews were conducted within the various battery industry sectors, including manufacturing, protection, and refurbishment companies, as well as the end users at mining operations. Each stage of the large-format battery design and manufacturing process was observed while exploring potential safety issues. Three battery manufacturing/refurbishing companies, two original equipment manufacturers (OEMs), three mine sites, and the international mine expo were visited; and discussions were held with engineers and end users at various locations. The visits were also supplemented by phone and e-mail discussions to gather information about large-format battery safety when site visits could not be scheduled.

III. Results

The analysis of the MSHA accident/illness/injury statistics database revealed the types of accidents that can be attributed to lead-acid batteries. Injuries were categorized into four major groupings based on the review of the MSHA injury database:

1. back/shoulder/muscle strains;
2. crushing/cutting hand injuries;
3. arc flash/acid burns;
4. others, not elsewhere classified (NEC).

The back/shoulder/muscle strains category included injuries sustained because of the weight of the battery cells or the battery assembly lids. Ranging from changing out individual cells to raising the lids for maintenance or cleaning, these cases highlight the issues involving overexertion, improper lifting techniques, and frequent interaction with heavy objects. The hand injuries category included cases in which the lids were improperly secured in the open position during maintenance and repair tasks, which resulted in a lid dropping on a mine worker's hand(s). These injuries entailed broken fingers and cuts that may have required stitches. The third category consisted of injuries sustained from explosions originating in the battery enclosures, injuries caused by arcing between terminals, and acid burns from spills. These cases were combined because of the common causality when the events were compared with each other. For example, an eye injury could occur from an arc flash caused by a dropped tool creating a short circuit, which, in turn, resulted in an explosion that sprayed acid on the mine worker's face. The NEC category refers to all other cases that include incidents such as nausea from exposure to hydrogen accumulation, which can occur during the charging process, and from minor cuts sustained during cleaning of battery assemblies.

The categories were organized based on the frequency of incidents, as depicted in Fig. 2. Crushing/cutting hand injuries had the highest number of reported cases, i.e., 40. The second leading category was arc flash/acid burn injuries, with 38 reported cases. Some of these cases were exacerbated by the lack of Personal Protective Equipment (PPE), such as face shields or rubber gloves. The third leading cause of injuries was back/shoulder/muscle strains, with 37 reported incidents. These injuries included the lifting of individual batteries and cells and opening heavy components such as the battery enclosure lids during maintenance tasks. Analysis of the accident data identified the types of questions to be asked and guided the emphasis that would be placed on research priorities when conducting the field investigations.

IV. Site Visit Observations

Battery assembly regulations, which are defined by MSHA in CFR Title 30, Part 7, Subpart C, are designed to separate the environment from the internal hazards of the batteries while protecting the batteries from the harsh external operating conditions that are typically encountered in mines. However, as identified by MSHA injury statistics, these assemblies are also directly relevant to a significant number of injuries because of their design and excessive weight. These injuries include strained muscles, crushed extremities, or cuts on fingers and hands.

In the following, the issues related to safety features for battery assemblies are analyzed, including innovative design changes by manufacturers to explore ways to reduce the impact of factors that contribute to these types of injuries.

1) Size of Lids

The size and weight of lids may contribute to back and shoulder injuries. Several lid configurations were observed in the field and varied from long rectangular lids to smaller square lids, depending on the manufacturer and equipment type. The two configurations are depicted in Figs. 3 and 4.

Weight distribution and handle placement pose challenges to users in terms of body positioning when raising the lids. The challenge is worsened in low coal seams where the limited vertical space creates more difficulty. The smaller size of the square lids can relieve the strain caused by the frequent need to open and close the lids for maintenance and repair work. The ease of opening the lids also affects the performance of maintenance and repair tasks, because a repairman is more likely to put off preventive maintenance if lids are difficult to open.

2) Battery Assembly Lid Material

Some of the overexertion and strain injuries associated with lids can also be attributed to the types of materials being used in their construction. MSHA prescribes criteria for designing battery assemblies in CFR Title 30, Part § 7.44. These criteria focus on the tensile strength of the material, the impact resistance of the assembly, and the flame resistance of the components used. To meet these criteria, the lids are commonly made of hot rolled steel. The hardened steel protects the batteries from being pierced or crushed in the event of a roof fall.

However, the metallic lids can also introduce hazards such as the potential to provide a conductive path for short circuits across battery terminals in the event of a damaged battery assembly. Although measures are taken to minimize that risk, such as the use of polyvinyl chloride insulation, the use of steel increases the weight of the lids and may impact musculoskeletal injuries.

Accordingly, manufacturers are also proactively considering the application of composite materials to construct new battery assembly lids and covers to reduce weight while maintaining the required strength and fire resistance. By designing battery assembly lids with a lighter nonmetallic material, manufacturers may contribute to reducing the number of musculoskeletal injuries suffered from handling the heavier rolled steel assemblies.

