

COAL MINE ELECTRICAL SYSTEM EVALUATION
VOLUME V - BATTERY AND BATTERY-CHARGING SAFETY

Prepared for
UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF MINES

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CERTIFICATION OF THE ABSENCE OF PATENTS AND INVENTIONS

This statement certifies that at the grant report date, no inventions have been developed from Grant G0155003. Consequently, no patents are pending.

Lloyd A. Morley, Project Director

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FOREWORD

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This report is a summary of the work recently completed as part of this grant during the period 5 November, 1975 to 4 November, 1976. This report was submitted by the authors on 15 February, 1977.

This technical report has been reviewed and approved.

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SUMMARY

The primary goal of this research report is to discuss safety considerations involved in the use of lead-acid batteries for traction purposes in underground coal mines.

In order to arrive at the objective, the topic of battery safety has been divided into two specific areas. The first deals with fact that batteries emit hydrogen gas during and after the charge cycle. Hydrogen gas can be the source of dangerous explosions or mine fires. The second major topic deals with the electrical nature of the battery and battery-charging systems, which also provides a source of mine fires as well as electrocution hazards.

In addition to the discussion on battery safety, a literature review has been undertaken to acquaint the reader with some basic concepts inherent to the battery usage process.

The result of this research is a set of design specifications and procedural recommendations directed at improving the safety factors inherent in any underground battery usage scheme.

CHAPTER I

INTRODUCTION

General

The battery-powered vehicle has become an important part of many underground coal mine haulage schemes, and several factors are responsible for the recent increase in popularity. The trend in industry today is towards conveyor belts for coal transport and rail systems for personnel and supply movement. Mines, which employ a-c face equipment and d-c trolley lines, can be subject to problems such as nuisance tripping of a-c circuit breakers from stray d-c ground currents. These currents, which often result from poor track bonding, ineffective trolley line insulators, or inadequate d-c to a-c ground system isolation, are eliminated when batteries are used to power locomotives.

Irregardless of the intermediate and main-line haulage methods, many operations have found it profitable to utilize articulated ram-dump haulers (Ramcars), tractor-trailer units, or scoops (front-end loader tractor units). When employed for face haulage, they eliminate the headaches involved with shuttle car trailing cables. In small conventional mines, the operator can be spared the cost of a loading machine and a separate machine for clean-up and supply haulage. For moderate to large production operations, the extreme mobility of the tractor-trailers and scoops has made them invaluable ancillary equipment for clean-up and supply in practically all longwall and many continuous operations.

The batteries themselves have been considerably improved. A prominent manufacturer reports a 70% increase in ampere-hours per cubic foot (Ah/ft^3) and a 39% increase in watt-hours/pounds (Wh/lb) over

earlier models (21). In addition, improvements in plate and grid design have increased the average service life of motive power batteries.

Statement of the Problem

Storage batteries have a relatively good underground safety record. However, the increased use of batteries has recently resulted in several fatalities and minor injuries (32). When comparing the number of these accidents against all electrical mishaps for the same period, the percentage of battery incidents is significantly high. This is indeed serious considering that battery utilization is just a small portion of underground mine electrical usage throughout the United States.

Hazards related to batteries fall into three broad categories:

1. batteries emit hydrogen, an explosive gas, while charging;
2. batteries and battery chargers are capable of delivering a fatal electric shock; and
3. batteries are a potential fire hazard.

In addition, a number of less catastrophic hazards may be encountered, including acid burns from spilled electrolyte, pinched fingers from careless handling, and so forth.

This document is intended as a review of the major hazards inherent to underground coal mine battery utilization. It is projected at present Federal regulations (generally USBM Schedule 2G and 30CFR75) and several new developments that have occurred in battery safety since they were last published. The report commences with a literature review which is followed by a topic-by-topic discussion of the various hazards, their cause, and available or possible means of preventing accidents. The information has been gathered piecemeal from a number of sources,

including journal articles, books, mine operators, governmental agencies, manufacturers, and actual underground field trips. After concluding statements, pointed at safe battery use, several topics suggested for future research, which have been discovered during this effort will be presented. For the reader's benefit, a review of present regulations is provided in the appendix.

CHAPTER II

LITERATURE REVIEW

General

Literature on battery safety is not particularly extensive, The typical literature reference consists of a paragraph in a journal article advising the operator to keep his battery tops clean. Much of the available material was written in the early days of storage batteries when they were a newly available alternative to mule haulage.

Brief History of Battery Safety

Although the storage battery had a variety of applications in the 1800's, successful use of the battery for traction purposes was not achieved until the turn of the Twentieth Century. Early mining batteries were designed with little consideration for safety. They were used to power gathering locomotives and replaced mules to a certain extent in nongassy mines where open lights were used.

The storage battery locomotive was soon recognized as having some important inherent safety advantages over trolley locomotives and cable-reel locomotives. Appleton (4) cites ". . .the danger of starting a fire from the short circuit and arc when the cable is parted," as an advantage of batteries. L. C. Ilsley (25) says of the battery locomotive:

"That its energy is self-contained and limited to the immediate zone of the locomotive is a safety factor of great importance. In the trolley type of equipment one necessarily uses the track return, and the danger zone from the return current may extend through the mine. Poor bonding or no bonding may force the return current back toward the face. A storage battery locomotive does not use or need the dangerous overhead trolley with its constant shock menace and fire hazard, and with the possibility of trolley or feeder circuits becoming a factor in the ignition of gas or coal-dust."

Early battery locomotives had open controllers, open motors, weak battery covers, battery jars that were prone to breakage, and crude, exposed wiring. In 1919, the U.S. Bureau of Mines issued Schedule 15, which set standards for permissible battery locomotive equipment.

Several incidents involving battery locomotives raises some questions concerning battery safety underground. A major mine explosion occurred at Federal Number Three mine, Everettsville, West Virginia, claiming the lives of 97 men. The resulting investigation traced the ignition to a battery locomotive (3). A report by C. W. Owings (36) contains the following description of another incident:

"The only gathering locomotive approved by the Bureau of Mines is the storage-battery locomotive. The motormen at the _____ mine, referred to in my paper, have used both, the storage-battery and this type (cable-reel) of locomotive; and their experiences in that gaseous mine is that the cable-reel locomotive is much safer than the storage-battery machine. The general superintendent of the mine told me of an occurrence that happened recently to one of their Government approved storage-battery locomotives, in its regular operation. One of the covers of the battery box, in some manner, had become dislodged, causing a short-circuit and flame in the battery box. The machine was then operating in a rib section giving off gas. The battery box, as we all know, cannot be enclosed and there is no way of shutting off the current. For that reason, the men were much alarmed, until one of the cable-reel locomotives was run up into the section and the other machine pulled it out into the intake air. The cable-reel permits the current to be instantly shut off in case of need from any cause. They feel that three years of comparative operation of these two types of equipment demonstrates that the cable-reel locomotive is much the safer machine in gas."

Owings (36) examined the facts pertaining to both incidents and concluded that battery locomotives were relatively safer than the other available gathering locomotive types. The Everettville explosion was created by a nonpermissible locomotive and could as easily have occurred from the use of other nonpermissible equipment. The second incident was later discovered to have resulted from a faulty cell that had accidentally been reversed. This caused the cell to emit hydrogen, which exploded and dislodged the box cover. Owings concluded that the occurrence was very rare, and that the risk of fire was greater when trailing cables were involved.

The shuttle car, introduced in 1938, was initially battery-powered. Cable reel shuttle cars soon became much more popular than the battery cars, probably due to the low capacity per unit weight of the batteries then available. In Great Britain, trackless battery-powered vehicles were widely felt to be unsafe. Explosions at Weetslade Colliery and Eppleton Colliery were the result of storage batteries (7). A consequence of these occurrences was twofold: battery-powered trackless vehicles were prohibited from nearly all British mines and the use of battery locomotives was restricted to types approved by the Minister.

In this country, however, battery-powered equipment is permitted in by the last open crosscut. Batteries have been greatly improved with regards to efficiency and, although not currently used to power shuttle cars, have a variety of other uses in coal mines.

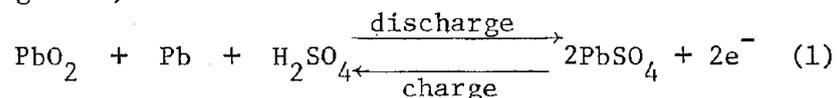
Basic Battery and Battery Charging Theory

Battery Types.

Two types of storage batteries have been employed in underground

traction applications. The nickel-iron or Edison cell is an alkaline type cell. The plates for this battery are constructed of nickel oxide and iron, immersed in an electrolyte of potassium hydroxide and lithium hydroxide. Edison cells were once popular in the mining industry because of their high reliability and minimum maintenance characteristics. Lead-acid batteries have replaced the Edison cell because of their high-energy-per-unit volume and high-power capability.

The basic lead-acid cell utilizes a lead peroxide (PbO_2) positive plate and a sponge lead (Pb) negative plate. These plates are suspended in a solution of dilute sulphuric acid (H_2SO_4). When a circuit is completed between the positive and negative plates, the following reaction occurs (See Figure 1):



When a large portion of the PbO_2 and Pb is in the form of PbSO_4 and H_2O , the battery is in need of charge. Charging a battery consists of supplying electricity to drive the reaction as shown in equation 1.

The number of times a lead-acid battery can be recharged is a function of:

1. the discharge level of the battery during its working cycle
2. the method used to charge the battery, and
3. the quality of battery maintenance.

Each of these parameters is independent of the others, and they will be considered separately.

