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ELECTROMAGNETIC INTERFERENCE WITH PROXIMITY DETECTION SYSTEMS

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ABSTRACT

In April 2016, MSHA began requiring the use of continuous personal dust monitors (cPDMs) to monitor and measure respirable mine dust exposures to underground coal miners. After the cPDM's implementation, mine operators discovered that it interfered with proximity detection systems (PDSs), thus exposing miners to potential striking and pinning hazards from continuous mining machines. NIOSH was sought out by MSHA and mining industry stakeholders to determine how the cPDM and PDS interact with each other. Accordingly, NIOSH investigated existing standards, developed test protocols, designed experiments, and conducted lab evaluations. Some interferences were observed to be caused by electromagnetic interference (EMI) from the cPDM. Results showed that there was no significant interference when the cPDM and the miner-wearable component of the PDS were separated by distances of 6 inches or greater. In this study, the cPDM and PAD needed to be at least 6 inches apart in order for them to be used simultaneously and reduce interference potential.

INTRODUCTION

Underground coal miners are exposed to a variety of hazards on a daily basis such as coal dust exposure, high noise levels, roof and rib falls, the potential for fires and explosions, and operating and working with heavy machinery. One of the hazardous jobs is operating or working nearby a continuous mining machine (CMM). According to Mine Safety and Health Administration (MSHA) statistics, 40 miners have been fatally struck or pinned by a CMM since 1984. In an effort to prevent future striking and pinning fatalities from occurring, proximity detection systems have been developed and are required on all operating CMMs in underground coal mines, with the exception of full-face CMMs, by 2018 (1,2).

Proximity detection systems (PDSs) are designed to alarm miners and stop machine motion in order to protect miners from being struck, pinned or crushed by CMMs(3). Currently, MSHA-approved PDSs, installed on CMMs, are based on the principle of magnetic flux density (B-field) (4,5). The system generates a magnetic field around a CMM and determines the relative distance a miner is from the CMM based on a detected magnetic flux density. A PDS typically consists of multiple magnetic field generators mounted at different places around the CMM, and personal alarm devices (PADs), which are worn by the miners to detect the magnetic flux density. When a miner, wearing a PAD, gets closer to the machine, the PAD detects a stronger magnetic field from the generators and detects a weaker magnetic field when a miner moves away from the machine. The magnetic field generators installed on CMMs typically produce modulated magnetic wave signals at frequencies between 10 kHz and 120 kHz. The magnetic fields are measured by three small magnetic coil antennas mounted on orthogonal axes inside of the PAD worn by the miner. According to Faraday's Law, the changing magnetic field induces a voltage in each coil antenna, and the voltage values are transmitted from the PAD back to a controller on the CMM wirelessly, typically at a frequency between 400 MHz and 2.5 GHz. These values are then used to determine the distance between the miner and the generators of the machine. Typically this information is used to determine when a miner wearing a PAD is in a warning zone or stop zone which would trigger different alarms and actions such as slowing the machine down or stopping it.

When implementing electronic devices like the PDS into an environment, electromagnetic compatibility (EMC) of the devices and electromagnetic interference (EMI) should be considered (6,7). EMI is an unintentional electromagnetic interaction between two electronic devices or systems in which one of the devices experiences a degradation in its performance and functionality. This relates to an electronic device's inherent ability to emit levels of electromagnetic energy that may potentially interfere with the proper operation of another device in its vicinity. EMC can be defined as the ability to control EMI so that two systems, in close proximity to each other, are able to operate as designed without any degradation in performance quality. The effects of EMC and EMI have, historically, been implicated in numerous incidents in which control systems failed, causing ships to run off course, aircraft to crash, and medical devices such as pacemakers and defibrillators to malfunction (8-10). These cases highlight the critical need to consider EMC/EMI in the design and integration of electronic devices into any given environment. Considerations to mitigate this phenomenon are critical in industries such as the military and medical fields, where faulty operation of equipment may result in costly repairs and even loss of life.