MSHA does provide requirements for battery assemblies constructed of alternative materials. The regulations and requirements, which are outlined by CFR Title 30, Part §7.44(a)(2), state that any battery assembly not made of hot rolled metal must possess "tensile strength and impact resistance of battery boxes for the same weight class." In addition to the tensile strength, the new material must also pass flammability and acid resistance testing outlined by CFR Title 30, Part §7.44(a)(4). Examples of alternative materials include hardened phenolic composites or injection-molded composites. While the use of alternative materials has been explored in countries such as South Africa, this area requires more research and must follow the proper approvals process before it can be implemented across the mining industry. A major benefit for doing so is the potential impact of reducing musculoskeletal injuries and promoting proper battery charging practices such as charging with all lids raised due to the reduced weight of the lids.

3) Lift Assists

An alternative solution to the weight issue presented by the heavy steel lids is the implementation of lift assists. Some manufacturers offer pneumatic lift assists to help address this risk (see Fig. 5). A lift assist helps raise the lids safely by reducing the musculoskeletal strain to which a mine worker is subjected. Thus, injuries attributed to the frequent raising and lowering of the battery lids for charging, maintenance, and repairs may be significantly reduced. These lift assists are relatively inexpensive and easy to replace if damaged. Furthermore, the costs of these assists may be offset by reducing the costs associated with lost-time injuries.

4) Stainless Steel Hinges/Rubber Covers

Another factor that contributes to the effort required to open lids is rusted hardware, which results in increased hinge friction. Lid hinges rust quickly in a wet mine environment. Some manufacturers offer stainless steel hinges to reduce the rusting problem.

Manufacturers also recommend the use of hinge covers. These covers serve a dual purpose as they effectively keep rock dust and dirt from the hinges while reducing the accumulation of debris inside the battery assembly (see Fig. 6). Debris accumulation can create a potential for a short circuit across battery terminals that may result in a battery fire or explosion. Note in Fig. 6 the amount of debris built up on the battery assembly surface that was effectively kept away from the battery's surface area and terminals by the use of hinge covers.

5) Cable Connectors

The charging cables and type of cable connectors play a major role in a battery's arcing potential. There were a number of cases, discussed during the interviews, which involved arcing when disconnecting cables. The discussions revolved around the susceptibility of dated two-pole connectors and cables to arcing. While the two-pole connector cables are no longer allowed in some states, there are still many small operations that use these connections because of legacy equipment and cost.

A five-pole look-ahead charging cable connector is a major improvement to the two-pole connector. This configuration, which is depicted in Fig. 7, consists of positive and negative pins, a ground pin, and two pins used to "look ahead." The two look-ahead pins serve the purpose of interlocking with the charging coupler and ensuring that there is a proper connection prior to starting the charging cycle. This feature also eliminates arcing when the charging cables are disconnected from the battery by tripping a circuit breaker before the power contacts are separated.

6) Breaker Boxes

Accident/illness/injury statistics show a small number of cases involving arcing when cables were pulled from the battery assembly (see Fig. 2). These reported cases, which are included in the arcing/acid burns category, often occurred during the maintenance and the charging of batteries because the batteries were not properly deenergized prior to the cables being disconnected. From an engineering standpoint, the addition of a circuit breaker on a battery assembly, as shown in Fig. 8, reduces that potential by providing a local method for deenergizing a battery.

While some OEMs are making this feature standard on 240-V models, it is not a practice that is being implemented by all mining companies. These interventions come at an added expense, which many operators may be unwilling or unable to incur. At an estimated $10 000 per installation, manufacturers realize that some mine operators will forgo this option unless there is a regulation requiring the use of such a safety feature. They consider this to be particularly true with intermittent-use Fig. 9. Debris and leakage buildup on terminals. vehicles, such as scoop tractors, where the cost associated with adding this feature causes end users not to choose it. However, the use of a battery circuit breaker can prevent arc flash burns sustained by workers while pulling cables from connectors prior to proper deenergization.

7) Intercell Connector Caps

Although the lids and covers of battery assemblies are made with hardened steel and are often insulated on the inside surface, intercell connector caps also provide another layer of protection. These intercell connector caps enclose the terminals and provide a thin layer of plastic to prevent arcing across the terminals. Noteworthy is the apparent absence of an intercell connector cap in Fig. 1. The intercell connector caps also serve the purpose of preventing arcing and shorting across terminals when tools are dropped or left in the battery assemblies. Although these intercell connector caps provide protection against short circuits between terminals, battery refurbishing companies revealed that these caps can have a

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negative impact by hiding electrolyte leakage and the buildup of debris at the battery terminals, as shown in Fig. 9, which can go unnoticed for an extended period. This can result in fires and even explosions caused by short circuits.

