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An Overview of Existing EMI Standards Applicable to Mining

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Abstract
Electromagnetic energy emitted from electronic devices has been known to interfere with other electronic systems, hindering their ability to function properly. Mines have many electronic devices critical to the health and safety of mine workers that could be negatively affected by electromagnetic interference (EMI). To ensure that devices are electromagnetically compatible, tests must first be conducted to measure emissions and check for immunity. There are many standards available across multiple industries that prescribe emission limits and test methods for electronic devices. Due to the unique environment of an underground mine, it may not be enough to simply adopt a standard from another industry to mining. A literature review has been conducted, and an overview of EMI standards in other industries will be provided in this paper. Also, an example of how a standard can be applied to mining equipment is presented. Finally, recommendations on standards which could potentially be applied to mining will also be included. This work will inform the mining industry of EMI standards in other industries so that mine workers and technology manufacturers have guidance of the steps that can be taken to investigate and reduce the impact of electromagnetic interference and potentially work toward electromagnetic compatibility. The findings and research involved in this effort can also be used to explore the need to develop mining-specific EMI recommendations and standards.

Keywords Electromagnetic interference · EMI/EMC standards · Underground mining · Mine safety

Abbreviations

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CE	Conducted emissions
CISPR	International Special Committee on Radio Interference
CS	Conducted susceptibility
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
ESA	Electronic subassembly
EUT	Equipment under test
FCC	Federal Communications Commission
FDA	Food and Drug Administration
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LISN	Line Impedance Stabilization Network
MSHA	Mine Safety and Health Administration
OATS	Open area test site
PDM	Personal dust monitor
PDS	Proximity detection system
RE	Radiated emissions
RF	Radio frequency
RS	Radiated susceptibility
RTCA	Radio Technical Commission for Aeronautics
SAE	Society for Automotive Engineers

1 Introduction

Electronic devices emit electromagnetic radiation, which can interfere with other devices and potentially prevent them from working properly. Globally, electromagnetic interference (EMI) has been implicated in many accidents that led to injuries and fatalities. It has caused weapons systems to fire unexpectedly, flight instruments to malfunction, and antilock braking systems on automobiles to fail [1]. This presents an especially critical challenge in mining as health and safety devices such as proximity detection systems and personal dust monitors have been introduced to enhance mine worker safety. With the potential for EMI to affect the performance

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of these systems, the risk of injuries and fatalities presents a major challenge.

The mining industry has made progress in understanding the impacts of EMI through research and development efforts. One example is the Mine Safety and Health Administration's (MSHA) program policy letters dealing with potential EMI produced by communication and electronic tracking systems on blasting circuits [2]. Above ground, electromagnetic emissions from mine equipment are subject to Federal Communications Commission (FCC) regulations. There are several EMI standards currently in use across multiple industries, but it may not be enough to simply adopt one of them into mining. An underground mine is a unique environment with tight spaces, low roof heights, and long tunnels with a variety of electronic devices and machinery working in close proximity. There has been some work done to summarize existing EMI standards [3] and to compare military and international standards [4, 5]. However, there is a need to examine how EMI standards can be adapted to a mining environment. To determine the need for mining-specific EMI recommendations, it is important for the mining industry to first consider existing EMI standards and how they can be applied to mining. A literature review has been conducted on existing EMI standards so that mine workers and technology manufacturers can learn how other industries achieve electromagnetic compatibility (EMC) and how they can ensure that the critical safety systems in mines work as intended.

2 What Do These Standards Contain?

Before getting into the specifics of each standard, it is important to know what kind of information can be found in an EMI standard. Devices can be characterized in terms of how much energy they emit and how much they can withstand while still working as intended. As a result, an EMI standard typically contains requirements for the following two key elements:

- Emissions
- Susceptibility/immunity

Existing standards usually include test methods and limits of emission and susceptibility. From there, the standards are broken down into sections based on the manner in which the devices emit or are exposed to electromagnetic energy. Devices emit energy through conduction and radiation. When they are exposed to energy it is referred to as susceptibility and are given a measure of immunity with respect to their ability to be exposed while maintaining functionality. Some examples of the types of tests that can be found in an EMI standard are shown in Fig. 1.

