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SURVEY OF ELECTROMAGNETIC EMISSIONS IN UNDERGROUND COAL MINES

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ABSTRACT

Modern electronic devices and systems used to enhance miner safety and health are becoming commonplace in underground coal mines. The ability for these devices and systems to function properly in the presence of electromagnetic emissions from other electronic and electrical devices and systems is not entirely understood. To investigate potential electromagnetic compatibility issues of critical mine electronic devices and systems, researchers from the National Institute for Occupational Safety and Health (NIOSH) are conducting surveys of electromagnetic emissions in underground coal mines. This paper presents the measurement system, methods, and results of electric field electromagnetic emission surveys conducted in three underground coal mine environments in the frequency range of 10 kHz to 1000 MHz. The survey data show that in some environments electric field electromagnetic emissions in underground coal mines approached or slightly exceeded limits as defined by other industrial sectors.

INTRODUCTION

Electrical and electronic systems commonly emit some level of electromagnetic energy into the environment, either intentionally (e.g., radio handsets) or unintentionally (e.g., variable frequency drives.) This energy has the potential to adversely impact the operation of other devices or systems—an effect commonly referred to as electromagnetic interference (EMI.) To limit the potential for EMI, numerous regulatory requirements and standards have been developed to ensure electromagnetic compatibility (EMC) among electronic devices and systems for most military, industrial, and consumer applications. Following are a few examples of regulatory requirements and standards regarding EMC: 47 CFR Part 15 – "*Telecommunication – Radio Frequency Devices;"* MIL-STD-462G – "*Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment;"* SAE J1113/1™ – "*Electromagnetic Compatibility Measurement Procedures and Limits for Components of Vehicles, Boats (up to 15 m), and Machines (Except Aircraft) (16.6 Hz to 18 GHz);"* and ISO® 33.100.01 – *Electromagnetic Compatibility in General.* [1-4].

Used for miner safety and health applications such as environmental monitoring, communications, tracking, proximity detection, and much more, complex electronic devices and systems are proliferating in the underground coal mining environment. However, due to an absence of regulatory requirements, standards, or guidelines for electromagnetic compatibility of electronic devices and systems deployed in underground mines, the ability of electronic devices and systems to co-exist without malfunctioning is often not ensured or even well understood [5]. A recent example of an instance of EMI in underground mines was that of a personal dust monitor (PDM) causing a proximity detection system (PDS) to fail when the PDM was placed in close proximity to a component of the PDS [6].

The potential for EMI among safety-critical electronic systems and devices is a serious threat that needs to be addressed in the mining industry. Research has been conducted to investigate EMI issues in mining around the world. For example, in the 1970s, the United States Bureau of Mines (USBM) awarded a series of contracts to survey the electromagnetic emissions in different mines, in view of the fact that the performance of communication and tracking systems, particularly through-the-earth communication systems, are largely impacted by the electromagnetic "noise" (i.e., interference) existing in the mining environment [7-9]. More recently, discussions of practical examples of EMI associated with underground mining equipment, methods for testing EMI of mining equipment, and EMC test standardization for mining equipment are covered in [10-12].

To better understand the electromagnetic environment in which critical electronic devices and systems may be operated, researchers from the National Institute for Occupational Safety and Health (NIOSH) are performing surveys of electromagnetic emissions in underground coal mines. The data from these surveys will assist original equipment manufacturers (OEMs) and mine operators in estimating electromagnetic emissions in typical mining environments to determine appropriate susceptibility limit levels for electronic devices and systems.

MEASUREMENT SYSTEM AND METHOD

Electromagnetic emission measurements are traditionally performed on a specific electronic component, device, or system using highly specialized equipment in a tightly controlled environment—one free from ambient sources of electromagnetic energy [2]. The development of a measurement system to conduct surveys of electromagnetic electric field (E-field) emissions in underground coal mines posed a unique set of challenges. The ability to measure the E-field emissions of a single component, device, or system in a controlled environment would not be practical in underground mining environments. Thus, only composite E-field electromagnetic emissions of mine survey areas would be measured. In addition, the measurement system itself could contribute to the composite E-field emissions being measured. Finally, system components need to be rugged, easily transportable to remote underground locations, and battery powered. With these factors in mind, a solution was developed utilizing the test system requirements of MIL-STD-461G RE102 – Radiated Emissions, Electric Field as a general guideline [2].

