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A COMPARISON OF EM EMISSION REDUCTION METHODS FOR PERSONAL DUST MONITORS

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ABSTRACT

The continuous personal dust monitor (CPDM) is an essential instrument for working in hazardous environments, is used to monitor real-time coal dust exposure, and is mandated by the Mine Safety and Health Administration (MSHA) for underground coal mines. Researchers from the National Institute for Occupational Safety and Health (NIOSH) found that it is possible for electromagnetic interference (EMI) between a CPDM and a proximity detection system (PDS) to occur. Various approaches have been taken by researchers and manufacturers to address this EMI issue. Administrative controls were recommended to keep the CPDM six inches away from the wearable PDS device. Shielding pouches were made to contain the electromagnetic (EM) emission from the CPDM. Metal shielding was added to major EM emitting components. EMI filtering with large capacitors was introduced to mitigate EMI. Most recently, a novel magnetic-field-cancellation-based approach was developed and achieved remarkable results. In this paper, we provide a comparison between these approaches. The pros and cons of each approach are presented and discussed, so that mining device manufacturers and operators can best evaluate the technology and controls that improve the health and safety of mine workers.

INTRODUCTION

Underground coal mine workers face a number of safety and health hazards in their daily work, including the risk of being struck by a piece of mobile equipment and the risk of being exposed to dust that can cause respiratory diseases. To address the safety hazard of being struck by one piece of equipment, the continuous mining machine, the Mine Safety and Health Administration (MSHA) requires (30 CFR § 75.1732) that these machines be equipped with a proximity detection system (PDS) [1]. These systems use low-frequency magnetic field signals sent between machine-mounted and miner-worn transceivers to determine the proximity of the miner relative to the machine and to automatically disable machine motion when a miner is detected in a hazardous location. To protect miners from the respiratory health hazard of dust, MSHA also requires (30 CFR § 70) that certain miners wear a continuous personal dust monitor (CPDM), which is a battery-powered dust sampling device that is worn on the miner's belt and provides continuous monitoring of the miner's dust exposure [2].

Both of these MSHA-mandated safety and health devices—the CPDM and the miner-worn component of the PDS—are typically worn on the miner's belt and maintaining the proper function of both devices is important to protecting the health and safety of the worker. However, after the introduction of both devices, it was brought to the attention of NIOSH researchers that abnormal behavior was observed when the two devices were worn close together. It was confirmed by the NIOSH team that electromagnetic interference (EMI) was responsible wherein electromagnetic noise emitted by the CPDM would cause the wearable component of the PDS to fail to detect when it was in close proximity to the continuous mining machine [3-6]. Clearly, this constitutes a significant safety risk as, during periods in which the interference is occurring, the miner is able to get hazardously close to the machine without receiving a proximity warning.

NIOSH researchers began a multi-year research effort to quantify and characterize the interference between these two devices as well as to develop and validate strategies to prevent or mitigate the interference. Several strategies were investigated, including administrative controls, shielding, filtering, and most recently a strategy based on magnetic field cancellation. Each of these strategies is discussed in the following sections, and results of the research are presented.

MEASUREMENT SETUP

To evaluate the effectiveness of EMI control methods, radiated electromagnetic (EM) emission measurements, in the following sections, except Filtering, are conducted using a COM-POWER AL-RE101 loop antenna. The antenna is placed 7 cm away from the CPDM on the cyclone side and is connected to a Tektronix® RSA5115B spectrum analyzer through a coaxial cable. Note the 7 cm distance is adopted from the radiated EM emission measurement defined in military standard MIL-STD-461 [7], RE101 testing.

To measure the effectiveness of filtering methods, conducted EM emission is measured (i.e., current). The current is measured by probing a resistor on the circuit board. The signal probe is then connected to the same spectrum analyzer described above.

For both setups, the spectrum analyzer is then set to detect peak values with 1 kHz resolution bandwidth up to 300 kHz frequency range. To capture the maximum emission value, a thousand sweeps within the frequency range are performed for about 10 seconds. Then the largest of the detected peak values of all the sweeps is recorded using max-hold function of spectrum analyzer.