8) Internal Sensors

Hydrogen is produced from the electrochemical process that occurs when lead-acid batteries are charged. Hydrogen has an explosive range of approximately 4%–74% in air and can initiate an explosion even when the oxygen content of the air is as low as 5% [3]. Monitoring hydrogen levels to prevent the accumulation of dangerous concentrations could eliminate the potential for an explosion. Personnel at one of the mines visited are currently exploring the use of infrared gas monitors to detect the accumulation of hydrogen in battery charging stations. This feature can alert mine workers of impending dangerous concentrations of hydrogen so that appropriate measures can be taken to neutralize the threat through ventilation controls.

9) Alternative Chemistries for Lead-Acid Batteries

This research effort focused on large-format lead-acid batteries due to their dominant use throughout the mining industry for power haulage, utility, and personnel-carrier vehicles. However, other chemistries are being explored to improve safety and efficiency related to battery lifecycle and energy produced. These battery types are relatively new and, by most accounts, are considered cost prohibitive. For example, lithium ion batteries are one of these newer chemistries being considered as a replacement for the lead-acid batteries; however, the cost associated with implementing lithium ion technology on such a large scale and concerns regarding the safety issues associated with incorporating them in such a large volume have discouraged their use. A majority of the manufacturers interviewed indicated that lithium ion batteries are cost prohibitive and that their use would not be feasible until the technology is further developed and is more affordable.

Another chemistry considered is sodium metal halides. The use of metal halide chemistries is currently being pursued by the mining division of one OEM. While there is much to learn about this battery chemistry and its operating parameters, its major appeal is that it would eliminate the frequent maintenance requirements that are associated with a lead-acid battery. Battery manufacturers developing this chemistry for use in mining applications stated that this chemistry provides higher energy density, weighs half the amount of typical lead-acid batteries, has a higher tolerance to extreme operating conditions, contains no harmful chemicals, and is virtually maintenance free. These features certainly have the potential for reducing injuries associated with battery maintenance.

V. Safety Considerations

The safety considerations were identified based on the information gathered from the field observations and interviews. These safety interventions should be accompanied by an adequate level of training for the mine personnel tasked with performing battery maintenance and repair. The injury statistics reviewed as part of this study suggest that this does not always occur. Some of the incident reports highlighted accidents that may have been prevented if personnel were properly trained to perform the tasks and were using the proper PPE and tools.

1) Personnel Training

Training is often provided by the battery manufacturers and the OEMs in the form of printed literature, videos, and on-site hands-on training. These training methods focus on the basic concepts of how a battery works, proper charging, and maintenance practices for cleaning and changing cells. These sources continue to play a significant role in mine worker safety. More recently, some mines have employed and trained mine workers to become dedicated battery technicians. The battery technicians are responsible for maintaining and transporting the batteries to their host vehicles in addition to record keeping for charging and cleaning cycles, visually inspecting batteries for damage, and determining repair schedules as needed. Assigning only qualified technicians to perform the day-to-day maintenance could help reduce accidents attributed to personnel not following proper handling recommendations established by battery manufacturers and performing inadequate repair techniques on batteries.

2) PPE

Another important safety consideration relates to wearing the proper PPE during battery maintenance and repair tasks. Performing a job hazard analysis for each maintenance and repair task could help determine the proper levels of PPE that should be worn. Chemical-resistant gloves, aprons, and face shields may help prevent battery acid injuries highlighted by the accident/illness/injury database analysis.

VI. Conclusion

NIOSH researchers have performed an analysis of injury statistics, conducted literature reviews, and executed a number of mine site and factory visits to investigate safety practices used with lead-acid batteries throughout the mining industry. The comprehensive review of MSHA accident/illness/injury statistics identified three significant injury groupings was the basis of discussion for the site visits and phone interviews.

The authors found that there were safety interventions and considerations that may be implemented to mitigate serious injuries encountered through the daily use, charging, and maintenance of these batteries. The authors also identified injuries that may have been preventable had the maintenance personnel worn the proper PPE and had been properly trained in recognizing the hazards present in performing specific tasks safely.

Overall, lead-acid battery manufacturers and end users have been proactive in addressing some of the injuries and fatalities that have been attributed to unsafe practices by incorporating safety features for added protection and developing regimented training programs for their mine workers. These safety features include the use of mechanical lifts to reduce the weight of the battery assembly lids, the use of “smarter” cable connectors to reduce, or even eliminate, arcing potential when connecting and disconnecting batteries, and the use of circuit breakers to deenergize equipment prior to disconnecting and connecting. They have also continued to develop new solutions to overcome some of the challenges experienced, such as exploring different materials for battery assembly construction and the use of sensors to monitor the concentration of hydrogen during the charging.

