

Mitigation of RF Radiation and Electromagnetic Interference from a Lithium-ion Battery Pack Used in Wearable Safety and Health Devices in the Mining Industry

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Abstract— Lithium-ion batteries are used widely to power various portable devices operated in many industries, including mining. The safety of using lithium-ion battery is, therefore, always a topic of concern. Researchers from the National Institute for Occupational Safety and Health (NIOSH) recently found that a personal dust monitor (PDM) powered by a lithium-ion battery could unintentionally produce RF radiation that electromagnetically interfered with the miner-wearable-component (MWC) of a magnetic proximity detection system (PDS) causing the MWC to function improperly. A PDM is worn by a miner to continuously monitor dust exposure. A PDS consists of its magnetic radiation antennas mounted on a mining machine to generate steady magnetic fields and an MWC that measures magnetic fields to determine if the miner is at a safe distance from the machine. If the miner is at an unsafe distance, the PDS will warn the miner or stop the machine to protect the miner from being pinned or struck. Electromagnetic interference from a PDM causes the PDS to fail to warn the miner and to stop the machine putting the miner at risk. In an effort to understand the nature of this interference, NIOSH researchers characterized RF emissions from the PDM and found that the lithium-ion battery pack was the strongest RF emission source among the internal components. NIOSH researchers also investigated different shielding materials as a mitigation strategy to reduce RF emissions and to prevent accidents potentially caused by interference with the PDS. The measurements of RF radiation from a PDM's lithium-ion battery and the results of the shielding material evaluation are presented in this paper.

1. INTRODUCTION

Lithium-ion (Li-ion) batteries are used widely to power various portable devices throughout the world. The safety implications of using Li-ion batteries are, therefore, always a concern for researchers and users. A main focus for lithium-ion battery safety has been the heat produced by the battery itself which creates the potential for fire. In this paper, we will present a different safety concern for lithium-ion batteries — namely, that RF radiation produced by the battery can have an effect on the performance of other devices.

Li-ion batteries consist of Li-ion cells. Although Li-ion cells can be different in structure, shape and even the materials used to construct them, they essentially consist of cathode, separator and anode layers enclosed in a metallic container or a laminated aluminum/polymer pouch. An organic electrolyte provides an ionic conducting medium for Li-ions to move back-and-forth between anode and cathode during charging and discharging. Electrical currents flowing in such cells generate electromagnetic (EM) emissions during their operation that increase with increasing load current [1]. As shown in Maleki et al. [1], Li-ion cell EM emissions depend on the design of the cells, such as the positions and lengths of the anode and cathode. To lower the EM emission of Li-ion cells, the authors in [1] present experimental results from cells with different design parameters. The authors also noted that the control circuit of Li-ion batteries can also impact EM emission. The control circuit is used to prevent batteries from overcharging and protect them from excessive discharging. During Li-ion battery research for spacecraft applications, it was recommended that standard electromagnetic compatibility (EMC) tests be performed to demonstrate that the electromagnetic characteristics (emission and susceptibility) of the unit using the battery, under normal operation, does not cause the unit to malfunction. Testing also demonstrates that the unit does not emit, radiate, or conduct interference, which could result in the malfunction of other devices [2]. NASA, in their “Guidelines on Lithium-ion Battery Use in Space Applications,” stated that battery electrical design should meet all electromagnetic interference (EMI) and compatibility requirements for the given application [3].

In the underground coal mining industry, respirable dust exposure is a major health concern. To address this concern, miners are required to wear a personal dust monitor (PDM), a belt-worn

device that continuously monitors their dust exposure. These devices are powered by a Li-ion battery pack. The PDM was recently found to unintentionally radiate EM energy which causes EMI with magnetic proximity detection systems (PDSs). A PDS is used to protect workers in proximity to a mining machine by preventing them from being pinned or struck by the machine. The magnetic emission antennas of a PDS are mounted on the machine and generate magnetic fields around the machine. A miner wears a miner-wearable component (MWC) of the PDS, which measures the field. The measurement is used to determine if the worker is at a safe distance from the machine. Workers generally wear both a PDM and an MWC together on their belts. Laboratory and field tests have demonstrated that the unintentionally radiated EM energy from the PDM sometimes interferes with the MWC resulting in a malfunction of the PDS, in some instances, this may briefly render the PDS inoperable. This creates a serious safety concern.