Throughout the experiments, the same CPDM device is tested for a fair comparison between different EMI mitigation methods. As mentioned above, the EM measurement here and afterward will focus on the cyclone side of the CPDM (Figure 1) because it has been found to have the highest EM emission. Additionally, As shown in Figure 2, the peak emission of the CPDM occurs at 100 kHz. Therefore, 100kHz is used as the comparison point for all control methods.

ADMINISTRATIVE CONTROL

Prior NIOSH research [4, 6] has shown that a simple yet effective method of mitigating EMI is to maintain a minimum distance between the CPDM and the wearable component of the PDS. Since the strength of the magnetic field decreases rapidly with distance, maintaining a minimum separation distance may be sufficient to ensure that an interference effect does not occur.

Figure 2 displays this separation distance effect, where the overall magnetic fields decrease as the separation distance increases, and there is 9.3 dB reduction at 100 kHz when the distance increases from 7 cm to 15.2 cm (6 inches). It should be noted that 6 inches is the minimum separation distance recommended by the manufacturer and adopted in the industry to ensure that the performance of a PDS is not affected by the EMI generated from a CPDM [4]. This administrative control method can be effectively achieved by, for example, wearing the two devices on opposite sides of the waist. However, practical considerations, such as additional items that must be worn on a miner's belt, may make it difficult for miners to follow this recommendation. And, as with all administrative controls, the effectiveness of this strategy depends on whether it is consistently and correctly followed. To best ensure that interference does not occur, it is preferable to have an engineering control that does not depend on maintaining separation distance.

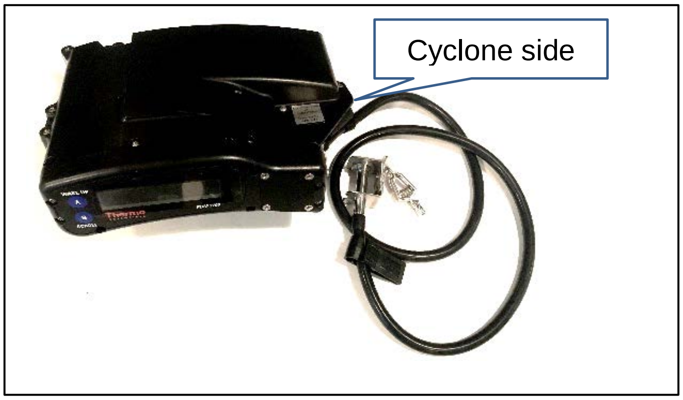


Figure 1. Image of personal dust monitor (CPDM) device.

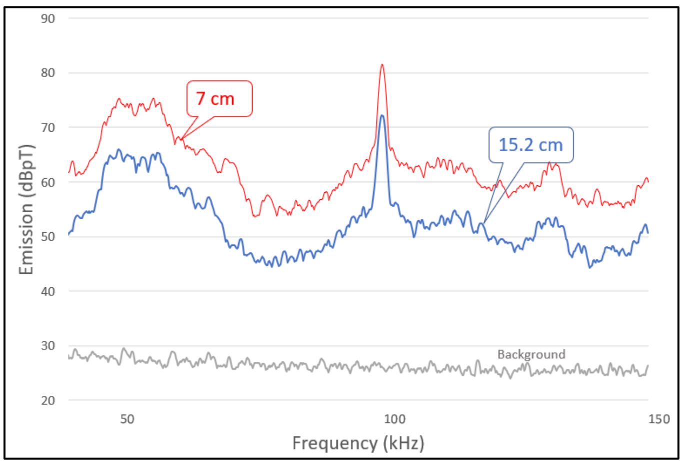


Figure 2. Measured EMI on the cyclone side of the CPDM at two different distances (7 cm and 15.2 cm).

SHIELDING

Device-level shielding

Not long after the discovery of the EMI issue between CPDM and PDS equipment, the PDS manufacturer made a copper-mesh pouch to enclose the CPDM, in the hope of resolving the issue by shielding EMI emitted by the CPDM. Its effectiveness and comparison with other shielding materials on the CPDM were previously studied by NIOSH researchers [4].

In the current study, the pouch product is re-evaluated and compared. Figure 3 shows the EM emission measurement results for the CPDM with and without the shielding pouch. As shown, there is about a 3.75 dB reduction in EM emission at 100 kHz for the CPDM using the pouch.