As new technologies and battery chemistries emerge, there may be new challenges and hazards to consider and overcome. However, these new technologies and chemistries may also provide the solutions to the challenges faced by manufacturers and end users of lead-acid batteries. Regardless of the technologies or chemistries used, the design features implemented should always consider the end user's safety, whether those features are for protection against immediate mechanical and electrical hazards or the long-term musculoskeletal injuries that may be developed over time.

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The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NIOSH. Reference to specific brand names does not imply endorsement by NIOSH.

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Biographies

Miguel Angel Reyes received the B.Sc. degree in electrical engineering from The University of Texas at El Paso, El Paso, TX, USA, in 2006.

His federal service has focused on promoting mine safety research through his involvement and contributions to the Mine Illumination, the Emergency Communication and Tracking, Battery Safety and Proximity Detection, and Collision Avoidance projects. He is currently an Electrical Safety Team Leader for the Electrical and Mechanical Systems Safety Branch with the Office of Mine Safety and Health Research, National Institute for Occupational Safety and Health, Pittsburgh, PA, USA. His research revolves around the evaluation, development, and validation of systems in both the laboratory setting and surface and underground coal mine environments.

Mr. Reyes is actively involved in several professional societies and organizations and has been invited to present his research in the U.S. and abroad.

Thomas Novak (M’83–SM’93–F’05) received the B.S. degree in electrical engineering from Pennsylvania State University, University Park, PA, USA, in 1975, the M.S. degree in mining engineering from the University of Pittsburgh, Pittsburgh, PA, in 1978, and the Ph.D. degree in mining engineering from Pennsylvania State University in 1984.

He currently holds the Alliance Coal Academic Chair in the Department of Mining Engineering, University of Kentucky, Lexington, KY, USA. His prior employment history includes the following: the Director of Mining Science and Technology with the National Institute for Occupational Safety and Health; the Department Head and C.T. Holland Professor of Mining and Minerals Engineering with Virginia Polytechnic Institute and State University, Blacksburg, VA, USA; and the Department Head and holder of the G. N. Drummond Chair in Civil and Environmental Engineering with The University of Alabama, Tuscaloosa, AL, USA.

Dr. Novak is a Registered Member of the Society of Mining Metallurgy and Exploration. He has served as a member of the IEEE Industry Applications Society (IAS) Executive Board and was the Chairman of its Process Industries Department (1994–1998) and Meetings Department (2000–2002). He also served as the Vice Chairman (1990–1992 and 2008–2010) and the Chairman (1992–1994 and 2010–2012) of the IAS Mining Industry Committee. He is also a Licensed Professional Engineer in the States of Alabama and Pennsylvania.

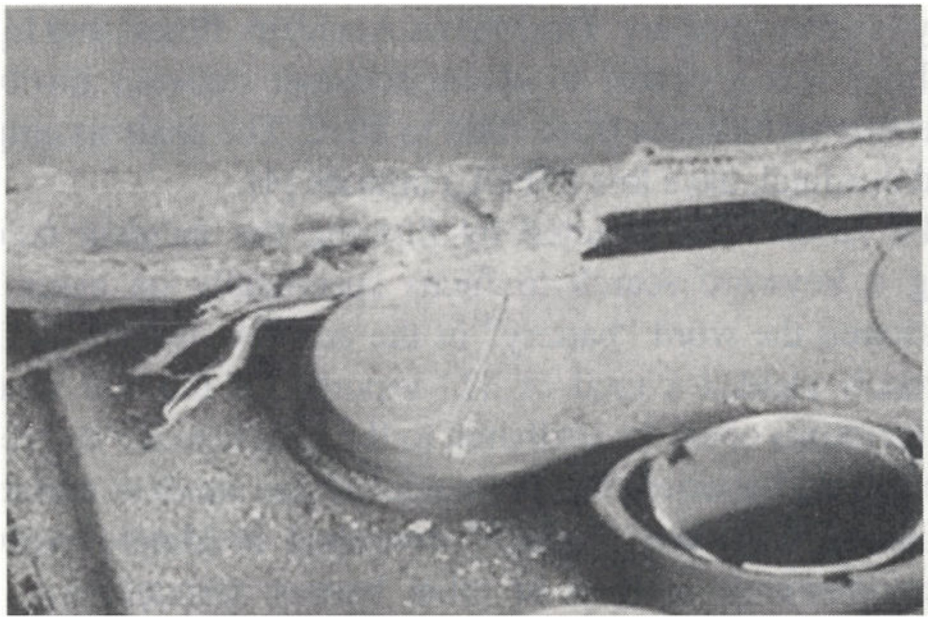

Fig. 1.
Scoop tractor battery showing terminal contact with steel battery tray.