Over the years, several standards have been developed to achieve compatibility between different electronic devices and to prevent the degradation of performance quality of these devices (11,12). Several administrative and engineering controls have also been incorporated to overcome these challenges and can include filtering of radio frequencies, shielding of electronic components, and recommendations for separation distances of devices to reduce the likelihood of EMI (14-16). With the promulgation of regulations mandating the use of electronic devices and sensors, the challenges of EMC and, by extension, EMI are being brought to the forefront.

One case of EMI transpired soon after the continuous personal dust monitor (cPDM) was required to be used to determine respirable dust exposure. The cPDMs are devices worn by a miner that continuously monitor and display the amount of respirable coal mine dust in the vicinity of the miner (17). The cPDM has an internal motor which drives a pump to continuously draw in air from the miner's breathing zone through a tube. The air is drawn through with a cyclone which only permits respirable size particles to collect on the filter, and the mass of the particles is determined by an oscillating microbalance. The results—the amount of dust in the vicinity of the miner—are displayed on a small screen. The cPDMs were thought to interfere with the performance of proximity detection systems.

Electromagnetic (EM) energy can be transferred between the source and victim devices via conduction, radiation, or both. An example of conducted interference is a source producing EM noise on its power cable which the noise then appears in the electrical supply and the victim's power cable, causing degradation in the victim's performance. An example of radiation interference is RF energy intentionally or unintentionally emitted by a source, such as the cPDM, which is intercepted by circuitry within a victim device, such as a proximity PAD, causing degradation in the victim's performance. In the case of the cPDM and the PAD, neither device has a power cord nor other electrically conducting appendage attached. Hence, there is no need to consider conduction type interference.

The cPDM is battery-operated and has a variety of electronic circuits to turn the battery-supplied DC voltage to an AC voltage in various frequencies. These circuits can generate radio frequency (RF) noise covering the frequencies in an extended range, including the operating frequency of the PDS. At a distance from a PDS generator, the amplitude of a measured B-field signal by a PAD could be not sufficiently greater than the RF noise (as characterized by signal-to-noise ratio (SNR)). In this case, the noise can significantly alter the signal received by the PAD. As a result, the PDS controller will determine a wrong location of the miner based on the erroneous signal received from the PAD.

Testing procedures for EMI or EMC independently evaluate the source and the victim device. The source device is evaluated for its emissions. Emissions can be either intentional, such as a broadcasting handheld radio or cellphone, or the emissions can be unintentional, as in the case of the cPDM voltage controller radiating RF energy. The victim is evaluated for its susceptibility or immunity to performance degradation from RF energy. For example, in our case, radiated emissions (RE) testing is necessary on the cPDM, and radiated susceptibility (RS) testing is necessary on the PAD. In this study, the emissions from the cPDM and other electronic devices commonly used in underground coal mines, as well as the susceptibility of the PDS system, were quantified in NIOSH's Pittsburgh Laboratory using military standards (MIL-STD-461E).

METHODS

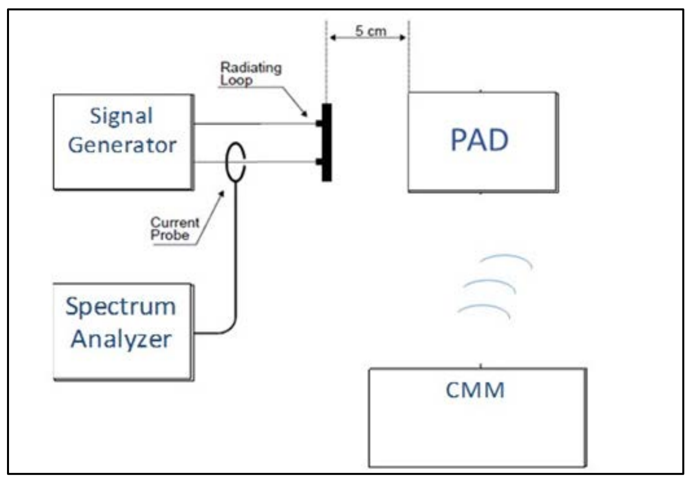
To quantify when the interaction between the cPDM and PDS results in an interference, the susceptibility of the PDS needs to be determined and then the emissions from the cPDM, at different distances from the PDS, need to be evaluated. This can also be performed to calculate compatibility between the PDS and other electronic devices used in underground coal mines.