To mitigate the interference problem, researchers at the National Institute for Occupational Safety and Health (NIOSH) conducted experiments and found that a separation distance of 15 cm between a PDM and an MWC significantly reduces interference [4, 5]. However, in some mine operation situations, it is not always practical to maintain a separation distance of 15 cm between the PDM and MWC. Electromagnetic shielding pouches and boxes made from copper mesh and mu-metal were also developed by NIOSH and other researchers to shield the entire PDM. Tests showed that those pouches could effectively reduce the needed separation distance between PDM and MWC to 5–10 cm [5, 6]. However, tests also showed that the pouches themselves could disturb the local magnetic field generated by the PDS due to the pouch or box being a metal structure. This disturbance was shown to significantly alter the accuracy of the PDS.

To search for a better mitigation solution, NIOSH researchers turned their focus towards the internal RF emission sources of the PDM. They measured radiations from individual internal components of the PDM, and found that the lithium-ion battery pack was the strongest radiation source among the three major EM radiating components: the mass transducer, the air pump motor and the Li-ion battery pack. NIOSH researchers then characterized the emissions of those three components. The EM radiation characteristics of and mitigation strategies for the air pump motor have been reported elsewhere [7].

The EM emission study of the battery laid the foundation for the development of mitigation strategies for it. The initial mitigation strategy investigated by NIOSH researchers was to shield the Li-ion battery pack.

2. PERSONAL DUST MONITOR AND PROXIMITY DETECTION SYSTEM

Workers in underground coal mines often wear a PDM and an MWC together on their belts to monitor respirable dust exposure and to protect them from being pinned and struck by a mining machine. Figure 1 shows a picture of a PDM (PDM 3700) manufactured by Thermo Fisher Scientific (Franklin, MA) and currently in use in the mining industry. It also shows an MWC for a magnetic proximity detection system manufactured by Strata Worldwide (Canonsburg, PA). Figure 2 shows one way these devices can be worn by mine workers on their belts.

A PDM contains a single Li-ion battery pack at the location shown in Figure 1. Figure 3 shows a picture of such a battery pack which consists of ten cylinder-shaped cells. The pack also includes a small battery control board located at one of the corners next to the cable connector. The rated output voltage of the battery pack is 7.4 V DC and the rated capacity is 11.5 Ah.

Although the battery pack used in the PDM outputs a DC voltage, the battery pack, acting as an RF antenna, radiates RF energy when currents in various frequencies, created by subsystems of the PDM, flow through it. Several major components of the PDM can produce these currents in various frequencies that flow through the battery pack. One of these components is the mass transducer. It uses an electronic circuit to generate an AC current to drive a magnetic oscillator. The magnetic oscillator is used to measure collected dust mass. The PDM also has circuitry to generate pulse-modulated voltages to drive an air pump motor and an electrical heating system. These components take a DC voltage as an input from the battery pack and produce AC currents in various frequencies. As these AC currents flow back through the battery pack, the battery pack serves as an unintentional antenna that radiates this electromagnetic energy. To understand the radiation characteristics of the battery pack, researchers at NIOSH developed a method to measure its RF radiation from 10 kHz to 150 kHz. This frequency range was of great interest because it covers the operating frequencies used by all current PDSs operating in US underground coal mines. To determine the radiation characteristics of the battery pack, all six faces of the battery pack were measured using established military standards [8]. The measurements showed that the radiation



Figure 1: The PDM 3700 by Thermo Fisher Scientific and MWC of a magnetic proximity detection system by Strata Worldwide.



Figure 2: An MWC of a PDS (left hand side) and a PDM 3700 (right hand side) worn by a manikin to demonstrate relative locations on a miner's belt.

intensities varied from face to face.