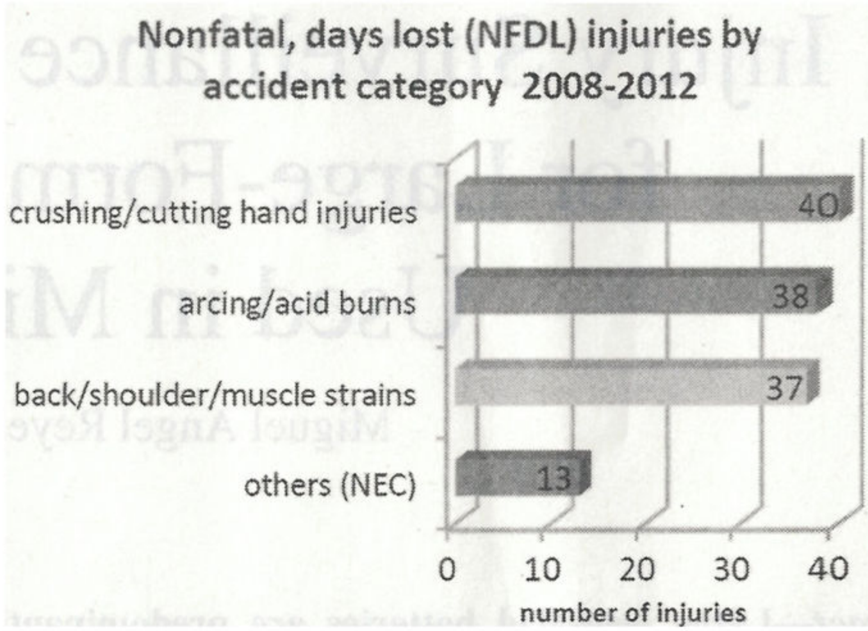

Fig. 2.

Types of injuries, from the MSHA accident, illness, and injury database.

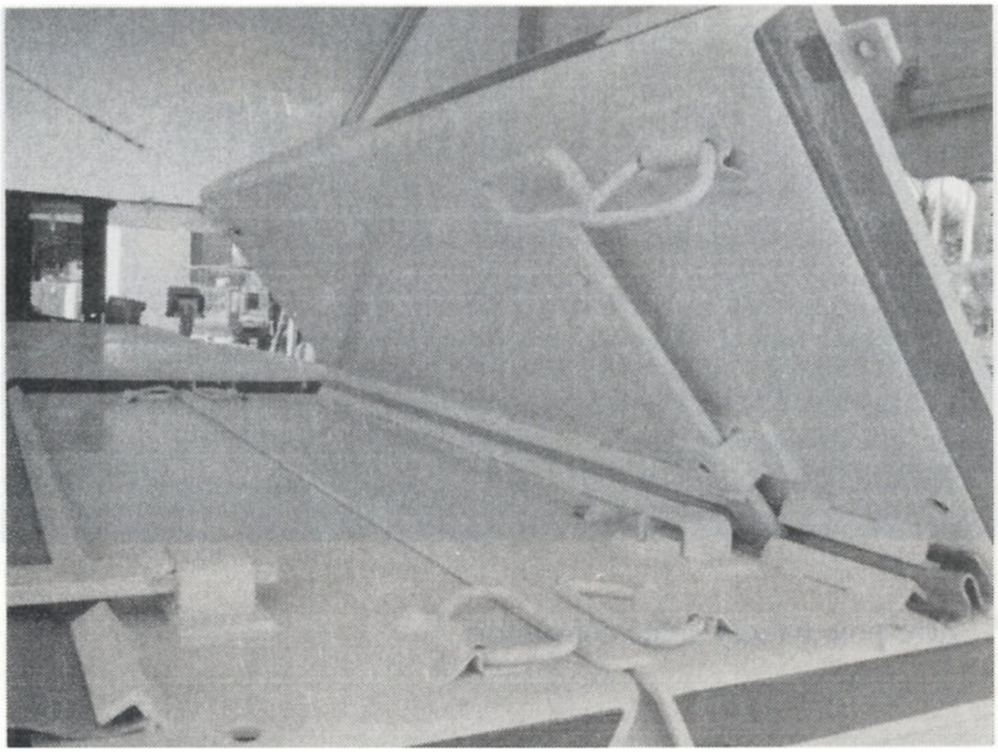

Fig. 3.
Rectangular-shaped battery assembly lids.