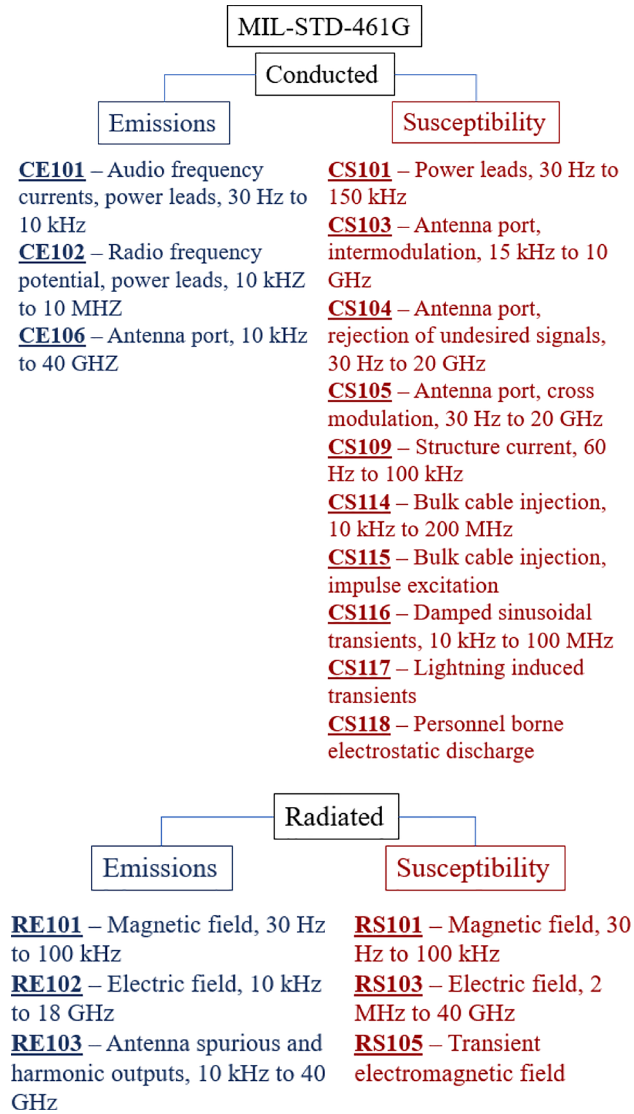

Fig. 1 EMI tests and limits with applicable frequency range included in MIL-STD-461G

2.1 Conducted Emissions

In conduction, EMI generated by the equipment under test (EUT) is coupled onto the power supply cord, interfering with the power supply. This could cause problems with other devices connected to the same power supply. Conducted EMI can also couple onto signal cables and impede communications. A typical conducted emissions test consists of the EUT, a line impedance stabilization network (LISN), and a spectrum analyzer. The EUT is usually placed on a table and connected to the LISN, which creates a standardized impedance. Since the impedance from AC power supplies can vary for different outlets, the LISN allows for repeatability of measurements. The LISN connects to the spectrum analyzer, which displays the magnitude of the electromagnetic disturbance across a frequency range. The measurement is then compared with the limit defined in the standard.

2.1.1 Radiated Emissions

Radiated emissions testing checks for the strength of the electromagnetic field that is intentionally/unintentionally created by the device. The tests are conducted in an open area test site (OATS), semi-anechoic chamber, or fully anechoic chamber. A semi-anechoic chamber is a room with its walls and ceiling lined with material that absorbs radio frequency (RF) waves, preventing background noise from interfering with the measurements. A fully anechoic chamber is the same as a semi-anechoic chamber, with the only difference being the RF absorber material also covers the floor. An OATS can be either inside or outside and does not have anything to shield the EUT or antenna from ambient signals. Some standards specify which test site must be used, while others have different instructions for each test site. The decision of which test area to choose depends on a few factors like cost and size of EUT. Regardless of the test site used, the radiated emissions test method remains the same. Typically, the EUT is placed on a table a certain distance away from the receiving antenna, depending on the standard. The strength of the electromagnetic field decreases as the distance from the EUT increases, so it is important to use the correct separation distance. The emissions from the device are recorded across a frequency range and compared with the defined limits. It is important to rotate the EUT 360° and, if the EUT is very large, adjust the antenna height to get the maximum amplitude of signal, since radiated emissions tend to be directional.

2.1.2 Susceptibility/Immunity Testing

Susceptibility or immunity tests are the opposite of emissions tests. In these tests, the device is subjected to an electromagnetic phenomenon while the performance of the device is observed. EMI standards for immunity describe the pass/fail criteria that is used to determine the device's level of susceptibility to EMI. There are four possible outcomes to immunity tests, and these are generally the same for most standards. The first is the device works as normal with no degradation of performance. Second, the device temporarily loses function during the test, but returns to normal after the test without operator intervention. Third, the device loses function during the test and needs operator intervention for it to return to normal. The operator intervention could be as simple as turning the power to the device back on. The final pass/fail category is that the device is permanently damaged as a result of the test. These criteria can be used to define the acceptable level depending on the device's intended use and how easy it would be to fix the problem.

2.1.3 Conducted Immunity

Conducted immunity tests are done to check how a device handles signals coupled onto power and signal leads. In addition to the EUT and power supply, conducted immunity tests typically include a signal generator, power amplifier, transducer, and current monitor probe. The standard will contain information regarding how to set up the test and whether any additional equipment is required. The signal generator is then set to the lowest test frequency and the signal is increased until it reaches the maximum power level, according to the standard. The functionality of the EUT is monitored while electromagnetic energy in a range of frequencies is injected into its power or signal leads. The operator assigns one of the four pass/fail categories based on the outcome of the test.