Measuring radiation susceptibility of the PDS

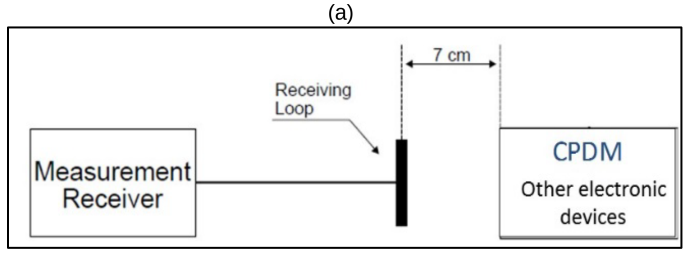
The strength of the magnetic field produced by generators installed around the CMM depends on the distance from the machine. The further the away the PAD is located, the more vulnerable the PDS is to EMI because of a low SNR. The susceptibility of the PDS, was therefore, evaluated at the edge of the warning zone, or the farthest point from the machine where the PDS detects the presence of the PAD indicating a miner located in the warning zone. At this point, the miner may be approaching a hazardous condition and the PDS will apply a safety function such as activating an alarm and/or reducing machine speed.

NIOSH worked with PDS manufacturer, Strata, to acquire a customized system to enable laboratory testing. The Strata system consists of software modifications described by Bissert et al., 2016 (18). The PDS features four electromagnetic (EM) field generators installed on CMM machines and PADs, or miner-wearable devices worn by the miners. The governing principle is that the closer a miner wearing a PAD gets to the CMM, the higher the magnetic flux density. When a miner is detected in hazardous proximity to the CMM, the proximity detection system first provides a visual and audible warning to indicate a "warning" zone incursion, then completely halts all machine tram and conveyor boom functionality if the miner enters the "stop" zone. The different zones are set depending upon the threshold of the magnetic flux density. The PAD detects the signal from the four generators and transmits the measurements of the signal to the PDS controller. The controller then calculates the position based upon the values of the generator signals. The customized system enables the reading of data streams generated by the controller. If a signal detected by the PAD from one of the generators shows a suddenly drastic change, the controller will freeze the signal from that generator and consider the signal to be invalid. The controller will continue using the last valid measurements to determine the PAD location. This scenario can also occur when a strong noise cripples a valid signal. If signals from two generators are frozen, the position of the miner detected by the PDS can show to be constant and frozen, allowing the miner to approach the machine without being identified by the PDS. This type of triangulation and indication of an interference is unique to the modified Strata system at NIOSH and is not part of the commercial version.

The apparatus (see Figure 1a) for military standard MIL-STD-461E RS101 was set up at the edge of the "warning zone" of the Strata PDS at the Pittsburgh Mining Research Division proximity detection laboratory (12). The susceptibility was then quantified using military standard RS101. In this setup as shown in Figure 1(a), an Agilent 33220A signal generator was used to feed a signal to a type 9230-1 radiating loop antenna, which generated a magnetic field to attack a PAD, and a Tektronix RSA5103A signal analyzer was used to measure the voltage from the current probe BCP-510. As signal level from the signal generator increases, the antenna current increases, and so does the voltage from the current probe. The current increase also results in strengthening the magnetic field generated by the antenna. The change of magnetic flux density with antenna current change could be quantitatively determined from the output voltage of the current probe. The threshold for EMI is identified when the magnetic flux density reaches a point at which the generated field is significantly interfering with the PAD. In this study, when the field caused two generator readings from the PAD to freeze, the magnetic flux density reading was defined as the threshold of EMI. In this procedure, the PAD was set 2 inches (5 cm) from the antenna and then the strength of the 10 kHz signal directed towards the PAD was increased. the test was repeated and the field was strengthened at different frequencies to determine the EMI threshold at those frequencies. Up to 37 frequencies were selected from 10 kHz to 146 kHz at a step of 0.5 kHz to 46 kHz. A small frequency step was taken for those of the selected frequencies close to 73.5 kHz, while a large step was taken for those far from 73.5 kHz. This procedure was repeated for several different positions around the CMM as well as four different orientations of the cPDM.