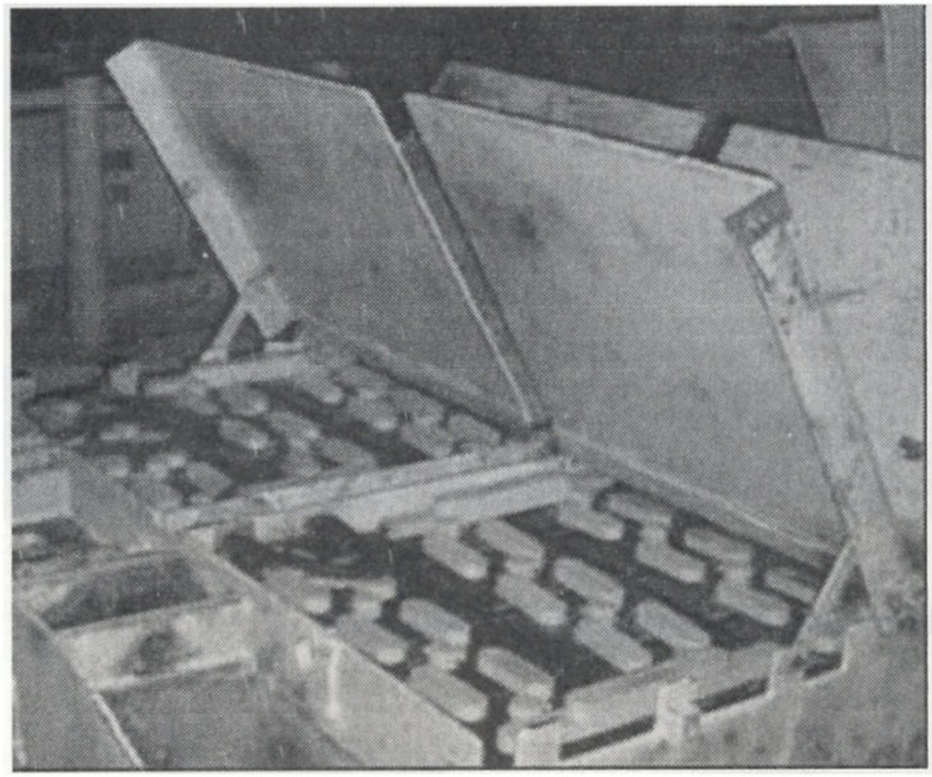

Fig. 4.
Square-shaped battery assembly lids.

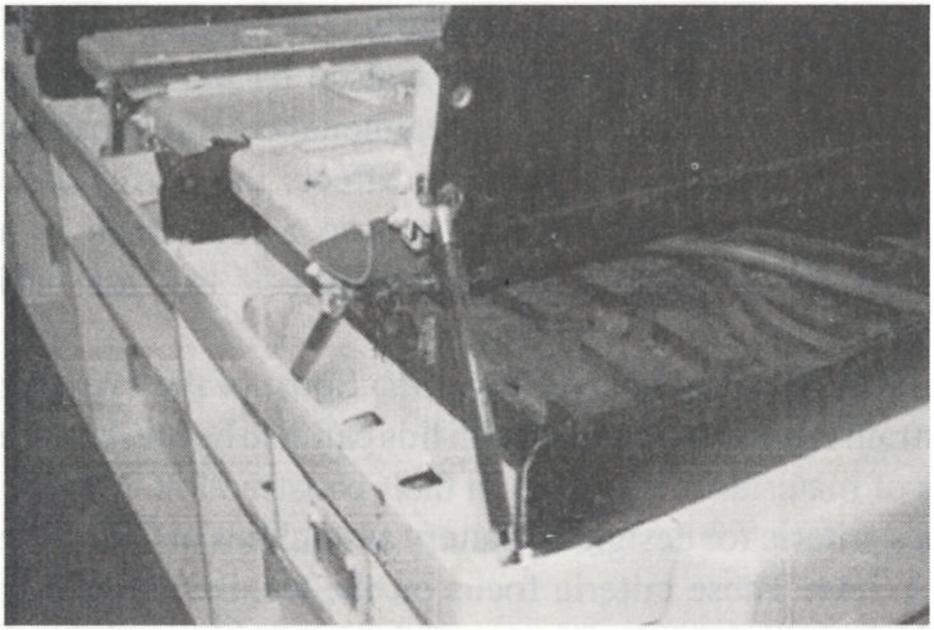

Fig. 5.
Battery assembly with a pneumatic lift assist.