Component-level shielding

While a device-level EMI shielding pouch made by the PDS manufacturer can alleviate the issue, the pouch adds extra weight and size to the device and hinders the dissipation of heat generated by the CPDM. A further investigation [3, 8] revealed that the major culprit of EMI was the battery of the CPDM. Therefore, an alternative solution is to wrap the battery pack with shielding materials (e.g., copper foil, steel mesh, etc.). EMI measurement on the cyclone side were taken when the battery was wrapped in 0.09 mm-thick copper foil for test purposes (Figure 4).

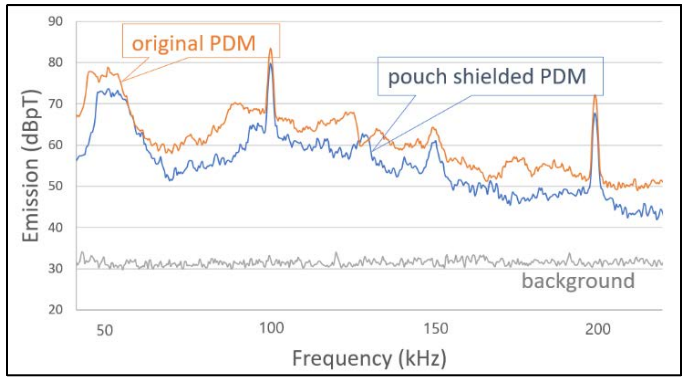


Figure 3. A comparison of measured EMI on the cyclone side of the CPDM when shielded in a copper-mesh pouch.

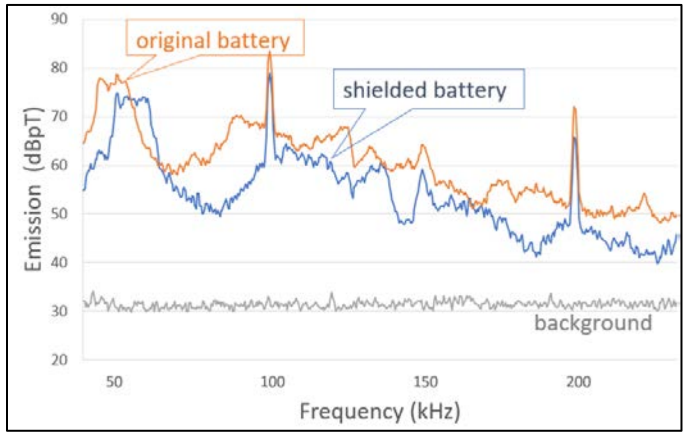


Figure 4. EMI measurement comparison on the cyclone side of the CPDM when using the original battery and the shielded battery.

As shown, at 100 kHz, there is a 4.6 dB reduction in EM emission. Compared to the shielding pouch, the copper foil shielding on the battery showed slightly better EMI reduction on the cyclone side of the CPDM. Although it is not a direct comparison between the two shieldings, as one is on the device level and the other is on the component level, there are a couple of things worth mentioning. First, there are some openings in the pouch that leak EM energy. These openings are needed for viewing the CPDM screen, allowing air to be drawn in to be sampled for dust, etc. Second, the battery is located on the cyclone side of the CPDM. Because it is the largest EM emission source, the shielding on the battery has a direct impact on reducing EMI on this side. Third, besides the battery, there are other strong EM emission sources in the CPDM, for example the DC-to-DC voltage converters, the air-pump motor, etc. The pouch tends to mitigate EM emission for the whole device, while the shielding on the battery is limited to the battery only.

FILTERING

While shielding is used to reduce radiated EM emissions, filters are used to reduce conducted EM emissions on the electrical circuits [9]. However, this has not been studied in the CPDM. This section examines the filtering methods used to reduce EM emissions from CPDMs. Since the largest EM emission source is the CPDM's battery, adding EMI filters across the battery power pins to suppress the EM emissions is a logical choice.

There are two classes of EMI filters, active filters and passive filters. Active filters are composed of transistors, op-amps, or integrated circuits. Active filtering's biggest limitation is that an external DC power supply is required for the filter circuit itself, since it cannot obtain its power from the input signal. This limitation excludes the option of using active filters on the battery pins, since the battery is the only source of power in the CPDM. On the other hand, passive filters are constructed using passive elements: resistors, inductors, and capacitors. They are also less expensive and simple to design. Therefore, they are commonly used to suppress EM emissions.