The effect of the discharge level on N, the number of times a battery can be recharged, is illustrated by : $N = \frac{k}{D^x}$ (2)

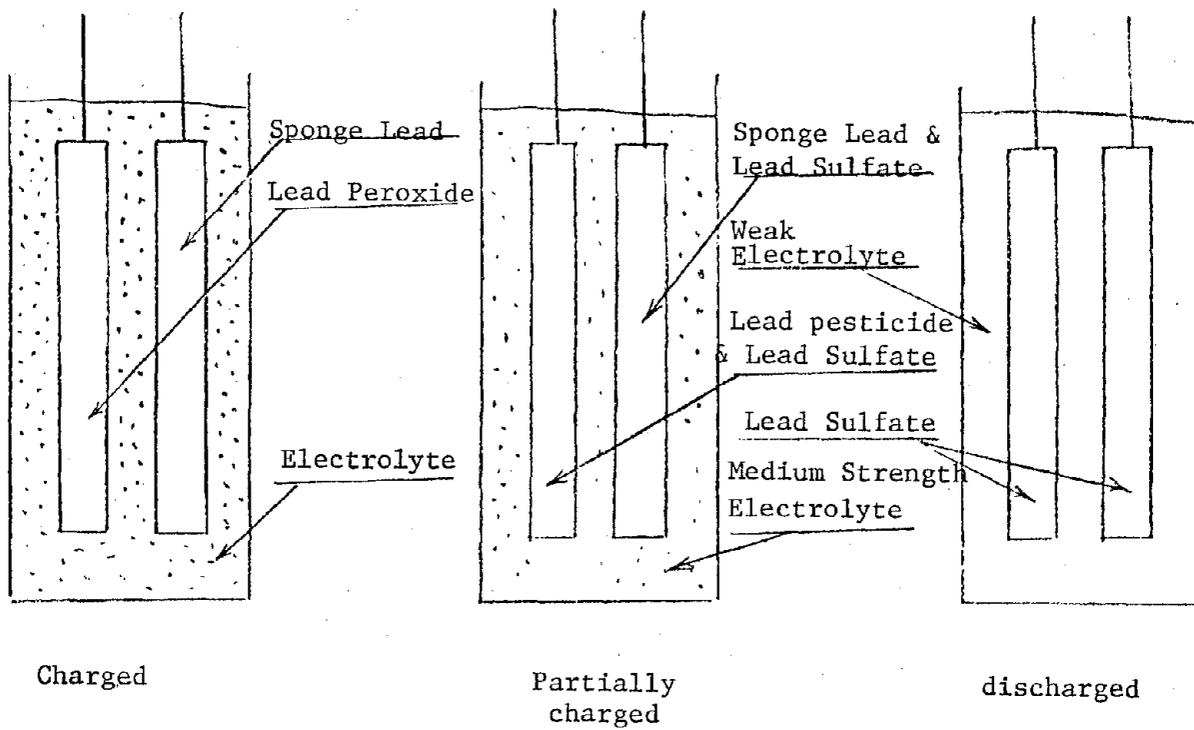


Figure 1. The Composition of a Lead-acid Battery in Various States of Charge. Adpated from K. W. Battery Co. (27).

where k and x are constants of the particular battery and D is the percent of total battery energy removed during a typical discharge. Equation 2 states that the theoretical number of times a battery can be recharged is inversely proportional to the discharge level raised to the power X . Battery manufacturers recommend that lead-acid batteries not be discharged below 80% of their capacity. Because it is difficult to determine the extent of battery discharge until the battery is dead, it suffices to say that a battery should be recharged when the machine it is powering begins to show signs of sluggishness, if not before.

The rate at which charge is restored to the lead-acid battery is an important consideration in getting the maximum number of charge cycles and maximum life out of the battery.

Most of the electricity supplied to a cell being charged is actually used to transform water and lead sulfate into sulphuric acid, lead, and lead peroxide. Some of the current is used to break the water down into its constituents,



which is called "gassing." The rate of gassing increases dramatically at a cell voltage of 2.37 V. It is at this level that increasing quantities of current become available for electrolysis because of the higher state of charge in the cell.

A certain amount of gassing is a necessary consequence of a good charge, which explains why water must periodically be added to batteries. However, excessive gassing causes damage to the plates, excessive water consumption, and excessive hydrogen evolution. For this reason, the amount of charging current must be regulated as the battery charges. Large amounts of H_2 and O_2 released during excessive

gassing cannot be detected by charger personnel. However, this condition is sometimes accompanied by amounts of H_2SO_4 released into the mine atmosphere which is easily identified.

Chargers.

The current supplied to the cell must be d-c, which can be obtained underground from the trolley distribution system. This source has one serious drawback: it is difficult to obtain the precise voltage requirements for charging.

Most mining batteries today are charged underground from the a-c distribution system, using a transformer-rectifier combination. Mercury-arc rectifiers were formerly used (19), but selenium or silicon rectifiers are universally employed today. Silicon diodes are generally considered to be the industry standard. Transformers, whether single-or-three-phase, generally have isolated secondaries.

There are several methods which are commonly used to control the rate of charge. Each one is designed to initiate the charge at a fairly high-current and then taper the rate off as the battery charge is restored. Charge rate control devices can be divided into two basic groups, either active or passive.

The most popular passive system uses modified constant potential or taper charging, where some value of ballast resistance is placed in series with the battery. This resistance limits initial charge current and gives a relatively flat current versus time curve throughout the charging cycle. The advantage of this method is its simplicity. Its disadvantages include the fact that the ballast resistor dissipates a rather large amount of energy and the charge rate does not coincide with what is considered optimal for lead-acid batteries. A variation

of the above system uses a timer to switch additional resistance in series with the battery, thereby reducing the rate of charge at some point in the charge cycle.

A common characteristic to all active systems is that information concerning the battery-charge level is used to control the charging current. This information is obtained through the use of a voltage sampling feedback system.

The simplest active system is another modification of the taper method previously mentioned, here a voltage-controlled relay switches additional resistance in series with the battery at a cell voltage of 2.37 V. This system, as with all active systems, must have different voltage thresholds for batteries with different numbers of cells.

Another popular method utilized a saturable-reactor type voltage transformer to feed the rectifier. The saturation level of the transformer core is controlled by a d-c current applied to a winding on the core. The secondary voltage is therefore regulated by voltage controlled current feedback from the battery. Output regulation usually begins at a battery voltage of 2.37 V. per cell and is varied to zero current at the end of the charge cycle.

A relatively new method uses an SCR rectifier in place of the silicon diodes. The SCR rectifier can be either full-wave or half-wave, and the firing angle is determined by a feedback circuit that senses battery voltage. The SCR system, as well as the other active systems, has an advantage over passive systems in that charge rate can be more accurately controlled using feedback principles. One disadvantage of SCR systems is that, in some designs a phase reference for firing the SCR's cannot be obtained with a full-wave rectifier (due to negligible

ripple) and a half-wave must be used. This results in less efficient rectification and, in some designs, in a chopped waveform which is not entirely suitable for battery charging.

Charge termination is achieved by several methods. Passive chargers generally use a timer, as do some active systems. The cell voltage or its rate of change can also be used to determine when the battery is fully charged.

Maintenance.

Proper battery maintenance is a very significant consideration in the determination of battery life. Battery manufacturers should provide a maintenance program with their batteries which includes the following information.

1. Specific Gravity Levels. One characteristic of the lead-acid battery is that electrolyte specific gravity is a function of the state of battery charge. Manufacturers should provide plots of electrolyte specific gravity versus discharge depth for their particular batteries.
2. Equalizing Schedules. Equalizing is the process by which all the cells in a battery are brought to the same voltage. All lead-acid batteries require periodic equalization; however, excessive equalization causes unnecessary battery deterioration.

There are several good articles in industrial applications magazines which deal with proper battery maintenance techniques. The following discussion is a guideline for a good battery maintenance program (29). The program involves three groups of activities,

those which should be performed during each charge period (daily), those that should be performed weekly, and those to be performed approximately once every three months. Accurate records should be kept of all maintenance activities for each battery. Records provide a convenient way to monitor individual battery performance, thus exposing deteriorating battery conditions before the battery becomes a safety hazard or the source of costly downtime.

Daily battery maintenance activities should include the monitoring of one of the battery cells (called the pilot cell), and any battery cell can be used as the pilot. The following cell characteristics should be recorded during each charge: specific gravity before and after charging, electrolyte temperature before and after charging, and the water level in the cell. If any of the pilot parameters fall outside those specified as acceptable by the manufacturer, all of the cells should be checked and corrective action should be taken. Other daily maintenance activities should include checking the battery for physical defects such as cracked cell plugs and insuring that the charger output voltage is correct.

The weekly maintenance program includes checking all battery cells for proper water level and cleaning the battery tops if corrosion is present. It should be noted that the water consumption of a good battery is generally equally distributed among the individual cells.

At every three months, it is a good practice to take a complete set of cell voltages and specific gravity readings at the end of an equalizing charge. These parameters should meet manufacturers specifications; if not, corrective action should be taken.

Summary.

The success or failure of a battery-powered mine transportation system is largely a function of the operator's ability to get maximum life from his batteries. It is also a function of the relative safety factor involved in battery usage. The following chapters provide a discussion of elements related to battery safety such as ventilation of the charging station and charger design.

CHAPTER III

VENTILATION

General

As was mentioned previously, a consequence of battery charging is the liberation of hydrogen gas near the charge cycle end. Modern battery chargers, however, are designed to prevent excessive "gassing" in the latter phases of charge. This is usually accomplished by a relay in the charger which automatically drops the charge rate to a very low value when a certain cell voltage is reached. For example, one popular design switches from an initial high rate down to 5 A per 100 Ah after the battery voltage has risen about 2.37 V per cell (5). Although this eliminates much of the gassing, it is impossible to properly charge a battery without producing some gas.

For this reason, some method is required to dilute the explosive gas and render it harmless. The traditional method is by forced ventilation of the charging room. Another possibility is the use of catalytic battery caps to remove hydrogen at the source. The concern is to always keep the concentration of hydrogen below its lower explosive level of 4%. Because of the catastrophic nature of underground explosions, Federal regulations limit the permissible concentration of H_2 in coal mine atmospheres to 0.8% (by volume), which provides a safety factor of 5 (See Appendix).

Calculations of H_2 Evolution

According to theory, one liter of water should disassociate to form approximately 622 liters of O_2 and about 1234 liters of H_2 .