2.1.4 Radiated Immunity

The setup of a radiated immunity test is very similar to that of a radiated emissions test. The antenna creates an electromagnetic field when given input from a signal generator, and the EUT is monitored while it is subjected to the electromagnetic field strengths and frequencies as specified in the standard. Because of the strength of the electromagnetic fields generated, immunity tests should only be done in a semi- or fully anechoic test chamber to comply with regulations on radio interference and protect measurement devices.

2.1.5 Other Types of Immunity Tests

There are a few other immunity tests done on products before they can be considered electromagnetically compatible. Electrostatic discharges, sparks caused by voltage differences, are applied to any area of the device that can be touched by humans. Electrical fast transient tests involve high-frequency bursts of electromagnetic disturbances to simulate the switching of inductive loads such as relays or motors. Surge testing is done to check how the device reacts to low-frequency power surges like lightning strikes or flyback voltage from a blown fuse. Other types of immunity tests include rated power magnetic fields, voltage dips, and short interruptions to name a few. Requirements for these tests can be found in the IEC 61000–4 series of standards.

Some standards exist that contain requirements for testing the effectiveness of electromagnetic shielding enclosures. A common mitigation technique for a device that is susceptible to EMI is to shield it from the radiation. IEEE Std 299–2006 [6] and ASTM D4935-18 [7] are two standards that provide specifications for testing EM shielding enclosures.

3 EMI Standards and Organizations

EMI has caused issues in mining when emissions from one electronic device interferes with another, causing it to malfunction. One example is that of personal dust monitors and powered air purifying respirators interfering with proximity detection systems, which exposes miners to striking and pinning hazards from continuous mining machines [8, 9]. Also, there is evidence of mining diesel engine locomotives and conveyor equipment in underground mines being susceptible to EMI [10]. National Institute for Occupational Safety and Health (NIOSH) researchers conducted a failure mode and effects analysis to assign priority for the evaluation of electromagnetic emissions and susceptibility among devices used in underground coal mining [11]. As more electronic devices are introduced to mines, it is expected that more EMI instances will occur which can lead to serious safety issues. Accordingly, there exists a need to investigate similar challenges in other industries and specifically draw from existing standards.

EMI has presented challenges to many different industries. Numerous standards organizations have attempted to mitigate the effects of EMI by developing requirements for the testing of electromagnetic emissions and susceptibility of electronic devices. It is possible that the mining industry can use other industries as a guide for the establishment of mining-specific EMI recommendations. In this section, we provide an overview of EMI in other industries and discuss whether any existing standards are applicable to mining based on their applications, test methods, or general requirements.

4 Military

Over the years, the United States military has experienced many problems caused by EMI, which has interfered with aircraft controls and defense systems [1]. The main military standard is MIL-STD-461, *Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*. The standard is constructed with input from representatives from the Army, Navy, and Air Force, and it is intended for use by agencies within the Department of Defense [12]. The most recent version is MIL-STD-461G, which was released in 2015. All electronic equipment used by the military must comply with this standard.

MIL-STD-461G contains requirements for conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility. In this case, susceptibility testing in the military is the same as immunity testing in other industries. This standard breaks down equipment into different categories based on applications such as ships, aircrafts, and vehicles. There are three subcategories for conducted emissions, CE101, CE102, and CE106. CE101 is applicable for power leads that obtain power from sources other than the EUT from 30 Hz to 10 kHz. It is intended to be used to measure audio frequency currents on surface ships, submarines, and Army and Navy aircraft. CE102 covers 10 kHz to 10 MHz and deals with radio frequency potential on power leads. CE106 addresses conducted emissions from antenna ports, covering the frequency range 10 kHz to 40 GHz. The conducted susceptibility requirements are broken down into 10 subcategories. CS101 provides limits for voltage and power to the EUT and is applicable from 30 Hz to 150 kHz. Any degradation of performance or deviation from specified indications is considered a failure. CS103, CS104, and CS105 cover antenna ports, CS114 and CS115 cover bulk cable injection methods, and CS118 deals with electrostatic discharge. There are a few other subcategories for transient immunity tests as well.

For radiated emissions and susceptibility, there are three subcategories each. RE101 sets the limit for magnetic field strength across a frequency range of 30 Hz to 100 kHz. The distance between the loop sensor and the EUT for this test is 7 cm. RE102, which covers electric field radiated emissions, has different frequency ranges depending on where the device will be used. This section is applicable from 10 kHz to 18 GHz for equipment on a ship's surface, submarines, Army and Navy aircrafts, and in space. For ground and Air Force applications, the requirements only cover 1 MHz to 18 GHz. Regardless of the application, the separation distance is 1 m. RE103 deals with spurious and harmonic emissions from antennas. RS101 and RS103 prescribe susceptibility limits for magnetic fields and electric fields, respectively. RS101 is applicable from 30 Hz to 100 kHz, while RS103 can be applied from 2 MHz to 40 GHz, although it is optional to test from 2 to 30 MHz and 18 GHz to 40 GHz. For the magnetic field test, the separation distance is 5 cm, and for the electric field test, the separation distance is 1 m. Finally, RS105 covers susceptibility to transient electromagnetic fields. It is important to note that MIL-STD-461G uses a peak detector for all measurements, while other standards typically use a quasi-peak or average peak detector. As a result, the limits are higher than what they would be had the military used a quasi-peak or average peak detector.