Our measurement results showed that the CPDM battery's current fluctuates substantially, with an average value of about 0.5 A (Figure 5). There is a significant AC current component on top of the DC current. This AC component is one of the reasons that the battery is the largest EM emission source of the CPDM.

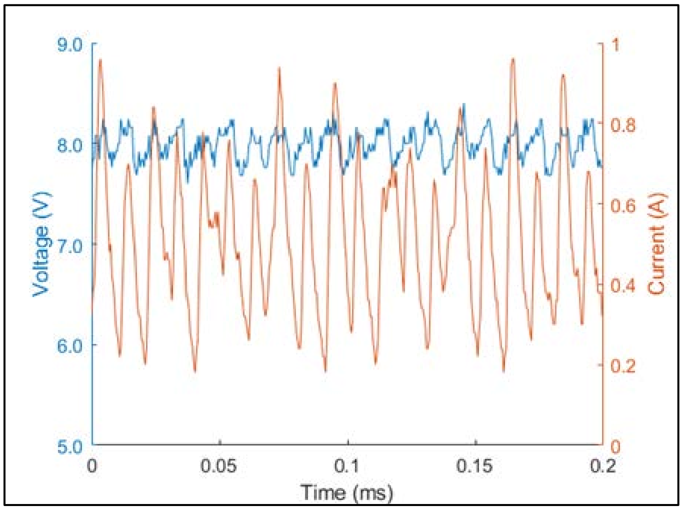


Figure 5. CPDM battery output voltage and current during operation.

Another interesting thing to note is that the output voltage of the CPDM battery is not as constant as might be expected (Figure 5). This might be caused by the internal resistance of the battery cells and/or the short circuit protection resistor on the battery management board inside the battery pack.

Two passive filters to reduce the EM emission of the battery were studied and are presented here: a capacitor filter and an inductor filter. A capacitor is known to be effective in limiting the change rate of voltage, while an inductor is effective in limiting the change rate of the current.

Capacitor Filtering

When a 4.7 uF capacitor is added as a passive filter between the battery's positive and negative power pins, the current and voltage output fluctuations decrease (Figure 6). The current fluctuation variance decreases by 47% and the voltage fluctuation variance decreases by 33%.

When recording the maximum current spectrum, the peak value at 100 kHz is shown to be reduced by 2.0 dB (Figure 7).

To achieve more reduction, especially in the low-frequency range, a larger capacitor is needed. When a 1,000 uF capacitor is used, the reduction is about 8.2 dB (Figure 7). A large capacitor is usually not desirable, not only because of its size, but also because of intrinsic safety requirements in underground coal mining. Furthermore, the benefit of capacitor filtering decreases in the high-frequency range (Figure 7) because the parasitic (inductive and resistive) impedance of the capacitor wires increases when frequency increases, which tends to nullify the filtering of capacitor.

Inductor Filtering

When a 4.7 uH inductor is added as a passive filter to the positive power pin, the battery's output current and voltage fluctuations are reduced (Figure 8).

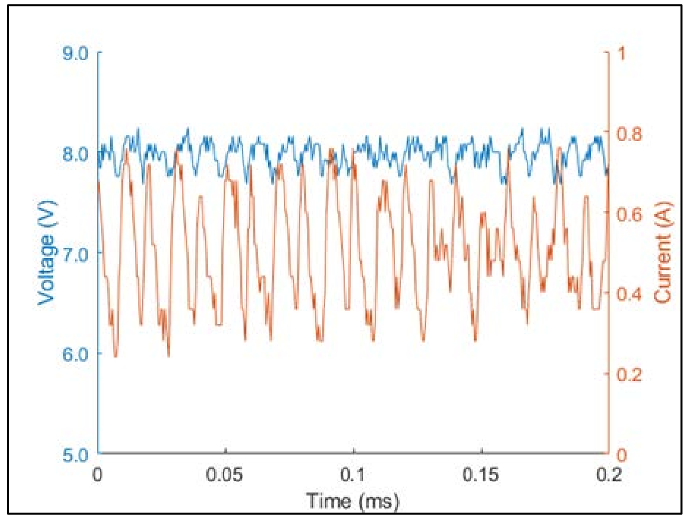


Figure 6. Voltage and current at battery output using a 4.7 uF capacitor as a passive filter.