Measurement System

The measurement system consisted of five primary components, including a battery-powered spectrum analyzer, two omni-directional antennas, an antenna stand, and a length of radio frequency (RF) coaxial cable.

At the core of the system was a spectrum analyzer. The spectrum analyzer used for the surveys was designed for field use, battery powered, ruggedized, and had reasonable performance.

MIL-STD-461G RE102 requires the use of omni-directional antennas below 200 MHz, a monopole from 10 kHz to 30 MHz and a biconical from 30 MHz to 200 MHz, and directional horn antennas above 200 MHz. However, as stated previously, the field studies were limited to measuring the composite E-field emissions of mine survey areas. As a result, a biconical antenna was used for measurements from 30 MHz to 1000 MHz.

A carbon fiber camera tripod was used for an antenna stand with a 20-ft length of LMR-400UF coaxial cable used to connect the spectrum analyzer to the antennas.

Table 1 lists the primary components of the measurement system.

Table 1. Measurement System Components.

Spectrum Analyzer	Anritsu MS2722C
Antenna 10 kHz – 30 MHz	A.H. Systems SAS-550-1B
Antenna 30 MHz – 1000 MHz	A.H. Systems SAS-545
Antenna stand	FEISOL CT-3441T
Coaxial Cable	20' LMR-400UF

Characterization of System Electromagnetic Emissions

It was recognized that E-field emissions from the measurement system's spectrum analyzer would contribute to the composite emissions of a mine survey area. If significant enough, the contribution of the spectrum analyzer's emissions could mask those that exist when the analyzer is not present, resulting in a misinterpretation of survey results. Therefore, the spectrum analyzer's emissions were characterized to be accounted for in the site survey emissions data.

Characterization of the spectrum analyzer's E-field emissions was accomplished through measurements using an RF shielded enclosure [5]. A baseline set of ambient environment measurements inside the enclosure were made with the antennas inside the enclosure and the spectrum analyzer external to the enclosure. The connection between an antenna and spectrum analyzer was made using an RF connector through a penetration in the wall of the enclosure. This configuration provided >100 dB of isolation between the spectrum analyzer and an antenna. A set series of measurements were then made with the spectrum analyzer inside the enclosure positioned in various orientations and distances as related to an antenna and the coaxial cable connecting the spectrum analyzer to an antenna.

The resultant measurement data revealed that spectrum analyzer emissions contributed significantly to the composite ambient E-field environment inside the RF shielded enclosure. The contribution was most significant in the 100 kHz to 30 MHz and 60 MHz to 1000 MHz frequency spans.

In the 100 kHz to 30 MHz frequency span, it was thought spurious and broadband spectrum analyzer emissions were being coupled to the coaxial cable connecting the analyzer to the antenna, resulting in common mode currents in the coaxial cable [5, 13]. The contribution of spectrum analyzer emissions to the measured composite environment of the shielded enclosure varied in the 10 MHz to 30 MHz region as a function of the coaxial cable's placement relative to the spectrum analyzer. The placement of the coaxial cable had little to no influence in the 100 kHz to 10 MHz frequency span.

In the 60 MHz to 1000 MHz frequency span, the spectrum analyzer's contribution to the composite ambient environment inside the RF shielded enclosure was believed to be in the form of radiated spurious emissions. Placement of the spectrum analyzer or coaxial cable relative to the antenna had very little influence on the level of measured spurious emissions.

Methods used to interpret the contribution of spectrum analyzer emissions to site survey area composite emissions data are covered in the Survey Site Results and Discussion section.

Typical E-field emissions from the spectrum analyzer measured inside the RF shielded enclosure compared to the measured ambient E-field inside the enclosure are shown in Figure 1.

The unusual "humps" in the data shown in Figure 1 from 30 MHz to 210 MHz and 210 MHz to 1000 MHz are the result of the antenna factors (correction factors used to calculate field strength) for the antennas used in these frequency ranges. Beyond the scope of this document, a detailed discussion on the concept of antenna factors can be found in [5, 14].