Signal from four generators around CMM
(a)



(b)

Figure 1. (a) the apparatus for military standard RS101 and (b) the apparatus for RE101.

Measuring EMI from electronic devices

The emissions from electronic devices were quantified using the military standard MIL-STD-461E RE101 (see apparatus in Figure 1(b)) (12). RE101 requires the electronic device to be 2.8 inches (7 cm) away from the antenna. In this test, a HP11966K magnetic field coil antenna was used to receive the RF noise generated by the PDM, and a Tektronix RSA5103A signal analyzer was used to store RF noise signals and perform the noise spectrum analysis. The emissions from the cPDM were measured for different orientations as shown in Figure 2.

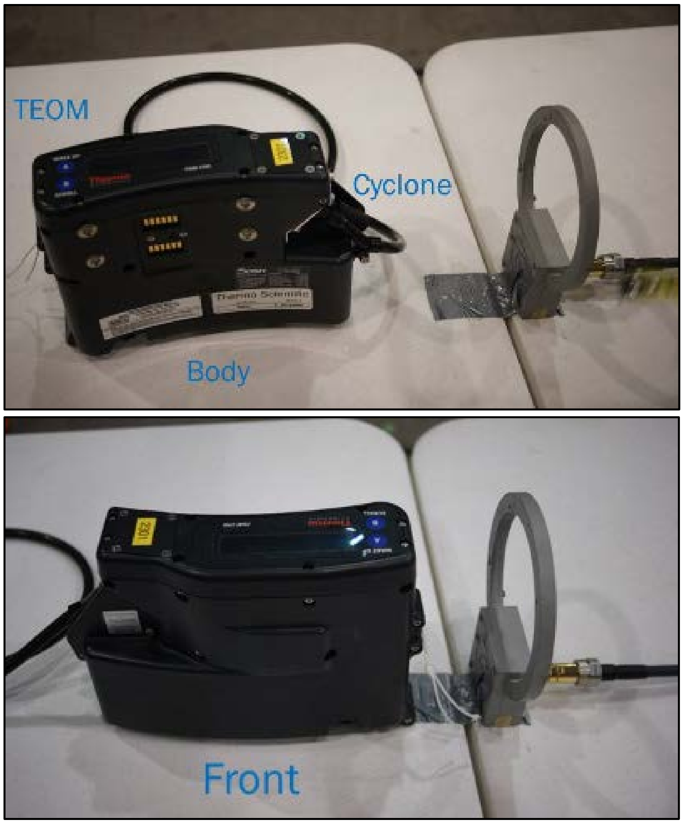


Figure 2. Positions of the cPDM tested.

In order to determine the EMI at different separation distances between the PAD and electronic device, the same test used in military standard RE101 was performed at different distances between the electronic device and the antenna. In addition to two cPDM 3700s, other electronic devices that are common in underground coal mines were also tested at various orientations. These instruments included an Industrial Scientific multi-gas analyzer MX4, an Industrial Scientific multi-gas analyzer MX6, a Kenwood radio, a Bosch GLM 80 laser distance finder, a Hilti PD 40 laser distance finder, and a Zefon Escort Elf Pump. The laser finders were tested with and without the distance ranging feature actuated, and the radio was tested in transmitting and not transmitting modes.

In addition to testing the PAD for susceptibility, researchers also tested the PDS system generators and control system to determine EMI on the receivers. This was based on a concern with the radio because it emits at a higher frequency and could interfere with the communication between the PAD and controller of the PDS. Therefore, the RE101 setup was used with an omni-directional antenna (Surecall SC-288W) for a frequency range between 698 and 960 MHz to measure the communications between the PAD and controller at the higher frequencies. The PAD of the PDS was placed 2.8 inches from the antenna, and the emissions from the PAD were measured. Then, the radio was keyed at different distances from the PAD.