Conversion Factors and Constants

$$1 \text{ liter H}_2\text{O} = 1000\text{g H}_2\text{O} = 1.816 \text{ pints H}_2\text{O}$$

$$\text{Molecular Weight of H}_2 : 2.016$$

$$\text{Molecular Weight of O}_2 : 31.998$$

$$1 \text{ Mole} = 22.4 \text{ liters of gas}$$

Calculation of Evolution

$$2 \text{ H}_2 + \text{O}_2 = (2)(2.016) + (1)(31.998) = 36.03 \text{ g/mole H}_2\text{O}$$

$$\frac{1000\text{g H}_2\text{O}}{36.03\text{g/mole H}_2\text{O}} = 27.76 \text{ mole H}_2\text{O}$$

$$\begin{aligned} 1000\text{g H}_2\text{O} &= 27.76 \text{ mole O}_2 + 2(27.76) \text{ mole H}_2 \\ &= (27.76)(22.4) \text{ liters O}_2 + (55.51)(22.4) \text{ liters H}_2 \\ &= 621.8 \text{ liters O}_2 + 1234.4 \text{ liters H}_2 \end{aligned}$$

$$1 \text{ liter H}_2\text{O} \rightarrow 621.8 \text{ O}_2 + 1234.4 \text{ liters H}_2$$

Figure 2. Calculation for Volumetric Evolution of H₂ and O₂ per Unit Volume of H₂O.

Calculations showing these amounts are provided in Figure 2. C & D Batteries use the following method, based on theoretical considerations, to appraise the amount of hydrogen evolved: (12)

"Each ampere-hour of overcharge₃ will dissociate 0.336 millimeter of water to form 0.161 ft³ of H₂ gas. This means that for every pint₃ of water dissociated during the recharge there will be 23 ft³ of H₂ gas released to the atmosphere."

However, it is generally not practical to estimate the quantity of water added to the battery to replace that which has been dissociated. The number of ampere-hours of overcharge may be assessed if charger characteristics are available, although this may also be difficult.

Yet, by assuming a typical charge characteristic, manufacturers have made it possible to estimate hydrogen evolution from the number of cells and rated ampere-hour capacity. Table 1 lists such formulas from three different manufacturers. As shown in the table, the H₂ evolution calculated from these equations is fairly consistent, ranging from 0.0024 to 0.0028 ft³/cell-A. These figures are applicable to the latter stages of the charge cycle (at cell voltages of 2.37 V and greater).

TABLE 1. Formulas to Estimate Hydrogen Evolution.

<u>Formula Number</u>	<u>Formula</u>	<u>Rate of H₂ Evolution Per Cell A-H</u>
1 (C&D)	(# of cells)(Rated A-H capacity) (0.0024) = ft ³ of H ₂ liberated in last 3 hours of charge	0.0008 ft ³ /hr
2 (EXIDE)	(4) ($\frac{A-H}{100}$) (# of cells) (0.016) = ft ³ of H ₂ liberated in last 3 hours of charge	0.0008 ft ³ /hr
3 (KW)	(# of cells) (A-H) (0.002948) = ft ³ of H ₂ liberated in last 4 hours of charge	0.0007 ft ³ /hr

Experimental Technique

In the course of this study, three visits to typical underground charging installations were performed. An objective of these trips was to evaluate the ventilation schemes at the charging stations.

Field equipment consisted of:

1. vane anemometer,
2. steel surveyors tape,

3. glass sample flasks (see Figure 3), and
4. MSA methanometer.

The sample flasks were specially made at the University's glass blowing shop from 1.0 liter volumetric flasks fitted with high-vacuum stopcocks. The flasks were evacuated with a vacuum pump prior to the field excursion. At the desired location, the stopcocks could be turned, and a mine atmosphere sample was drawn into the flask.

Samples were analyzed by gas chromatography at a Penn State laboratory. The process used a molecular sieve to separate the constituents, and then a thermal conductivity bridge to measure the hydrogen concentration. Argon gas was employed as a carrier because its thermal conductivity (3.88 cal/cm sec/deg at 0°C) offers good contrast to that of hydrogen (33.6 cal/cm sec/deg at 0°C). Actual concentrations were conservatively estimated to deviate less than 10% from the values obtained by this method.

Because of hydrogen's low density, samples were taken six-inches from the roof in areas of suspected high H₂ concentration. An MSA catalytic combustion methanometer was used to pinpoint anomalous concentrations although, in general, H₂ concentrations were too low for detection by this instrument.

To estimate airflow, air velocities were measured with a smoke tube or, if possible, with a vane anemometer. Room dimensions were taken with a surveyors tape. Results will now be idscussed on a mine-by-mine basis.

Mine One.

The first mine visited was a fairly small operation which employed

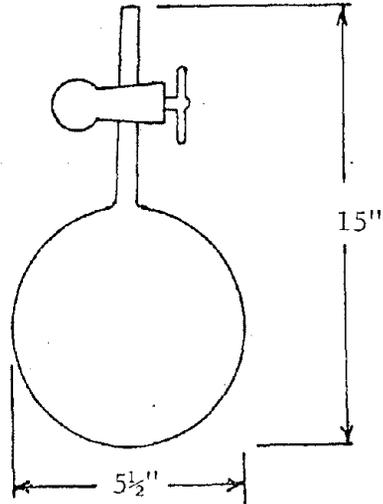


Figure 3. Sample Flask.

Jeffrey Ramcars for face haulage. Charging was performed underground in charging stations located near the working sections.

The particular station visited was constructed to charge up to four batteries simultaneously; a plan-view is provided in Figure 4. Four Exide chargers were located in a crosscut turned from the belt entry. Charging cables were taken through conduits, across the belt, to the battery room. The battery room consisted of a blocked-off portion of an entry and crosscut and was lined with corrugated siding to make it fireproof.

The station was on a separate split of intake air. The air flowed past the chargers and was then taken over the belt to the battery room through eleven 6" diameter tubes. After ventilating the batteries, the air flowed directly to a return airway.

Measurements indicated that 1140 cfm of fresh air was flowing through the station, as it passed over the batteries and into an

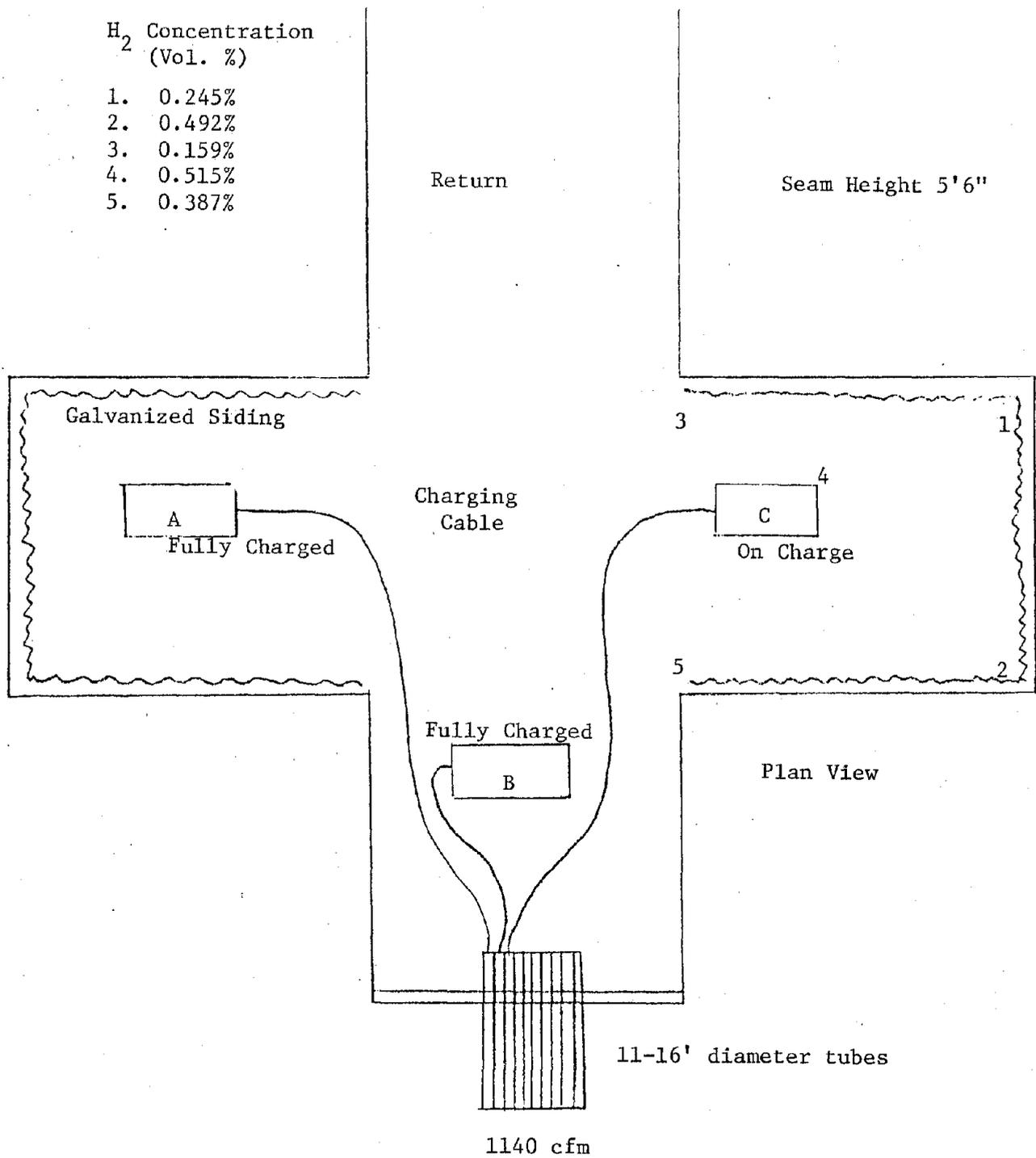


Figure 4. Sketch of Charging Station of Mine One.

adjacent return airway. According to a battery manufacturer's formula (formula 2 , Table 1), the four 550 A batteries that the station was capable of simultaneously charging would require 440 cfm of fresh air to dilute the hydrogen to the legal limit of 0.8%.

If the room could be assumed to be free of H_2 to begin with, then additional dilution would be expected as the gas mixed with the air in the room. However, in this case, batteries were being charged in and out regularly. The air in the room must be assumed to have some H_2 concentration at all times, therefore, a steady-state calculation must be used.

Only one battery (battery C) was on charge at the time of the measurements, but it was nearing the end of charge and was gassing heavily. Gas samples taken in the area of the battery had hydrogen concentrations ranging between 0.15% and 0.52%. These concentrations are somewhat higher than expected for only one battery on charge. A glance at the battery room configuration shows that the battery being charged is not in the mainflow of air. Ventilation here would be improved if some mainstream air was diverted into the charging-room side pocket.