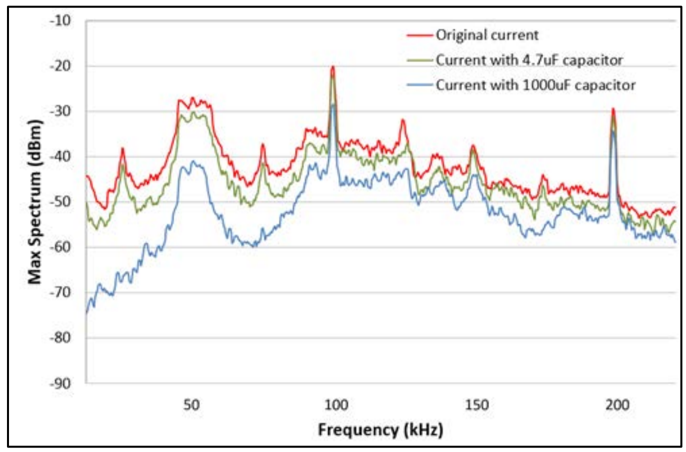


Figure 7. Battery current max spectrum when using 4.7 uF and 1,000 uF capacitors.

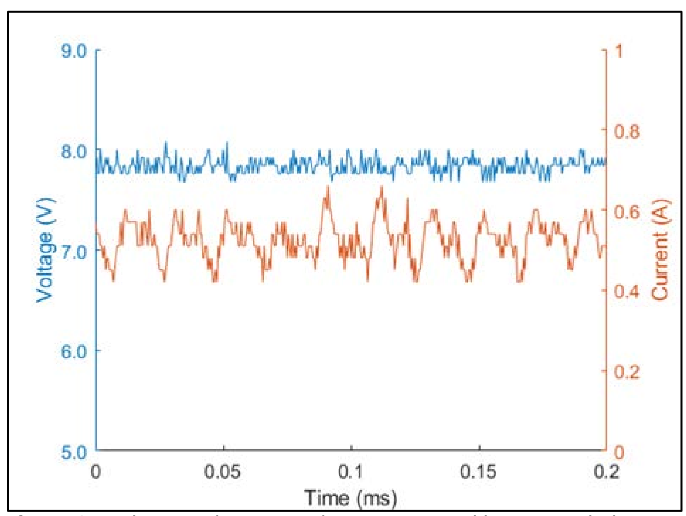


Figure 8. Voltage and current at battery output with a 4.7 uH inductor.

Experimentation showed that a 4.7 uH inductor is very effective in reducing the fluctuation of both the voltage and current of the battery. The current fluctuation variance decreases by 93% and the voltage fluctuation variance by 71% (Figure 8). From the current spectrum, the data shows that the reduction at 100 kHz is about 13.2 dB (Figure 9), which is much greater than that of a capacitor filter at 1,000 uF

(Figure 7). By comparison, the spectrum of a larger inductor at 10 uH yields a reduction of about 17.8 dB at 100 kHz (Figure 9).

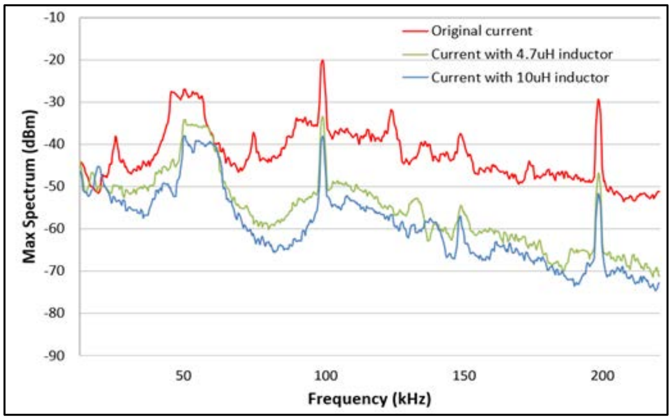


Figure 9. Battery current max spectrum when using 4.7 uH and 10 uH inductors.