An MWC also a Li-ion powered device, includes a set of magnetic field sensors to detect and measure the magnetic fields generated by the machine-mounted PDS antennas. The measurements are wirelessly transferred to the PDS control unit to determine the distance between the MWC and the machine. The ability of an MWC to detect and report the magnetic fields of a PDS was found to be affected by unintentional EM emission from a PDM when they are in close proximity to each other.

3. METHOD AND EXPERIMENTAL SETUP FOR BATTERY EMISSION MEASUREMENT

To quantify the emission of the PDM battery pack, NIOSH researchers developed a method by referring to the RE101 magnetic radiated emission measurement procedures of MIL-STD 461 [8].

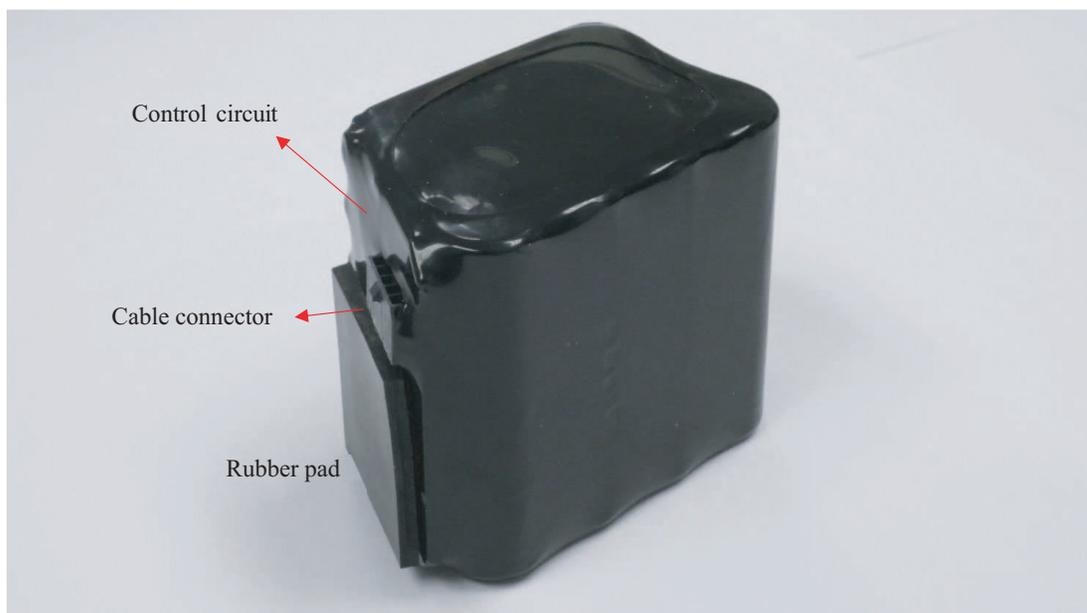


Figure 3: A lithium-ion battery pack from a personal dust monitor (PDM) tested in this research.

Figure 4 shows the basic experimental setup for measuring the emission of the battery pack. A battery pack was removed from its PDM case in order to minimize the influence of the magnetic field emitted by other internal components of the PDM. The battery pack and its PDM unit were set 60 cm apart, and connected by an electrical cable. The battery was positioned on a wooden platform with the face to be measured facing a magnetic loop receiving antenna (AL-RE101). As required by the RE101 test procedures, the distance between the face to be measured and the antenna was set at 7 cm [8]. The measured signal from the AL-RE101 was fed into an RSA5103 signal analyzer for processing. The AL-RE101 has a usable frequency range of 10 Hz to 1 MHz. As stated earlier, the emission measurement range of interest in this experiment was from 10 kHz to 150 kHz. Normal operation of the PDM was maintained throughout the measurement process.