Mine Two.

A second mine had a different mode of battery utilization, with a correspondingly different charging station set-up. The mine utilized battery scoops for supply haulage, 5-ton battery locomotives, and some battery-powered jeeps for personnel transport. Charging was performed underground, with the batteries remaining on the vehicle for the entire charge cycle.

The particular station visited is sketched in Figure 5 and was designed to accommodate one scoop tractor. The charger was located in a portion of a crosscut bounded on one side by an intake airway and on the other side by a concrete block brattice. The station was fireproofed with corrugated metal separating it from the rib.

The station was on a separate split of air, with a 3-1/4" plastic pipe connecting the battery room to the return airway through a hole in the brattice. A calculation based on air velocities through the tubes and on their cross-sectional area indicated about 25 cfm flowed from the room into the returns.

The charging station was equipped to charge a pair of 48 V batteries of about 500 A combined capacity. According to formula 2, Table 1, approximately 40 cfm of fresh air would dilute the gas to a 0.8% H₂ concentration.

A tractor was driven into the charging station and placed on charge. Although its batteries were fully charged, the charger was adjusted by maintenance personnel to deliver additional charging current at the low-rate. The batteries were thus gassing heavily. After an hour, bottle samples were taken 6" from the roof at five locations in the battery room. These bottles were subsequently analyzed for hydrogen. Concentrations ranged from 0.012% to 0.073% (by volume). These concentrations are very low.

In this situation the room can be assumed to be appreciably free of hydrogen gas by the time each battery begins its gassing phase. Hence, dilution by room volume would be a factor in this case. The room had dimensions 18.5 by 29 by 4.5 ft and contained 2414 ft³ of assumed fresh air at the start of gassing. Assuming

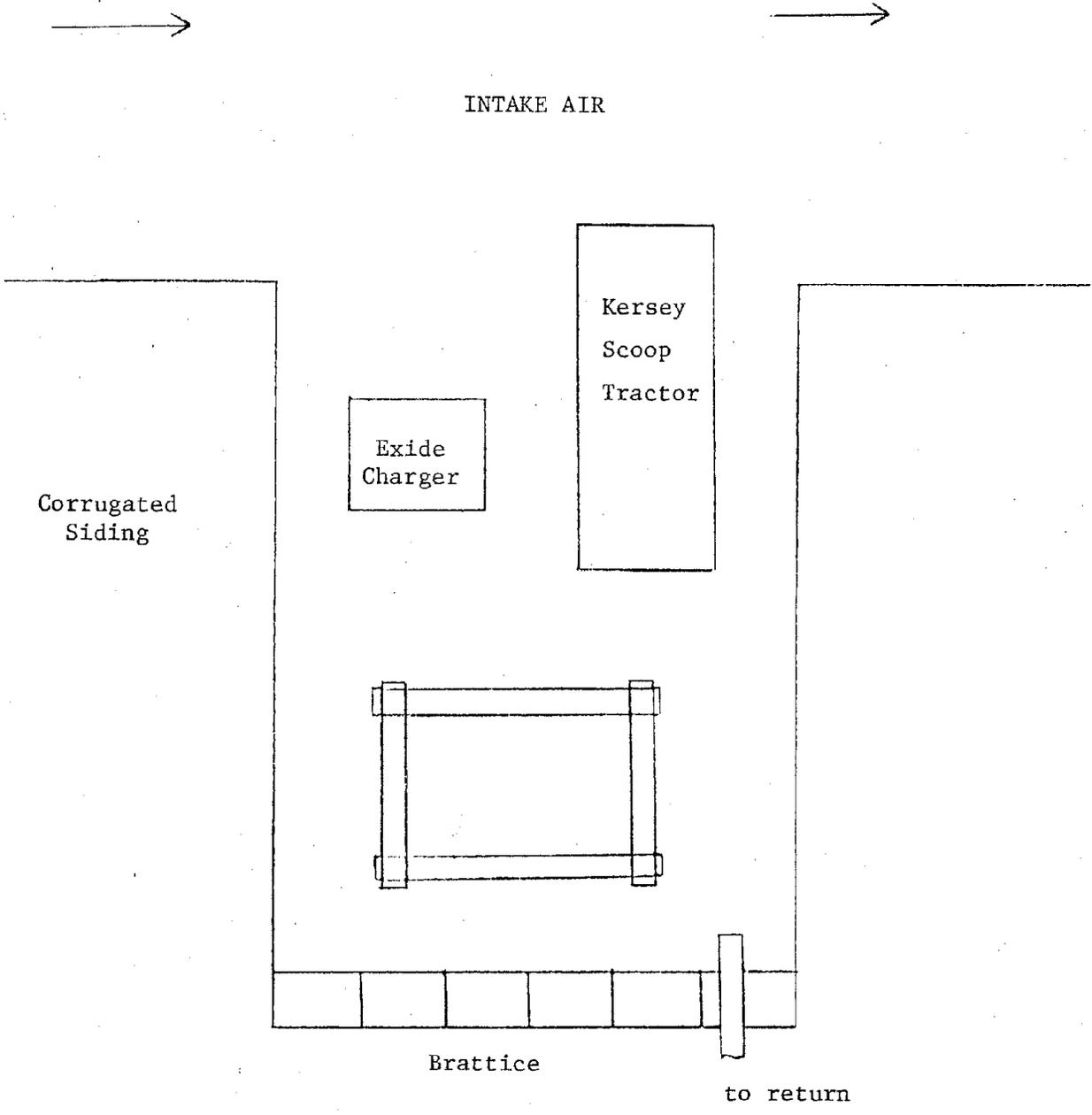


Figure 5. Sketch of Charging Station of Mine Two.

perfect mixing of the gas, the following calculation approximates the situation in one hour:

$$19.2 \text{ ft}^3 \text{ H}_2 \div (2414 \text{ ft}^3 \text{ air in room} + (25 \times 60) \text{ ft}^3/\text{hour airflow}) \\ = .0049 = 0.49\% \text{ H}_2 .$$

It is evident that even though the room had a relatively small airflow, the dilution provided was adequate for the small amount of gas produced. In view of the very small observed concentrations in the room, it is possible that a very small amount of gas escaped into the adjacent intake airway. This would have a negligible effect on the quality of the intake air.

Mine Three.

The third operation visited was a small mine employing tractor-trailers for face haulage. Several batteries were charged underground in a big charging station. The charging station (see Figure 6) consisted of two rooms, however, since most of the batteries were charged in one wing of the station, the ventilation study was performed in that wing.

The room was quite large, approximately 100 by 17 by 8 ft. Air velocity was estimated at 21 ft/min using a smoke tube. Air flow quantity is equal to the product of air velocity and air flow cross-section of 21 ft/min times $(17 \times 8) \text{ ft}^2 = 2856 \text{ ft}^3/\text{min}$. Assuming the maximum situation of four 64 cell, 765 A batteries on charge and gassing heavily, 156 ft^3 of H_2 would be generated each hour (formula 2). Considering that batteries are constantly on charge in the station, the room volume will not be entered into the calculations. A calculated 0.09% hydrogen is expected in the room, which is a safe figure.

Actual concentrations were found to vary between 0.025% and 0.005%,

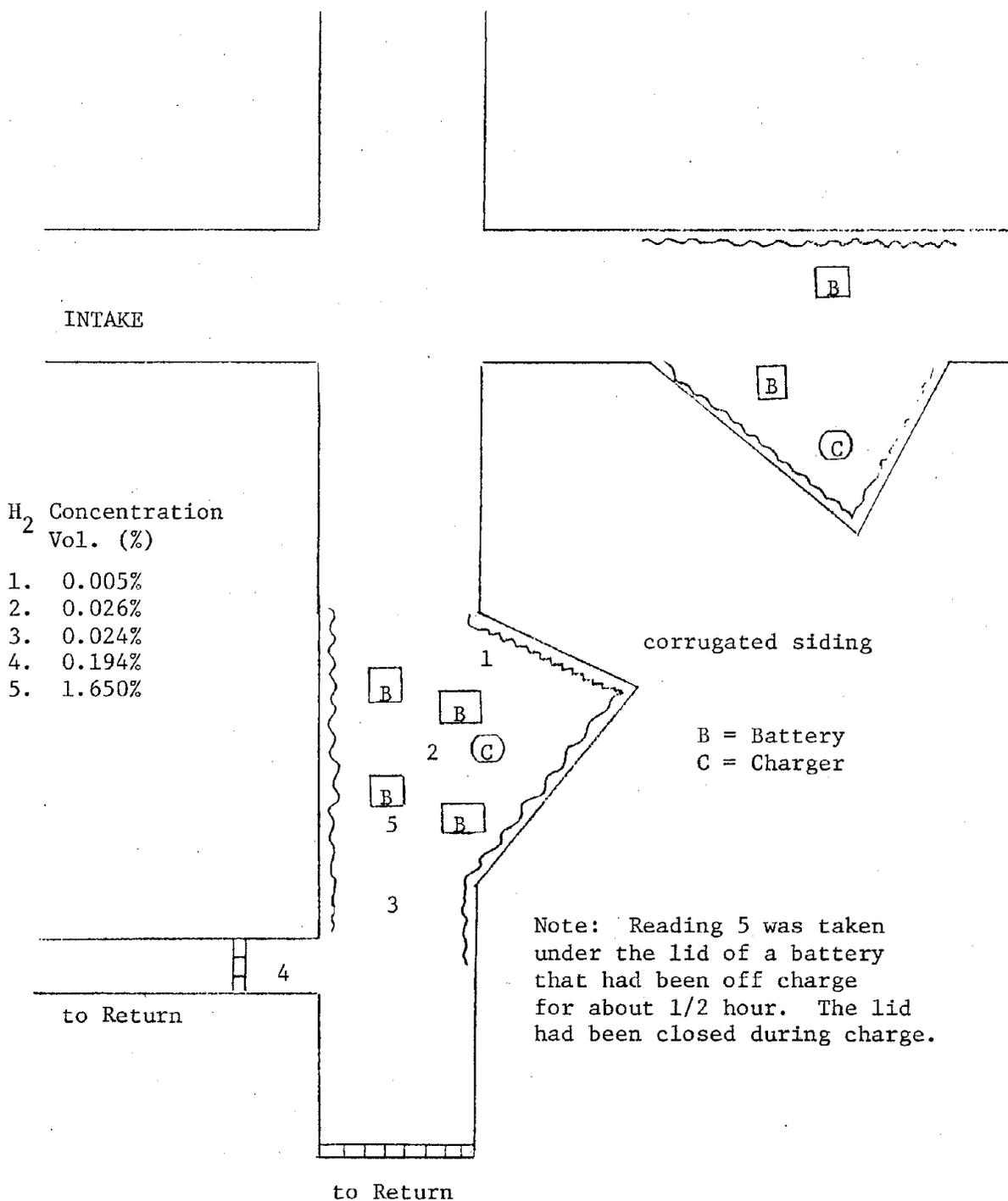


Figure 6. Sketch of Charging Station on Mine Three.

which is well within legal limits and compares favorably with the calculated maximum of 0.09%. Ventilation in this case may be considered excellent for the number of batteries charged.