There are a few examples of the military standard being implemented in mining. In the Case Study section below, we describe the emissions testing of a personal dust monitor according to RE101 and susceptibility testing of a proximity detection system according to RS101. Additionally, NIOSH researchers used RE101 test methods to compare the effectiveness of different shielding materials [13, 14].

Military standards tend to have lower limits than others, which makes sense considering the potential loss of life if military equipment fails. If a device is declared electromagnetically compatible for military use, then it might be safe for mines, too. However, a mine environment is different from the environments in which military devices are intended to be used, so it is important to consider how military requirements can be applied to mining devices to ensure electromagnetic compatibility. The military standard is one of the most comprehensive EMI standards available in terms of the number and variety of tests defined. It can be useful for mining as it covers many types of EMI scenarios involving critical safety and operational systems that may be similar to those encountered in a mine. Also, other industries have shown that MIL-STD-461G can be successfully applied to non-military applications, which will be discussed in a following section.

5 Federal Communications Commission (FCC)

The FCC sets limits for all non-military radio-frequency emissions in the United States. Title 47, Part 15 of the Code of Federal Regulations (47 CFR 15) contains the FCC's rules regarding unwanted emissions [15]. Electronic devices sold in the United States must comply with Part 15 before they can be on the market. The FCC does not set any immunity requirements; it is only concerned with emissions. As previously mentioned, the equipment used on the surface at mine sites should already be complicit with FCC regulations, but underground devices do not have to follow these rules. FCC Part 15 states that tunnel radio systems may operate without license as long as the surrounding earth attenuates the radiated signal, and it mentions a mine as an environment that fits the criteria [15]. If that requirement is satisfied, then an intentional radiator may be used on any frequency without restrictions. However, it could still be useful to be aware of FCC limits so the levels are not exceeded if the equipment is used outside of a mine.

FCC Part 15 includes regulations for the operation of intentional and unintentional radiators of electromagnetic energy without a license. The specifications are further broken down into Class A and Class B equipment, which depends on how the devices are marketed. Class A devices are intended to be used in commercial, industrial, or business environments. Class B devices are designed for residential use. Mining equipment could therefore be considered as Class A devices. Both intentional and unintentional radiators need to be considered. Radios and other communication devices are classified as intentional radiators, while cap lamps, methane monitors, and personal dust monitors would fall under the unintentional category. The intentional radiators are held to lower limits than unintentional radiators for both conducted and radiated emissions. The FCC's limits for conducted emissions cover the frequency range 0.15 MHz to 30 MHz. The radiated emissions limits go from 30 to 960 MHz, and then have a flat limit for emissions above 960 MHz. For intentional radiators only, there are additional requirements for emissions below 30 MHz down to 0.009 MHz. The tests for Class A unintentional radiators use a separation distance of 10 m, while intentional radiator tests are done at 3 m for emissions at 30 MHz or above, and either 30 m or 300 m if the frequency is below 30 MHz. The measurements are done with a quasi-peak detector.

6 IEC and CISPR

In 1934, the International Electrotechnical Commission (IEC) formed the International Special Committee on Radio Interference (CISPR) as a response to the growing number of issues that electronic devices caused for broadcast equipment. The goal was to create one set of requirements to ensure that appliances traded internationally were electromagnetically compatible [16]. Today, IEC and CISPR maintain numerous standards that are used in multiple industries. The IEC 61000 series encompasses many different test methods and limits for achieving electromagnetic compatibility. For example, IEC 61000–6-4:2018 [17] has limits for emissions in industrial environments, IEC 61000–6-2:2016 [18] prescribes immunity requirements, and the IEC 61000–4 series [19] covers testing and measurement techniques for electromagnetic compatibility. A standard that has some relevance to mining is IEC 61326–3-1:2017, which has immunity requirements for devices intended to perform safety-related functions [20]. This standard provides an overview of the different types of immunity tests and their limits to inform readers on the applicable standards to select. It contains the immunity test values for radiated electromagnetic fields, conducted disturbances, electrostatic discharge, electrical fast transient (or burst), and voltage dips.

A CISPR standard that could be useful for mining is CISPR 11, which has emission limits and methods of measurement for industrial, scientific, and medical equipment [21]. The most recent version is CISPR 11:2015, which includes amendments added in 2016 and 2019. This standard divides equipment into groups and classes based on the nature of the equipment and its intended use. Group 2 encompasses "all ISM RF equipment in which radio-frequency energy in the frequency range 9 kHz to 400 GHz is intentionally generated and used or only used locally, in the form of electromagnetic radiation, inductive and/or capacitive coupling, for the treatment of material, for inspection/analysis purposes, or for transfer of electromagnetic energy"

[21]. Group 1 contains all equipment that is not included in Group 2. Class A equipment is suitable for use in all locations other than residential environments, while Class B equipment can be used in residential environments. For mining purposes, it is best to focus on requirements for Group 1, Class A equipment.