Separation distances: The next step was to validate the separation distances determined by the emissions from the cPDM and the susceptibility of the PDS based upon RE101 and RS101 testing. The PAD was inserted on a belt worn by a manikin. The manikin was moved to within the warning zone of the proximity detection system in the laboratory at the location which demonstrated the worst case of susceptibility based upon RS101 results. The responses of the four generators were recorded. The number of times the system froze was also recorded. This test was designed to provide a baseline of the number of times the PDS would freeze without the influence of the cPDM. Now a cPDM was added to the belt (as seen in Figure 3) at 6 inches from the PAD. The above experiment was repeated using separation distances of 3, 5, 8, and 11 inches.

Figure 3. The cPDM and PAD of PDS inserted onto a belt of a manikin to quantify the effects of the cPDM on the PDS.

Results and Discussion

Results showed that the cPDM interfered with the function of the PDS at three out of the four orientations tested when 2.8 inches away from the PAD. Figure 4 shows the emissions measured from the cPDM when it was 2.8 inches from the antenna when using military standard RE101, with the susceptibility curve showing the lowest values out of the several orientations tested with RS101. The level of EMI from the cPDM in this measurement would be what is exposed to the PAD when the devices are 2.8 inches from each other. This EMI at positions front, body, and cyclone was above the susceptibility curve at a range of frequencies—hence the cPDM could interfere with the PDS. The emissions were below the susceptibility curve when the TEOM side was close to the PAD, showing that when the cPDM TEOM side is towards the PAD, the EMI may not influence the PDS.

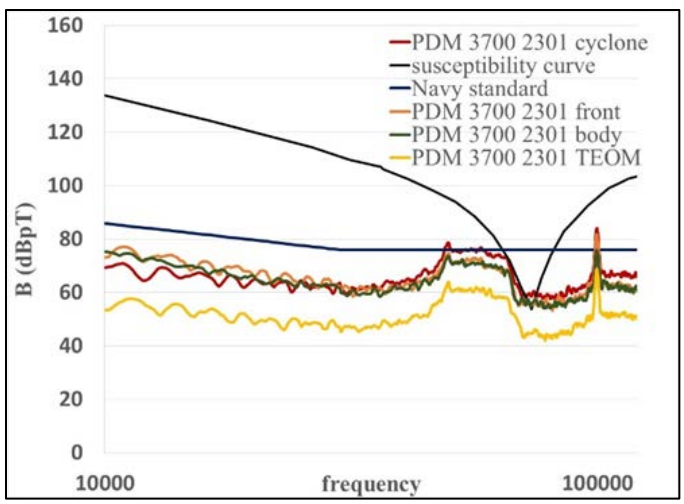


Figure 4. Graph showing that the EMI emitted from the cPDM was above the susceptibility curve for the PDS at the cyclone, front, and body positions.

This test was also repeated using a different cPDM to confirm accuracy of results. These levels of EMI were not just the result of the characteristics of one instrument, for the EMI was consistent for two different instruments (see Figure 5). The cPDM's influence on the PDS was confirmed when it was placed within 2.8 inches of the PAD while the PDS was operated. In these circumstances, during testing at the NIOSH Pittsburgh laboratory, it was observed that the cPDM would cause the signal from the generators of the PDS to freeze. The position of the miner indicated by the PDS would then be stationary no matter where the miner was actually located, allowing the miner to approach the CMM without being detected.

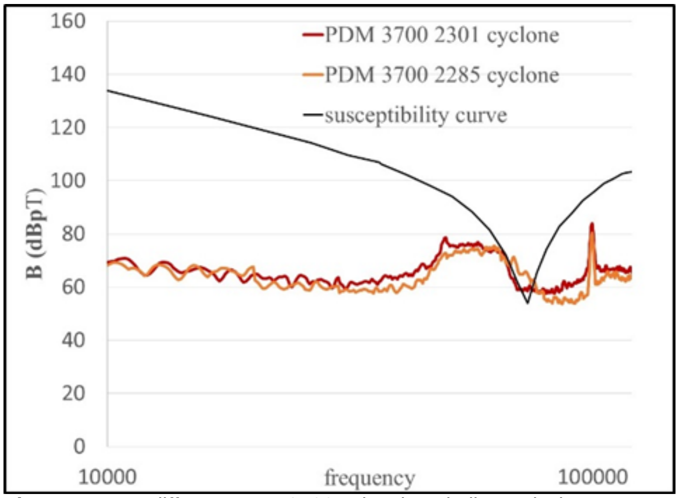


Figure 5. Two different PDM 3700s showing similar emissions.