In summary, it can be said that measured H_2 concentrations were approximately consistent with calculated values. If hydrogen evolution is estimated by one of the formulas provided by the manufacturers, dilution requirements should be realistically estimated.

Discussion

General. The present maximum allowable H_2 concentration in underground coal mines is 0.8% by volume. Since the lower explosive level of H_2 is approximately 4%, this represents a safety factor of 5. This is analogous to the maximum allowable methane concentration of one-fifth its lower explosive level, and seems reasonable.

Battery lids should remain open during charging for ventilation purposes, unless catalytic battery caps are employed. This precaution is often neglected in industry today, especially in low coal. Due to the small volume of the space above the battery top, dangerous accumulations of H_2 are likely to accumulate there.

Separate Split of Fresh Air. Present regulations stipulate a separate split of fresh air for underground charging stations. While this is a good safety precaution, there are certain cases where it may not be necessary.

Some mines use battery equipment for face haulage and require very large battery-charging stations which are capable of generating considerable volumes of gas. The majority of modern mines use only a few battery vehicles, mostly for supply haulage, and in these mines

charging stations may only have a capacity for one tractor at any given time.

Consider the following hypothetical example. Suppose a mine was designed with 20 x 5 ft entries. A charging station with one battery charger is located in a panel intake entry, where the average air velocity is 400 fpm. The resulting airflow is 40,000 cubic feet per minute.

Assume the station was designed to charge scoop tractors powered by 765 A, 64 cell batteries. During the gassing phase of the charge (the last three hours), the battery would evolve (using formula 2):

$$(5) \left(\frac{765 \text{ A}}{100} \right) (64 \text{ cells}) (.016) = 39 \text{ ft}^3 \text{ gas per hour.}$$

The total volume percentage of hydrogen contained in the air in by the charging station can be calculated assuming perfect mixing of the two gases. This assumption is not unreasonable considering the following.

1. H_2 is a very mobile gas. It is difficult to retain hydrogen in any type of sampling container because of this. Hydrogen's extreme mobility results from its low molecular mass. Graham's Law states that the diffusion rate of a gas is inversely proportional to the square root of its molecular mass.
2. With the velocities normally encountered in a mine intake airway, the air is flowing in the turbulent regime. Turbulent airflow is a definite aid to dilution.

No literature is known to exist on the mixability of hydrogen with air in a mine entry. However, given the properties of the gases involved, the turbulent nature of the airflow, and allowing an enormous safety factor, the hazard of a hydrogen explosion would be negligible.

$$39 \text{ ft}^3/\text{hr} \div 60 = 0.65 \text{ ft}^3/\text{min} \text{ (gas)}$$

$$0.65 \text{ ft}^3/\text{min} \text{ (gas)} \div 40,000 \text{ ft}^3/\text{min} \text{ (air)} = 0.000016$$

$$0.000016 \times 100\% = 0.0016\% \text{ gas.} \quad (5)$$

Since the lower explosive level of H_2 is 4%, this represents a safety factor of 2,500. It would not be unreasonable to permit this type of situation.

The battery charger would, of course, be de-energized along with the rest of the electrical system in the event of a fan stoppage or other electrical ventilation failure. Also, some provision would have to be made to insure that the station was directly in the mainstream of the ventilating air and not in a small side pocket with no circulation. Possible charger placements are shown in Figure 7.

One very important factor which could affect gas mixing to a large degree is the location of the charger. If it were located in the intake airway, the hydrogen would quickly be diluted. However, if the station were located out of the way, in a crosscut, it is conceivable that a pocket of H_2 could accumulate. The latter situation must be avoided, either by placing a curtain or fan to ensure airflow through the charging station or by leaving the vehicle parked in the intake airway.

Dilution is an attractive prospect in many circumstances. The advantages are:

1. dilution eliminates the need to provide an expensive separate air split for a small (one vehicle) charging station, which may advance frequently as the face advances, and
2. it increases ventilation at the face by eliminating a

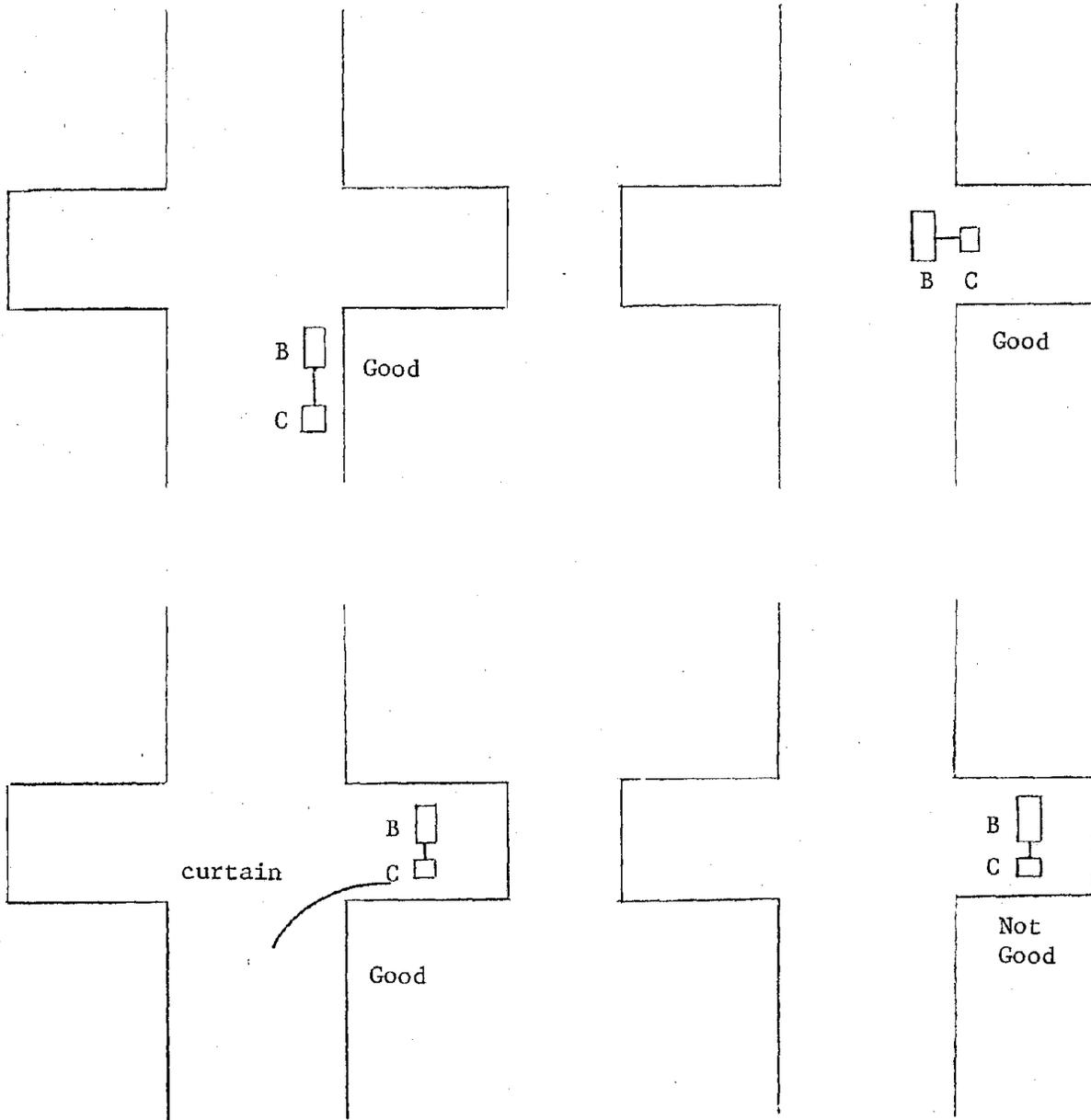


Figure 7. Possible Charger Placements in an Intake Entry for a Charger Not Designed to be on a Separate Split.

source of air leakage to the returns.

In instances where H₂ evolution calculations and air quantity measurements indicate excessive H₂ concentration, the separate split of air is mandatory. Current Federal regulations do not stipulate any minimum airflow quantities for this split. Without guidelines to insure sufficient airflow over the batteries, many companies may not be providing enough air in their separate splits to dilute the gas before it flows into the return. Since it is simple to estimate airflow, but more expensive to determine hydrogen concentration, some guidelines for dilution requirements are perhaps in order.

From the previously discussed formula for calculating H₂ evolution, batteries in the final stages of charge evolve hydrogen approximately according to the following:

$$(5) \left(\frac{\text{Ah}}{100} \right) (\# \text{ Cells}) (0.016) = \text{feet}^3 \text{ H}_2/\text{hr.}$$

Accordingly, dilution requirements could be calculated by:

$$Q_{(\text{cm})} = \frac{(5) \left(\frac{\text{A}}{100} \right) (\# \text{ cells}) (0.016)}{(0.008) (60)} - \frac{(5) \left(\frac{\text{A}}{100} \right) (\# \text{ cells}) (0.016)}{60} \quad (7)$$

This quantity of air would be the minimum necessary to dilute the H₂ produced to 0.8% hydrogen, not allowing for dilution by room volume. Battery stations on a separate air split should have an airflow of at least Q (cfm). To simplify calculations if could be assumed that all batteries were 120-cell, 700 A (the present upper limit in battery size). Then, each battery would require about 140 cfm of air for good ventilation. Airflow requirements could be estimated from:

$$(\text{No Batteries})(140) = \text{cfm ventilating air necessary for an adequate separate split.} \quad (8)$$

The preceding discussion considers the factor of providing

enough ventilation to dilute evolved hydrogen gas. However, Federal law requires that all air currents used to ventilate structures or areas enclosing electrical installations shall be coursed directly into a return airway. This presumably is to avoid contamination of intake air with smoke from a possible fire. In view of this regulation, it cannot be recommended here that battery chargers should not be on a separate split, even though evidence suggests that this would be safe from a hydrogen dilution standpoint.