CISPR 11:2015 has limits for conducted and radiated emissions. The frequency range for conducted emissions is 150 kHz to 30 MHz. The standard provides limits using either a quasi-peak or average peak detector. The limits are broken down further based on the rated power to the EUT, with one category each for less than 20 kVA, between 20 and 75 kVA, and greater than 75 kVA. As the power increases, the voltage limit also increases. CISPR 11:2015 also gives different requirements for AC and DC power ports. For DC power ports, there are current limits in addition to voltage limits.

The radiated emissions testing can either be conducted at a test site or in situ, with the test sites divided into subcategories, including open area test sites, semi-anechoic chambers, and fully anechoic rooms. For open area test sites and semi-anechoic chambers, the separation distance can be either 30 m, 10 m, or 3 m. The only option is 3 m for fully anechoic rooms. Like the conducted emissions, there are subcategories for rated power. All measurements for radiated emissions are done with a quasi-peak detector.

The emissions limits in CISPR 11:2015 are very similar to the limits in FCC Part 15 for unintentional radiators. In fact, the conducted emissions limits are the same in both standards. Both CISPR and FCC, however, generally have higher emissions limits than the military. Since they are intended for general applications, the IEC and CISPR standards can provide alternative requirements for mining if there are situations where the military standard's limits are not applicable, or frequency ranges are outside what is typically encountered in mining. Also, the standards focused on safety-related devices are relevant for mining, as safety is the primary motivation for addressing EMI issues.

7 ANSI and IEEE

There are a few more organizations that develop general EMI standards. The American National Standards Institute (ANSI) Accredited Standards Committee C63 is a coordinating body that develops standards with input from government organizations, industry members, and testing laboratories [22]. The FCC refers to some ANSI C63 standards for measurement protocols in Title 47 of the Code of Federal Regulations. There are two main emissions standards from ANSI. Standard C63.4–2014 [23] covers radio-noise emissions from unintentional radiators in the frequency range 9 kHz to 40 GHz. Standard C63.10–2013 [24] covers unlicensed wireless transmitters. In addition to the emission-related standards, ANSI published C63.15–2017 [25], which provided a recommended practice document to measure immunity of electrical and electronic equipment and complements the emission measurement procedures outlined in C63.4–2014. It is important to note that C63.15–2017 is a recommendation, not a standard, and its purpose is to provide guidance to manufacturers who want to go beyond applicable regulations to maximize product reliability.

The Institute of Electrical and Electronics Engineers (IEEE) has EMI standards of their own for emissions limits and for testing shielding enclosures. If shielding material is used to mitigate EMI in certain electronic devices in underground mines, the previously mentioned IEEE Std 299–2006 [6] can be applied to ensure the shielding materials successfully reduce emissions or enhance susceptibility. Additionally, a standard that could have some applicability to mining safety is IEEE Std 1848–2020 [26]. This standard provides methods for managing safety and risk levels due to EMI.

8 Automotive

The automotive industry follows many standards to ensure the electromagnetic compatibility of automobiles [27]. Over the years, digital control modules and sensors have been added to vehicles, increasing the importance for equipment manufacturers to have a set of standards to reference to establish consistency across the automotive industry [28]. The Society of Automotive Engineers (SAE) and the International Organization for Standardization (ISO) are two organizations that develop standards for vehicles. SAE has multiple series of application-based standards. The J1113 series [29] covers components of vehicles, boats, and machines. The J551 series [30] applies to entire vehicles, and the J1752 series [31] covers integrated circuits. Over the last 20 years, ten J1113 standards have been determined to be technically identical to the equivalent ISO 11452 road vehicle standards [32] and were subsequently withdrawn to avoid conflict with the international standards bodies [33]. Six were withdrawn in 2010, three were pulled back from 2002–2006, and, most recently, part 21 was cancelled in 2013.

An ISO standard of interest to mining is ISO 13766–1:2018, which contains EMC requirements for earth-moving and building construction machinery [34]. This would be particularly relevant in ensuring that the continuous mining machine is able to operate as intended, even in the presence of electromagnetic radiation. Testing under ISO 13766–1:2018 can be done with the whole machine or an electronic subassembly (ESA), since it can be difficult to find a test site that can accommodate the size of earth-moving machinery. However, the ESA tests have different limits.