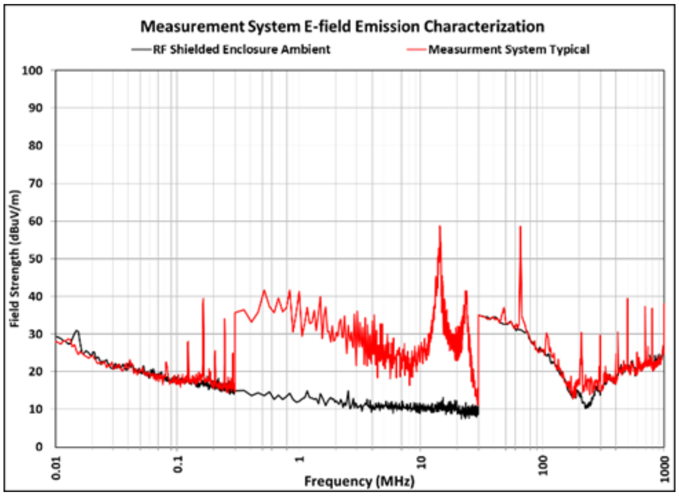

Figure 1. Typical Measurement System E-Field Emissions.

Measurement Method

As stated previously, only composite E-field emissions of an underground survey area would be measured. As such, system antennas were adjusted to a height of 1 m and placed in the approximate center of the survey area. However, if a device or system suspected of having high-level emissions would be present in any given survey area, measurements would be made at antenna separation distances of 1 and 3 m from the device or system in question. When possible, electrical mains power to a survey area would be disconnected for one set of measurements to characterize the ambient E-field environment of the area.

The spectrum analyzer was configured to capture the maximum emissions in a survey area over periods of time ranging from 1 minute at lower frequencies to 5 minutes at the higher frequencies. Beyond the scope of this document, discussions on longer monitoring periods at higher frequencies as well as general concepts of spectrum analysis are covered in [15].

SURVEY SITES

E-field electromagnetic surveys were taken in three underground coal mine environments—two in NIOSH's Experimental Mine and one in an active eastern high-seam coal mine.

NIOSH Experimental Mine

The NIOSH Experimental Mine is a small research facility located on NIOSH's Bruceton campus near Pittsburgh Pennsylvania. Being a drift mine, the overburden varies from 0 m to 35 m.

The first area surveyed, referred to as the "quiet area," is located in a crosscut off a main entry approximately 300 m inby from the portal. The area had no lighting and only minimal electrical conductors present.

The second survey area, referred to as the "power center," is located roughly in the center of the mine. The switch-house, which provided main electrical power to the mine, is located in the power center. The switch-house is fed 4160 volts alternating current (VAC) via an 8-in borehole from the surface and provides three phase 480 VAC to the mine. Used for research activities, there were also numerous other metallic-lined boreholes of varying sizes to the surface located in the power center. Lighting was provided by consumer grade A19/E26 LED bulbs.

A known intentional radiator in both survey areas was an Innovative Wireless Technologies (IWT) communication and tracking system, which operated in the 915 MHz Industrial, Scientific, and Medical (ISM) frequency band. Mine page phones were present in the survey areas as well.

Quiet area and power center survey areas are shown in Figures 2 and 3, respectively.

Figure 2. NIOSH Experimental Mine Quiet Area.

Figure 3. NIOSH Experimental Mine Power Center.

Eastern High-seam Coal Mine

The eastern high-seam coal mine was an active longwall production mine located in the eastern United States. The mine covered in excess of four-square miles, was accessed by multiple shafts, and had overburden of approximately 550 m.

The survey area, referred to as the "belt control area," was located well within the mine. The area was fairly confined and housed two 300-horsepower belt drive motors, variable frequency drives (VFDs) to control motor speed, programmable logic controllers (PLCs), and electronics supporting the human/machine interface (HMI.) Known intentional radiators included a Strata communication and tracking system and a leaky feeder communications system in the 915 MHz ISM and very high frequency (VHF) frequency bands, respectively.

The belt control survey area is shown in Figure 4.