Tray Ventilation. The British have been concerned with the ventilation of storage battery containers since the early 1950's. Robinson (40) performed a number of ventilation effectiveness tests in battery boxes. He produced a replica of a common British locomotive battery in which hydrogen could be introduced at a controlled rate and samples could be withdrawn at regular intervals. The location and size of vents could also be controlled during the experiment.

Robinson found that venting at the highest point in the container was most effective but had a weakening effect on the box lid. A gap under the edges of the tray lid worked well if additional venting was provided at the bottom of the dead space above the cell tops.

Robinson's experiments were planned on the premise that the lids would remain open during charging. After charging, a small amount of hydrogen is still emitted, which he assumed would be less than 3.0 cfm/hr per 25,000 cell-Ah. He concluded that with this rate of H₂ evolution, battery boxes can easily be ventilated by means of windows and without recourse to forced ventilation.

Titman (45) performed experiments to determine the actual rate

of emission of gas from discharging lead-acid cells. He found that the gas emission rate for a short time after charging exceeded that assumed by Robinson. Titman (46) tested the effects of increased emission rate on the hydrogen concentration under the battery container lid. With the container in his experiment, the hydrogen concentration did not rise above 2% until the hydrogen feed rate was increased to ten times the standard rate or $30 \text{ ft}^3/\text{hr}$ per 25,000 cell Ah.

These researchers proved that it is relatively easy to ventilate a battery box effectively when the battery is discharging. However, a charging battery can be expected to liberate $60 \text{ ft}^3/\text{hr}$ per 25,000 cell-Ah. However, to the authors' knowledge, no experiments have been conducted concerning the ventilation of battery boxes with lids closed during the charge cycle. It is believed that explosive concentrations would result in this case, unless forced ventilation was applied, or the venting slots were so large as to considerably weaken the battery box. Some research in this area would be enlightening.

Catalyst Battery Caps. Ventilation is the traditional method employed by the mining industry for disposing of the gas produced by battery charging. There is an interesting alternative, however, which offers quite a number of advantages. The Hydro-Catalator Corporation has developed a catalyst battery cap which converts hydrogen and oxygen back into water (24). The caps have the dual function of preventing the escape of any hydrogen from the cells and restraining the loss of any water from the cells.

The safety advantages of this scheme are considerable. No additional ventilation would be required, either of the tray or of the charging station itself. The battery lids would not have to be opened

for charging, a big factor in low coal. The explosion hazard associated with batteries would be eliminated. Since watering of the cells would not be required, no electrolyte would be spilled on top, and the possibility of surface leakage (explained later) would be greatly minimized. Tray corrosion by spilled electrolyte would also be greatly reduced.

These caps have been in use for quite some time in various applications ranging from torpedo batteries to batteries for salt-mine personnel carriers. They have proven to be reliable and effective. OSHA accepts the catalyst battery caps and use in construction and general industry as an alternative to ventilation (24).

The only drawback to these devices is their cost: about \$4.00 each for small lots to \$2.50 for larger quantities. Assuming a cost of \$3.00 per cap, this would raise the cost of a 48-cell battery about \$150, a 64-cell battery \$180, and a 120-cell battery about \$360. While this may seem excessive, the cost of providing a separate split of air for each battery and of paying a man to top-up cells and clean the battery tops would probably exceed this figure in the long run.

Summary

Evidence suggests that, from a hydrogen dilution standpoint, it would be safe not to isolate charging stations on a separate split of air, coursing used air directly into the returns, as long as a sufficient quantity of air passes over the station. However, Federal regulations pertaining to the ventilation of electrical installations prohibit a change in charging station ventilation requirements to be made here. It suffices to say that, regardless of the configuration of the charging station ventilation system, the quantity of air flow should not be less

than 150 cfm for each battery on charge.

CHAPTER IV

GROUND FAULTS IN BATTERIES

General

A battery is designed to be an electrically floating system, insulated from its tray, which is at ground potential. Three situations can occur which can connect the battery with its tray.

1. Current may leak across the battery surface to the steel tray; this is referred to as surface leakage.
2. A poorly insulated or damaged cable, bushing, and so forth may contact the tray causing a fault condition.
3. A rock fall or collision may force the battery box cover down onto the battery terminals, shorting one or more to ground.

Batteries could be solidly connected at one end to the tray with a conductor, as is done with the automobile starting battery. However, this would greatly aggravate any surface leakage problems that might occur and could allow a very large current to flow in the case of a single ground fault of type 2 or 3 above.

Surface Leakage

Since lead-acid traction batteries are quite heavy, often weighing several thousand pounds, the only presently available material which is suitable for tray construction is heavy-gauge steel. Steel is a good conductor of electricity, a disadvantage when used to support an isolated system such as a battery. After a battery has been in operation, coal dust mixed with spilled electrolyte can form a conducting path across the battery top, from the cell terminals to the

tray. If these paths are permitted to accumulate, a number of low-resistance paths may form between the various cell terminals and the tray. Since the terminals are at different potentials, currents tend to circulate across the battery top and through the tray, and may cause three problems.

1. Currents circulating in resistive loops cause heating. This heating is proportional to I^2R , where I is the leakage current and R is resistance of leakage path. When R is low enough to permit a substantial current to flow, a smoldering fire may ensue. This hazard is compounded by the often explosive hydrogen concentrations which occur in the battery above the electrolyte level.
2. The presence of paths from the cell terminals to the tray cause a shock hazard for mining personnel. A man leaning against a battery box and touching an exposed terminal could be shocked. Terminal to tray conducting paths present an especially serious hazard when the battery is charging and the charger design or a fault within the charger permits d-c to flow in the ground. This condition, when combined with poor grounding practices, was the cause of a recent fatal electrocution (see Chapter V).
3. Circulating currents represent wasted battery power and may reduce the amount of time a battery can be used before recharging is necessary. They also tend to increase tray corrosion.

Faults

Another potentially hazardous situation which may occur in

batteries is the low-resistance-ground fault. A damaged cable in contact with the tray would typify this type of situation. Since the battery is theoretically a floating system, a single such fault would cause no current flow. The effect of surface leakage paths would cause a certain level of current, depending upon their resistance. However, two simultaneous low-resistance-ground faults would permit extremely high-currents to flow. Because of the low internal resistance of lead-acid batteries, currents on the order of 10,000 A may exist for a short duration, depending on the contact resistance of the fault. A very difficult situation could result because batteries cannot be de-energized: a fire caused by faults would be very difficult to extinguish until the battery was discharged.

Discussion

The surface leakage problem has been recognized by battery manufacturers for some time. The virtues of keeping battery tops clean have repeatedly been emphasized. An example is the following excerpt taken from a typical maintenance article: (22)

"If the battery tops become wet and dirty, or if tray corrosion is visible, give the battery a soda wash. Mix a handful of bicarbonate of soda (baking soda) in a bucket of water. Pour this solution over the top of the battery, using one full bucket per tray. Be sure vent caps are in place. Water will dry, leaving some dry soda on the battery top. It is good practice to give batteries a soda wash once a month. If a battery is accidentally flooded (acid spilled on cell tops) due to overfilling cells, give soda wash as soon as possible."

If mine batteries were always kept clean and dry, the surface leakage problems would be greatly reduced. However, cleaning is often neglected in the mining industry, especially in low coal. Some alternative way of reducing this problem would be advisable.

Most batteries now in use underground have a thick coating of paint on their trays. This reduces leakage somewhat but is prone to deterioration by chipping, abrasion, and attack by battery acid. Recently, however, three manufacturers have begun coating their battery boxes inside and out with a tough vinyl compound. This product, known as "plastisol" is readily available and can be sprayed onto any properly prepared steel surface. For example, one prominent manufacturer, after sand-blasting and priming the steel, sprays 0.03" thickness on the tray, except under the cover, where a 0.06" layer is applied. A significant reduction in surface leakage problems results. Plastisol (or a similar material) is a simple, relatively inexpensive addition to battery safety.

To further increase the safety of batteries, however, exposed intercell connectors must be insulated in some manner. While this sounds simple, any insulating coating applied to the connectors reduces their heat transfer capabilities. Since batteries lose about 80% of their heat through the intercell connectors, this can be a serious problem.

Leading battery manufacturers have recently been competing to produce a "dead-top battery," and at least two manufacturers now offer totally insulated intercell connectors as an option on their mining batteries. The system should greatly reduce the possibility of surface leakage and also remove the possibility of dangerous arcing caused by a tool dropped across the battery top.

British researchers have also been aware of surface leakage hazards. Statham and Littlewood (44) realized the need for detection and isolation of surface leakage and ground faults in batteries. They

developed a fault detection system designed to be fitted to the battery or battery charger. The circuit shown in Figure 8 provides a simple method for detecting ground faults that might occur between the battery and its load. One problem with the circuit is that a large portion of the battery itself cannot be protected. For instance, a fault occurring at point A in Figure 8 would produce no current flow through the current relay. Figure 9 is a plot of relay current versus fault position on the battery; it is assumed that the current relay shunt is set at 1000Ω and that a 200 V traction battery is used.

In order to increase the sensitivity of their circuit to battery surface leakage faults, Stratham and Littlewood proposed installing switches at points X and Y (of Figure 8). These switches would be alternately opened and closed by a mechanical or solid-state device. The dotted line in Figure 9 shows the new position-sensitivity curve resulting from the modified circuit. The entire battery could be protected in this manner, although sensitivity still varies with fault position for surface leakage faults.