There are not any conducted immunity or emissions requirements in this standard. For those limits, it redirects to ISO 7637–2:2011 [35] and ISO 16750–2:2012 [36]. The only requirement it gives for radiated immunity is that the EUT must withstand a field strength of 30 V/m without specifying a separation distance. There are more detailed requirements for radiated emissions. Unlike the previous standards mentioned in this review, ISO 13766–1:2018 classifies emissions as broadband or narrowband. The broadband measurements use quasi-peak detection, while the narrowband measurements use average peak. The applicable frequency range is 30 MHz to 1,000 MHz, just like the FCC and CISPR standards. The separation distance can be either 10 m or 3 m. In general, the ISO limits are lower than CISPR 11:2015 and the FCC for unintentional radiators, but higher than that of FCC for intentional radiators.

9 Medical

The EMI difficulties experienced by the medical industry are similar to the problems faced in mining safety. In a hospital environment, there are many electronic devices operating in close proximity, all of which are critical to the health and safety of the patient. EMI has been suspected of causing the malfunction of medical devices that resulted in serious injuries and deaths [37]. The Food and Drug Administration (FDA) regulates the sale of medical equipment in the United States and ensures that these devices are electromagnetically compatible. A common standard that is recognized by the FDA is IEC 60601–1-2:2014 [38]. This standard sets requirements for basic safety and general performance of medical devices. It is based on CISPR emissions limits and immunity requirements conceived by the IEC Technical Committee 77. Standards from other organizations such as ANSI C63, ISO, and the Association for the Advancement of Medical Instrumentation have been used in combination to achieve medical device EMC [39]. The medical industry's focus on EMC as it pertains to health and safety could provide guidance for the mining industry. Some of the medical EMI standards might be applicable to testing safety devices in mining.

10 Nuclear

Another industry that must be careful in dealing with electromagnetic interference to ensure worker safety is the nuclear industry. EMI can cause unexpected reactor shutdowns, false alarms, and high noise on monitoring equipment [40]. A minor malfunction in an electronic device at a nuclear site could have major consequences, so it is an interesting industry to consider for mining purposes. The U.S. Nuclear Regulatory Commission endorses standards from the military, IEC, and IEEE, including MIL-STD-461G and IEC 61000–4, for use in a nuclear power plant. The IEC produces a nuclear-specific standard IEC 62003:2020 [41] that establishes requirements based on the applicable limits in the IEC 61000 series. Also, the IEEE working group 2.16 maintains the standard P2425 [42] for EMC testing of electrical equipment at nuclear facilities. From a mining perspective, it could be beneficial to look at how the nuclear industry incorporates standards from different bodies into nuclear applications. A similar approach could be taken to develop mining-specific EMI standards.

11 Aviation

In the aviation industry, the Radio Technical Commission for Aeronautics (RTCA) is a volunteer organization in the United States that establishes EMI requirements. RTCA DO-160G [43] is the main standard, and it describes environmental conditions and test procedures for airborne equipment. This could be applicable to mining because an aircraft has many critical electronic devices working close together in a confined space. EMI has already been blamed for multiple deadly air disasters in the past, so achieving electromagnetic compatibility has become a top priority for the aviation industry.

Table 1 contains a summary of the industries and standards included in this section. In each case, the most recent version of each standard was considered. It is possible that updated versions of the standards have been released since the writing of this document.

EMI standards in these industries can provide a basis for mining-specific standards. They show how a standards document should be structured, as well as the type of information that should be included, such as instructions for setting up and running the test, allowable limits of emissions and susceptibility, test facility descriptions, list of equipment and instrumentation, etc. Although they are intended for different applications and environments, these standards serve the same purpose of ensuring that safety–critical electronic systems can function properly. By looking at EMI in other industries, we can learn how they address similar problems. In each of the industries discussed in this paper, a minor malfunction in an electronic device can have major consequences. For these reasons, it may be possible to adopt standards from other industries, or at least some components of the standards, to mining. In order to determine the applicability of existing standards, research must be completed to better understand the electromagnetic environment of a mine. An example of this research is presented in the following section.

Table 1 Summary of EMI Standards Cited in this Paper

Organization/ Industry	Relevant Standards
Military	MIL-STD-461G
FCC	47 CFR 15
IEC	IEC 61000–6-4:2018, IEC 61000–6-2:2016, IEC 61000–4, IEC 61326–3-1:2017
CISPR	CISPR 11:2015
ANSI	C63.4–2014, C63.10–2013, C63.15–2017
IEEE	Std 299–2006, Std 1848–2020
Automotive	SAE J1113, SAE J551, SAE J1752, ISO 11452, ISO 13766–1:2018, ISO 7637–2:2011, ISO 16750–2:2012
Medical	IEC 60601–1-2:2014
Nuclear	IEC 62003:2020, IEEE P2425
Aviation	RTCA DO-160G

12 Characterizing Electronic Systems Used in Coal Mines Based on Existing EMI Standards—A Case Study

As previously stated, an EMI standard typically includes testing methods for characterizing the emission and/or susceptibility level of a device, along with the corresponding allowable maximum or minimum levels, depending on the category of the tests. Generally, the emission limits given in an EMI standard represent the maximum levels that a device can emit while susceptibility limits specify the minimum interference levels that a device must withstand without showing any abnormal functions.