These results do not mean that the cPDM is emitting high EMI, for the emission levels from the cPDM were shown (see Figure 4) in our test to be below the Navy EMI standards (EMI levels where all electronic equipment must be below to be used in the Navy and ensure compatibility with other systems), except for a few peaks in the cyclone position which were just barely at or above the level. However, even though they were below the Navy standard, the emissions were above the susceptibility of the PDS, meaning that at 2.8 inches apart the cPDM and PDS cannot be operated simultaneously. Further, the susceptibility curve of the PDS demonstrated what levels of EMI are necessary to influence the PDS from other electronic devices commonly used in underground coal mines as well.

One way to mitigate the influence of EMI is to separate the PAD from the cPDM using EMC distance. For this purpose, EMI measurements were collected with the cPDM at different distances from the antenna. As seen in Figure 6 (where cPDM position was the worst case for emissions of EMI levels), when the cPDM is 6 inches from the antenna, the EMI is now below the susceptibility of the PDS. Therefore, a 6-inch separation distance between the cPDM and PAD should result in no significant interference, meaning that the two devices tested in this laboratory can operate simultaneously if kept at least 6 inches apart.

After the cPDM, other electronic devices commonly used in underground coal mines were also tested (see Table 1). As with the cPDM, the emissions were compared to the PDS susceptibility curve to determine if the device would influence the PDS. In addition, each device was tested at different distances from the antenna. The Zeflon Elf pump and the Bosch GLM 80 laser distance finder did not provide levels of EMI which would potentially cause an observable interference until they were 2 inches from a PAD. The gas analyzers tested did not provide observable interference even when 2 inches from a PAD. Similar to the cPDM, the Hilti PD 40 laser distance finder did emit EMI levels which could influence the performance of the system when less than 6 inches from the PAD.. Unlike the cPDM, this interference would only be intermittent since it only occurred when the ranging feature was actuated. The Kenwood radio did not provide EMI at the frequencies tested in RE101 but would cause a potential interference to the PDS when keyed at the higher frequencies (900 MHz). The PAD communicates with the controller on the CMM indicating the position of the miner in the 400-900 MHz range, and when keyed as great as 29 inches from PAD, the radio interfered with this signal. Again, like the laser distance finder, this interference was intermittent, for it only happened when the radio was keyed. A separation distance of at least 6 inches where EMI at 10-120 kHz did not influence the PDS applied to all electronic devices tested in this study. The electronic devices do not represent all of the instruments used in underground coal mines, but this paper provides information on some common ones.

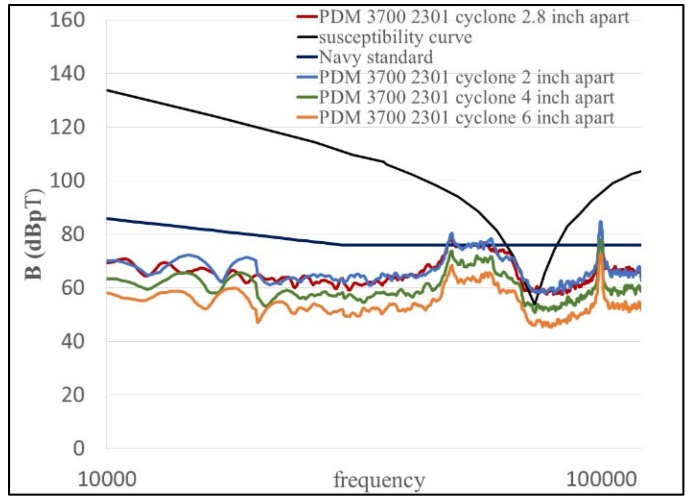


Figure 6. The EMI of the cPDM at the cyclone position (worst case) at different distances from the antenna. No significant EMI was observed when 6 inches were between cPDM and antenna.