SITE SURVEY RESULTS AND DISCUSSION

Composite Emissions Limits

In the absence of regulatory requirements, standards, or guidelines regarding electromagnetic compatibility of electronic devices and systems deployed in underground mines, a method was needed to determine reasonable E-field emission thresholds (limits) for the study. Referencing the Electric Power Research Institute's (EPRI) *"Guidelines for Electromagnetic Interference Testing of Power Plant Equipment"* TR-102303 Revisions 3 and 2, E-Field emissions limits were developed [16, 17].

The first limits referenced from TR-102303 Revision 3 are the 10-m regulatory requirements of 47 CFR Part 15 [1]. However, achieving a 10-m separation distance in underground mines would be difficult under many circumstances. As such, it was decided to convert the limits for 10 m separation to 1 m, which would be achievable in most cases. The conversion from 10 m to 1 m is only an estimation, due to the complexities of radio frequency (RF) fields propagating from an antenna as a function of distance, but provides an approximation for area survey measurements [14].

Figure 4. Eastern High-seam Coal Mine Belt Control Area.

The second limits referenced from TR-102303 Revision 3 are the requirements of MIL-STD-461G RE102 for Navy Fixed and Air Force ground applications [2].

The shortcomings of 47 CFR Part 15 and MIL-STD-461G RE102 are the starting points of the limits' frequency ranges, 30 MHz and 2 MHz, respectively. To address this, a third set of limits were referenced from the EPRI *"Guidelines for Electromagnetic Interference Testing of Power Plant Equipment"* TR-102303 Revision 2 [17]. While omitted from TR-102303 Revision 3, these limits covered the frequency range of 10 kHz to 10 GHz and allowed for a somewhat higher level of E-field electromagnetic emissions than 47 CFR Part 15 and were relevant for measuring composite E-field emissions in an industrial setting.

Contribution of Measurement System Emissions to Site Survey Results

As discussed in the Measurement System and Method Section, the measurement system's spectrum analyzer emissions were characterized to be accounted for in the site survey composite emissions data. However, interpreting the level of the spectrum analyzer's contribution was much more challenging than anticipated. The contribution was not static in all frequency regions but would vary as a function of two predominant factors—location of the spectrum analyzer relative to the system's coaxial cable and the overall environmental characteristics of the site survey area.

In the 300 kHz to 10 MHz frequency range, the contribution of spectrum analyzer emissions to the composite emissions in a survey area appeared static and closely matched the typical characterized emissions. Survey area composite emissions levels below the typical characterized emissions of the spectrum analyzer could not be identified as they were masked by the spectrum analyzer emissions. Survey site area composite emission levels above the typical characterized emissions of the spectrum analyzer were not mask and thus could be identified.

The contribution of spectrum analyzer emissions to the composite emissions in a survey area was more dynamic in the 10 MHz to 30 MHz frequency range. This was most likely due to the positioning of the analyzer relative to the system's coaxial cable during measurements. In most cases, the contribution of spectrum analyzer emissions to composite emissions in a survey area was lower than the typical characterized emissions. However, even though the contribution was lower, site area composite emissions levels below the typical characterized emissions of the spectrum analyzer could not be determined as they may or may not have been masked by spectrum analyzer emissions. Consequently, in the 10 MHz to 30 MHz frequency range, only survey site area composite emissions levels significantly above the typical characterized emissions of the spectrum analyzer could be identified.

Above 60 MHz, spectrum analyzer emissions did not significantly contribute to the composite emissions of a survey area. This could most likely be attributed to the larger size of the survey areas that allowed the spurious emissions to dissipate rather than be contained as they were in the RF shielded enclosure.

Identified as "Measurement System Typical," typical spectrum analyzer emissions are presented in the site survey data plots for reference.

NIOSH Experimental Mine – Quiet Area

E-field electromagnetic emissions measurements in the NIOSH Experimental Mine's quiet area were taken for two scenarios—mine power off and mine power on. To achieve the mine power off state, power feeding the mine was disconnected at the surface transformers. In addition, battery backups for the IWT communications and tracking system were disconnected. As there were no known or suspected sources of emissions in the survey area, the antennas were placed in a deadheaded crosscut off a main entry.