As an example, in this section we present some of our measurement results pertaining to characterizing the emission and susceptibility of devices used in underground coal mines based on existing EMI standards. In particular, the two devices selected for investigation are a personal dust monitor (PDM) and a proximity detection system (PDS). The two selected devices have been involved in EMI incidents in U.S. underground coal mines in which the performance of the proximity detection system was being affected when the miner-wearable components were located close to the personal dust monitor [8]. After conducting a review of existing standards, the MIL-STD-461G standard was selected for its applicability to evaluating the interaction between the two devices. We chose the military standard because it is a widely accepted standard that often serves as the basis for many other standards developed in different industries. The original frequency range covered in RE101 under MIL-STD-461G is from 30 Hz to 100 kHz. We decided to slightly expand the frequency range because our target device of PDS operates at 73 kHz which is very close to the original upper limit of 100 kHz.

Figure 2 shows the measured magnetic fields from the PDM at a distance of 7 cm, based on the measurement method specified in RE101 of MIL-STD-461G. Key measurement parameters have been specified in RE101, including the detailed requirements for the test equipment involved (e.g., the diameter and number of turns of the loop antenna), measurement setup, measurement procedures, and finally the data presentation. These measurement details are specified in order to ensure the measurement repeatability and consistency so that the results are repeatable.

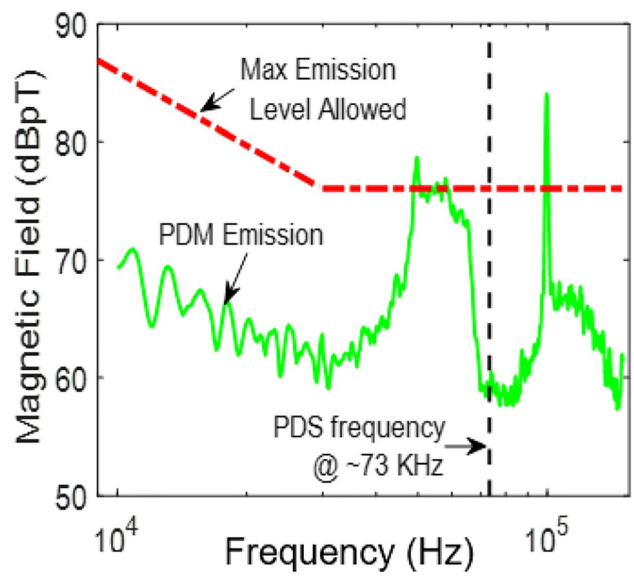

Fig. 2 Radiated emission test result of a PDM based on RE101 of MIL-STD-461G

The maximum emission level allowed is plotted in Fig. 2 for comparison. It should be noted that different military environments have different allowable limits and the emission limit plotted in Fig. 2 is the limit for all Navy applications, which is relatively strict as compared to other applications, such as Army applications. It can be found from Fig. 2 that at some frequencies (e.g., in the frequency bands between 48 and 59 kHz and around 99.6 kHz) the emissions

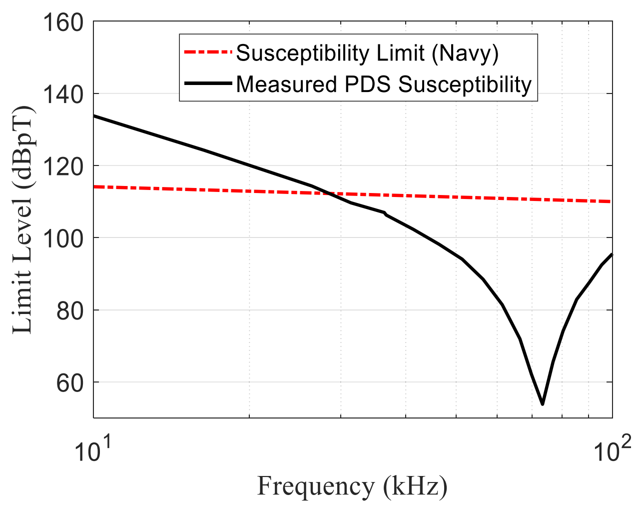

Fig. 3 Susceptibility test result of a PDS based on RS101 of MIL-STD-461G

from the tested PDM exceed the maximum limits allowed in Navy applications. At 73 kHz, which is the frequency at which the PDS operates, the emission from the PDM is about 18 dB below the given maximum emission limit. It is also important to note that while the applicable range of RE101 is from 30 Hz to 100 kHz, the frequency range we tested is from 10 to 150 kHz.

The application of this standard was helpful in evaluating these devices; however, it did highlight the need to consider the mining environment to establish the mining-specific thresholds to better reflect the emission and susceptibility levels of different electronic devices used in underground coal mines.