Table 1. Distances between PAD and electronic device when the EMI would affect the PDS.

Device	Distance when EMI would influence PDS
PDM 3700	less than 6 inches
IS multi-gas analyzer MX4	less than 2 inches
IS multi-gas analyzer MX6	less than 2 inches
Kenwood Radio	Only in higher frequency
Bosch GLM 80 laser distance finder	2 inches and less
Hilti PD 40 laser distance finder	less than 6 inches
Zefcon Escort Elf pump	2 inches and less

The separation distance or EMC distance of at least 6 inches from the cPDM is based upon the EMI levels and susceptibility measurements. Next, this mitigation strategy needed to be validated with the PDS system. Since the cPDM provides the worst EMI of the devices tested and is most likely to be close to the PAD, this device was used to validate the RE101 and RS101 results. The cPDM and PAD were placed at different distances from each other and the influence of the cPDM on the PDS was quantified. The values of the generators were recorded first with just the PAD and no cPDM (baseline), and then with the cPDM present at different distances from the PAD. This experiment was performed at the position around the CMM which would be the most susceptible to EMI based upon RS101 testing.

As seen in Figure 7, when the PAD and cPDM were less than 6 inches apart, the PDS system was influenced as indicated by several instances of the readout being frozen. However, when the PAD and cPDM were at least 6 inches from each other, the number of times the PDS system was frozen was close to baseline. A 6-inch EMC separation distance between the PAD and cPDM resulted in little to no influence on the PDS, while a separation distance less than 6 inches resulted in some influence on the performance of the PDS.

CONCLUSION

When close enough to the PAD of a PDS, some electronic devices used in underground coal mines can result in an interference of the system. The main device of concern in this study is the cPDM, for this device is most likely to be used consistently near the PAD and produces constant EMI to the cPDM (not intermittent EMI as with a radio or distance range finder). At least a 6-inch EMC separation distance between the cPDM and PAD was observed to reduce the EMI to levels which have no significant interference on the PDS for the systems tested. This conclusion was first drawn from a military standard RE101 test and then validated with the actual PDS system. This separation distance is consistent with PDS manufacturer recommendations (19, 20).

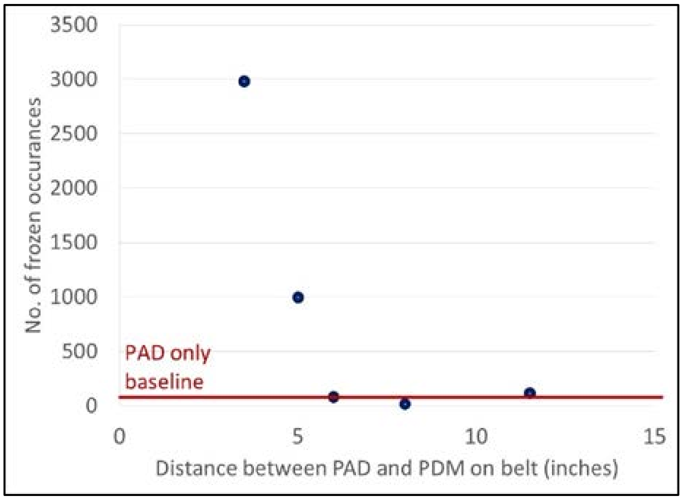


Figure 7. Graph showing that when less than 6 inches were between PDM and PAD, the PDS would malfunction periodically, but the PDM had little to no influence on the PDS with 6 inches or greater separation distance.

This EMC separation distance was determined with just one type of PDS and in the laboratory. Therefore, further testing with other PDSs as well as field data would be beneficial. Beneficial future work could also investigate other EMI mitigation strategies besides separation distance, such as shielding of EMI sources and investigating methods to detect these types of interferences and compensate for them. Currently, manufacturers of PDSs and electronic devices are involved in some of this testing such as a PAD which identifies the presence of an interference, shielding around EMI sources, and shielded pouches for electronic devices.

DISCLAIMER

Mention of a company name or product does not constitute an endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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