Virr and Pearson (51) devised an electronic a-c injection system which would provide protection sensitivity independent of fault location. They utilized a system of red and green lamps to indicate a "not safe" or "safe" condition. Although Virr and Pearson recommended mounting the device on each battery, this would not be necessary for trackless battery-powered vehicles since a device on the charger would be sufficient to prevent an unsafe battery from being charged. Since the development of surface leakage presumably takes place gradually with accumulation of conducting material on the battery top, continual monitoring of each individual battery is probably unnecessary.

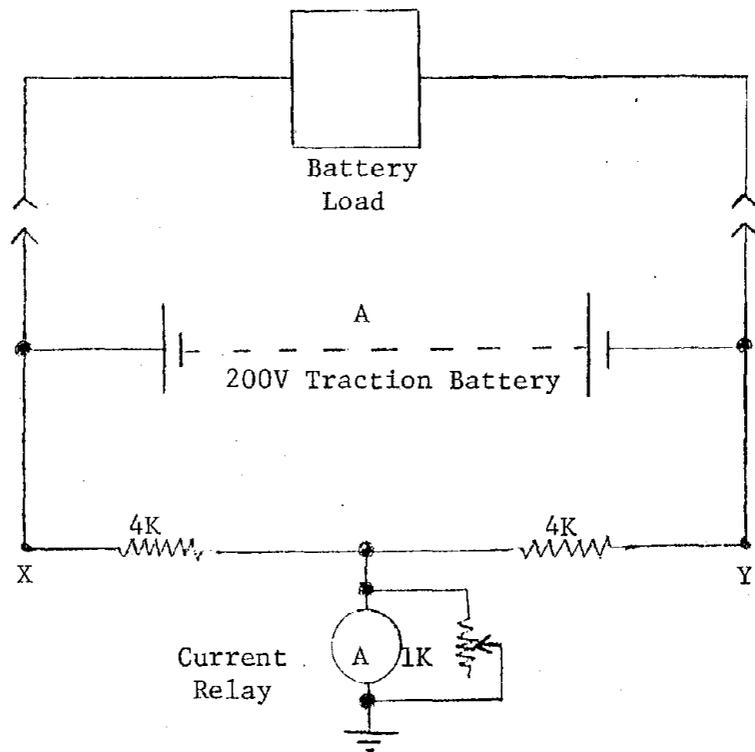


Figure 8. Circuit For Detecting Faults in Batteries Adapted From Statlam and Littlewood (42).

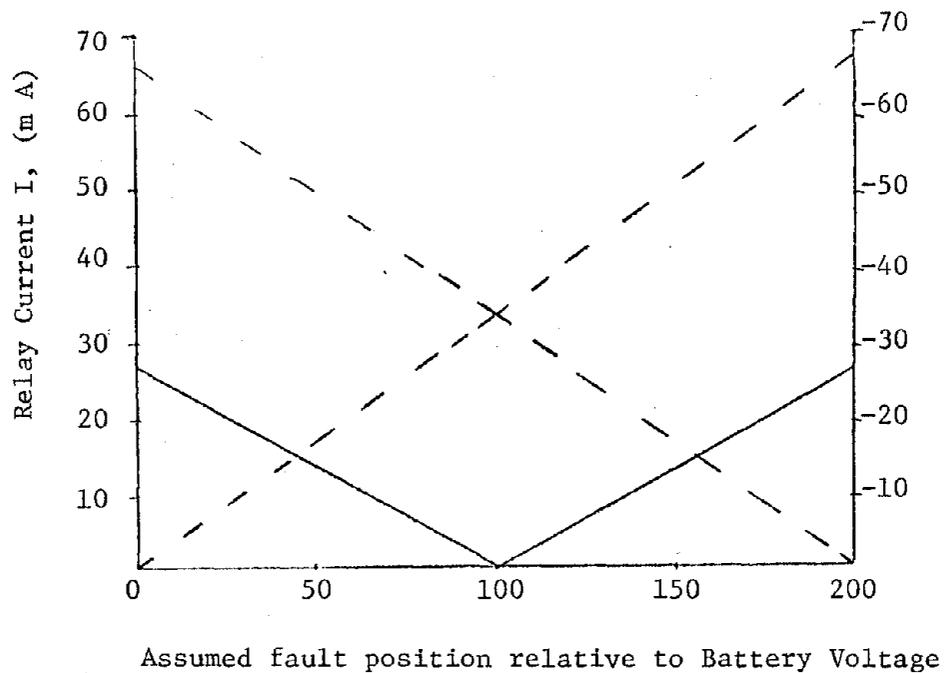


Figure 9. Curve of Relay Current for Various Fault Positions on Battery From Statlam and Littlewood (42).

Low-resistance faults to the tray or vehicle frame caused by damage to cables, and so on, represent a different problem. As previously mentioned, no provision is currently available for de-energizing a faulted battery, which would continue to discharge until its stored energy was dissipated.

Some form of circuit breaker between the cells of the battery would provide a way to sectionalize the battery in the event of a fault. In conditions of excessive current flow the intercell connectors might themselves act as protective fuses, melting down when their current carrying capacity was exceeded. Some additional research would be necessary to determine if intercell sectionalizing breakers are necessary, how many should be installed in each battery, and where they should be located.

Summary

Proper isolation of the battery electrical system from the mine ground system is a prerequisite to safe battery use. The reliability of battery isolation can be greatly enhanced by following the maintenance and design suggestions given in this chapter. Total electrical safety for any battery installation is, however, a function of charger characteristics as well as battery isolation. Battery chargers will be considered in the next chapter.

CHAPTER V

CHARGING

General

Four battery-related fatalities which occurred in U. S. mines in the last five years were electrocutions involving battery chargers (32). A brief review of these accidents would shed some light on the hazards associated with the charging process.

1. A scoop operator was electrocuted when his body came in contact with the frame of a scoop tractor that was being charged. During the subsequent investigation, it was found that a potential difference of 260 V existed between the tractor frame and mine floor when the charger was energized. The cause of this was a low-resistance surface leakage fault current between the battery and battery tray which caused the tray, and the tractor frame on which it was resting, to become energized. Faulty insulation between the primary and secondary windings on one arm of the three-phase transformer permitted secondary current to flow in the ground.

Several precautions might have prevented this accident. If the battery had been totally insulated from its tray (with plastisol, for example), the tractor frame would not have been at the higher potential. The charger should have been designed to avoid the possibility of a transformer fault; however, the glaring error here was the failure of mine personnel to properly ground the steel frame of the tractor while it was being charged.

2. A utility man received a fatal electric shock when his body contacted the frame of a battery charger. A fault existed within the

charger which caused 210 V and 114 V to exist between the charger frame and earth. Despite the fact that the primary cause of the electrocution was a worn bushing which failed to insulate the timer circuit from the charger frame, a proper frame ground again could have prevented the fatality.

3. An electrician was fatally injured when he came in contact with a bare conductor on the charging leads of a battery charger while connecting the charger to the vehicle. The electrician was standing in water while attempting to connect the battery. Although the charger switch was in the off position, a primary-to-secondary fault in the charger transformer circumvented the switch (which interrupted a primary lead only) and caused the lead to become energized.

The accident could have been avoided if the charger had been kept in a dry location, the transformer had been designed to prevent primary-to-secondary faults, and the charging leads had been properly insulated.

4. A transit man was electrocuted when he contacted the battery ground clamp, which was attached to the charger frame. The charger frame was energized due to a fault within the charger. The investigation showed the accident to be due to inadequate safety grounds on the frames of all the electrical equipment in the mine.

Transformer Faults

The secondary winding of most traction battery-charger transformers, whether single-phase or three-phase, is isolated from the mine power system ground. There are several reasons for this.

1. An isolated system provides protection against electrocution of a person at ground potential who touches a live conductor.

2. A ground would provide an additional path for battery surface leakage current, which is undesirable.
3. The secondary of the three-phase transformer, which feeds the rectifier, is generally delta connected. A zig-zag is required for grounding, which is an additional expense.

It is obvious from the preceding section that transformers cannot always be relied upon to maintain secondary isolation. Transient overvoltages and excessive vibration (for example) can cause transformer winding insulation failures, which can result in a direct connection between the primary and secondary winding. Whether such a connection is direct or through the transformer core, the path permits secondary current to flow in the primary ground. An unisolated secondary does not present an especially hazardous situation unless it occurs with both the following conditions:

1. a fault, which energizes a machine frame such as the battery charger or battery vehicle, and
2. nonexistent or poor grounding practices.

Since both of these conditions are possible in the mine environment, it is necessary to ensure that an isolated system remains isolated. This can only be accomplished with improved transformer designs (over those commonly used).

One possible method of insuring electrical isolation between the secondary winding and ground is to install a grounded metallic shield between the primary and secondary windings. Connection between a primary or secondary winding and such a shield would allow excessive ground current to flow, tripping at least a phase unbalance or ground overcurrent relay out by the charger. Therefore, the shield method

provides a technique for detecting transformer faults.

Another scheme for insuring secondary isolation is the cast coil method where the transformer core and coils are coated with an epoxy material. Casting is achieved by inserting the fully assembled transformer into a cast and then pouring an epoxy material into the cast. After hardening, the epoxy occupies a space between the primary winding and the core and, if desired, the space between the primary and secondary winding. The cast coil method can be used for preventing primary-to-secondary transformer faults.

The transformer secondary could be deliberately grounded, and ground-check devices could be used to insure that machine frames remain at ground potential. Battery surface leakage to ground could be monitored using one of the methods mentioned in the previous chapter, with charge being prevented in the case of excessive leakage.

Protective Circuitry

Battery chargers are available with a wide variety of protective devices. Some manufacturers provide little more than overcurrent protection while others include additional protection against problems such as a-c transients and exposed live charger plugs. The purpose of this section is to list and discuss various protective devices which might be used in charger design.

Panel Interlocks. Mine battery chargers, designed to accommodate batteries of various voltages, require internal adjustment to change the d-c output voltage. Chargers that have fuse protected outputs also require access to the internal charger circuitry in order to check or change out fuses. Panel interlocks, which interrupt charger input power when access panels are removed, could prevent mine personnel

from working on live circuits. This is common practice on practically every other piece of mine power equipment. The technique works by breaking the incoming ground system thereby enabling the outby ground-check monitor to trip its circuit breaker. Often, emergency stop switches are included with external access so anyone at the equipment can quickly trip the power.