As expected, the E-field electromagnetic emissions in the quiet area were extremely low and well below the limits developed for the study. The only significant emissions measured were those coming from the test system itself. Emissions below 100 kHz were slightly evaluated from those measured during the field system's characterization in an RF shielded enclosure. These emissions can be attributed to general ambient E-field emissions that exist in underground environments [18]. The difference in the level of emissions in this region are possibly due to the measurements being taken on different days at different times of the day.

The NIOSH Experimental Mine quite area measurement results for power off and on are shown in Figures 5 and 6.

NIOSH Experimental Mine – Power Center

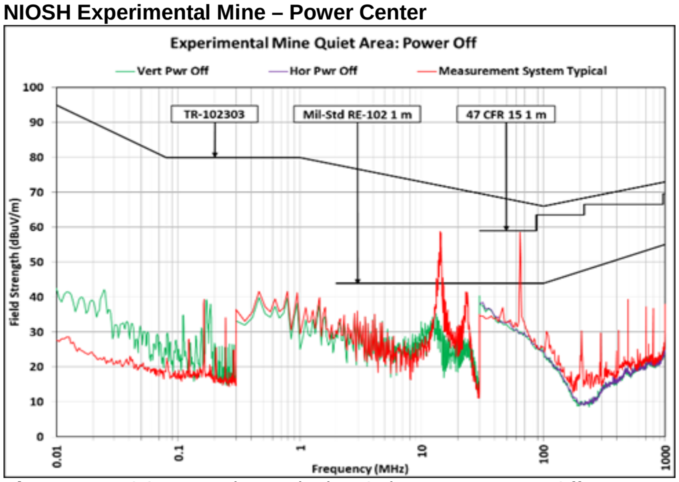

Figure 5. NIOSH Experimental Mine Quiet Area – Power Off.

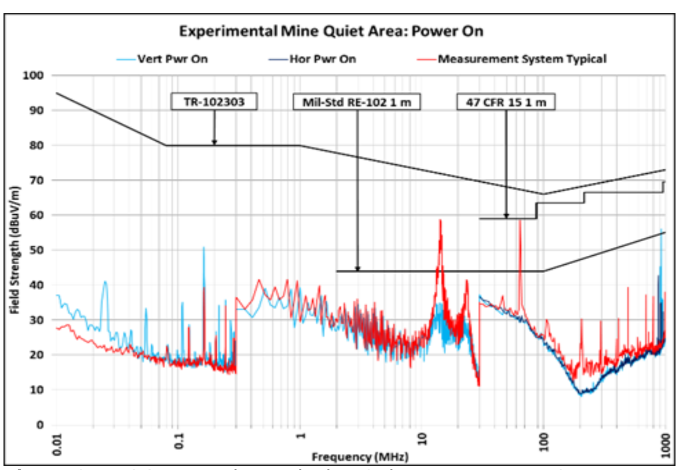

Figure 6. NIOSH Experimental Mine Quiet Area – Power On.

E-field electromagnetic emissions measurements in the NIOSH Experimental Mine's power center were also taken for two scenarios—mine power off and mine power on with the battery backups for the IWT communications and tracking system disconnected. The most significant known E-field emitter in the survey area was the switch-house, which provided main electrical power to the mine. Measurements were made with the antennas placed at a 1-m separation distance from the switch-house.

Unlike the quiet area, elevated E-field emissions were measured in the power center in the 10 kHz to 10 MHz frequency range for both the "Power Off" and "Power On" states.

Power off – With the power off, emissions were noted in two distinct frequency ranges – 10 kHz to 200 kHz and 500 kHz to 1700 kHz.

As in the quiet area of the NIOSH Experimental Mine, the elevated emissions in the 10 kHz to 200 kHz range can be attributed to ambient E-field emissions that exist in underground environments. The shallower overburden of the power center area combined with the transformer feeding the mine's electrical power as well as the industrial controls for the mine's ventilation fan on the surface above the power center could have all contributed to the emissions in the frequency region being slightly higher than those in the quiet area.

The emissions in the 500 kHz to 1700 kHz fall were in the U.S. commercial AM broadcast band. The presence of commercial AM broadcast signals underground can be attributed to the parasitic coupling and transmission of these signals onto the electrical wires feeding the power center's switch-house [19].