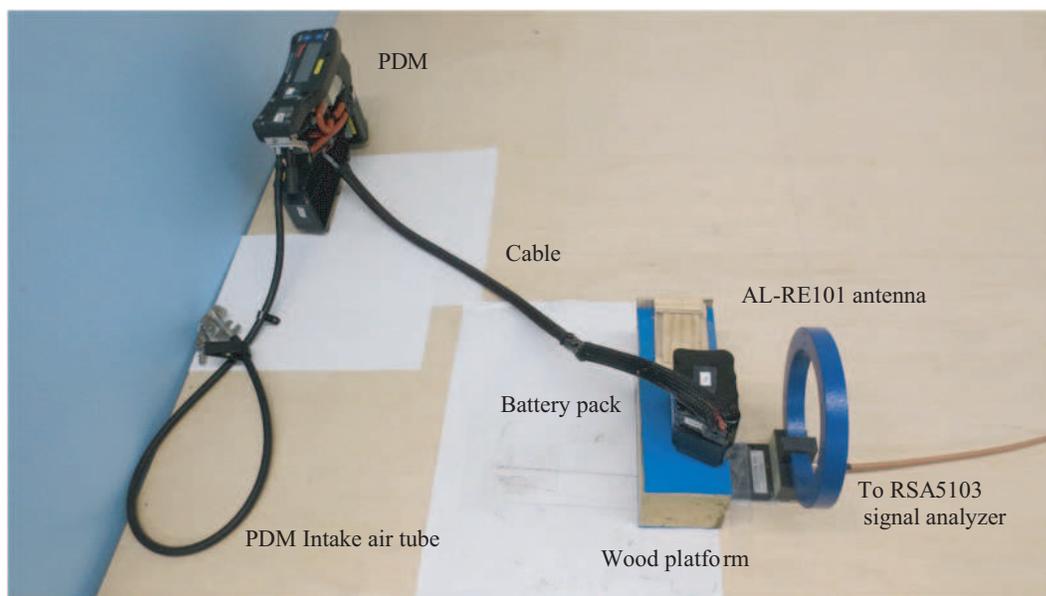


Figure 4: Experimental setup for magnetic emission measurement of the isolated PDM battery pack.

4. PDM BATTERY PACK EM EMISSION MEASUREMENT RESULTS

Figure 5 shows the EM emission curves measured from the six faces of the isolated battery pack of the PDM ranging from 10 kHz to 150 kHz. The x -axis of the chart is a log scale with unit of frequency (Hz), and the y -axis is a linear scale with unit of dB pico-tesla (dBpT) for magnetic flux density. For the purpose of identifying whether the emission of the battery pack could interfere with an MWC, the susceptibility curve of an MWC from a commercial magnetic proximity detection system produced by Strata WorldWide is shown on the chart in a “V” shape curve labeled Susceptibility(PDS). The MWC was, as shown in the chart, found to have the highest susceptibility (or the lowest susceptibility value) at 73 kHz, which is the operating frequency of this PDS.

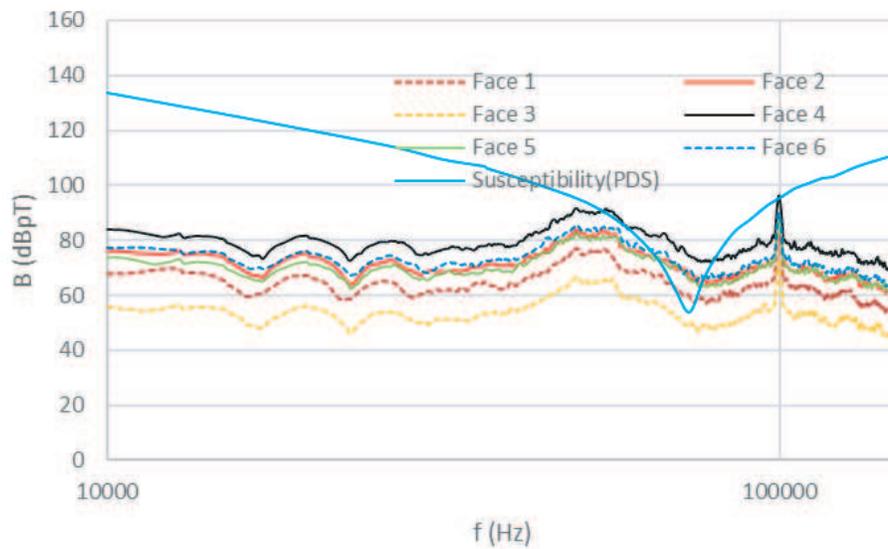


Figure 5: Comparison of the RF emissions of the six faces of the lithium-ion battery of the PDM to the susceptibility of the miner-wearable-component (MWC) of a magnetic proximity detection system.