Figure 3 shows the result of characterizing the susceptibility (i.e., the highest emission level that a device can tolerate without showing any malfunction, degradation of performance, or deviation from specified indications) of a PDS based on RS101 of MIL-STD-461G. The susceptibility limits for Navy applications are also plotted for reference. Similar to RE101, RS101 also specifies details to ensure measurement repeatability and consistency.

As shown in Fig. 3, there is a null in the measured PDS susceptibility curve. Such a null occurs at 73.3 kHz, implying that the PDS is most vulnerable to EMI at 73.3 kHz, which is the operating frequency of the system. The susceptibility of the PDS increases as the frequency moves away from 73.3 kHz. There is a significant portion (e.g., in the frequency band between 28 and 100 kHz) of the measured PDS susceptibilities below the given Navy limit, indicating that susceptibility of the PDS would need to be improved to be used in Navy applications. Again, in terms of mining applications, it is expected that the testing method specified in RS101 might still be applicable, but the susceptibility limits should be explored further to define a susceptibility limit that would be based on the actual EM environment in underground coal mines.

According to Fig. 2, the emissions of the PDM at 73.3 kHz, the operating frequency of the PDS, is about 60 dBpT. In Fig. 3, at the same frequency, the susceptibility of the PDS is approximately the same as the PDM emissions, which explains the malfunction of the PDS when the PDM gets too close. This shows how susceptibility and emission testing can identify potential problems before they are encountered in an actual mine. There are a few approaches, focused on administrative and engineering controls, to help mitigate this challenge. Research showed that if the PDM and PDS are separated by at least 6 inches, both devices can be used simultaneously without an EMI concern [8]. Implementing recommendations and solutions that would promote this separation distance may be a practical solution. In situations where a minimum separation distance is not possible or effective, engineering controls such as shielding material can be used to protect the victim of EMI or limit unintended emissions from the source. Another method is to redesign the devices to produce less EMI or be less susceptible, however, there is a cost and time investment associated with this approach that may be prohibitive.

13 Mining-Specific EMI Standards/Recommendations

Looking ahead, if it is determined that mining-specific EMI recommendations are required, there are a few questions that need to be considered. Questions such as: What is the intended use for each device? Is it going to be operating close to any other devices? What are the consequences if it stops working for a certain period of time? How critical is the device to miner safety? What are the allowable emissions limits before it interferes with other devices? What is the susceptibility threshold before a device stops working as intended? The most important aspect is that safety devices must be able to perform their intended function. The most conservative approach to work towards compatibility in a mine would be to test every electronic device for emissions and susceptibility according to MIL-STD-461G, because it has lower limits for emissions than the other standards in this paper. This profile could be used to cover every type of electronic device interaction and can help to develop guidelines for product development with EMC in mind. When there is the opportunity for different limits based on application, the safest option can be chosen. If electronic devices are assessed for emissions and susceptibility based on mining-specific thresholds, then achieving electromagnetic compatibility in the mining environment can be realized with future product development and introduction of new technologies.

The emissions levels of each device can be found using the test methods outlined in standards such as MIL-STD-461G and IEC 61000–4-3:2020. Once the typical emissions in a mine are determined, there will be a better understanding of the level of immunity that is required for safety devices. Also, the performance criteria need to be established for each device since there is some variation for what is considered a failure. If a radio used for communication is briefly disabled due to EMI, it may not pose a serious threat to health and safety in the way that an improperly functioning proximity detection system could relative to the potential for pinning and striking accidents. There is additional work that must be performed to characterize the mining environment and better understand the electromagnetic challenges in the mine environment. By looking at other industries, the mining industry can potentially adopt measurement standards and may be able to develop mining-specific recommendations that can ultimately lead to electromagnetic compatibility.

14 Limitations

The literature review investigated a variety of industries with proven records in electromagnetic standards and research. The standards mentioned here were chosen because they have certain aspects, such as test methods, applications, or general requirements, that could be useful for mining. Accordingly, one of the limitations is that not all applicable standards and recommendations may have been included in the review. As the NIOSH Mining Program continues to conduct research in the topic of electromagnetic interference, additional standards may be explored and referenced.

15 Conclusion

As new technologies are introduced to mines, the number of potential sources of EMI will increase. Investigating this topic is especially critical because EMI poses challenges that may lead to injuries and fatalities to mine workers. An overview of the organizations that establish EMI requirements is provided, along with standards from those organizations that could be referenced to serve the mining industry. There are standards that can be employed to test mining equipment, but there is a need to further review how they can be applied to evaluate electronic devices used in mining. A review of existing standards revealed a number of methodologies and emission/susceptibility limits that can be explored to assess applicability and potentially develop mining-specific recommendations. Further research is required to investigate mining specific applications and conditions that may point to the need for an EMC standard to be created specifically for mining applications. Some of the standards mentioned in this paper could be used as a basis to establish test methods and protocols. Mining industry stakeholders can use the information presented in this paper to learn how other industries approach electromagnetic interference and electromagnetic compatibility through the use of standards and explore their applicability to solve challenges already being encountered in underground mines.

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Declarations

Conflicts of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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