Power on – There were significant emissions near the switch-house with the mine's power on. In some regions from 60 kHz to 200 MHz, the emissions exceeded MIL-STD-461G RE102 and TR-102303 limits. These types of E-field emissions can be expected from industrial electrical equipment and are generated by the internal electronics of the equipment.

The NIOSH Experimental Mine power center measurement results for power off and power on are shown in Figures 7 and 8.

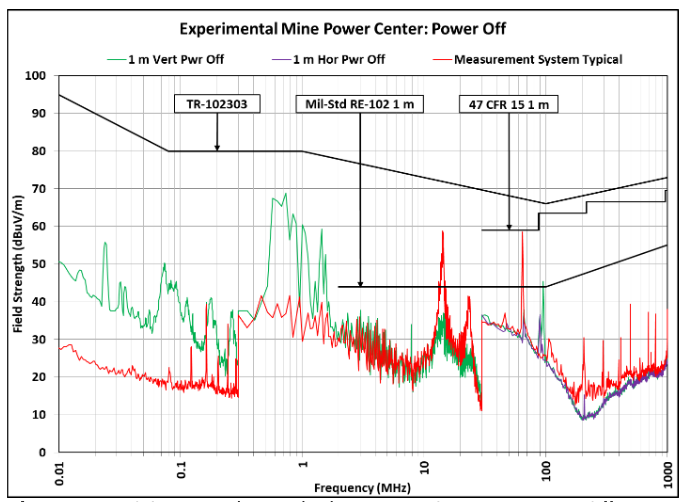

Figure 7. NIOSH Experimental Mine Power Center – Power Off.

Eastern High-seam Coal Mine

As an active production coal mine, it was not practical to shut off power to the mine or the survey area for even a short period of time. As a result, all measurements were made with electrical equipment in the survey area in an energized state. There were numerous sources of known and suspected E-field emission sources in the survey area including numerous control panels housing various electrical control systems including variable frequency drives (VFDs), an atmospheric monitoring system (AMS), an emergency communication and tracking system, and a very high frequency (VHF) related production leaky-feeder communications system. Given the limited time allowed to make measurements, it was decided to perform measurements near the most significant known source of emissions—the electrical panel housing the VFDs. Normally, separation distances are measured perpendicular to the face of a known emitter of emissions. However, due to the space constraints of the survey area, antennas were placed 1 and 3 m longitudinally from the face of the control panel housing the VFDs.

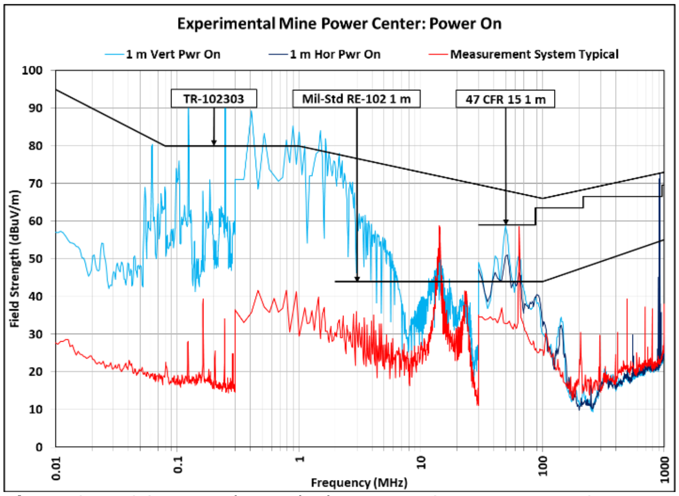

Figure 8. NIOSH Experimental Mine Power Center – Power On.

Similar to the NIOSH Experimental Mine's power center, from 10 kHz to 30 MHz, E-field electromagnetic emission levels near the control panel housing the VFDs were significant. For both 1 and 3-m separation distances, the emissions approached or exceeded MIL-STD-461G RE102 and TR-102303 limits. VFDs are known to be significant emitters of E-field emissions below 30 MHz, so high levels were not unexpected.