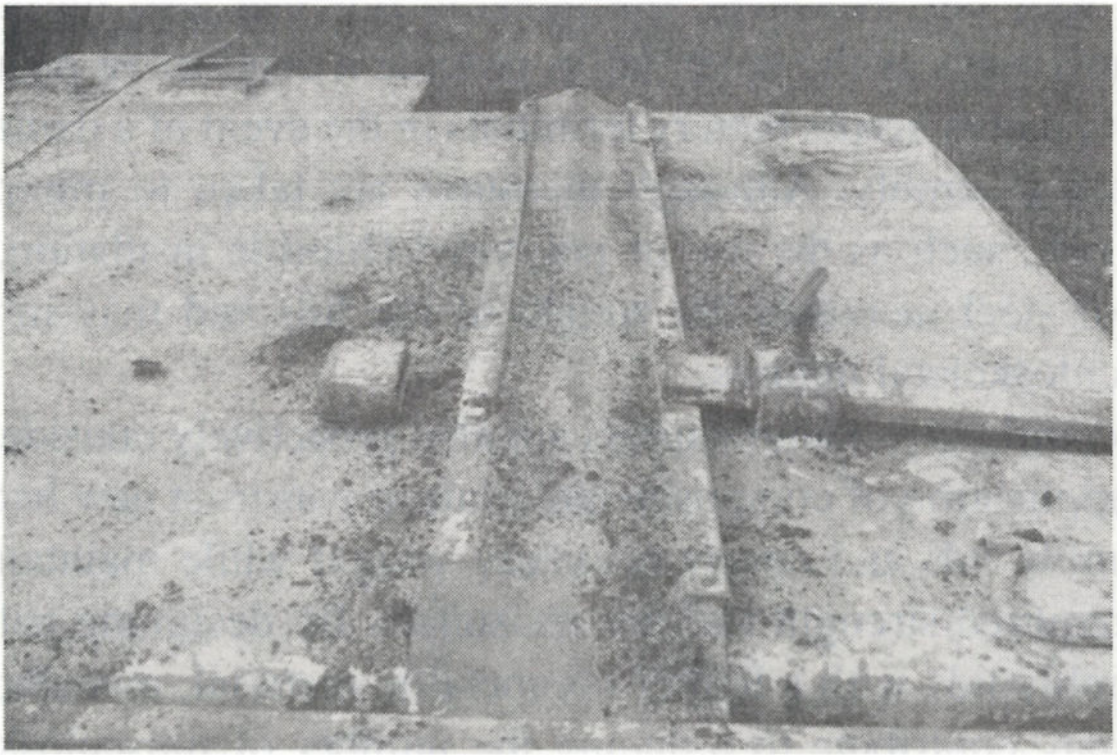

Fig. 6.
Battery assembly with hinge cover.

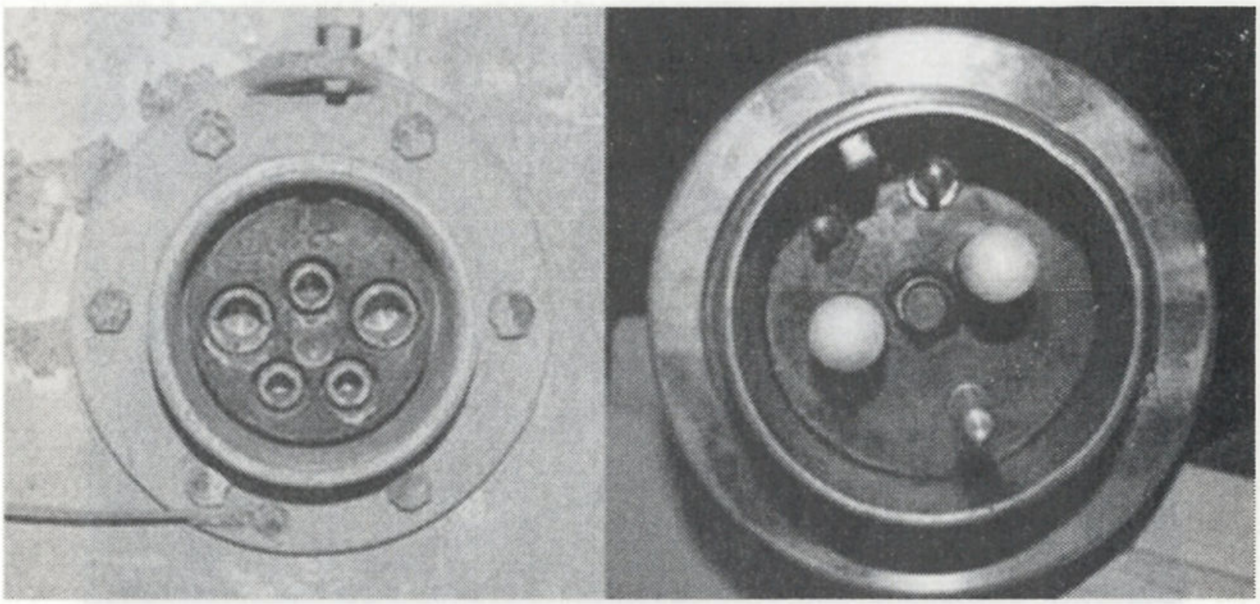

Fig. 7.
Five-pole battery cable connectors.