Grounding. Failure to properly ground battery chargers and batteries being charged has led to several serious accidents. Federal laws concerning grounding are explicit, and most incidents have resulted from noncompliance rather than any inadequacy in the laws.

It is not uncommon in underground charging stations to find ground conductors absent or disconnected from battery vehicles. These practices firmly indicate that battery charger ground leads should be monitored. Besides insuring ground continuity, a ground-check circuit would:

1. de-energize the charge plug in the case where it is removed from receptacle on the battery box before the charge cycle is complete and
2. prevent an arc from occurring during plug removal.

Protective Coating for Charger Frame

Two of the fatalities mentioned resulted from faults caused by some internal circuitry contacting the charger frame. One charger manufacturer claims that an epoxy compound is applied to their charger cabinet interior effectively insulates it from faults. It is conceivable that the inside and outside of a charger cabinet could be coated with plastisol or some other suitable substance to reduce the possibility of a fault.

Summary

Considering safe electrical practice as well as the foregoing, the following are suggestions for mine battery-charger designs.

1. The input cable to the charger should contain a monitored ground to insure that the charger frame remains at ground potential.
2. The charger should be equipped with panel interlocks which deenergize the charger at the outby source when access panels are removed.
3. The charger should have an emergency off switch located in a conspicuous place on the charger frame. This switch should not be spring-loaded, thus requiring resetting after use.
4. The charger frame should be coated with an insulating material on the inside and outside. Such a requirement is not absolutely necessary if the frame is connected to a monitored grounding conductor from its power source.
5. The power transformer should be of the cast core type with epoxy filler between the core and primary coil and between the primary and secondary coils; otherwise, there should be a grounded metallic shield between the primary and secondary windings (the Faraday shielding is preferred).
6. The power transformer should have transient overvoltage protection.
7. The power transformer secondary and all d-c components should be isolated from the system ground.
8. The charger should be equipped with a ground-check monitor which insures that the battery box remains at ground potential.
9. The d-c connection between the charger and battery box should consist of a single cable with appropriate ground and ground-

check conductors.

10. The d-c couplers should be of the type which interrupt the ground-check circuit before the charging circuit.
11. Any semiconductor rectifier, charge rate control, or timer circuitry should be protected against transient overvoltages.
12. The power rectifiers should have protective overtemperature relays.
13. The charger should have overcurrent protection on both the input and output.
14. The charger should have a meter or similar device which indicates the state of battery charge.
15. The charger should contain circuitry which prevents a battery of the wrong voltage from being charged; otherwise, keyed battery couplers should be employed.
16. The charger should contain battery surface leakage detection circuitry which prevents a leaky battery from being charged.
17. The charger time circuitry should operate in a failsafe manner to prevent battery overcharge.

The inclusion of these devices and techniques in mine chargers should practically eliminate electrocution hazards. Items 6, 11, and 12 are indirectly pointed at personnel protection through equipment protection. Obviously, a schematic incorporating these thoughts could be presented in this report but, as there is sometimes many methods to adequately provide the recommended protection, such a diagram would be superfluous.

CHAPTER VI

CONCLUSIONS

This study has been projected as a review of the major hazards inherent to underground coal mine battery utilization. Through the course of work, some significant findings have been made, noteworthy enough to restate them here. In general, they can be considered as suggestions for changes in, or additions to, present battery-related Federal regulations.

1. Battery cells should be totally insulated from the battery box they are contained in. The battery box should be coated inside and outside, except for the outside bottom portion, with an adequate insulating material bonded to the wall. The inside and outside of the battery box cover should also be so coated. An adequate insulating medium can be considered to be plastisol or a similar material.

2. Power transformers in battery chargers should be designed to prevent the possibility of a fault between the primary and secondary windings. The power switch for the battery charger should interrupt the circuit on the low side of the charger.

3. Battery chargers should be designed with panel interlocks which de-energize the charger power supply at its source when charger access panels are removed.

4. Battery chargers should be equipped with a device which will de-energize the charging leads when they are disconnected from the battery. Basically, a ground-check monitor system would afford this protection.

5. Battery lids should be raised when the batteries are being charged, unless the batteries are fitted with approved catalyst battery caps.

6. In terms of hydrogen emission and gas dilution standpoints alone, evidence suggests that it would be safe not to isolate charging stations on a separate split of air, coursing used air directly into returns, as long as an adequate quantity of air passes over the station. However, considering Federal regulations pertaining to electrical installations, a change in charging station ventilation requirements cannot be made here. Yet, the quantity of air should not be less than 150 cfm for each battery being charged.

7. The Federal requirement to de-energize the mine electrical power system in event of a mine ventiation failure, already mentioned in this report, brings about a moot point concerning battery employment not yet mentioned but reserved for here. De-energization should include all non-permissible battery-powered systems at the source. As batteries are independent and cannot sense a mandatory power short-down, a "dead-man" type device may be necessary on all battery-powered vehicles, timed to interrupt the battery power 20 minutes after the machine is stopped. After which, the operator would be required to engage an "interlock" before again using the machine.

Suggestions for Future Research

From this study, a number of questions surfaced concerning battery safety. The following list of suggested research topics might help answer some of these questions:

1. Common sense dictates that battery box covers be opened

during charging, but the precaution is often neglected. It is questionable whether a closed battery box had adequate ventilation during the last three hours of charge. To resolve this question, some testing should be carried out along the lines of research performed by Robinson (38) and Titman (43,44) in Great Britain twenty years ago. The purpose of this research would be to determine the safety of charging with the lid closed and the ventilation requirements that might be necessary.

2. The effectiveness of catalyst battery caps should be evaluated. If they prove effective and reliable for mining employment, a provision including them in Federal regulations should be considered. Research could be similar to that for battery box ventilation (see above).

3. The problem of removing power from a shorted battery and during ventilation shutdowns should be investigated. Even though battery leads outside the box are presently required to have short-circuit protection, a fault inside the battery or shorted intercell connectors could not be cleared. Batteries perhaps should be sectionalized, possibly by replacing some of the intercell connectors with some form of switch. Forms of "dead-man" power removal should be delineated if such devices are deemed mandatory.

4. The arcing, which occurs when present battery chargers are disconnected from the batteries before the charge is terminated, should be investigated. Tests could be conducted with batteries in various stages of charge, using an actual charger or a simulation, could be devised to evaluate the size of the arc and whether it represents a personnel hazard. If this proves to be the case, the interlock system could be developed to prevent arcing.

5. A surface leakage and fault detecting device similar to that developed by Virr and Pearson (49) could be designed and tested. The device could be fitted to the battery charger and designed to prevent an unsafe battery from being charged.

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APPENDIX
REVIEW OF PRESENT REGULATIONS

REVIEW OF PRESENT REGULATIONS

The following is a list of current battery-related regulations.

A. USDI, Bureau of Mines, Electrical Motor Driven Equipment and Accessories, Schedule 2G (March 1968).

18.41 (f) For a mobile battery-powered machine, a plug padlocked to the receptacle will be acceptable in lieu of an interlock, provided the plug is held in place by a threaded ring or equivalent mechanical fastening in addition to the padlock. A connector within a padlocked enclosure will be acceptable.

18.44 (a) A battery box (tray), including the cover, shall be made of steel, the thickness of which is to be based on the total weight of the battery and tray, as follows:

Weight	Thickness
2,000 lb maximum-----	3/16"
2,001 - 4,500 lb -----	1/4"
Over 4,500 lb-----	5/16"

Materials other than steel that provide equivalent strength will be considered.

(b) Battery-box covers shall be lined with a flame-resistant insulating material, preferably bonded to the inside of the cover, unless equivalent protection is provided.

(c) Battery-box covers shall be provided with a means for securing them in closed position.

(d) Battery boxes shall be adequately ventilated. The size and locations of openings for ventilation shall prevent access to cell terminals.

(e) Battery cells shall be insulated from the battery-box walls and supported on insulating material. Insulating materials that may be subject to chemical reaction with electrolyte shall be treated to resist such action.

(f) Drainage holes shall be provided in the bottom of each battery box.

(g) Cell terminals shall be "burned" on. Bolted connector (two-bolt type) may be accepted on end terminals.

(h) Battery connections shall be so designed that battery potential will be minimized between adjacent cells, and total battery potential shall not be available between adjacent cells.

(i) Cables within a battery box shall be protected against abrasion of the insulation.

(j) Each wire or cable leaving a battery box on storage-battery-operated equipment shall have short-circuit protection in an explosion-proof enclosure as close as practicable to the battery terminals. A protective device installed within a nearby explosion-proof enclosure will be acceptable provided the exposed portion of the cable from the battery box to the enclosure does not exceed approximately 36 inches in length; in addition, special care shall be taken to protect each wire or cable from damage.

(k) A diagram showing the battery connections between cells and between trays shall be submitted. The number, type, rating, and manufacturer of the battery cells shall be included in specifications.

18.47 (b) A battery-powered machine shall not have a nameplate rating exceeding 240 volts, nominal (120 lead-acid cells or equivalent.)

B. USDI, Bureau of Mines, Title 30, Chapter I, Part 75.

75.301-5 Notwithstanding the provisions of (75.301-2), for the purpose of preventing explosions from gases other than methane, the following gases shall not be allowed to accumulate in excess of the concentrations listed below:

- (a) Carbon Monoxide (CO) - 2.5 volume per centum
- (b) Hydrogen (H₂) - 0.80 volume per centum
- (c) Hydrogen sulfide (H₂S) - 0.80 volume per centum
- (d), Etc.

75.1105 Underground transformer stations, battery charging stations, substations, compressor stations, shops, and permanent pumps shall be housed in fireproof structures or areas. Air currents used to ventilate structures or areas enclosing electrical installations shall be coursed directly into the return. Other underground structures installed in a coal mine as the secretary may prescribe shall be of fireproof construction.

75.1100-2 (e) Electrical installations (1) Two portable fire extinguishers or one extinguisher having at least twice the minimum capacity specified for a portable fire extinguisher in 75.1100-1 (e) shall be provided at each permanent electrical installation.