The elevated emissions above 30 MHz were a phenomenon of the measurement system itself. Emission levels below 30 MHz were high enough to cause input overload conditions on the spectrum analyzer when performing measurements above 30 MHz. To resolve the overload conditions, the configuration of the spectrum analyzer was modified as needed during the measurements which resulted in reductions of the system's sensitivity and increases of the system's noise floor. Once again, beyond the scope of this document, discussions on the impact of spectrum analyzer settings on sensitivity as well as general concepts of spectrum analysis are covered in [15].

The Eastern High-seam Coal Mine measurement results for 1 and 3 m are shown in Figures 9 and 10.

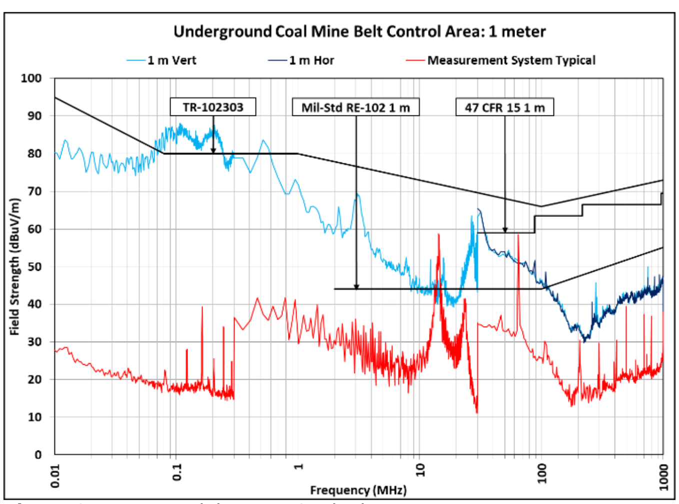

Figure 9. Eastern High-seam Coal Mine – 1 m.

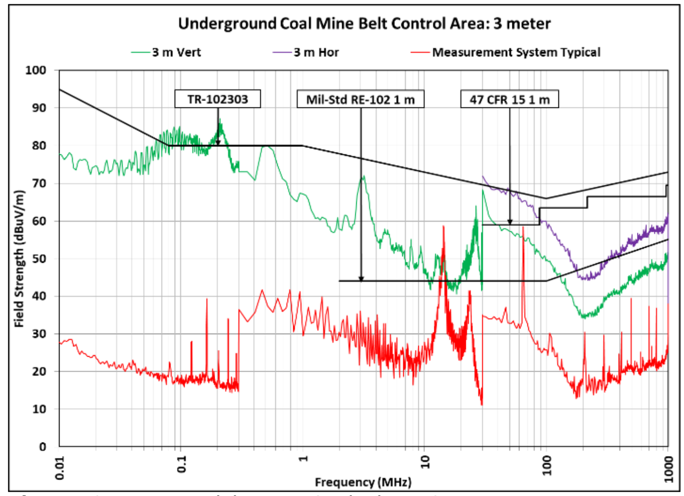

Figure 10. Eastern High-seam Coal Mine – 3 m.

SUMMARY

There are currently no regulatory requirements, standards, or guidelines for electromagnetic compatibility of electronic devices and systems deployed in underground mines. This could result in devices or systems malfunctioning as a result of EMI. In order to understand typical E-field electromagnetic emissions in underground coal mines, a measurement method and a portable measurement system were developed to survey emissions in different mining environments. Sample survey results are presented in this report. This study has revealed E-field electromagnetic emissions in underground coal mines can approach or exceed EPRI TR-102303 guidelines and MIL-STD-461G RE102 limits. Due to the absence of regulatory requirements, standards, or guidelines, it is unknown if such emission levels could pose a threat to the electromagnetic compatibility of electronic devices and systems deployed in underground mines.

This study also demonstrated the challenges in measuring E-field emissions in underground mining environments. Admittedly, the contribution of spectrum analyzer emissions to site survey area composite emissions had a much greater impact on the ability to interpret data than originally anticipated. Mitigation methods are being explored to significantly reduce, if not eliminate, this problem. Initial experiments of placing the spectrum analyzer inside a portable shielded enclosure while making measurements show great promise. In addition, an antenna has been identified for use in the 30 MHz to 200 MHz frequency span which will smooth the usual "hump" in this region. These changes will allow for improved, and more easily evaluated, measurement data.

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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 (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company name or product does not constitute endorsement by NIOSH.

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