This chart provides a systematic and practical tool to determine whether emission from the battery pack can cause EMI with the MWC. Interference can happen whenever an emission curve is found above the MWC susceptibility curve. As shown in Figure 5, although the emissions of the battery pack from each face differ, five out of six emission curves indicate that the battery pack can interfere with the MWC around the 73 kHz frequency. Measurements showed that the emissions from Faces 1, 2, 4, 5, 6 are about 6.6 dB, 14.0 dB, 20.9 dB, 12.1 dB and 15.5 dB higher than the susceptibility of the MWC at 73 kHz, respectively. Face 3 was the only face found to have an emission intensity lower than the susceptibility of the MWC by 4.0 dB at 73 kHz. This raises a concern about the safe operation of these two safety and health devices if no mitigation strategies are taken to prevent interference.

5. SHIELDING STUDY FOR THE PDM BATTERY

To mitigate the effect of high RF emission from the PDM’s Li-ion battery pack, NIOSH researchers developed small enclosures to shield the battery. Several cost-effective materials were selected to construct these enclosures to determine their effectiveness. The materials tested were aluminum foil of 0.0254-mm (0.001-in) thickness, aluminum foil of 0.0508-mm (0.002 in) thickness, copper foil of 0.016256-mm (0.00064-in) thickness, copper mesh of 0.1143-mm (0.0045-in) diameter wire with 0.1397-mm (0.0055-in) openings and stainless steel mesh of 0.09906-mm (0.0039-in) diameter wire and 0.09906-mm (0.0039-in) openings.

Figure 6 shows the battery pack with the shielding enclosure made of copper mesh. The enclosure was held in place by adhesive tape. Figure 7 shows the measurement results from the six faces, which allows a calculation for the emission change of the battery pack with the shielding enclosure. The emissions from all of six faces of the battery pack were significantly reduced as compared with the emissions for the unshielded battery shown in Figure 5 where no shielding was applied. Figure 8 shows the emission attenuations of the individual faces of the battery pack with the copper mesh

at 73 kHz. Figure 9 shows the average emission attenuations over the six faces of the battery with shielding enclosures made from each of the different materials tried.

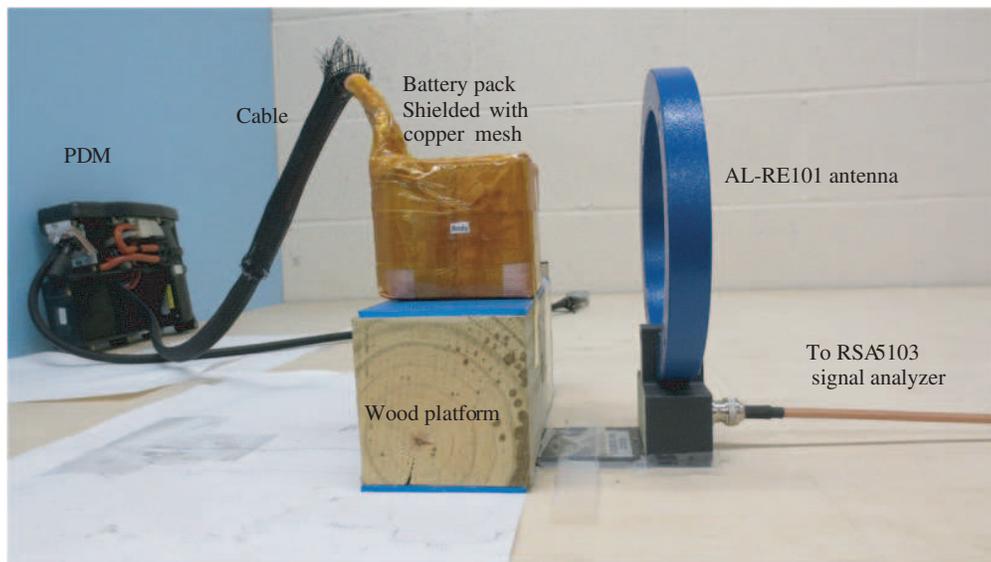


Figure 6: The battery completely shielded with copper mesh made of 0.1143-mm (0.0045-in) diameter wire and 0.1397-mm (0.0055-in) openings.