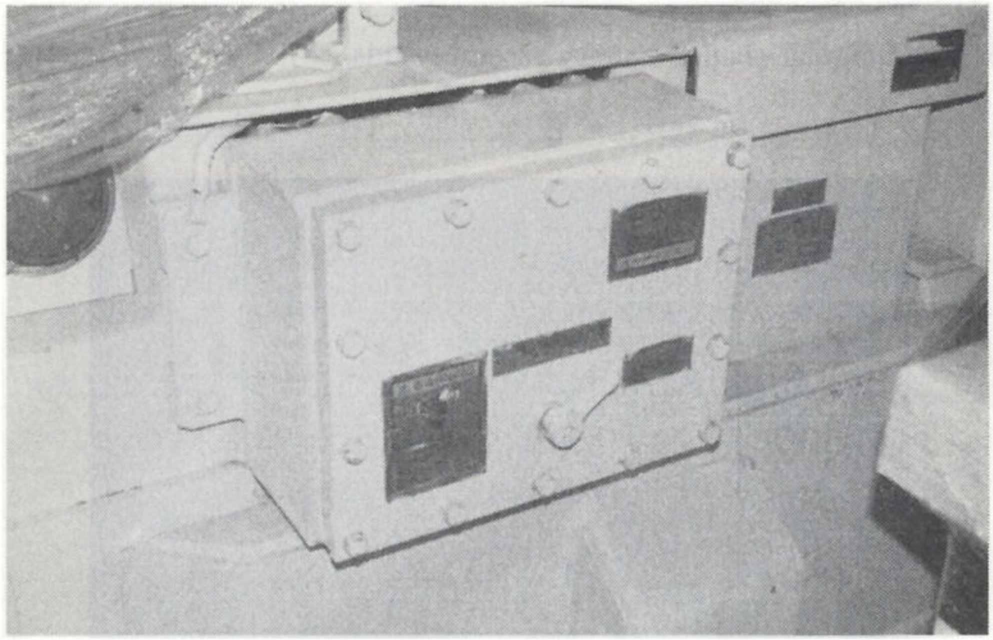

Fig. 8.
Side-mounted battery circuit breaker box.

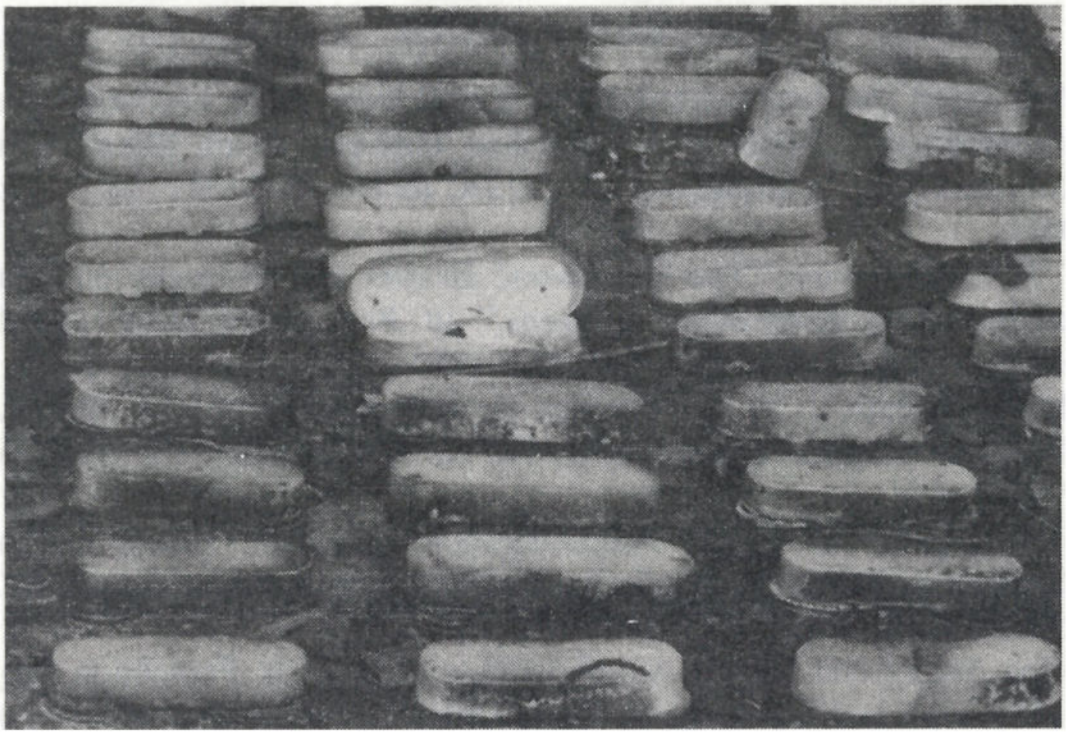

Fig. 9.
Debris and leakage buildup on terminals.