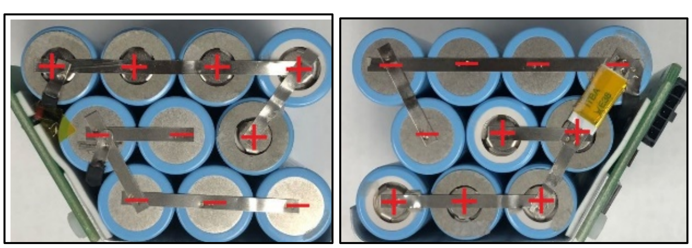
The benefit of using an inductor filter comes with a cost. During normal operation, there is about a 0.23 V voltage drop across a 4.7 uH inductor, and about a 0.29 V voltage drop across a 10 uH inductor. A more significant concern about this voltage drop is that it is not constant. The voltage drop depends on the working stage of the CPDM, which demand varying level of AC currents. This variation will add complexity and uncertainty to the battery health monitor function inside the CPDM. This function usually relies on the battery output voltage to gauge the remaining charge and capacity of the battery. An inaccurate battery charge or capacity estimation could result in either shorter device use time or use at states of discharge lower than intended. Neither case is desirable.

MAGNETIC-FIELD CANCELLATION METHOD

Recently, a new EMI reduction method was proposed for multi-cell batteries by NIOSH researchers [10, 11]. The method is based on the magnetic field cancellation concept that was found in biomagnetism [12-15], scanning electron microscope (SEM) [16], and magnetic resonance imaging (MRI) [17, 18] technologies, but the concept has not been commonly used in combating EMI issues. One reason for this is the complexity and cost of designing a sophisticated circuit system that produces the counter-magnetic field. As a result, magnetic field cancellation is only used in some special-purpose machines or systems.

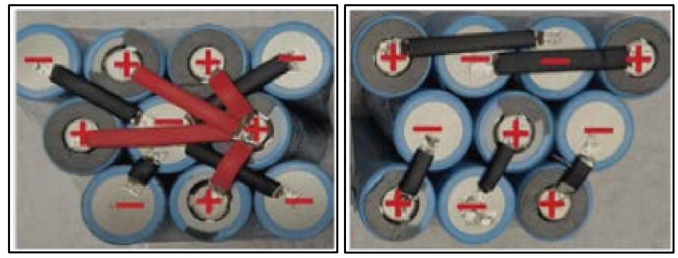
In previous research, the magnetic-field cancellation method is applied to the battery of CPDM device (Figure 10). The basic idea is to cluster the battery cells into pairs, and then for every two pairs, connects them in a way so that their current flow directions are opposing each other. Repeat the process so that it is done to all possible pairs. See more details in [10, 11].

A new battery configuration (Figure 11) was developed to reduce EM emission following a method proposed for multi-cell batteries [10, 11]. The new battery configuration and the stock battery configuration (Figure 10) are both a 2S/5P (2 series and 5 parallel) structure, providing a nominal 7.4 V output and 16 Ah capacity.



(a) Top view (b) Bottom view

Figure 10. Stock battery configuration [10, 11].



(a) Top view (b) Bottom view

Figure 11. New battery configuration based on magnetic-field cancellation method [10, 11].

This study found that, the EMI measurement of the CPDM with the new battery reduced EM emission by 11 dB at 100 kHz (Figure 12).

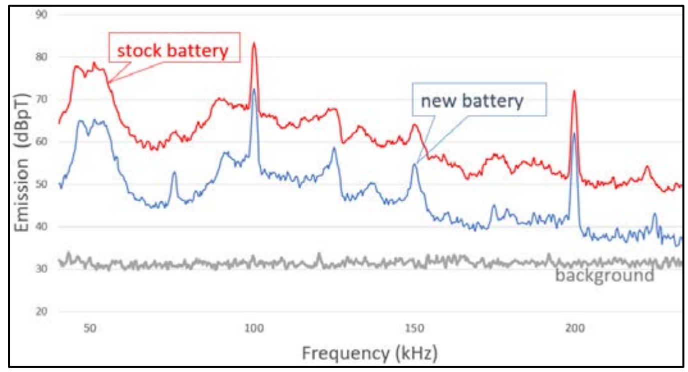


Figure 12. EMI measurement comparison on the cyclone side of CPDM when using a stock battery and new magnetic-field cancellation designed battery.