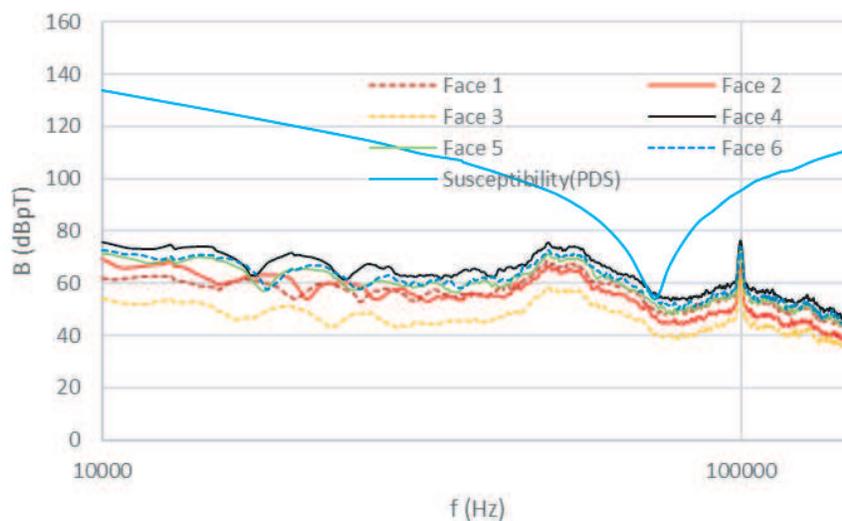


Figure 7: The attenuated emissions of the six faces of the battery pack shielded by the copper mesh made of 0.1143-mm (0.0045-in) diameter wire and 0.1397-mm (0.0055-in) openings.

6. DISCUSSION

As shown in Figure 5, the emissions from the battery pack are different for each face. The difference can be up to 25 dB. This suggests that the orientation of the battery within the personal dust monitor (PDM) can make a difference in electromagnetic interference caused by emissions of the PDM. Probably, such emission characteristics of the battery pack can be used to mitigate emission by orienting the battery pack with its strongest emitting face in the direction least likely to cause EMI.

As shown in Figure 8, the emission attenuation rates of the battery pack with the same shielding material also differ from face to face. This suggests that the shielding material would not change the characteristics of the directional emission of the battery pack.

As shown in Figure 9, the emission attenuation rates for the battery pack are different when different shielding materials are used. Copper and aluminum were found to perform the best

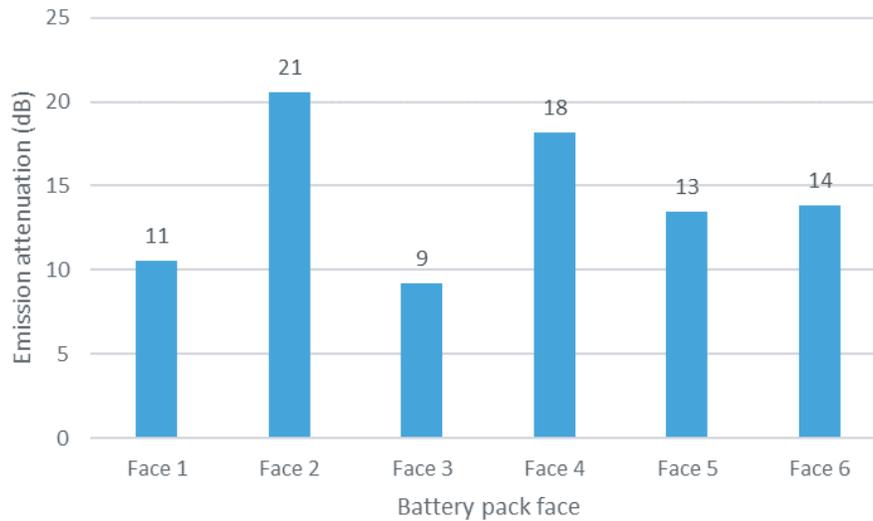


Figure 8: The emission attenuations of the battery pack with copper mesh enclosure at 73 kHz.

based on the attenuation measurements for the battery pack in the frequency range from 10 kHz to 150 kHz. The figure also shows that more attenuation is achieved with a thicker enclosure.

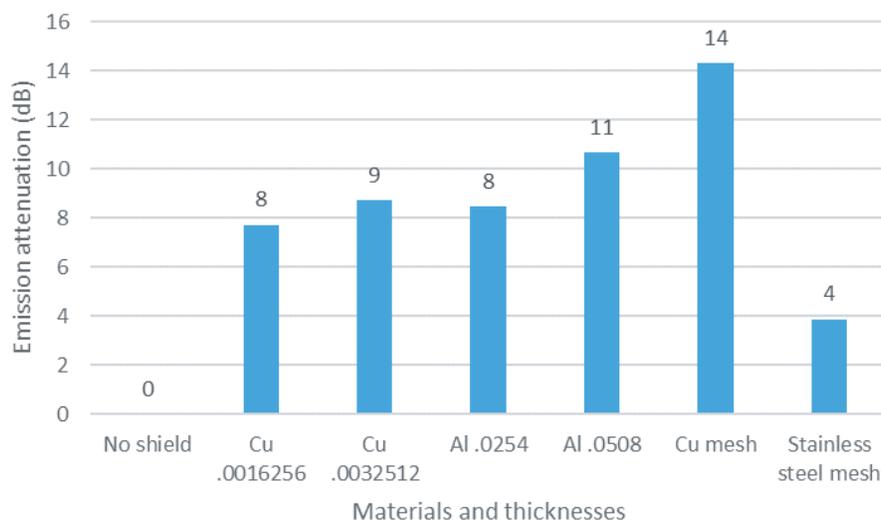


Figure 9: Average emission attenuations over the six faces of the battery pack with shielding enclosures in different material and thicknesses at 73 kHz where “Cu .0016256” denotes copper in thickness of 0.0016256 mm, “Cu .0032512” copper in thickness of 0.0032512 mm, “Al .0254” aluminum in thickness of 0.0254 mm, “Al .0508” aluminum in thickness of 0.0508 mm, “Cu mesh” copper mesh in 0.01143-mm diameter wire and 0.1397 mm openings, and “Stainless steel mesh” denotes stainless steel mesh in 0.09906-mm diameter wire and 0.09906-mm openings.

Past studies show that the EM emission intensity and patterns from a lithium-ion battery vary with the internal structure of the battery [1]. This suggests that emissions from Li-ion batteries can be different if manufacturers use different battery design structures. It may be possible to choose those batteries with the least emission for an application that has stringent EMC requirements.

7. LIMITATION

The mitigation strategy presented in this paper was limited only to shielding materials and did not explore other potential strategies such as the use of electronic filters which can be used to filter out AC currents flowing through the battery pack to mitigate its EM emission.

8. CONCLUSIONS

This paper presents the EM emission measurements of a lithium-ion battery pack used in a personal dust monitor (PDM). The unintentional emission of the battery pack was found to be sufficiently strong to interfere with the miner-wearable (MWC) of a proximity detection system (PDS). The measurements show that the emission intensity was different from different faces of the battery pack suggesting that the battery emission is directional. The paper also presents the emission measurement results of the battery pack with shielding enclosures constructed of different materials in different thicknesses. The measurements indicated that copper and aluminum had the highest emission attenuation rates. The measurements also showed that the thicker the shielding material, the higher the attenuation rate. The findings in this study can be used to help design EMI mitigation strategies for Li-ion battery packs used in the PDM and other Li-ion-battery-powered devices to prevent EMI and ensure electromagnetic compatibility (EMC) among those devices.

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Disclaimer

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

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