Performance evaluation

Would the change of battery configuration disturb the normal operation of CPDM or impact the performance of CPDM? Small-scale operational testing was performed to determine the new battery configuration's effect on a CPDM performance. Four CPDM units were used with two having stock battery packs and two having reconfigured battery packs. Three types of tests were performed.

The first type of tests was to check the stability of airflow and general operational function. With full charged batteries, all four units were programed to run six hours. During this time, their air flows were examined with an air flow calibrator, and error codes and other indications of poor operation were monitored.

The second type of tests was to evaluate the battery duration. After charging for at least 12 hours, and the four units were then set to run 12 hours. Similar to the first type of test, air flow data were examined and error code and other indication of poor operation were monitored during the tests.

The third type of tests were performed to measure the coal dust concentration in a chamber. Three tests were performed on each unit for six hours and results were recorded. The battery packs were then switched so that each CPDM unit was powered by another type of battery pack. Three more dust collection tests were performed, repeating the procedure of the first three tests.

All the results indicated that there is less than 1% difference between mean concentration for measurements associated with stock and new battery, and the median values are also very similar. The CPDM with the new battery configuration performed in the same manner as the one with stock battery configuration, as they delivered the same voltage and amperage. This outcome was expected since cell arrangement should be inconsequential.

DISCUSSION

Different EMI control methods were discussed in this paper to address the EMI issue that can occur between a CPDM and a PDS.

Each has its advantages and disadvantages. Administrative control of keeping a minimum distance between two devices is the simplest method and is an effective method. It could be used in conjunction with engineering control methods if they are insufficient or impracticable. As found in [4], some of the engineering controls, e.g. shielding pouch, reduce the emissions from the CPDM but not enough to eliminate the need for a separation distance altogether. Other strategies, e.g. inductor filtering and magnetic-field cancellation on the battery, may be able to reduce emissions sufficiently without additional control measures.

Shielding is a very common method and can reduce radiated EM emission effectively if properly handled. The main disadvantages of shielding are that it adds weight, space, and cost. It also requires complete closure of the shielded object, which is often a challenging task.

Filtering is another common method that is used to reduce EM emission from electrical devices. Fundamentally, filtering controls EM emission by suppressing it at the source (i.e., reducing the variation of voltage or current flowing through the wires and components on circuit boards.) Capacitor filtering plays a key role in almost all modern electronics. Inductor filtering is very effective in reducing current variations, but it also causes a voltage drop which can be undesirable in many applications. Furthermore, inductors tend to require space due to their size, adding cost, weight, and size to both the circuit boards and devices.

Magnetic field cancellation is an established concept, yet was recently discovered to be an effective EMI control method as well [10]. Experimental results on the CPDM shows this control method can successfully reduce EM emission by as much as 11 dB, which is comparable to using a 1,000 uF of capacitor filtering or 4.7 uH of inductor filtering. The merit of the magnetic-field cancellation method is that it does not increase weight or size of the battery or device. It also does not require a redesign of the circuit boards, which is very important for devices already in use. Furthermore, this method can be applied to many battery-powered devices used in mining and other industries. The disadvantage of this method is that it requires certain conditions to apply (e.g., there exists multiple pairs of cells that are configurable to leverage coherently opposing current loops). Not all applications will be conducive this requirement. Another disadvantage of this method is that it adds complexity to the wiring of the battery cells' cathodes and anodes and some battery assembly processes may not be adaptable to such change.

CONCLUSION

Battery packs can be a major source of EM emission. In the case of the CPDM, the battery is the largest EM emission source and causes a documented EMI issue between CPDM and PDS devices used in underground mining. The administrative control, shielding, and filtering are traditional methods that can be used to mitigate this EMI issue. Each has its own pros and cons. The recently discovered magnetic field cancellation method proved effective in reducing EM emission in a multi-cylindrical-cell battery in a CPDM. As greater numbers of cells are packed into batteries, this new method provides a fresh perspective for industry during battery pack design from an EM compatibility point of view, mitigating or preventing unwanted battery EMI issues.

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

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